Wider Application of Additions in Self-compacting Concrete

A thesis submitted to University College London

for the degree of Doctor of Philosophy

By

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Miao Liu confirms that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

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Abstract

Compared to normally vibrated concrete (NVC), self-compacting concrete (SCC) possesses enhanced qualities and improves productivity and working conditions due to the elimination of compaction. SCC generally has a higher powder content than NVC and thus it is necessary to replace some of the cement by additions to achieve an economical and durable concrete.

The established benefits of using low volumes of fly ash in SCC, high volumes of fly ash in NVC and the search for uses of waste glass led to the research on the possibilities of use higher fly ash contents than hitherto and ground glass as an addition in SCC whilst maintaining satisfactory properties.

Mix design methods, tests, target properties and constituent materials were selected. This was followed by investigating the influence of fly ash and ground glass on the mortar fraction of the SCC and then using these results to produce concrete mixes with the target fresh properties. Hardened concrete of these mixes were measured and the relationships between these investigated.

The results show that for constant filling ability of the SCC, replacement of cement with fly ash or ground glass requires an increase in water/powder ratio and a reduction in superplasticiser dosage. Both additions degraded the passing ability, consistence retention and hardened properties but not to a prohibitive extent. SCC with up 80% cement replaced by fly ash or glass volume ratio of 6.4% is possible and the material properties of SCC are similar to those of NVC.

Also the UCL method of mix design was extended to higher coarse aggregate contents and different additions.

The project can lead to the use of higher volume fly ash and ground glass in SCC, thus widening the types of additions available for SCC, saving landfill and reduce CO_2 emissions by the use of less cement.

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Glossary of Terms

The following terms are applied in this project.

Addition: ‘Finely divided material used in concrete in order to improve certain properties or to achieve certain properties, including two types: nearly inert additions (Type I) and pozzolanic or latent hydraulic additions’ (Type II) as defined by British Standard (BS EN 206 - 1, 2000).

Admixture: ‘Material added in small quantities during the mixing progress to modify the properties of the mixture’ as defined by British Standard (BS EN 934-2, 2001).

Alkali-silica reaction (ASR): An adverse chemical reaction that occurs in concrete, between certain aggregates containing a high proportion of reactive silica and alkali coming from cement when there is a supply of water (Neville, 1996): the reactive silica reacts with the hydroxyl ions in concrete pore solutions and produces a gel, which imbibes water and swells. This causes expansion and subsequent cracking, weakening the cement-aggregate bond.

Apparent viscosity: The viscosity of a non-Newtonian material at a particular shear rate, given by the slope of the straight line from the origin to the particular point.

Binder: The total amount of cement and Type II addition.

Consistence retention: The period of duration of the fresh properties.

Embodied carbon (ECO_2): CO_2 released in the life time of a product, commonly including the period from the extraction of raw materials until the product leaves the factory gate, known as cradle to gate.

Filling ability: The ability to flow under its own weight and to completely fill the formwork.

Fine mortar: A fraction of concrete includes cement and particles less than 0.25 mm in fine aggregate, used in CBI mix design method.

Fluidity: The ease of flow of fresh concrete.

High-volume fly ash (HVFA) concrete: A concrete in which at least 50% cement is replaced by fly ash by volume.

GGBS: Ground granulated blast furnace slag which is a by-product from iron factory.

ITZ: Interfacial transition zone.

Mortar: A fraction of the concrete excluding coarse aggregate, composed of paste and sand.

Normally vibrated concrete (NVC): A concrete compacted by vibrating equipment to remove the entrapped air after placing.

Passing ability: The ability to flow through and around obstacles such as reinforcement and narrow spaces without blocking.

Paste: A fraction of the concrete excluding aggregates, composed of water, cement, powder and admixtures if there is.

Plastic viscosity: The resistance to flow for a material.

Powder: The materials of particle size smaller than 0.125 mm.

Pozzolana: A ‘siliceous or siliceous and aluminous material which in itself possesses little or no cementititous value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties’ (ASTM C 618, 2003).

Rheology: The ‘science of deformation and flow of matter’ (Tattersall and Banfill, 1983).

Robustness: The ability of SCC to retain its fresh property when the quality and quantity of constituent materials and the environmental conditions change.

Segregation resistance: The ability to remain homogeneous during and after transporting and placing.

Self-compacting concrete (SCC): ‘A concrete that is able to flow under its own weight and completely fill the formwork, while maintaining homogeneity even in the presence of congested reinforcement, and then consolidating without the need for vibrating compaction’ as defined by the Concrete Society and BRE (2005).

Slump flow: The mean diameter of the spread of fresh concrete in the slump flow test.

Thixotropy: ‘A decrease of apparent viscosity under shear stress, followed by gradual recovery when the stress is removed. The effect is time-dependent.’ (Barnes, 1997).

Viscosity-modifying agent (VMA): A type of admixture added to fresh concrete to improve segregation resistance and robustness.

W/B: Water to binder ratio.

W/C: Water to cement ratio.

W/P: Water to powder ratio.

Yield stress: The initial stress to flow.

Chapter 1 Introduction

This chapter introduces the development and application of self-compacting concrete (SCC), and then describes the background, aims and scope of this project; the thesis structure is also described.

1.1 Introduction to self-compacting concrete

In general, a newly placed concrete is compacted by vibrating equipment to remove the entrapped air, thus making it dense and homogeneous; this is referred to as normally vibrated concrete (NVC) in this thesis. Compaction is the key to producing good concrete with optimum strength and durability (The Concrete Society and BRE, 2005). However, in Japan in the early 1980's, because of the increasing reinforcement volumes with smaller bar diameters and a reduction in skilled construction workers, full compaction was difficult to obtain or judge, leading to poor quality concrete (Okamura and Ouchi, 1999).

Professor Okamura therefore proposed a concept for a design of concrete independent of the need for compaction. Ozawa and Maekawa produced the first prototype of SCC at the University of Tokyo in 1988 (Ozawa et al., 1989; RILEM TC 174 SCC, 2000).

Since that time SCC has gone from a laboratory novelty to practical applications all over the world. The increasing numbers of papers published every year that deal with all aspects of SCC, e.g. mix design, rheological and physical properties and applications in practice, indicate research on this technology is thriving.

Recommendations on the design and applications of SCC in construction have now been developed by many professional societies, including the American Concrete Institute (ACI), the American Society for Testing and Materials (ASTM), Center for Advanced Cement-Based Materials (ACBM), Precast Consulting Services (PCI) and Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages (RILEM) etc.

Symposiums and workshops on this topic have been organized by these societies and several test methods have been or are in the process of standardization.

1.1.1 Advantages and disadvantages of self-compacting concrete

Compared to NVC, SCC possesses enhanced qualities, and its use improves productivity and working conditions (De Schutter et al., 2008; The Concrete Society and BRE, 2005).

Because compaction is eliminated, the internal segregation between solid particles and the surrounding liquid is avoided which results in less porous transition zones between paste and aggregate and a more even colour of the concrete (RILEM TC 174 SCC, 2000). Improved strength, durability and finish of SCC can therefore be anticipated.

Very good finish effect is shown in Figure 1-1, a pure cement SCC placed in a steel mould, demoulded 24h after casting. The surface is so smooth and dense that it can reflect light.

Figure 1-1 Excellent finish of a neat cement SCC

For much concrete construction, the structural performance is improved by increasing reinforcement volumes, limiting cracking by using smaller bar diameters and using complex formwork, all of which increase the difficulty of compaction (Okamura and Ouchi, 2003a; RILEM TC 174 SCC, 2000). SCC meets the above developments by making casting homogeneous concrete in congested structures possible; it also improves efficiency and effectiveness on site by reducing the construction time and labour cost.

SCC also improves the workplace environment by reducing noise pollution and eliminating the health problems related to the use of vibration equipment such as ‘white fingers’ and deafness (RILEM TC 174 SCC, 2000). SCC is therefore called ‘the quiet revolution in concrete construction’ (The Concrete Society and BRE, 2005).

As a result, the precast concrete products industry has become the biggest user of SCC in Europe (Skarendahl, 2003).

SCC requires higher powder and admixture (particularly superplasticisers) contents than NVC and so the material cost is higher (The Concrete Society and BRE, 2005). It was reported that in most cases, the cost increase ranged from 20% to 60% compared to similar grade NVC (Nehdi et al., 2004; Ozawa, 2001). However, in very large structures, increased material cost by using SCC was outweighed by savings in labour costs and construction time (Billberg, 1999). The benefits of SCC were fully displayed in a composite sandwich system, which involves casting SCC and NVC in layers within the same structural elements (Okamura and Ouchi, 2003a; Ouchi, 2001; Ozawa, 2001).

The increased content of powder and admixture also leads to higher sensitivity (i.e. reduced robustness) of SCC to material variation than that of NVC; thus greater care with quality control is required (Walraven, 1998).

1.1.2 Definition and properties of self-compacting concrete

It is important at this stage to define SCC and its characteristics. Literally, self-compacting characteristics are related to the fresh properties. The definitions of SCC given in the literature vary, a most common one is that ‘a concrete that is able to flow under its own weight and completely fill the formwork, while maintaining homogeneity even in the presence of congested reinforcement, and then consolidating without the need for vibrating compaction' (The Concrete Society and BRE, 2005).

SCC has three essential fresh properties: filling ability, passing ability and segregation resistance (Testing-SCC, 2005; The Concrete Society and BRE, 2005). Filling ability is the characteristic of SCC to flow under its own weight and to completely fill the formwork. Passing ability is the characteristic of SCC to flow through and around obstacles such as reinforcement and narrow spaces without blocking. Segregation resistance is the characteristic of SCC to remain homogeneous during and after transporting and placing. It is passing ability that distinguishes SCC from other high consistence concrete (Domone, 2000).

Additional properties, such as robustness and consistence retention, are also important in applications of SCC. Robustness refers to the ability of SCC to retain its fresh property when the quality and quantity of constituent materials and the environmental conditions change. Consistence retention refers to the period of duration of the fresh properties.

A number of commonly used tests are subsequently described for evaluating the fresh properties. There is no difference in test methods for hardened properties (strength, stiffness, and durability etc.) between SCC and NVC.

Both fresh and hardened properties are key to the successful application of SCC. SCC therefore can be designed by fresh or hardened requirements.

1.2 Background of the project

To ensure its high filling ability, flow without blockage and to maintain homogeneity, SCC requires a reduction in coarse aggregate content and hence a high cement content which can increase cost and also cause temperature rise during hydration as well as possibly affect other properties such as creep and shrinkage. Therefore significant quantities of additions are often incorporated to replace some of the cement, to enhance the fresh properties and reduce heat generation. There is the potential for extending both the quantity and type of additions and the study of two of these, fly ash and ground glass is the subject of the research reported in this thesis.

The use of fly ash in concrete is well established and widespread; it is not only economical but also improves the fresh and hardened properties of the concrete. It also helps to solve the problem of storage and disposal of the ash. Typical usage is about 15~30% replacement of cement. High-volume fly ash (HVFA) concrete, with more than 50% cement replaced by fly ash, developed by Canadian Centre for Mineral and Energy Technology (CANMET) in 1985, is attractive for environmental and sustainability reasons.

When used in SCC, fly ash helps to maintain the viscosity of concrete, reduces the risk of blocking and decreases the amount of superplasticiser required to achieve similar fresh properties. In order to extend the concept of HVFA concrete to SCC, high-volume fly ash SCC (HVFA SCC), in which at least 40% cement is replaced by fly ash by mass, has been studied because of its sustainability and reduced cost. Some investigations have been made on SCC incorporating up to 60% fly ash but there has been little systematic work on SCC with higher fly ash content to date and little information is available on their hardened properties.

Due to the large quantities of waste glass disposed every year, how to reuse it to prevent environmental problems becomes a pressing research topic.

Crushed or ground glass, ranging from powder to coarse aggregate, has been used in concrete for many years. Compared with natural aggregate, glass aggregate is hard but brittle; it has angular particle shapes, a relatively smoother surface, higher friability and poorer shape; and it does not absorb water. Therefore, the fluidity and strength of concrete using glass aggregate decrease with an increase in the glass aggregate content. It is also low in water absorption and shrinkage, and high in resistance to abrasion.

Glass powder has been used as a cement replacement material or filler in concrete. Glass contains high silica and is X-ray amorphous; it is a potential pozzolana. Its pozzolanic reactivity depends on the size of the particles; the dividing size between cementitious and inert materials varies in different research. The fluidity of concrete in which cement is replaced by glass powder, decreases with an increase in glass content because of its angular shape. Strength of concrete with glass powder, which depends on the size and content of glass, is comparable to or better than the concrete without glass. The drying shrinkage of concrete with glass powder is higher and decreases with an increase in the fineness of the glass. In addition, the colour of glass does not have significant effect on fluidity and strength of the concrete.

However using glass powder or aggregate is still not common at present because of the concern regarding alkali-silica reaction (ASR). Silica rich glass may react with the alkali in the pore solution of concrete and leads to potential durability problems. The expansion could be reduced by using pozzolanic materials such as silica fume, metakaolin, fly ash and ground granulated blast furnace slag (GGBS) which can reduce the alkali concentration in concrete. In addition, fine glass powder could suppress ASR expansion.

Replacing cement by glass powder in concrete turns out to be a higher value choice than glass aggregate, not only because it makes full use of its physical and chemical properties but also because it can replace cement which is more expensive than aggregate, thus offering greater economic and environmental advantages. It is anticipated that more superplasticiser will be needed to meet the fresh properties requirement of SCC with glass powder.

1.3 Aims and scope of the project

The objectives of my research are, for SCC produced with readily available constituent materials, to investigate the feasibility of using

- higher fly ash contents than hitherto whilst maintaining satisfactory properties
- ground glass as an addition

thus widening the quantity and the type of additions available to SCC producers and users.

The research comprised three stages:

1. Selection of mix design methods, tests, target properties and constituent materials;
2. Production of HVFA SCC and measurement of its fresh and hardened properties, including strength and durability; and
3. Determination of the extent to which ground glass can be used in SCC.

In the first stage it was necessary to select and develop appropriate mix design and production procedures. This made use of the approach used previously at UCL and elsewhere of first carrying out tests on the mortar fraction to determine appropriate combinations of cement, additions, water and admixtures before moving on to concrete trial mixes. Concrete tests were thereby minimised.

The aim of stage 2 was to produce SCC mixes incorporating levels up to 80% cement replacement by fly ash with all mixes having the same fresh properties. The hardened properties of these mixes were then investigated, included measurement of compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), dynamic elastic modulus (Ed) and sorptivity.

To my knowledge, no other work has been done on the application of ground glass in SCC. It was necessary in mix design and development to recognize the differences between glass powder and cement. For example, the near-zero water absorption of glass leads to no shrinkage and improvement in the mix rheology. Due to its angular shape, the water requirement to maintain the same filling ability was anticipated to be higher than with cement alone. Also, since glass is brittle, there may be some reduction in strength.

The aim was to produce SCC mixes incorporating some ground glass with all mixes having the same fresh properties. Sorptivity, compressive and tensile strength, UPV and Ed of SCC mixes with satisfactory fresh properties were measured and compared. ASR tests were performed on the mortar to ensure the safe use of glass in SCC.

1.4 Thesis structure

Chapter 2 reviews and summarises the relevant literature on the fresh and hardened properties, testing methods, criteria, constituent materials and mix designs of SCC. A detailed review of fly ash and glass powder as additions to concrete and SCC is demonstrated.

Chapter 3 includes conclusions from literature review of direct relevance to this project, the overall objective of the project and the stages and scope of the test programme planned.

Chapter 4 demonstrates the mixing procedures, test methods for the fresh paste, mortar and concrete and hardened concrete and methods of data evaluation.

Chapter 5 describes and discusses all the constituent materials used in the research. Water, aggregate, cement, fly ash and ground glass were selected due to their locality, convenience, availability and consistent supply. A single superplasticiser was chosen for the remainder of the research by comparing eight superplasticisers' influences on mortar. The performance of four superplasticiser/VMA combinations was also assessed.

Chapter 6 compares and discusses three mix design methods. This leads to selection of UCL method, which has the advantages of being simple and efficient; using clearer correlations between the properties of mortar and SCC and being suitable for local materials.

In Chapter 7 and Chapter 8 the studies of SCC with increasing levels of fly ash and ground glass respectively are demonstrated and discussed. Tests on mortar were first carried out to assess the effects on spread and V-funnel time which then led to a set of concrete mixes with similar target fresh properties. These mixes were then tested for compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), dynamic elastic modulus (Ed) at ages from 7 to

180 days and water absorption up to 500 hours. Alkali-silica reaction (ASR) tests were performed on the mortar mixes with glass.

In Chapter 9, the whole set of test results are combined and analysed. Some correlations found throughout the project are demonstrated and discussed. This follows by conclusions for the whole project and suggestions for further work in Chapter 10.

Chapter 2 Literature Review

The widespread research and development of SCC in the past two decades has led to a substantial and increasing number of publications of all types. In this chapter those considered most relevant to the current study are reviewed and summarised here.

A brief introduction to the fresh and hardened properties is followed by a discussion of test methods, constituent materials and mix designs. A detailed review of fly ash and glass powder as additions to concrete and SCC is demonstrated. Because this project focuses on laboratory experiments, concrete production and site practice are only briefly mentioned.

2.1 Properties of self-compacting concrete

This section introduces the fresh properties of SCC and the principles of how these are achieved. The mechanical properties and durability are then also briefly reviewed.

2.1.1 Categories

SCC is often classified as one of three types, powder, VMA or combined type, depending on the method of providing viscosity (Dehn et al., 2000; Holschemacher and Klug, 2002; Nawa et al., 1998).

- Powder-type SCC is characterized by a low W/P ratio and a high powder content, which are required to limit the free water content and increase the plastic viscosity.

  This was the first prototype of SCC generated. The key to success is to increase the powder content while decreasing the W/P ratio and use a superplasticiser to provide consistence. Because of the high powder content, powder-type SCC mixes are sensitive to changes in constituent materials. Usually additions are used to replace cement to control strength and heat of hydration. Due to the low W/P ratio, such concretes are anticipated to have a high strength and shrinkage, and low permeability.

Attention should be paid to the interactions of superplasticisers and powders.

- VMA-type SCC is characterized by a high viscosity modifying agent (VMA) dosage, which is added primarily for increasing the plastic viscosity.

  Compared with powder-type SCC, VMA-type is higher in superplasticiser dosage or W/P ratio to obtain the required filling ability. Powder content is less because viscosity is controlled by the addition of VMA.

  Attention should be paid to the compatibility between superplasticisers and VMAs.

- Combined-type SCC is developed to improve the robustness of powder-type SCC by adding a small amount of VMA. In such mixes, the VMA contents are less than those in the VMA-type SCC; the powder content and W/P ratio are less than those in the powder-type SCC. Viscosity is provided by the VMA along with powder.

  This type of SCC was reported to have high filling ability, high segregation resistance and improved robustness (Khayat and Guizani, 1997). Attention should be paid to the compatibility between superplasticisers, VMAs and powders.

However, since there is no distinct division among the above three types, SCC is more conveniently divided into two kinds: with or without VMA.

2.1.1.1 Typical mix proportions

SCC has the same constituent materials as those for NVC but their relative proportions differ and need to be carefully selected. Generally speaking, a lower coarse aggregate content and higher amounts of additions and cement, and admixtures (particularly superplasticisers) are required to achieve self-compacting properties.

This can be seen from the mix proportions of a typical mid-range NVC, (C40 and 75 mm slump, designed according to the BRE method (1997) for 20 mm uncrushed coarse aggregate) and the ranges for SCC shown in Table 2-1. The mix design is shown in Appendix 1.

Table 2-1 Mix proportion of a NVC and typical ranges of SCC

	NVC (C40, 75 mm slump)	SCC (Domone, 2006b; The Concrete Society and BRE, 2005)
Coarse aggregate/concrete (%) by vol.	42	28.0 – 38.6
Water/powder (by wt.)	0.55	0.26 – 0.48
Paste/concrete (%) by vol.	32	30.4 – 41.5
Powder content (kg/m^3)	375	385 – 635
Sand/mortar (%) by vol.	44	38.1 – 52.9

As shown, the coarse aggregate and W/P ratio of NVC are significantly higher than those of SCC, the powder content is less, and the paste volume and sand/mortar volume ratio are within the SCC range.

2.1.2 Fresh properties

SCC has the characteristics of filling ability, passing ability, segregation resistance, robustness and consistence retention (refer to 1.1.2) and these characteristics should remain during transport and placing.

- Filling ability reflects the deformability of SCC, i.e. the ability of fresh concrete to change its shape under its own weight (Khayat, 1999b; Okamura and Ozawa, 1995). Deformability includes two aspects: the deformation capacity is the maximum ability to deform, that is, how far concrete can flow; and deformation velocity refers to the time taken for the concrete to finish flowing, that is, how fast concrete can flow. Filling ability is a balance between deformation capacity and deformation velocity. For example, a concrete with high deformation capacity and very low deformation velocity tended to be very viscous and would take long time to fill the formwork (RILEM TC 174 SCC, 2000).

- Passing ability is unique to SCC. It determines how well the mix can flow through confined and constricted spaces and narrow openings, which ensures its particular applications in densely reinforced structures such as bridge decks, abutments, tunnel linings or tubing segments. It depends on the risk of blocking which results from the interaction between constituent materials and obstacles.

- Segregation resistance is sometimes called ‘stability’. Since SCC is composed of materials of different sizes and specific gravities, it is susceptible to segregation. Segregation includes that between water and solid or between paste and aggregate or between mortar and coarse aggregate in both stationary and flowing states (RILEM TC 174 SCC, 2000).

The above three key properties are to some extent related and inter-dependent. A change in one property will normally result in a change in one or both of the others. Both poor filling ability and segregation can cause insufficient passing ability, i.e. blocking. Risks of segregation increase as filling ability increases. SCC is actually a trade-off between filling ability and segregation resistance as shown in Figure 2-1.

SCC is ‘a very broad group of concretes with a wide range of properties’ and can be adjusted to suit different applications. For example, the filling ability of SCC used in sloping ramps was lower than that for trench footings; the required passing ability of SCC depended on the bar spacing; the requirement for segregation resistance would vary with transport and placing methods (The Concrete Society and BRE, 2005).

The fresh properties of SCC are influenced by the variation in the fineness and moisture content of the aggregates, different batches of superplasticiser or cement and changes in the environmental conditions such as temperature and humidity etc. SCC should have some tolerance to such changes.

- Robustness is the ability of the concrete to maintain its properties with such variations. The fewer changes in the properties, the more robust SCC is.

- Consistence retention is sometimes called 'open time' during which SCC retains its properties, which is important for transportation and placing, particularly of in-situ concrete.

The mechanism of achieving the required properties of SCC is, summarised in Figure 2-1.

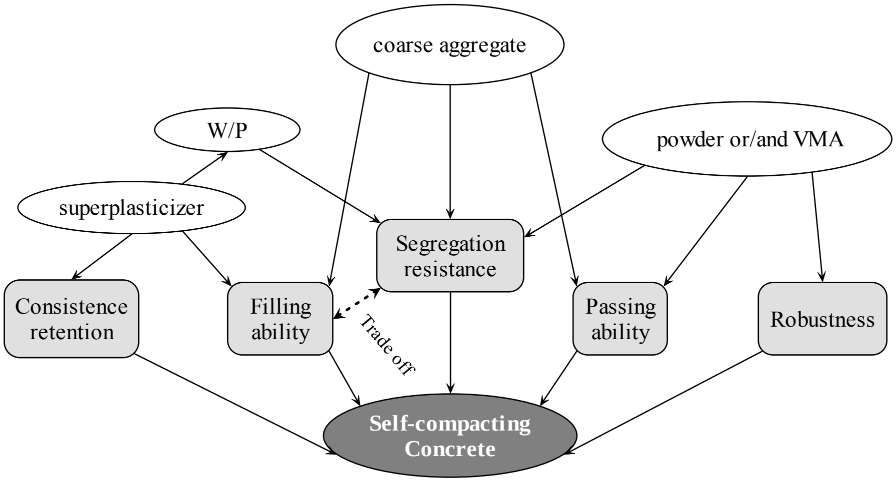

Figure 2-1 Schematic of ways to achieve SCC

2.1.2.1 Filling ability

SCC must flow into the intended area without segregation. To achieve a high filling ability (refer to 1.1.2), it is necessary to reduce inter-particle friction among solid particles (coarse aggregate, sand and powder) in concrete by using a superplasticiser and a lower coarse aggregate content (Khayat, 1999b; Sonebi and Bartos, 2002) as shown in Figure 2-1.

Adding more water could improve filling ability by decreasing inter-particle friction, but it also reduces viscosity, thus leading to segregation. Too much water also leads to undesirable influences on strength and durability. That is, too small and too large W/P ratios both result in poor filling ability.

Unlike water addition, which reduces both the yield stress and viscosity, the incorporation of a superplasticiser not only reduces the inter-particle friction by dispersing cement particles but also maintains the deformation capacity and viscosity. It also imparts less effect on hardened properties than water.

Particle size distribution also affects filling ability. Inter-particle friction can be reduced by using continuously graded materials, aggregates and powder (Khayat, 1999b; Sonebi et al., 2001).

2.1.2.2 Passing ability

When SCC is placed in structures with congested reinforcement, it must pass smoothly between the bars without blocking. Blocking results from the interaction among aggregate particles and between aggregate particles and reinforcement. When concrete approaches a narrow space, the different flowing velocities of the mortar and coarse aggregate lead to a locally increased content of coarse aggregate (Noguchi et al., 1999; Okamura and Ouchi, 2003b). Some aggregates may bridge or arch at small openings which block the rest of the concrete, as shown in Figure 2-2 adapted from RILEM TC 174 SCC (2000).

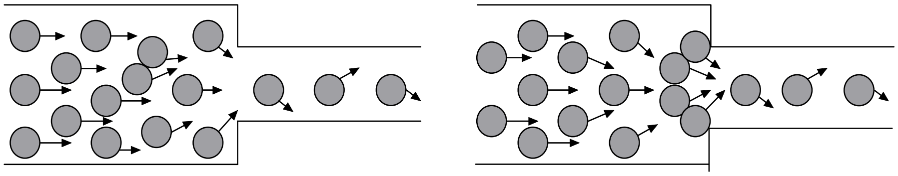

Figure 2-2 Schematic of blocking (RILEM TC 174 SCC, 2000)

Therefore blocking mainly depends on the size, shape and content of coarse aggregate (Okamura, 1997). A reduction in coarse aggregate content and lowering the size are both effective in inhibiting blocking. Paste volume of the concrete is also an important factor on blocking (Billberg et al., 2004). Another conclusion of Billberg et al. is that blocking depends mainly on the yield stress, whereas plastic viscosity does not influence the passing ability of SCC.

However, a paste with sufficient viscosity also prevents local increases in coarse aggregate and hence blocking is avoided. By incorporating powders such as fly ash, GGBS and limestone powder, viscosity increases because of better distribution and particle packing (Edamatsu et al., 1999). Another way to ensure sufficient viscosity is the use of VMA (refer to 2.4.1.2).

As shown in Figure 2-1, passing ability is therefore achieved by a reduction in coarse aggregate size and content and use of VMA or proper selection of powder.

2.1.2.3 Segregation resistance

Free water, which cannot attach to the solid particles and moves freely in the concrete, is the main influence on segregation (Ozawa et al., 1990). Segregation which happens during placing is called dynamic segregation. After placing, if coarse aggregate settles and the free water rises causing bleeding, this is called static segregation. Bleeding water reaches the concrete surface or is trapped under obstacles such as coarse aggregate and reinforcement bars which weakens the interfacial zone and results in impaired strength and durability.

As shown in Figure 2-1, enhancement of segregation resistance includes binding extra free water by lower W/P ratio, use of VMA or a high volume of powder, hence providing proper viscosity to ensure homogeneous flow. Limiting the size and content of coarse aggregate are also effective in inhibiting segregation.

2.1.2.4 Robustness

Since its three fresh properties are essentially incompatible and SCC is made with high admixture and powder contents, it is less tolerant of material and proportion variations than NVC. Among these, the influences of variations in the moisture content of aggregate and superplasticiser dosage can be significant (Billberg, 1999; Embrorg and Hedin, 1999).

Robustness is improved by the proper selection of powder and the use of VMA to increase the viscosity. The effect of the incorporation of VMA on the improved robustness of SCC to water content change is shown in Figure 2-3 adapted from The Concrete Society and BRE (2005). It can be seen that the gradients of all mixes without VMA are steeper than those with VMA. The average of change in slump flow (refer to 2.2.3.1) with an increase in water content from 0 to 10 kg/m^3 is about 36 mm and 69 mm for SCC with and without VMA respectively. The improvement on robustness depends on the nature of VMA (refer to 2.4.1.2).

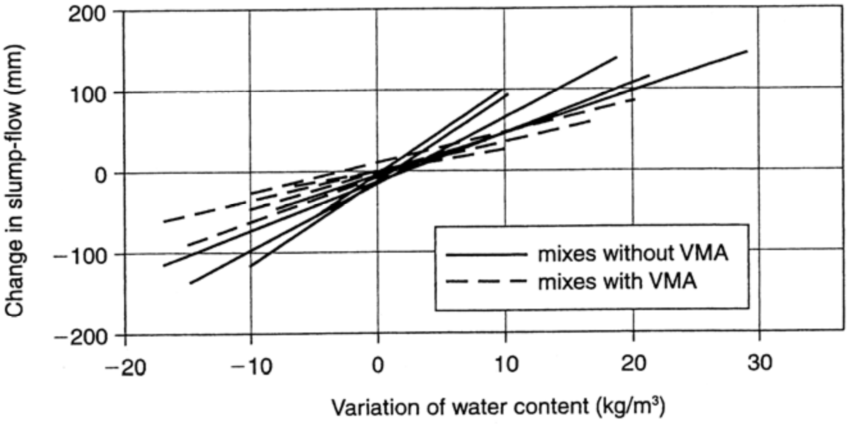

Figure 2-3 Effect of variations in water content on the slump flow of powder and VMA-type SCC (The Concrete Society and BRE, 2005)

A robust SCC can accept 5~10 litre/m^3 change in water content and still maintain its required properties (SCC European Project Group, 2005). Therefore, variations of water and superplasticiser content can be used to test robustness.

2.1.2.5 Consistence retention

During transporting and placing, the fresh properties of SCC after mixing should be maintained close to their initial level, usually for 60~90 minutes (Kasemchaisiri and Tangermsirikul, 2008; RILEM TC 174 SCC, 2000; Sonebi and Bartos, 2000).

Consistence loss mainly results from the powder-superplasticiser interaction due to different effects of powder on the adsorption of water and admixtures (Khayat, 1999b) and the lower adsorption of superplasticisers on the hydrated phases of cement (Uchikawa et al., 1995). The polycarboxylate-type superplasticiser can provide a higher consistence retention (Hanehara and Yamada, 1999). In addition, the composition of cement and additions, the formation and coagulation of cement hydrates (Bonen and Sarkar, 1995), the

W/P ratio and the chemical structure of the superplasticiser also affect the consistence retention (Felekoglu and Sarikahya, 2007; Yamada et al., 2000). The influences of constituent materials on consistence retention are discussed in more detail in 2.4 below.

2.1.2.6 Rheology and fresh concrete

Fresh concrete is a complex, multi-phase system with time-dependent properties in a non-linear manner. It has been studied through rheology for many years which is also crucial for the development of SCC. Rheology and the links to fresh properties are reviewed in this section.

Rheology is 'the science of deformation and flow of matter' (Tattersall and Banfill, 1983). Yield stress, plastic viscosity and thixotropy are important rheological terms to analyse fresh concrete. For flowing materials, the common models are sketched out in Figure 2-4.

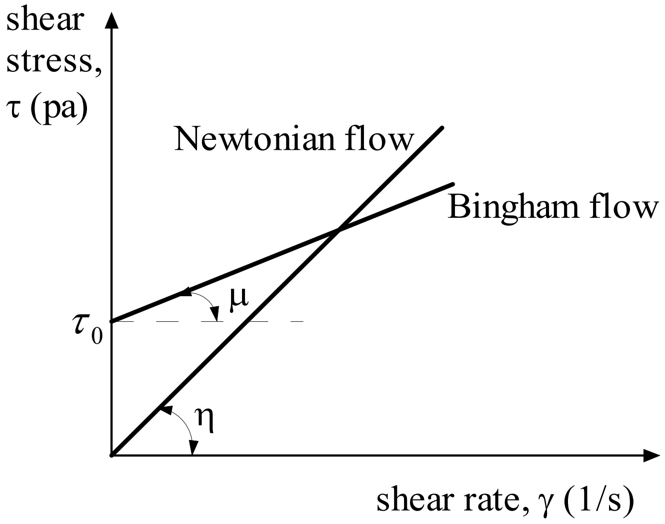

Figure 2-4 Newtonian and Bingham flow models

Newtonian liquids, such as water and oil, show a linear relationship between shear stress (τ) and shear rate (γ) shown in Figure 2-4 as

$$\tau = \eta\gamma$$

where η is the coefficient of viscosity.

The Bingham model applies to fresh concrete, which can resist stresses lower than the yield stress without flowing but at higher stresses a linear relationship exists between shear stress and shear rate shown in Figure 2-4 as

$$\tau = \tau_0 + \gamma.\mu$$

where τ , τ_0 and μ are shear stress, yield stress and plastic viscosity respectively.

The characteristic values of Bingham fluid are the yield stress (τ_0) and plastic viscosity (μ). Figure 2-4 shows that yield stress (the initial stress to flow) is the intercept on the shear stress axis. Plastic viscosity is the slope angle of the shear stress vs. shear rate relationship. Concrete starts to flow only when the shear stress exceeds the yield stress (τ_0). The plastic viscosity makes the flow stable once the yield stress is exceeded. Higher yield stress provides more resistance to start the flow whereas higher viscosity prevents the flow of concrete. It is therefore important to measure both yield stress and plastic viscosity to fully describe the behaviour of a fresh concrete.

Sometimes when fitting the Bingham model to the measured behaviour a negative value is obtained for the yield stress which means the mix does not follow this model. In this case, the flow can be better described by the Herschel-Bulkey model (Bui et al., 2002a; De Larrard et al., 1998; Tang et al., 2001) as

$$\tau = \tau_0 + a.\gamma^b$$

where τ_0 is the yield stress, a and b are constants, γ is the rate of shear strain.

This approximation involves three parameters τ_0 , a and b . However it is difficult to link them to empirical test results (Cauberg and Dieryck, 2005). Rheological tests on SCC showed that the paste can exhibit shear-thickening behaviour (Cyr et al., 2000). Other researchers suggested however that the apparent shear-thickening behaviour of SCC may result from the lack of steady state in testing procedures; so relaxation periods were considered (Geiker et al., 2002b).

Thixotropy is also an important rheological term to describe fresh concrete. Thixotropy is a 'decrease of apparent viscosity under shear stress, followed by gradual recovery when the stress is removed. The effect is time-dependent' (Barnes, 1997). Thus, after SCC is cast into the form, a structural build-up occurs and viscosity increases. The concrete, to some extent, supports its own weight which results in low pressure on formwork and a high casting rate (Koehler et al., 2005a). The thixotropic property reduces the risk of segregation after placing. It relates to formwork pressure which is not described in detail.

Rheologically speaking, SCC has a low yield stress and sufficient plastic viscosity to ensure a balance between its fresh properties. A low yield value is needed to improve deformation capacity, while viscosity is essential to maintain a homogeneous system during handling and placing until the start of hardening. Sufficient viscosity is required to ensure proper deformation velocity, passing ability and segregation resistance.

Rheological properties of SCC

Table 2-2 Bingham parameters of SCC in different countries (Wallevik, 2003)

Country	Yield stress (Pa)	Viscosity (Pa.s)	Country	Yield stress (Pa)	Viscosity (Pa.s)
Denmark	30~60	<40	Norway	10~50	30~45
France	0~10	>60	Sweden	0~30	50~100
Germany	0~10	60~90	Switzerland	0~50	10~20
Holland	0~10	60~120	U.K.	10~50	50~80
Iceland	10~50	20~40	U.S.A.	0~20	40~120
Japan	0~30	50~120			

Practice has varied with regard to the suitable rheological properties for SCC in different applications shown in Table 2-2 adapted from Wallevik (2003). On the whole, the yield stress of SCC is much lower (less than 60 Pa) than that of normal concrete (100~1000 Pa), but the plastic viscosity of SCC is of the same order as that of normal concrete, 20~200 Pa.s.

If the plastic viscosity is lower than 40 Pa.s, SCC should have a significant yield value to maintain sufficient homogeneity; if the plastic viscosity is higher than 70 Pa.s, the yield value must approach zero to achieve satisfactory filling ability, thus SCC is viscous but highly deformable (Wallevik, 2003).

Figure 2-5 adapted from Newman and Choo (2003) shows the effects of different materials on the rheological properties for concretes in general. Incorporation of superplasticisers decreases the yield stress dramatically but does not change the viscosity very much. At some point, superplasticisers increase the viscosity. Compared with superplasticisers, water decreases both the yield stress and the viscosity. The side effect of the change in water content in concrete is that it may result in segregation. Paste is another important factor on the Bingham parameters. Addition of paste will result in a decrease in yield stress and an increase in viscosity. Replacing cement with fly ash or GGBS leads to a decrease in the yield stress of concrete. Their effects on viscosity are different: fly ash reduces the viscosity while GGBS increases it. This may be due to the sphere particle shape of fly ash.

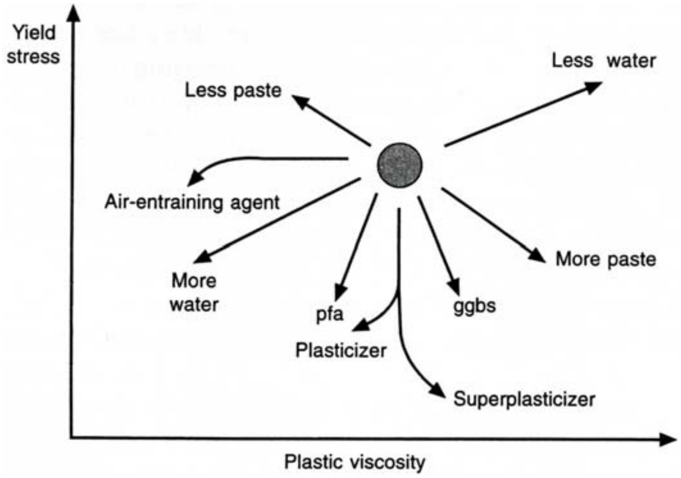

Figure 2-5 General effects of concrete constituents on the Bingham parameters (Newman and Choo, 2003)

The above effects are also applicable to SCC which is produced by the same constituent materials as general concretes. Figure 2-5 thus can be used for reference: to produce a SCC, a low yield stress can be achieved by adding superplasticiser, water, paste or some powders; viscosity can be controlled by changing the paste content or adding some powders. In addition, a VMA is generally used to achieve the required viscosity of SCC.

Therefore, SCC usually includes a larger amount of powder. Besides fly ash and GGBS, other powders commonly used in SCC (not shown in Figure 2-5) include silica fume and limestone powder. The effects of powder on the rheological properties are important to SCC, which however are not only different in values but contradictory in the published papers. Taking silica fume as an example, Carlsward (2003) reported that it increased the yield stress and the viscosity; Zhang and Han (2000) however had a completely contrary conclusion. These results show that the influence varies greatly with different types and quantities.

The effects of constituent materials of SCC are further discussed in 2.4.

Rheological relationships between SCC and corresponding matrix phase

Studies on the paste (Pedersen and Smelpass, 2003) or mortar (Jin, 2002) have shown that the rheological properties of the matrix are important to achieve the required fresh properties of SCC.

Due to the lower content of coarse aggregate in SCC, mortar exerts more effects on fresh SCC than on NVC. It not only provides lubrication by wrapping coarse aggregates and filling the voids among particles, it also possesses similar fresh properties to SCC; that is, a low yield stress and proper viscosity to ensure the required filling ability without blocking and segregation. Mortar is, thus an integral part of SCC mix design (refer to 2.5.1) and it has also formed a central part of Jin's research (Jin, 2002; Jin and Domone, 2002). Self-compacting mortar is a precondition of the successful production of SCC.

2.1.3 Hardened properties

Important engineering properties such as strength, dimensional changes and durability mainly depend on the pore system, such as the total surface area, the total pore volume, the pore size distribution and the pore connectivity (Neville, 1996).

Concrete is a complex system including a wide range of pore sizes and is a structure which changes with time. Numerous papers have been published concerning all aspects of the hardened properties of SCC, often in comparison with NVC. A brief review is summarised in this section.

2.1.3.1 Hydration

The same hydration mechanism governs SCC as that of NVC (RILEM TC 174 SCC, 2000). However a higher content of admixtures and powder materials may exert some influence on hydration development. For example, incorporation of limestone powder in SCC led to a shorter induction period, an increase in hydration reaction and the appearance of a third hydration peak (Poppe and Schutter, 2005). Fine powder particles acted like heterogeneous nucleation sites to accelerate hydration (Kadri and Duval, 2002). The setting time of SCC was reported to be twice as long as that of NVC due to the superplasticiser and fly ash used (Byun et al., 1998).

2.1.3.2 Microstructure

Since vibration makes water accumulate on the surfaces of coarse aggregate particles, NVC tends to contain a porous matrix and weak interfacial zones which result in inferiorities in hardened properties.

Elimination of the compacting process and incorporation of powders led to a denser cement matrix and improved interface between aggregates and paste (Petersson et al., 1998; Tragardh, 1999). For example, the difference in the interfacial transition zone between the top and bottom of a wall made from SCC was much lower than that made from NVC (Zhu et al., 2004).

2.1.3.3 Strength

Strength is one of the most important properties specified for concrete because it is a direct reflection of the capacity of the structure to resist forces and it is a reasonable indicator of other properties.

Cementing efficiency factor

For concrete in which cement is replaced by additions, the influence of the addition on strength varies with its properties and replacement levels. This can be expressed by a cementing efficiency factor (k) which converts the amount of additions to the equivalent amount of cement that would make the same contribution to strength (BS EN 206 - 1, 2000). The total equivalent cement content is then C + k F, where C and F are the content of cement and addition respectively. Thus the value of water to cement ratio (W/C) becomes W/(C+ k F) which is referred to as the equivalent W/C ratio, where W is the water content.

Table 2-3 Cement efficiency factor of concrete

	ADDITIONS	% binder	k	REFERENCE
NVC	Silica fume	5~15%	2.1~3.1 (28d)	(Wong and Razak, 2005)
			2.4~3.3 (180d)	
	Fly ash	15~ 40%	0.4	(Comite Euro-International du Beto, 1993)
		<25%	0.40[1]	(BS EN 206 - 1, 2000)
		15~ 75%	0.3 (7d)	(Babu and Rao, 1996)
			0.5 (28d)	
			0.6 (90d)	
	GGBS	10~80%	0.90 (28d)	(Ganesh Babu and Sree Rama Kumar, 2000)
SCC	Fly ash	20~ 60%	0.56 (28d)	(Domone, 2007)
	GGBS	37~ 44%	0.86 (28d)	
	Limestone powder	15~ 55%	0.29 (28d)	
	chalk powder	25~ 55%	0.23 (28d)	

Table 2-3 shows the cement efficiency factor for NVC and SCC from different investigations for concrete with CEM I Portland cement. As shown, it varies with different addition types and it increases with concrete ages but decreases

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[1] For with CEMI 42.5N cement and higher

with replacement levels. The differences of *k* between NVC and SCC incorporating GGBS and fly ash are not noticeable.

Table 2-3 also shows that the pozzolanic nature of different additions: silica fume is the most active, and then GGBS and fly ash; the reactivity of limestone and chalk powder is similar; fly ash shows significant increase with the curing time while limestone powder does not vary much.

In addition, the contributions of additions were also dependent on the W/C ratio, cement type and addition quality (Bijen and van Selst, 1993).

Compressive strength

Where the W/P ratios are similar, the compressive strength and the strength development of SCC are not significantly different from NVC. The strength development of SCC and NVC over a period of time is also similar (Dehn et al., 2000; Domone, 2007; Gibbs and Zhu, 1999; Holschemacher and Klug, 2002; Klug and Holschemacher, 2003; RILEM TC 174 SCC, 2000; Sonebi and Bartos, 2000).

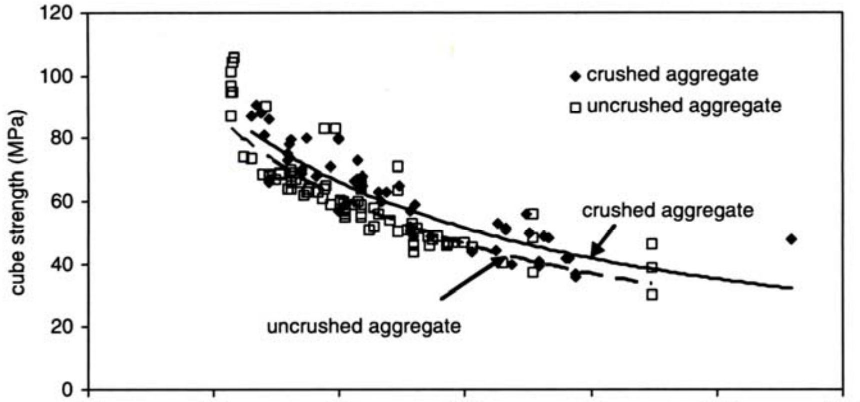


Figure 2-6 The relationship between the cube compressive strength and the equivalent water to cement ratio (Domone, 2007)

There is a good relationship between compressive cube strengths and the equivalent water to cement ratio of SCC shown in Figure 2-6 (Domone, 2007).

The difference in strength between SCC with crushed and uncrushed aggregate is 4 MPa which is half of the typical value (8MPa) assumed for NVC. The reasons given by Domone are the more homogeneous matrix and the less coarse aggregate used. The influence of the difference between aggregates on SCC is not therefore as decisively significant as with NVC.

The compressive strength of SCC at 28 days varied from 20 to 100 MPa depending on W/P ratio and powder composition (Domone, 2006b), which shows SCC could be used in various conditions.

Tensile strength

Where the W/P ratios are similar, the splitting tensile strength of SCC was higher than that of NVC (Holschemacher and Klug, 2002; Zhu et al., 2004); the tensile to compressive strength ratio of SCC was 10~30% higher than that of NVC (Gibbs and Zhu, 1999; Gram and Pentti, 1999). This probably results from the better microstructure of SCC.

2.1.3.4 Elastic modulus

Elastic modulus is used to calculate the elastic deflection, which is a controlling parameter in design of slabs, prestressed and post-tensioned structures.

The elastic modulus is the ratio between stress and strain. For concrete the stress-strain curve is non-linear, from which different elastic moduli can be determined. Static modulus (Es) is the slope of the tangent to the curve at a particukar stress while dynamic modulus (Ed) is the slope of the tangent to the curves at the origin. Es is usually 0.8~0.85 of Ed depending on the compressive strength and other factors (Illston and Domone, 2001).

It is known that the elastic modulus of concrete depends on the Young's moduli of the constituents and their volume ratio. It decreases with lower aggregate contents, or with higher cement contents or higher porosity.

Since the coarse aggregate content of SCC is less than NVC, the elastic modulus of SCC might be anticipated to be lower. This was confirmed by Dehn et al.

(2000). Holschemacher and Klug (2002) analysed their database and found that the elastic modulus of SCC could be 20% lower than that of NVC made of the same aggregate with the same strength. Another analysis based on a vast amount of literature showed that the elastic modulus of SCC was 40% lower than that of NVC at low cube compressive strength; but the difference reduced to less than 5% at higher strength (90~100 MPa) (Domone, 2007). Nevertheless, the difference was in the range of the CEB-FIB Model Code (Domone, 2007; Holschemacher and Klug, 2002).

2.1.3.5 Bond properties

The bond between reinforcement and concrete is important considering the wide application of reinforcement in concrete.

Inferior bond often results from bleeding or segregation of the concrete. Water and air rise and are trapped under the bars which lead to an uneven bond strength along the bars, which is called the top bar effect. Bond strength is, thus higher in the lower parts of a concrete element and decreases at higher levels.

For this reason, effective bond strength may improve the structural performance and protect the reinforcement from corrosion. Bond strength varies with the size, type and position of the bars.

Because of the improved homogeneity, the top bar effect was less distinctive in SCC (Domone, 2007; Holschemacher and Klug, 2002); the bond to steel of SCC was similar to (de Almeida Filho FM et al., 2005) or better than that of NVC (Chan et al., 2003; Collepardi et al., 2005; Dehn et al., 2000; Domone, 2007). The bond strength of SCC was 10~40% higher than that of NVC with the same strength grade 35 and 60 MPa for a bar diameter of 12 and 20 mm (Zhu et al., 2004).

2.1.3.6 Shrinkage and creep

Volume change, e.g. shrinkage, is important for concrete because it produces tensile stress within the concrete leading to adverse cracks which makes it possible for gas, water and harmful chemicals to penetrate into the concrete and cause further durability problems. Shrinkage was important for prestressed concrete because it relaxed the prestressing force, thus reducing structural capacity (Atis, 2003).

It is also a time-dependent deformation, including autogenous and drying shrinkage. Autogenous shrinkage occurs because the volume of the hydration products is less than that of water and cement. It depends on the W/C ratio and the age of the concrete, and increased if the W/C ratio is reduced; it was apparent when the W/C ratio is less than 0.38 (Persson, 1997). Drying shrinkage results from the loss of water from the cement paste into the atmosphere. Water held by capillary tension is one of the important factors influencing the drying shrinkage.

The use of a higher content of paste, powder and superplasticiser in SCC all may contribute to higher shrinkage and creep than in NVC. The drying shrinkage of SCC was found to be 10~50% higher than that of NVC (Holschemacher and Klug, 2002; Suksawang et al., 2006). However, it was reported that SCC's denser microstructure suppresses drying shrinkage (The Concrete Society and BRE, 2005), and lower shrinkage of SCC was reported (Bouzoubaa and Lachemi, 2001; Sonebi and Bartos, 2000). Application of limestone powder in SCC was found to reduce shrinkage (Bui and Montgomery, 1999a; Chopin et al., 2003). Other studies reported that the amount of shrinkage of SCC did not differ from that of NVC when the compressive strength was the same (Persson, 2001; Poppe and Schutter, 2003). The above contradictions may be the result of different experimental procedures, specimen sizes and material properties.

Creep is defined as the gradual increase in strain for a constant applied stress. It is also a time-dependent deformation. Creep takes place in the cement paste and is influenced by porosity which relates to the W/C ratio. As cement hydrates and porosity decreases, creep decreases. In addition, aggregates restrain the creep of paste. For this reason, a higher amount of aggregates and a higher elastic modulus of aggregates will lead to a reduced creep.

Persson (2001) confirmed that creep was influenced by cement paste porosity and reduces with an increase in strength in the same way for both SCC and NVC. The creep of SCC is anticipated to be higher than NVC due to its higher cement paste. However, no general statement about the creep of SCC can be given due to the lack of and contradictory nature of existing data (Holschemacher and Klug, 2002).

Nevertheless, the shrinkage and creep of SCC are influenced by the W/P ratio and curing methods in the same way as for NVC.

2.1.3.7 Durability

Durability is a general analysis of the service life and the performance of concrete in an aggressive environment. Physical damage to concrete includes wetting/drying, freeze/thaw or heating/cooling cycles. Chemical damage consists of sulphate attack, acid attack, chloride attack and alkali-silica reaction (ASR) in which water acts as a carrier. All are greatly related to the resistance of the cover layer to transport mechanisms such as permeation, absorption and diffusion of gas and liquid. Thus oxygen permeability, water sorptivity and chloride conductivity have often been defined as three durability indexes due to the simple and inexpensive test methods (Alexander and Magee, 1999).

A brief summary of water transport in concrete and other durability aspects of SCC are demonstrated as follows.

Sorption is the water movement driven by capillary action in short-term exposure in partially dry concrete. The rate of water uptake by a porous material is defined as sorptivity. It has been considered as an important criterion to assess the durability of concrete (Ho and Chirgwin, 1996). The pore system of the paste and the interfacial zone has a great influence on sorptivity. The interfacial zone is porous but it is the hardened paste, the only continuous phase in concrete, that controls the ingress and transportation of water (Sabir et al., 1998). Sorptivity of SCC was only 30~40% of those of NVC with the same strength grade C40 (Zhu and Bartos, 2003).

Diffusion is the water movement driven by a concentration gradient in long-term exposure. For example, the durability of concrete in the sea is largely determined by the diffusivity of the chloride solution entering and moving through the matrix. Chloride diffusivity depends on the tortuosity of the pores instead of the total porosity. Since fly ash particles made concrete dense, concrete incorporating fly ash was reported to have a lower chloride diffusivity (Zhu and Bartos, 2003). On the other hand, Tang et al (1999) reported a higher chloride diffusivity than NVC because of the poor dispersion of powders. It is interesting to note that the diffusivity of SCC with VMA is higher than NVC and powder-type SCC (Zhu and Bartos, 2003). This confirms that the powders used in SCC improve packing density leading to a denser structure. Diffusion and capillary action are the primary mechanisms of ingress of water. Diffusion was a very slow process and it accounted for about 30% of the overall water intake whereas sorption accounts for about 70% (Neithalath, 2006).

Capillary porosity has a very important influence on hardened properties and is useful for predicting the durability (Yaman et al., 2002). The capillary transport especially near concrete surface is the dominant invasion mechanism. An increase in the porosity of the cover concrete leads to more water and more dissolved chemical flowing through the surface, and thus, more durability problems. The relationships between water absorption and some durability such as the resistance of concrete to carbonation and chloride (De Schutter and Audenaert, 2004), freezing/thawing cycling and wet/dry cycles (Martys and Ferraris, 1997) were investigated. Capillary suction was influenced by the moisture state of the specimen, the ambient conditions, curing conditions and testing procedures (Hall, 1989).

Permeability is a process in which water is transported under a hydrostatic pressure differential. The main influences on permeation include the paste volume, the pore structure and the interfacial zone between the mortar and aggregates. The overall porosity of SCC was lower than that of NVC of equivalent strength because of the higher powder content, lower W/P ratio and improved microstructure (Tragardh, 1999; Zhu et al., 2004; Zhu and Bartos, 2003). Zhu and Bartos reported that the oxygen permeability for SCC was only 30~40% of that of NVC with the same strength grade C40.

Other investigations on durability between SCC and NVC include:

- SCC with limestone powder exhibited better internal frost resistance than NVC with the same W/C ratio and air content but there was little difference between SCC and NVC for salt (NaCl) and sulphate resistance (Persson, 2003).
- The tests (Al-Tamimi and Sonebi, 2003) of SCC with 47% carboniferous limestone powder (less than 100 μm) and a W/P ratio of 0.36, and a neat cement NVC with the same strength (W/P ratio of 0.46), immersed in a sulphuric and hydrochloric acid solution, showed that at 18 weeks, the mass loss due to sulphate attack of SCC was only half that of NVC in a sulphuric acid solution; but in a hydrochloric acid solution, SCC incurred about 2.2% more mass loss than NVC. The author concluded that SCC performed better than NVC in a sulphuric solution but was more susceptible to hydrochloric acid attack. This difference between SCC and NVC might be due to the difference in constituent materials: the higher cement content in NVC contributed more calcium hydroxide than in SCC; the lower W/P ratio used and the incorporation of limestone, which is finer than cement, both led to a denser matrix of SCC than NVC.
- SCC exhibited lower resistance to freeze-thaw than NVC (Zhu and Bartos, 2003).
- Few fire tests have been done on SCC. Cylinders with different mix proportions of strength up to 104 MPa of SCC were tested; slight spalling occurred for SCC; the degree of spalling also depended on the type of additions used (Vanwalleghem et al., 2003). SCC was more susceptible to spalling than NVC with the same strength grade (Bostrom, 2003; Noumowe et al., 2006). This may be attributed to the denser microstructure of SCC.

2.1.4 Conclusions

SCC flows under its own weight without segregation, and passes through restricted areas without blocking. This is clearly significantly different to NVC. The key properties of SCC are filling ability, passing ability and segregation resistance. Robustness and consistence retention are also important to the use of SCC.

SCC is not a new concrete, but rather a sophisticated and evolving technology. It requires a fundamental understanding of both the fresh and hardened properties, which vary in a wide range.

In comparison with NVC, SCC can only be achieved with the use of chemical admixtures and mineral additions. Fresh properties of SCC are obtained by properly adjusting the constituent materials. SCC is characterised by low yield stress and proper viscosity. These are obtained by using superplasticisers, reducing the volume of coarse aggregate, limiting free water content by either incorporating a high amount of powder and/or the addition of VMAs.

Nevertheless, because of elimination of compaction and lower W/P ratio, its performance is comparable or better than that of NVC. Any differences in the hardened properties and durability are largely within the normal range that might be anticipated for NVC. These differences are summarised as follows:

- Hydration, compressive strength and strength development of SCC and NVC do not differ significantly under comparable conditions.

- Splitting strength, fire spalling and elastic modulus of SCC and NVC are different.

- No consistent results are given for shrinkage and creep.

The reason for the difference in hardened properties and durability between NVC and SCC may lie in:

- Better microstructures and homogeneity of SCC

- Higher contents of superplasticisers, VMA or powder

Water movement, especially sorption near surface concrete is one of the most important properties for evaluating the durability of concrete.

Although there are some differences in hardened properties between SCC and NVC, those differences can be attributed to their different mix proportions. Most comparisons are made between SCC and NVC and based on the same strength. Since SCC can be designed from fresh-property requirements, it is necessary to infer its hardened properties and durability from fresh properties. Further research on the influence of fresh properties on hardened properties and durability might be useful.

2.2 Mixing procedure and test methods

An effective mixing procedure leads to a homogeneous mix, which is the precondition for reliable test results. It is important to carefully control the mixing procedures and test methods to obtain consistent results.

Suitable mixing procedures and test methods to assess SCC properties are discussed in this section.

2.2.1 Mixing procedure

Mixing procedures in this project refers to all the parameters during mixing, such as the type of mixer (2.2.1.1), the mixing temperature (2.2.1.2), the mixing duration (2.2.1.3), the relaxation time (2.2.1.4) and the introduction of the superplasticiser (2.2.1.5). All may affect the performance of SCC.

2.2.1.1 Mixer

The mixer is the key element in concrete production. Those commonly used in SCC are shown in Table 2-4 (Aarre and Domone, 2004; De Schutter et al., 2008; Deshpande and Olek, 2005; The SCC European Project Group, 2005). Among them, the forced action mixers are generally preferred.

Table 2-4 Mixers for SCC (Aarre and Domone, 2004; De Schutter et al., 2008; Deshpande and Olek, 2005; The SCC European Project Group, 2005)

Classification		Typical composition	Mixing efficiency order
Free-fall mixers (tilting drum, drum mixers or gravity mixers)		Mixer drum and mixing blades	3
Forced action mixers	Pan mixers	A vertical axis of rotation, cylindrical and horizontal pan (fixed or rotating), one or two sets of rotating blades	1
	Pug mill mixers	A horizontal drum, one or two rotating horizontal shafts with attached blades	2
M-Y mixer (mixing by using gravity)		A set of mixing units but with no moving parts, assembled into a stationary vertical column	

For SCC, the importance of a mixer is to provide uniform mixing and to fully disperse admixtures and additions. In general SCC needs intensive mixing since it has a high paste content and a viscous nature. The more intense the mixing is, the more effective the breakdown of the agglomeration which leads to a lower yield stress and plastic viscosity (Roy and Asaga, 1979). It is therefore anticipated that intensive mixing may decrease the superplasticiser requirements to maintain the same filling ability.

However, it has been reported that intensive mixing procedures led to more superplasticiser or less water for the concrete being needed to reach the same filling ability for the following reasons (Takada et al., 1998a; Takada et al., 1999):

- intensive mixing dispersed agglomerated particles more efficiently and tore off the initial hydration product from the binder surface, thus more superplasticiser was required to obtain the same slump flow;
- the pieces of hydration products acted as a lubricant, thus making concrete less viscous, thus less water was needed;
- intensive mixing led to a larger amount of air, which was small and might act as lubricant among aggregate particles, thus making concrete less viscous.

2.2.1.2 Mixing temperature

It is anticipated that the environment temperature at which concrete is mixed and tested affects its fresh properties. At a high ambient temperature, the consistence of SCC will be low due to the enhanced hydration of the cement, and vice-versa. The slump flow of a SCC with 20% fly ash (refer to Appendix 8) increased from 703 mm to 795 mm when the temperature increased from 17°C to 21°C. Thus the environmental conditions, e.g. temperature, should be kept constant. 20±2°C was recommended by a European project Testing-SCC (Aarre and Domone, 2004).

2.2.1.3 Mixing duration

Various mixing durations have been reported. Khayat et al (1999a) achieved an optimum mixing in a pan mixer in 4 minutes in total by first mixing the sand with parts of the water. Edamatsu et al (1999) chose a mixing time of 3 minutes in total, for a forced twin shaft mixer. Petterson (1998) used a longer mixing procedure of 6 minutes in total beginning with a dry processing with all materials except water.

In general, the mixing time for SCC is longer than that for NVC to ensure complete structural breakdown because of the difference in constituent materials (Chopin et al., 2004; Emborg, 2000). A mixing time exceeding 5 minutes was preferred (Pedersen and Smelpass, 2003).

2.2.1.4 Relaxation time

Cement particles exhibit structural breakdown or rebuilding of particles when a different shear rate is applied to a fresh cementitious system during the rheological tests (Tattersall and Banfill, 1983). That is, as the shear rate increases, cement particles are broken into small flocks; as the shear rate is reduced, flocks start to coagulate again, and the suspension reverts to its original structure.

The time taken to obtain a steady-state flow is referred to as relaxation time, which is the precondition for consistent and reliable test results. Lack of a steady state led to over-estimation of the viscosity and underestimation of the yield stress (Geiker et al., 2002a).

In general, relaxation time of SCC is longer than that of NVC due to its low W/P ratio (Geiker, 2003).

2.2.1.5 Introduction of superplasticiser

The introduction of superplastiziers into concrete has an influence on SCC's performance. Superplasticiser can be added at the end of the mixing, which leads to a more flowable mix; or it can be added with water during mixing; the two different methods lead to different values of spread and flow time (Schwartzentruber et al., 2006).

There are two ways of introducing superplasticisers. One is called "simultaneous addition", which means the superplasticiser is dissolved in all the mixing water and then mixed with other materials. This resulted in the superplasticiser having direct contact with the fresh cement (Takada et al., 1998b).

The second is referred to as "delayed or later addition", in which all the constituent materials except the superplasticiser are mixed with part of the total mixing water and then the superplasticiser is dissolved with the remaining water and added after a specified time; the cement had contact with water first and with the superplasticiser some time later (Aiad, 2003; Uchikawa et al., 1995).

Tests on melamine formaldehyde sulfonate (MFS) and naphthalene formaldehyde (NFS) in cement paste showed that the delayed method improved superplasticisers' efficiency compared to simultaneous addition (Aiad et al., 2002). This was confirmed by Schwartzentruber et al (2006).

Aiad (2003) reported an optimum delayed addition time of MFS and NFS of 10~15 minutes for Portland cement and sulphate-resisting cement.

Jin (2002) found that delayed addition of 2~4 minutes for a naphthalene- and melamine-based superplasticisers and 0~0.5 minutes for a polycarboxylate based superplasticisers produced mixes with higher filling ability and better consistence retention.

These effects of delayed addition may be due to the following reasons (Uchikawa et al., 1995): the amount of superplasticisers adsorbed in the delayed addition is smaller than that in the simultaneous method, so more free superplasticisers are available to improve consistence and consistence retention. The lower the amount of admixtures adsorbed by cement, the higher the filling ability as shown in Figure 2-24.

As a result, delayed addition of superplasticisers is a useful way to improve the consistence and the consistence retention or to decrease the W/C ratio. The results, however, depended on the type of superplasticiser: the effects were remarkable in the later addition of aminosulfonic acid-based and naphthalenesulfonic acid-based superplasticisers, while the difference between simultaneous and delayed addition methods was less noticeable in polycarboxylic acid-based and lignin sulfonic acid-based superplasticisers (Uchikawa et al., 1995).

2.2.2 Tests on fresh paste/mortar

Tests on the fresh paste or mortar phases of SCC have been used extensively for the selection of constituent materials and in mix design. The tests are described here and their uses discussed in 2.5.1.

2.2.2.1 Spread and V-funnel tests

The spread and the V-funnel tests have been widely used to design SCC (Okamura et al., 1993), to study the interactions between cement, admixtures and additions (Jacobs and Hunkeler, 1999; Lachemi et al., 2004b) and to choose suitable constituent materials (Domone, 2006a) for the following reasons:

- These two tests have a sound rheological basis: good correlations have been found between spread and yield stress, and between V-funnel time and plastic viscosity of mortars tested (shown in Figure 2-7 (Jin and Domone, 2002)).

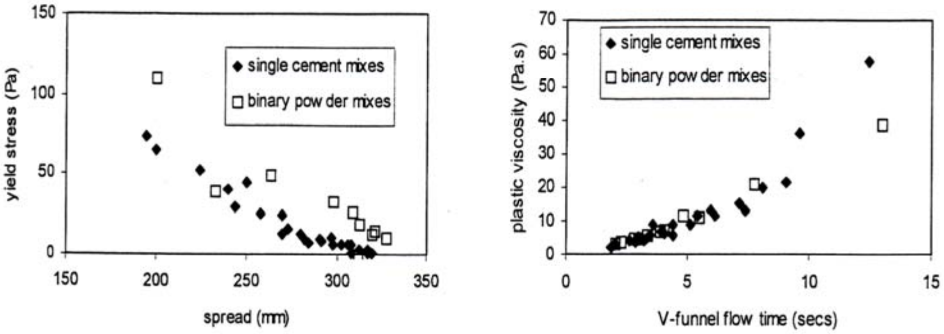


Figure 2-7 Relationships between yield stress and spread, between viscosity and V-funnel time of mortar (Jin and Domone, 2002)

- This agrees with published findings (Roy and Roussel, 2005; Schwartzentruber et al., 2006). Therefore the combined use of these tests will give an adequate analysis of the mortar rheology.

- Spread and V-funnel time also have good correlations with SCC filling ability (discussed further in 2.5.1.2).

- The mortar tests are simple and efficient, which needs far less sample size and are simpler to perform than concrete trials.

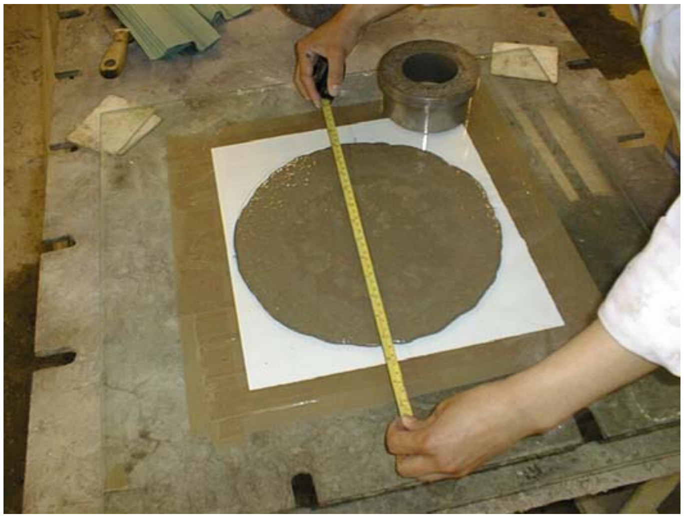


Figure 2-8 Spread test for mortar

Figure 2-9 V-funnel test for mortar

Figure 2-8 and Figure 2-9 show the apparatus for the spread and the V-funnel tests respectively, the sizes of which vary. The dimensions of those used in UCL and a more detailed test procedure are in 4.3.

Spread is the average of the diameters in two perpendicular directions of the deformed sample after mortar stops flowing. The V-funnel test is proposed to indicate the viscosity of the sample by recording the time from opening the gate until the first day light can be seen from the top.

The spread value and V-funnel time is converted into relative flow area (Ra) and relative velocity (Rv) respectively in the general-purpose mix design method (refer to 2.5.1) as

Relative flow area $$Ra = (\frac{F}{F_0})^2 - 1$$

Relative flow velocity $$Rv = \frac{10}{t}$$

where F, F_0, t, are the flow values of the sample calculated from the average of the diameters at two right-angle directions, the diameter of the flow cone base (100 mm) and the average time of the last two of three V-funnel times respectively.

Spread and the V-funnel tests can be performed on mortars and pastes. The relationship between Ra and Rv of a mortar has been used to design SCC (refer to 2.5.1.1). The relationship between Ra and W/P volume ratio was used to study the characteristics of the additions in concrete (Domone and Chai, 1997).

2.2.3 Tests on fresh self-compacting concrete

As discussed in 2.1.1, the major fresh properties of SCC are different from those of NVC and, thus tests for NVC are not suitable for SCC.

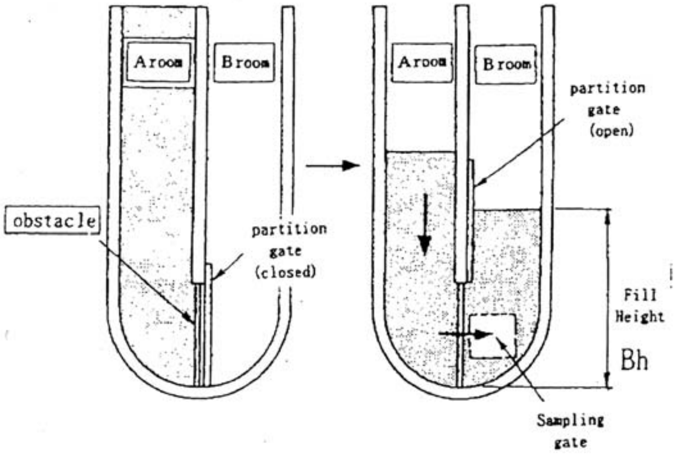


Figure 2-10 U test (Okamura et al., 1993)

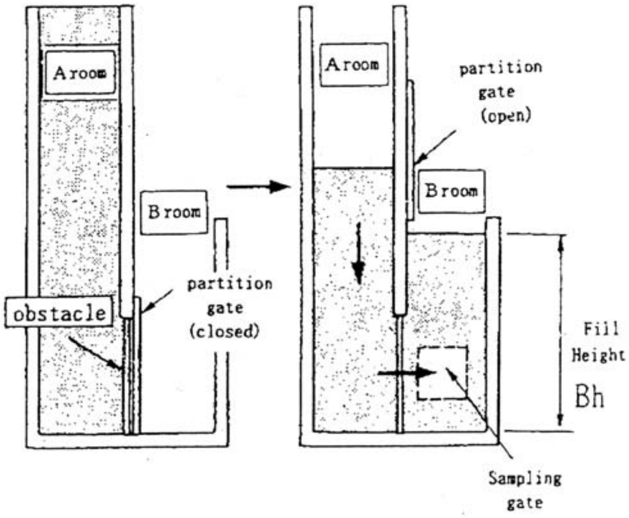


Figure 2-11 Box test (Ouchi, 1998; Pelova et al., 1998)

So far, many tests and apparatus for SCC have been proposed for evaluating the fresh properties. In the early development of SCC, the U-test shown in Figure 2-10 (Okamura et al., 1993) and its modified version the box-test shown in Figure 2-11 (Ouchi, 1998; Pelova et al., 1998) were used to evaluate SCC.

In these tests, concrete flows from the left compartment, through a gate made of three reinforcement bars and moves into the right compartment. The height of the concrete in the right part after the concrete stops flowing is the fill height. A fill height of over 300 mm was recommended as acceptable for SCC.

Box tests on concrete and the V-funnel tests on mortar were combined to evaluate SCC (Edamatsu et al., 1999). Fill height is related to both filling ability and passing ability of SCC. However, segregation was not measured.

The horizontal mesh test shown in Figure 2-12 (Ozawa et al., 1992a) and the fill box test shown in Figure 2-13 (Pelova et al., 1998; Takada et al., 1999) were designed to evaluate the deformability and segregation resistance of concrete. Concrete was poured into a formwork which contained meshes of reinforcement bars at the bottom (vertical mesh test) or many horizontal bars (fill box test), and then flowed through the meshes or the bars. The volume of concrete which passed through meshes in the vertical mesh test or the height differences of concrete in the fill box test was used to evaluate SCC.

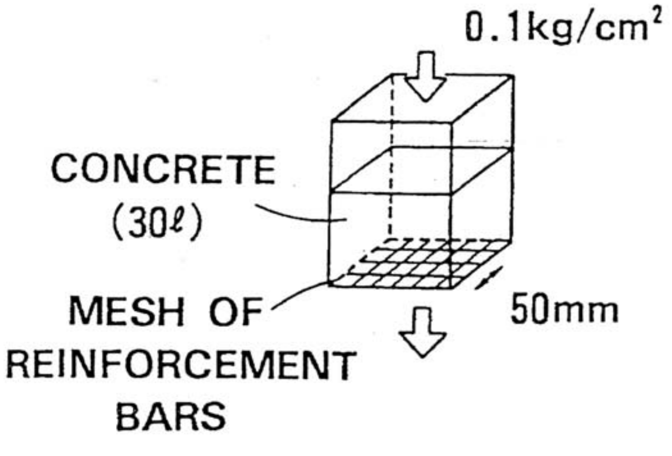
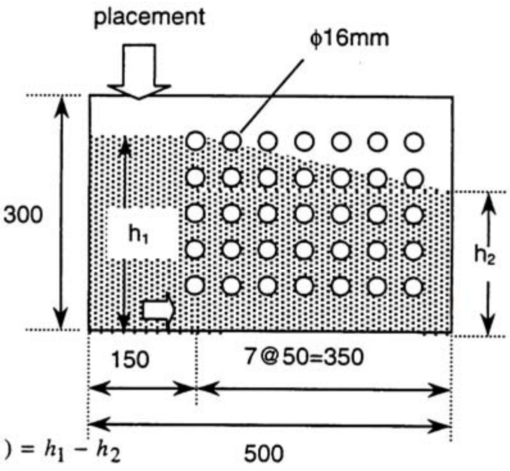


Figure 2-12 Vertical mesh test (Ozawa et al., 1992a)



$$\Delta h(mm) = h_1 - h_2$$

$$F(\%) = (h_1 + h_2) \times \frac{350}{2} / (h_1 \times 350) \times 100 = \frac{h_1 + h_2}{2h_1} \times 100$$

Figure 2-13 Fill box test (Pelova et al., 1998; Takada et al., 1999)

These tests are rather rigorous considering the number of meshes or bars in the formwork. Their final results are the compound effects of filling ability, passing ability and segregation of SCC.

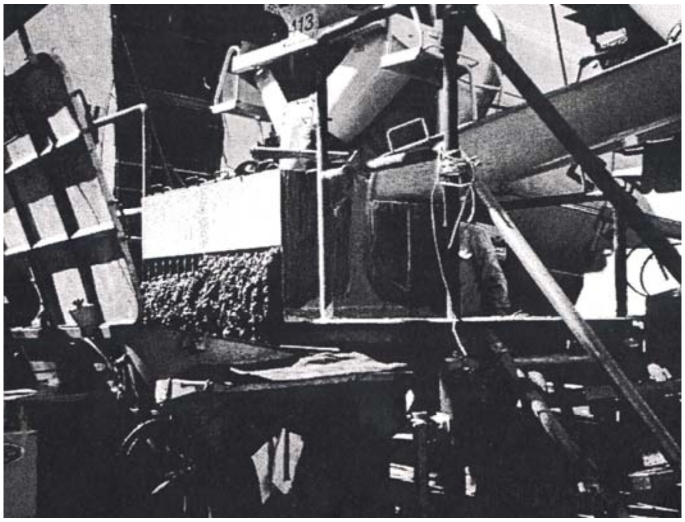


Figure 2-14 Acceptance test in situ (Ouchi, 1998)

The acceptance test as shown in Figure 2-14 (Ouchi, 1998) was set up in a construction site and designed to evaluate the overall fresh properties. Concrete was poured into the apparatus which contained many reinforcement bars. The concrete was regarded as SCC only if it flows through the apparatus. This test was used at the construction site of the LNG tank of Osaka Gas.

The acceptance test can be used to distinguish good and bad SCC. It, however, cannot provide a quantitative value to identify how good or bad a concrete is. As a result, it is less likely to be used to study and compare different SCCs.

It seems from above that, in the early development of SCC, a single universal test was tried to evaluate the overall performance or to differentiate good and bad mixes. This, as shown in 2.1.2, is impossible because SCC’s key properties are interrelated. A combination of several tests are commonly used nowadays, each of which aims to evaluate one aspect of SCC. This is often useful to find the particular failure in production, e.g. a problem of poor filling ability, or blocking or segregation. Then design methods can be adjusted accordingly.

These early tests are seldom used nowadays and are not discussed further. The following are demonstrated and discussed because they are standardized or widely accepted, easy to perform and might be standardized; or the apparatus involved is simple and inexpensive; or the results derived have good reproducibility and repeatability or have good relationships with Bingham parameters.

2.2.3.1 Filling ability tests

Two aspects of SCC, deformation capacity and deformation velocity, are evaluated by filling ability tests, which include the slump flow test, the V-funnel test and the Orimet test.

Slump flow test

The slump flow test in some aspects is similar to the slump test performed on NVC except no compaction is involved. Slump and slump flow measures vertical and horizontal changes respectively.

The slump flow test is widely used to evaluate the deformation capacity of concrete under its own weight without external forces against the friction of the plate. As shown in Figure 2-15, slump flow is the diameter of the concrete flowing over a level plate after a slump cone is lifted. The higher the slump flow value is, the greater the deformation capacity of the concrete, provided that no segregation occurs. A more detailed test procedure is in 4.3.

Figure 2-15 Slump flow test

T500, the time from lifting to the concrete reaching a 500 mm diameter, is popularly used to indicate the deformation rate. The higher the T500 value is, the lower the deformation rate of the concrete.

Sgregation (refer to 2.1.2.3) can be visually evaluated by observing the flowing process and the edge of the spread after concrete stops. The occurrence of a halo of paste or unevenly distributed coarse aggregate is considered as an indication of segregation, which demonstrates that the concrete segregates during the test and may segregate after placing. However the lack of segregation during the slump flow test cannot ensure that the mix is resistant to segregation (Testing-SCC, 2005). It is therefore insufficient to detect segregation by visual observation only.

In the slump flow test, the concrete stops flowing when the shear stress of the sample becomes equal to or smaller than the yield stress. Consequently, the slump flow corresponded well to the yield stress of SCC with correlation coefficient (R^2) being 0.76, and it decreased with an increase in yield stress

(Testing-SCC, 2005). This confirms that the yield stress must be the dominant factor that governs the slump flow diameter. The plastic viscosity also affected slump flow but the influence can be negligible compared to that of yield stress and concrete density (Reinhardt and Wustholz, 2006). Other factors such as surface tension can also affect the measurements and should not be ignored.

Bouzoubaâ and Lachemi (2001) reported that the slump flow was determined first by the superplasticiser dosage then the W/P ratio and fly ash replacement. However, Sonebi (2004) showed that the water/(cement+fly ash) ratio had the greatest effect on the slump flow for SCCs incorporating fly ash.

T500 showed good correlations with the plastic viscosity (R^2=0.76) but rather poor correlations with the yield stress (R^2 below 0.4) (Testing-SCC, 2005). The major factor influencing T500 value is plastic viscosity. In other words, plastic viscosity can be expressed as T500 time provided there is no segregation.

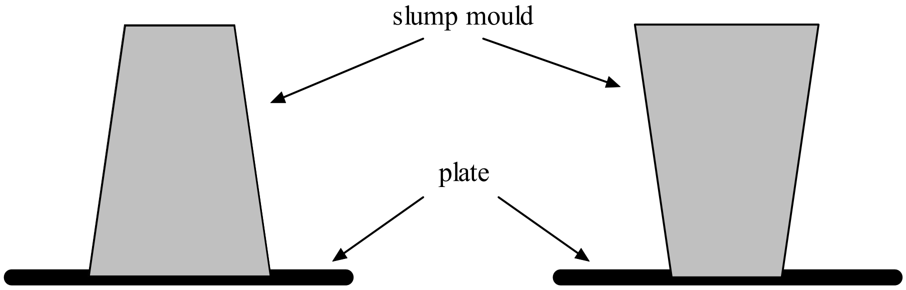


Figure 2-16 Schematic of upright and inverted slump mould in slump flow test

The slump flow test can also be performed by inverting the mould (shown in Figure 2-16) to prevent the mould from floating up when filled. However, the results of the upright and inverted cone are not comparable.

In order to minimise the influence of the operator on the values of slump flow and T500, an automatized slump flow equipment, the camflow (Gram, 2005), was developed but is not widely used.

V-funnel test

The V-funnel test is performed by measuring the time for the concrete to flow out of the funnel under its own weight as shown in Figure 2-17. A more detailed test procedure is in 4.3.

Figure 2-17 V-funnel test for concrete

This test is used to evaluate deformation velocity, which is affected by the passing ability and segregation resistance of concrete. A long V-funnel time can relate to either a low deformation capacity due to high inter-particle friction, or blockage of the flow. For example, a concrete with a high slump flow value and a long V-funnel time may indicate the concrete is segregated and blockage may happen in the outlet gate of the V-funnel. As a result, the V-funnel time is related to plastic viscosity provided there is no segregation and blockage.

V-funnel time showed reasonable good correlations with plastic viscosity ($R^2 \approx 0.6$) but rather poor correlations with yield stress (Testing-SCC, 2005). Reinhardt and Wustholz (2006) also demonstrated that T500 measurement was a better indicator of plastic viscosity than V-funnel time because the V-funnel test was influenced by blockage.

Various sizes of V-funnels have been used: a top dimension of 495 mm by 75 mm and a bottom opening of 75 mm by 75 mm by Ferraris et al. (2000); a total height of 572 mm including a 150 mm long square pipe by Okamura and Ouchi

(2003b); a top dimension of 515 mm by 75 mm, with a bottom opening of 65 mm by 75 mm and a total height of 600 mm with a 150 mm long square pipe by De Schutter (2005).

Orimet test

The Orimet test is based on the same principle as the V-funnel test to assess the deformation velocity through restricted areas without blocking during the flow.

The apparatus consists of a vertical casting pipe 600 mm long and 120 mm in diameter with a 70~90 mm orifice at the bottom which is supported by a tripod as shown in Figure 2-18 (Bartos, 1998; Sonebi and Bartos, 2000; Sonebi and Bartos, 2002). Orimet time is the period of time it takes for concrete to flow out of the vertical pipe, which is also related to plastic viscosity when the concrete is free of blocking and segregation.

Figure 2-18 Orimet test

It was reported that the Orimet test was more sensitive to passing ability, segregation and the operator than the V-funnel test (Aarre and Domone, 2004). For this reason, the V-funnel test is a better indicator of filling ability than the Orimet test.

2.2.3.2 Passing ability tests

Among the apparatus designed to measure the passing ability, the L-box test and J-ring test, in various dimensions and shapes, are most commonly used.

L-box test

The L-box test evaluates the passing ability of SCC in a confined space. The L-box is composed of a vertical arm and a horizontal arm as shown in Figure 2-19. The concrete flows from the vertical arm, through reinforcing bars and into the horizontal arm of the box. A more detailed test procedure is in 4.3.

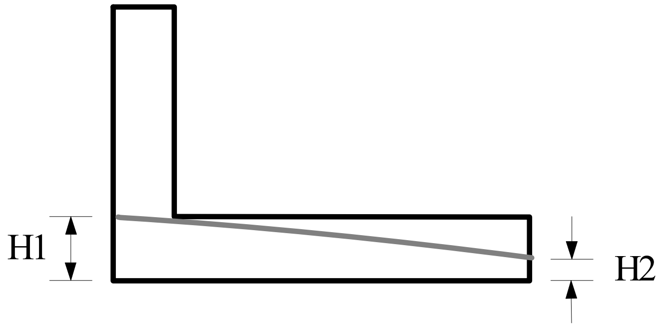


Figure 2-19 Schematic of L-box

Once the test is completed, the ratio of the heights of the concrete at the two ends of the box, called the blocking ratio (BR), is used to evaluate the passing ability with obstructions as

$$BR = \frac{H_2}{H_1}$$

If the SCC has perfect fresh properties, the blocking ratio is then equal to 1. Conversely, the blocking ratio is equal to 0 if the concrete is too stiff or segregated. Blocking ratio is useful for SCC applications involving complex shapes, and congested reinforcement.

The times for the concrete to flow along 200mm and 400 mm of the horizontal arm, T200 and T400 respectively, were used to evaluate the deformation rate previously but are not widely used now.

Segregation can be visually checked. If the coarse aggregate is not evenly distributed along the trough or it is wedged between the reinforcing bars, this maybe an indicator of segregation.

L-boxes of different sizes with different reinforcing bars and gaps were used (Bui et al., 2002a; Petersson, 1997). Investigations showed that the L-box was sensitive to blocking and that it was more difficult for concrete to pass three bars than the two bars (Sedran and De Larrard, 1999).

The test depends on the operator, for example, in regard to the lifting speed of the gate (Nguyen et al., 2006): If the gate was lifted slowly and there was no segregation, the final shape of the concrete was determined by yield stress and there were correlations between blocking ratio to the ratio of yield stress to specific gravity; the difference between two results with and without steel bars were small which according to Nguyen et al (2006) can be used to detect dynamic segregation.

J-ring test

The J-ring test, on the other hand, simulates a flow through reinforcement in an unconfined condition. The apparatus is composed of a ring with 16 or 18 vertical reinforcing rods, a slump cone and a rigid plate as shown in Figure 2-20.

Figure 2-20 J-ring test

When the cone is lifted, the concrete has to pass through the reinforcing bars as it flows across the plate. The passing ability is expressed as the average height difference between the concrete inside and outside the bars, called the step height. The final spread diameter of the concrete in two perpendicular directions is also measured. Segregation resistance can be visually evaluated by observing the periphery after the concrete has stopped flowing. A more detailed test procedure is in 4.3.

Different geometries of the J-ring and different bar arrangements have been developed. In order to study the combined effects of the size and space between the reinforcing bars in practice, the diameter of J-ring was increased from 300 mm to 500 mm with even spaces between the bars (Tam et al., 2005). This modification makes it possible to replicate the actual reinforcement in a structure by varying the number, the size or the configurations of the bars. However, it is impractical to constantly change the bar spacing in testing. In addition, using various dimensions of bars and bar spacing makes comparisons impossible.

Testing-SCC project (2005) showed that when L-box and the J-ring tests were carried out simultaneously and the distance between the bars was similar, the blocking ratio in the L-box test correlated well with the step height in the J-ring test; a linear relationship was obtained in which the blocking ratio of more than 0.8 corresponded to the step height of less than 10 mm.

2.2.3.3 Segregation tests

Several empirical tests have been proposed to evaluate static segregation. However, no methods have yet been proposed for dynamic segregation.

Visual examination

The visual examination method (PCI-TR, 2003) was carried out by inspecting the periphery of the concrete after measuring the slump flow value and rating it from 0 to 3. However it is an inadequate method because it relies on the experience of the performer and fails to evaluate segregation quantitatively.

Settlement column test

The settlement column segregation test (Ye et al., 2005) was performed by placing the concrete into three cylindrical sections of 200 mm in height and 100 mm in diameter and allowing them to rest for 20 minutes. Then the concrete in the top and the bottom sections were wet sieved and dried out; the degree of segregation was expressed as the percentage of the weight difference between the top and the bottom sections divided by the average weight of the dried-out coarse aggregate retained on the sieve (approach 1). A high percentage meant that the upper part of the column contained a similar coarse aggregate content to that in the bottom part, which indicated that the concrete did not segregate; whereas a low value was evidence of segregation.

Another version of the column segregation test is for SCC in the hardened state; the distribution of the aggregation in different levels of a cut cylinder was visually inspected, counted or analysed which also indicated segregation (Shen et al., 2005). The more coarse aggregate in the bottom level, the more chance the concrete will segregate.

Other versions of the column segregation test involving vibration in the method (Xie et al., 2005) are not discussed here.

However, compared with the penetration and sieve analysis tests, the settlement column test was complex and least able to detect segregation of fresh concrete (Cussigh and Bonnard, 2004).

Penetration test

Static segregation was evaluated by measuring the penetration depth of a penetration cylinder, as shown in Figure 2-21 (Bui et al., 2002b), 45 seconds after releasing it into the concrete sample in the vertical arm of L-box. It was reported that no vertical segregation occurs if the penetration depth is less than 8 mm.

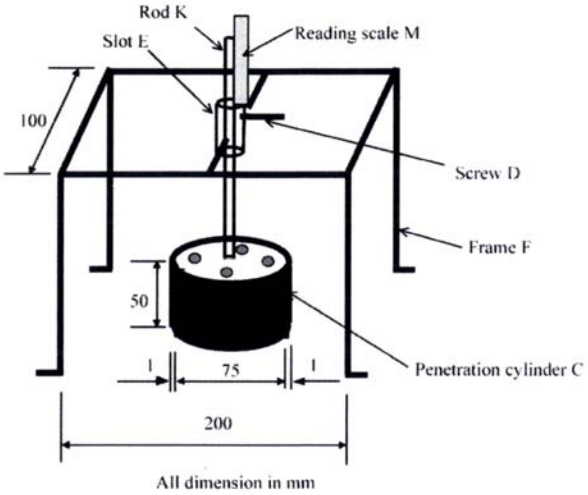


Figure 2-21 Penetration test by Bui et al (2002b)

The equipment shown in Figure 2-21 was adopted in the Testing-SCC project but the penetration test was performed on the concrete in a bucket after the concrete had been left to stand still for 2 minutes (Cussigh and Bonnard, 2004); the higher the penetration depth, the greater the possibility of the concrete segregating. There was a good correlation between penetration depth and segregation index in the sieve stability test below (Cussigh and Bonnard, 2004).

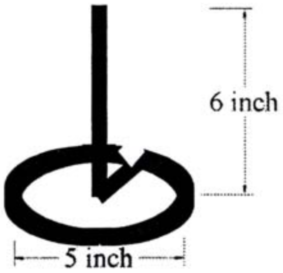


Figure 2-22 Segregation probe by Shen et al (2005)

Another version of the apparatus used a 100 or 130 mm diameter ring connected to a 150 mm high rod marked with a scale with a total weight of 18 g as shown in Figure 2-22 (Shen et al., 2005); the concrete was stable if the depth is less than 7 mm.

Sieve stability test

The potential for static segregation can be evaluated by a simple sieve stability test, which measures the amount of laitance passing through a 5 mm sieve after a standard period, which is called sieve segregation or segregation index. A more detailed test procedure is in 4.3.7. The more mortar passing through the sieve, the higher segregation index, which indicates the higher risks of segregation in concrete after placing.

2.2.3.4 Robustness tests

Among the influences on the robustness of concrete, water variation is the most important factor affecting robustness (refer to 2.1.2.4). This is therefore usually used to test robustness. Water variations of 5~10 litre/m^3 were used by the European Project Group (2005) to test robustness.

2.2.3.5 Consistence retention tests

"Consistence" is a general analysis of the performance of fresh concrete. Consistence retention tests, just as the name implies, are used to evaluate a concrete's capacity to maintain its fresh property or the change of its characteristics after a specific time, e.g., the slump flow loss of 1 hour after mixing is used, which corresponds to the filling ability retention. By analogy, changes in passing ability evaluated by the step height in the J-ring test or the blocking ratio in the L-box test and the changes in segregation resistance evaluated by the sieve segregation or the penetration depth also can be used to study the passing ability retention and segregation resistance retention.

2.2.3.6 Recommended tests

Since filling ability, passing ability and segregation resistance are closely related (refer to 2.1), it is difficult to separate each property. A European research project 'Measurement of properties of fresh self-compacting concrete' (acronym "Testing-SCC" demonstrated that no single test was sufficient enough to assess SCC's key properties. Similarly no single test can characterise the properties of SCC. As a result, a combination of several tests and various types of apparatus will give a better analysis of SCC. That is, each mix should be verified by tests for different characteristics of SCC. This has been adopted by many countries.

The following tests were recommended by Testing-SCC (2005) for draft standards: the slump flow test and T500 time for filling ability, the L-box test and the J-ring for passing ability, and the sieve stability test for segregation resistance; three other tests were recommended as alternative methods: the V-funnel test and the Orimet test for filling ability, and the penetration test for segregation. These tests can evaluate each key property of SCC quantitatively and were recommended by a European guideline (The SCC European Project Group, 2005).

Testing-SCC (2005) proposed suitable test methods to identify SCC's key fresh properties, demonstrated the accuracy of each test method, confirmed the scientific basis of these tests by rheological studies, recommended acceptance for various applications and established agreed guidelines leading to standards for the test methods in European countries. This has promoted a faster and wider use of SCC in Europe and world wide.

2.2.3.7 Rheological tests

Rheology is always a helpful tool in studying and understanding concrete. The Bingham model (refer to 2.1.2.6) is usually used to analyse concrete. Rheological tests aim to measure the Bingham parameters. Various concrete rheometers have been designed to measure both the yield stress or the plastic viscosity (two-point tests) or only the viscosity (single-point tests) such as Tattersall's two-point rheometer (Tattersall and Banfill, 1983) and BML (T.Sedran, 2000; Wallevik and Nielsson, 1998). The most recent rheometer is IBB (Ferraris et al., 2000) and BTRHEOM (Reinhardt and Wustholz, 2006). All are commonly used in the study of SCC. All rheological tests measure the Bingham parameters in an indirect manner.

In general, two-point rheometers apply a shear rate and measure the shear stress response of the concrete, which provides the relationship between the torque and rotating speed as

$T = g + h N$

where T and N are torque and rotating speed respectively.

The test results, g and h, are constants related to the yield stress and the plastic viscosity respectively. By calibration with fluids of known rheological properties, e.g. oil, it is therefore possible to express the yield stress and the plastic viscosity in units.

However, oil is a Newtonian liquid (refer to Figure 2-4) whereas concrete is a Bingham flow mixture, which means that the shear stress vs. shear slope is dependent on the shear rate. If an ideal material can be found, it will be possible to calibrate different rheometers and compare their results.

Rheometers are usually complex and expensive. Nearly all rheological tests are limited to use in laboratories. Because of the different sizes and mechanisms involved, it was difficult to compare the measurements (Koehler et al., 2005b). In addition, concrete performance cannot be predicted by rheological tests on its constituent materials.

Some improvements have been made. E.P. Koehler et al (2005c) made a low-cost, portable rheometer. Gregori et al (2005) designed a falling ball viscometer. However, they are not widely accepted.

On the other hand, empirical tests, as described in 2.2.3, are widely used in laboratories and construction sites because of the inexpensive equipment involved and their simple and rapid execution. In addition, good correlations between empirical test results and rheological parameters have been published (Jin and Domone, 2002; Roy and Roussel, 2005; Saak et al., 2004; Schwartzentruber et al., 2006). The combined use of empirical tests can give an adequate analysis of the rheological characteristics of SCC.

2.2.4 Precision of the tests and recommendations

It is necessary to know the possible errors that the tests may produce in order to properly interpret results. The accuracy of tests is evaluated by repeatability and reproducibility, which are statistical measures of the error inherent in test methods.

"Repeatability" is defined as the difference between two results performed by the same operator, using the same test method and apparatus, measured on identical material in the same laboratory and environment within a short period of time, that will be exceeded only once in twenty times (BS ISO 5725-6, 1994).

"Reproducibility" is defined as the difference between two results performed by different operators, using the same test method but different apparatus, measured on identical material in different laboratories and environment within a short period of time that will be exceeded only once in twenty times (BS ISO 6725-6, 1994).

With a probability of 95%, repeatability (r) and reproducibility (R) are obtained by multiplying the standard deviation of repeatability (SD_r) and reproducibility (SD_R), with a factor of 2.8[2] as

$$r = 2.8\ SD_r$$

$$R = 2.8\ SD_R$$

This means, the maximum difference between any two of the twenty measurements by the same operator should be less than r, and that between any two of the twenty measurements by different operators should be less than R.

Concrete is a variable material and its properties change with time. For this reason, the standard requirements for repeatability and reproducibility cannot be

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[2] $2.8 \approx 1.96\sqrt{2}$, the factor 1.96 for 95% probability and $\sqrt{2}$ for two test results.

completely fulfilled. However, the change in SCC's fresh properties is small, which can be minimised by performing the tests on fresh SCC within a short period of time.

Taking the above into account, the accuracy of the most commonly used test methods were evaluated by the Testing-SCC project (De Schutter, 2005) as shown in Table 2-5 .

Table 2-5 Precision of SCC tests evaluated by the Testing-SCC project (De Schutter, 2005)

Tests		Classes	Repeatability	Reproducibility
Slump flow test	Slump flow (mm) (± 50)	<600	N.A.	N.A.
		600~750	42	43
		>750	22	28
	T500 (secs) (± 0.5)	<3.5	0.66	0.88
		3.5~6.0	1.18	1.18
		>6.0	N.A.	N.A.
V-funnel test	V-funnel time (t_v) (secs) (± 2)	3~15	0.335 t_v -0.62	0.502 t_v -0.943
		>15	4.4	6.6
Orimet test	Orimet time (t_o) (secs) (± 2)	3~15	0.433 t_o -0.594	0.472 t_o -0.28
		>15	6.6	6.8
J-ring test	Spread (mm)	<600	59	67
		600~750	46	46
		>750	25	31
	Step height (mm) (± 5)	≤20	4.6	4.9
		>20	7.8	7.8
L-box test	blocking ratio (B_L)	≤0.35	0.463 B_L -0.011	0.425 B_L -0.029
		>0.35	0.18	0.18
Penetration test	Penetration depth (P) (mm) (± 5)	≤17	0.59 P + 1.7	0.59 P + 1.7
		>17	12	12
Sieve stability test	Sieve segregation (%) (± 5)	≤20	3.7	3.7

It can be seen from Table 2-5 that:

- there is no significant difference between repeatability and reproducibility of those tests investigated, which means the accuracy depends on the operator;
- for spread greater than 750mm, the accuracy of the slump flow test is better;
- the V-funnel and the Orimet tests exhibit similar accuracy and the measurement errors increase with the flow time;

- the sieve stability test measures segregation with a better accuracy than the penetration test: for example, for a typical value of sieve segregation of 13% and penetration depth of 17 mm, the repeatability of the sieve stability test and the penetration test are 3.7 and 12 respectively.

The J-ring test showed better accuracy than the L-box test, the coefficient of variation of the J-ring test and L-box test being 27~29% and 50~55% respectively (De Schutter, 2005).

Therefore, a single measurement can be precise enough to assess some aspects of the performance of SCC.

2.2.5 Conclusions

SCC is usually mixed in a forced mixer with longer mixing time, and admixtures are added at different stages during the mixing. Using the delayed addition method can maximise the efficiency of the superplasticiser. The mixer, the sequence of mixing, temperature and duration of mixing therefore should be kept constant in either production or in a test programme to obtain consistent and reliable test results. In laboratory tests, special attention must be paid to the addition methods of admixtures.

Mortar tests are widely used to design and evaluate SCC. The spread and the V-funnel time of mortar will correlate with the slump flow and the V-funnel time of concrete.

The slump flow test is the most common method to assess the filling ability. Deformation capacity can be evaluated by slump flow in the slump flow test; deformation velocity in the absence of obstructions is assessed by T500 time in the slump flow test; V-funnel and Orimet time are used to evaluate the deformation velocity through restricted areas without blocking during the flow. None of these tests are sufficient enough to detect segregation. The yield stress shows quite good correlations with slump flow; the plastic viscosity correlates well to T500, Orimet time, and V-funnel time according to the correlation coefficient from high to low.

The L-box test and the J-ring test have been used to measure the passing ability of SCC, on the confined and unconfined conditions respectively. Both tests have gained popularity in different countries.

Among the existing segregation tests, the penetration test and the sieve stability test can measure static segregation qualitatively. They are gaining popularity due to higher accuracy. However, there are no suitable tests for dynamic segregation.

Water variations of 5~10 litre/m^3 were used to test robustness. Fresh properties after some time can be used to test consistence retention.

Test combinations are recommended to give a complete analysis of fresh properties of SCC: the slump flow test and the V-funnel test or the Orimet test for filling ability, the L-box test and the J-ring test for passing ability, the penetration test and the sieve stability test for static segregation.

The relationships between empirical values and Bingham parameters show that easily-performed empirical tests instead of the more complex rheological tests can be used to evaluate the fresh properties of mortar and SCC.

Repeatability and reproducibility are used to evaluate the accuracy of SCC test values. Errors in measurement can be minimised by completing tests within a short period of time when SCC maintains its fresh properties.

Investigation has shown that there is no significant difference between repeatability and reproducibility of tests on fresh SCC. A single measurement can be precise enough to assess the performance of SCC.

2.3 Criteria

Since SCC was first produced, great efforts have been made to produce guidelines and standardised methods of specification and testing. Some of the widely accepted guidelines are demonstrated in this section.

2.3.1 Guidelines in Japan

Originally developed in Japan, SCC was extensively investigated by several different organizations in the 1990's. Based on the results of each research, recommendations were made to spread the benefits and to take the technology of SCC into practical use. The following pioneering recommendations provided complete information for researchers, producers and users up to that time.

- 'Recommendations for mix design and construction practice of high consistence concrete' by the Architectural Institute of Japan in 1997.
- 'Recommendation for construction of self-compacting concrete' by the Japan Society of Civil Engineers in 1998.
- 'Manual for manufacturing of self-compacting concrete' by the National Ready-mixed Concrete Industry Association of Japan in 1998.

These defined SCC's characteristics and many technical terms, listed applicable materials, provided typical methods to design and judge acceptable performance, and also covered the requirements of production and quality control on site. They classified SCC into three types (powder, viscosity and combined), ranked its characteristics according to reinforcement conditions, related SCC performance with Bingham parameters and emphasized the importance of surface moisture of aggregate on the production. They established a solid base for further research and developments.

However, different organizations produced different recommendations, and there were no national standards for SCC test methods.

Similarly, subsequent research on SCC that has been carried out in individual organizations in North America and Canada has not produced any co-ordinated or national recommendations.

2.3.2 Guidelines in Europe

SCC has been growing rapidly across Europe since mid 1990's. As a result, many guidelines were proposed in European countries.

The first edition of European guidelines was produced in 2002:

- "Specification and Guidelines for Self-Compacting Concrete by the European Federation of Producers and Contractors of Specialist Products for Structures" by EFNARA in February 2002.

These were based on the latest research results and abundant practical experience. It defined SCC's key properties (filling ability, passing ability and segregation resistance) more clearly and specified the requirements for constituent materials and practical applications of SCC.

It stated that besides fly ash, silica fume and GGBS, finely crushed stone, ground glass and pigments all can be used in SCC, which encouraged studies on more types of powders in SCC. Steel or polymer fibres could also be used which extends SCC to wider applications. The guidelines provided typical test combinations and acceptance criteria for SCC with a maximum aggregate size up to 20 mm and slump flow in the range of 650~800 mm, which is more flowable than that in Japan. Compared with those in Japan, SCCs in Europe are higher in fine aggregate content and lower in powder content. Some tests developed in the early stages of SCC development, e.g. U-box test and the filling box test were described. The sieve stability test for segregation and a value of 5~15% were recommended. They also recommended tolerances, for example, ±50 mm for slump flow but this was based on experience not on precise data. It did not specify mix design methods, but took an example based on Japanese's general purpose method and provided typical ranges of mix proportions of SCC.

These guidelines were updated in 2005:

- The European guidelines for SCC (The SCC European Project Group, 2005) and provided state of the art information for producers, designers, users, specifiers and purchasers.

Based on increasing amounts of research and experience, these guidelines properly defined SCC, classified its various properties, proposed test methods and the potential for standards, provided information of constituent materials and overall properties, and recommended acceptance values for various applications. It therefore has been gradually accepted by many countries beyond Europe.

The recommended classes of SCC are summarised in Table 2-6 (Testing-SCC, 2005; The Concrete Society and BRE, 2005).

Table 2-6 European classes on SCC (Testing-SCC, 2005; The Concrete Society and BRE, 2005)

Property	Class				
Filling ability	SF1	Slump flow (mm)		550~650	
	SF2			660~750	
	SF3			760~850	
	VS1/VF1	T500 (s)	≤ 2	V-funnel time (s)	≤ 8
	VS2/VF2		> 2		9~25
Passing ability	PA1	blocking ratio of L-box	≥ 0.80 (2 bars)	Step height in the J-ring (mm)	$S_J \leq 15$ (59 mm bar spacing)
	PA2		≥ 0.80 (3 bars)		$S_J \leq 15$ (41 mm bar spacing)
Segregation resistance	SR1	Sieve segregation (%)		≤ 20	
	SR2			≤ 15	

The deformation capacity of SCC is divided into three classes based on slump flow, SF1, SF2 and SF3 which are for low, good and high filling ability respectively.

- SF1 is the minimum requirement for SCC. Mixes of slump flow less than 600 mm may require minor vibration in practical applications.
- Mixes of SF2 are suitable for most practical applications. A case study indicates that nearly half of the applications of SCCs fell in class SF1 and 35% in SF2 (Domone, 2006b).

- Mixes SF3 usually flow very easily, rapidly and for long distances which may be required in casting of very complex shapes or heavily reinforced concrete elements. Particular attention must be paid to the passing ability and segregation resistance of the concrete in this range to ensure its homogeneity.

The deformation velocity of SCC is classified two grades:

- T500 from the slump flow test ≤ 2 seconds or V-funnel time (tv) ≤ 8 seconds which indicates high deformation velocity;

- T500 more than 2 seconds or tv in the range of 9~25 seconds indicating low or moderate deformation velocity.

The typical range of T500 and tv are 2~5 seconds and 5~12 seconds respectively. It should be noted that no segregation is the prerequisite to the measurements of T500 and tv.

Passing ability of SCC can be classified by the blocking ratio of L-box (BR). The minimum value of BR is recommended as 0.80. Mixes with BR ≥ 0.80 with 2 bars have adequate passing ability for general-purpose applications with light or no reinforcement. Mixes with BR ≥0.80 with 3 bars are suitable for placing into formwork with more closely spaced, denser reinforcement.

The passing ability also can be classified by the step height of the J-ring (S_J):

- S_J of 1~10 mm indicating low risk of blocking. SCC is suitable for dense reinforcement structures. No blocking was reported if S_J is less than10 mm for a SCC with V-funnel time of 4~7 seconds and slump flow of 750~800 mm (Wustholz, 2003).

- S_J in the range of 10~20 mm indicating moderate to high risk of blocking. SCC is suitable for structures with widely spaced or no reinforcement and few obstacles.

The typical range of S_J and BR are 3~20 mm and 0.85~0.95 respectively.

Segregation index (SI) of SCC has two classes: mixes with SI ≤15 have good resistance to static segregation; mixes with SI ≤20 show adequate resistance to static segregation. The typical range of SI is 10~20%. The mixes of SI less than 5% may be too viscous to be self-compacted.

2.3.3 Conclusions

Guidelines for SCC have been proposed by individual institutions, but most recent European guidelines (2005) is the first co-ordinated cross-border recommendation and is widely accepted beyond Europe. It recommends suitable test methods to evaluate filling ability, passing ability and segregation resistance and divides each property into two or three classes by slump flow, T500 or V-funnel time, blocking ratio of L-box or step height in the J-ring and sieve segregation respectively. This guideline has been assisting a further development of SCC and spread its applications world wide.

However, there has no standardized tests on SCC's other fresh properties such as dynamic segregation, consistence retention and robustness. It is still impossible to give a complete analysis of SCC.

2.4 Constituent materials

Most materials suitable for NVC can be used to produce SCC, but they produce more effects on the fresh properties of SCC than on those of NVC. Local materials have been used in SCC over the past ten years.

The types, the roles of the constituent materials in SCC and their effects on the fresh and hardened properties are reviewed in this section.

2.4.1 Admixtures

An admixture is a 'material added in small quantities during the mixing progress to modify the properties of the mixture' (BS EN 934-2, 2001). There are many admixtures that have been reported as used in SCC, but superplasticisers are the essential ingredients. Viscosity modifying agents (VMAs) may be also used to enhance the viscosity and the segregation resistance.

2.4.1.1 Superplasticisers

When cement mixes with water, cement particles always flocculate and agglomerate because of Van der Waals forces and electrostatic attractive forces generated by the electric charge on the surface of the particles. This results in a large amount of free water being trapped in the flocs, which reduces the consistence of concrete.

Water reducing agents and superplasticisers attach to the cement particles, imparting a negative surface charge and, thus causing electrostatic repulsion, which in turn breaks the flocculation and agglomeration, and liberate the trapped water as shown in Figure 2-23.

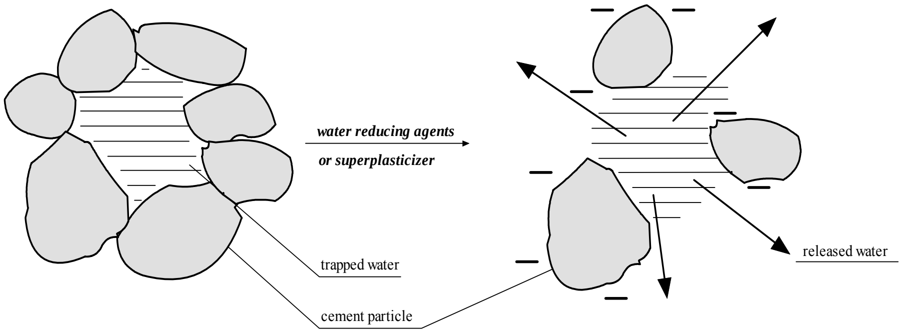


Figure 2-23 The effect of water reducing agents or superplasticisers on the flocculation of cement particles

As superplasticisers induce greater electrostatic and steric repulsive forces than the water reducing agents, they result in a greater consistence performance and a longer consistence retention (Bonen and Shah, 2005; Uchikawa et al., 1995).

Superplasticiser types

Sari et al (1999) reported a nanometric, amorphous, silica can act as superplasticiser. However, the most commonly used are inorganic superplasticisers.

Inorganic superplasticisers used in SCC can be divided into two types according to their dispersion mechanism: those based on electrostatic repulsion and those based on steric repulsion.

Those mainly based on electrostatic repulsive forces include naphthalene sulfonate (NF), melamine sulfonate (MF) and amino sulfonate based agents. All of them contain a sulfonic group in the molecule which imparts a negative charge on the cement particles, thus causing dispersion (Kim et al., 2000; Nawa et al., 1998).

Superplasticisers mainly based on steric repulsive forces include polycarboxylate based agents. They have a molecular structure composed of a backbone of a long straight chain of carbon atoms with side ethylene oxide (EO) chains which absorb water and produce a thick layer on the cement surface, thus generating effective steric repulsion (Yamada et al., 2000). In addition, the carboxyl group in the molecule also gives a negative charge to cement particles, thus providing some electrostatic particle repulsion. However this is weaker than that of the sulfonic group (Uchikawa et al., 1995).

The newly developed polycarboxylic acid-based superplasticiser is able to provide high consistence, proper viscosity and long consistence retention even in a small amount and at low W/C ratio. It is therefore especially suitable for SCC and is the most commonly used.

Adsorption and consistence performance

Superplasticisers are thought to be adsorbed onto the cement particles and then to disperse them, which causes the initial consistence performance of the cementitious system. For this reason, it is important to study the adsorption behaviour of superplasticisers.

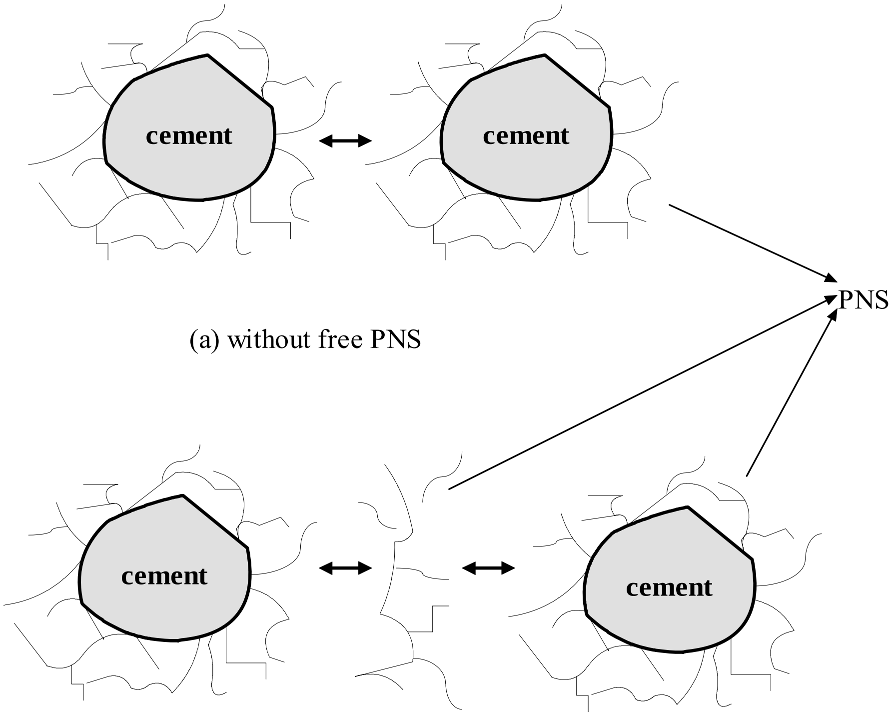
The adsorption capacity of those based on electrostatic repulsion is mainly determined by the degree of polymerisation, cement fineness and C_3A content (Bonen and Sarkar, 1995): the higher the molecular weight of the superplasticiser, the greater the superplasticiser uptake; a low specific surface and a low C_3A content in the cement result in a lower superplasticiser adsorption. The superplasticisers based on steric repulsion, which have shorter polyoxyethylene side chains and higher degrees of backbone polymerisation, show higher adsorption (Yamada et al., 2000).

Temperature has a large effect on the adsorption rate of superplasticisers (Okamura and Ozawa, 1995). At high temperatures, adsorption is accelerated. Time is also an important factor. There is a tendency to reduced consistence with time. In addition, the effect of superplasticisers also depend on the powders (refer to 2.4.3) and mixing methods (refer to 2.2.1). These are the main defects of superplasticisers, which significantly affect SCC performance.

The effect of superplasticisers and water on the consistence performance of a cement paste was studied by testing the spreads of pastes with different superplasticisers and different W/C ratios (Yamada et al., 2000). Their results showed that where the W/C ratio was below 0.25, the effect of the W/C ratio on consistence was significant; on the other hand, the spread of the paste was more sensitive to a superplasticiser dosage with a W/C ratio higher than 0.35. For this reason SCC is not very robust. Small fluctuations in the water or superplasticiser content can have a great influence on the consistence performance of SCC.

One of the causes of consistence loss is considered to be the consumption of superplasticisers with time. Kim et al (2000) showed that there is an inverse relationship between the amount of polynaphthalene sulfonate (PNS) adsorbed and the spread values of a paste at 30 minutes, which was made by different types of cement. They found that the greater the amount of PNS adsorbed by the cement paste, the higher the consistence loss. This is explained in Figure 2-24.

As previously stated, the adsorbed PNS imparts a negative electrical charge on the surface of the cement particles, thus causing electrostatic repulsive forces; this is the cause of the initial improvement in the consistence of the paste. However, as the cement hydration proceeds, the PNS combined with the hydrated products cannot improve the consistence; it is the remaining or “free” PNS in the solution that provides the continued consistence. Thus the more PNS that is adsorbed, the less free PNS remains, resulting in a lower consistence retention.



(a) without free PNS

(b) with free PNS

Figure 2-24 Repulsive forces (a) without free PNS and (b) with free PNS

Delayed addition (refer to 2.2.1.5) of superplasticisers such as sulfonated naphthalene polymer, acrylate-methacrylate co-polymer, vinyl copolymer and polycarboxylic ether studied in Jin’s project (2002), can reduce this consumption and restore the consistence performance of mortar. By adding the superplasticiser with a part of mixing water some time after mixing, this allows some free superplasticisers to be available in the system.

Superplasticisers containing a sulfonic group often suffer from rapid consistence loss (Mehta, 1999). Bonen and Sarkar (1995) studied pastes composed of PNS and different cement types, which revealed that the consistence retention is correlated to the ionic strength of the pore solutions, that is, the higher the ionic strength, the greater the consistence loss; PNS increases the ionic strength, thus leading to a greater consistence loss.

Polycarboxylic acid-based superplasticisers have been more widely used in SCC in the past ten years due to their higher dispersing effect, longer consistence retention and greater robustness (Collepardi et al., 2005). They reduce yield stress significantly, maintain plastic viscosity but do not have secondary effects on setting time and air content (Yamada et al., 2000). Also their chemical structure is more flexible and can be modified to suit various needs. Some have been developed specifically for SCC. For example, a higher dispersing action was achieved by increasing the polyoxyethylene side chains and sulfonic groups and decreasing the degree of the backbone polymerization (Uchikawa et al., 1997). Consistence retention of longer than 2 hours was successfully maintained by bonding the polyoxyethylene side-chain to the backbone of copolymer (Felekoglu and Arikahya, 2008).

Setting

Although various types of superplasticiser exist, adding superplasticisers always causes some delay in the setting time (Uchikawa et al., 1995) because the polymer chains are adsorbed onto the cement grains and interfere with the precipitation of various minerals into solutions which slow the hydration rate (Khayat and Guizani, 1997). As a result, a higher dosage of superplasticiser or using a superplasticiser with a higher adsorption capacity will have a longer retardation effect on the cementitious system. This was confirmed in a paste composed of a Type I cement, a W/C ratio of 0.40 and a naphthalene-based superplasticiser (Khayat and Yahia, 1997): the initial setting time of the paste increased from 5.3 to 11.5 hours with the increase in the superplasticiser dosage from 0 to 0.8% by the mass of cement.

It was found both initial and final setting were delayed by increasing the sulfonic and carboxylic groups in the aqueous phase of polycarboxylic acid-based superplasticiser (Jolicoeur and Simard, 1998; Yamada et al., 2000).

It seems from the literature that the design of a superplasticiser for concrete is based on the cement paste performance. There is no research found that verify a superplasticiser's function by testing a paste composed of cement and additions. This is expected since the quality of the addition is not as stable as cement.

However for SCC incorporating a large amount of additions, the dispersing functions of superplasticisers will to some extent be affected by additions' characteristics. That is, superplasticisers may not fully do their work on concrete with additions. Therefore it is necessary to do laboratory trials in designing a SCC.

2.4.1.2 Viscosity modifying agents

VMAs can be divided into two types depending on the mechanism of action: adsorptive and non-adsorptive (Nawa et al., 1998; Yammamuro et al., 1997).

Adsorptive VMAs act on cement. After addition, they are adsorbed onto the surface of the cement particles and form a bridge structure, thus imparting viscosity to the concrete. Superplasticisers and VMAs will compete for the adsorption site.

The amount of superplasticisers in the presence of adsorptive VMAs are shown in Figure 2-25 (Nawa et al., 1998). The greater the surface of the cement particle occupied by adsorptive VMAs, the smaller the amounts of superplasticisers that are adsorbed, which leads to a reduction of consistence. This type includes cellulose-based water-soluble polymers and acrylic-based water-soluble polymers.

On the other hand, non-adsorptive VMAs act on water. They increase the plastic viscosity of concrete because either their water-soluble polymer chains imbibe some free water or through the linking of their own molecules (Khayat, 1999b). As a result, some consistence of concrete is retained. The amount of superplasticisers in the presence of non-adsorptive VMAs are shown in Figure 2-25 (Nawa et al., 1998). The amount of superplasticisers adsorbed does not change with an increase in the non-adsorptive VMAs added. Thus the plastic viscosity of mortar increases, but the spread value may not change.

Non-adsorptive VMAs therefore do not compete with superplasticisers for the cement surface. This unique property is especially suitable for SCC. They therefore can be added with suitable superplasticisers to produce a SCC with high filling ability and adequate viscosity. This type includes glycol-based water-soluble polymers, bio-polymers, polysaccharide polymers e.g. welan and diutan gum, micro organisms and inorganic materials with a high surface area such as silica fume.

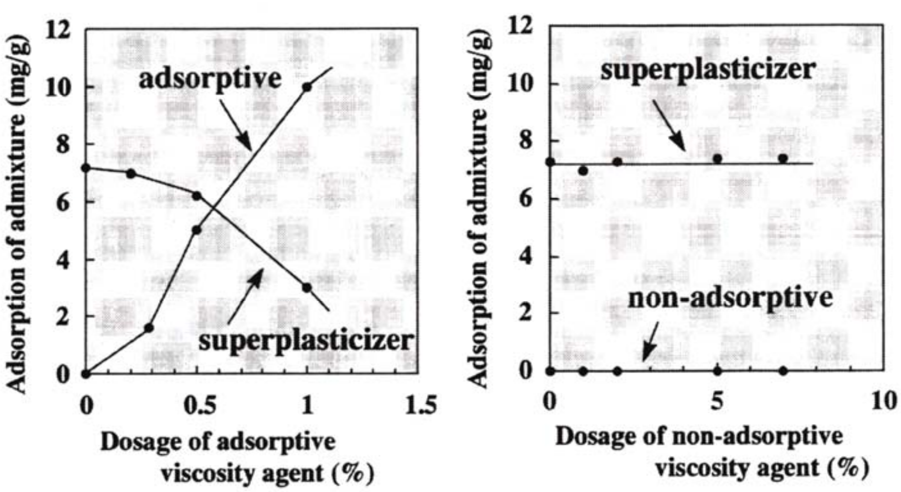


Figure 2-25 The amount of superplasticisers adsorbed with different amount of viscosity modifying agents (Nawa et al., 1998)

It was found that the molecular weights of non-adsorptive VMAs determined their effects on viscosity; a suitable range for SCC may be from 10,000 to 100,000 (Yammamuro et al., 1997).

Welan and diutan gum were first used in Japan and are now frequently used in North America. Both of them are anionic, long-chain biopolymers with sugar backbones substituted with sugar side chains, produced by a controlled aerobic fermentation process (Khayat, 1998). They are high molecular weight polysaccharides, about 2 million for welan gum and 2.9~5.2 million for diutan gum; they are thixotropic and can be used at low concentrations to improve the stability and robustness of SCC without having a significant effect on consistence, thus making quality control easier. Compared to welan gum, diutan gum has a longer side-chain, a larger molecular weight and is more thixotropic (Khayat and Ghezal, 2003; Phyfferoen et al., 2002). For example, welan gum was used as 0.05~0.20% by the mass of cementitious materials or 0.10~0.40%

by the mass of water (Khayat, 1998). In addition, they did not entrap a large volume of air (Khayat, 1995).

However, both welan and diutan gum are expensive. Starch, precipitated silica and new polysaccharide-based VMAs have been studied in an attempt to reduce cost (Lachemi et al., 2004b; Rols et al., 1999): SCCs with these new VMAs had comparable or even better fresh and hardened properties than those with welan gum; and less dosage of these new VMAs were used to produce SCCs with the same consistence as SCCs using welan gum (Lachemi et al., 2004b).

Moreover, additions such as silica fume can act as a VMA. Nanosilica was used as the VMA to study the influences of constituent materials on the rheological properties of the paste of SCC (El Barrak et al., 2009): it had very fine particle size and very large surface area; it acted on the concrete at rest rather than during the flow. Its composition is unclear.

Compatibility

The interactions between superplasticisers and adsorptive VMAs are important to produce SCC. If the compatibility becomes poor, greater consistence loss or segregation occurs, and the SCC degrades. With non-adsorptive VMAs such as welan gum, their long-chain polymers and those in the superplasticiser can restrain one another; in consequence, larger superplasticiser dosage is required for a particular filling ability (Takada et al., 1999).

It is generally thought that the compatibility is closely related to the molecular weight of VMAs and the chemical structure of superplasticiser (Nawa et al., 1998). However, the mechanism is still not clear.

It has been reported that the cellulose-derivative VMAs could be used in conjunction with melamine-based superplasticisers but were incompatible with naphthalene-based superplasticisers; welan gum was compatible with both melamine-based and naphthalene-based superplasticisers (Khayat, 1998).

Rheology

VMAs increase the yield stress and the plastic viscosity; mixes with a VMA show a thixotropic behaviour (Khayat, 1998); that is, they exhibit high viscosity at low shear rate but the viscosity is reduced with the increase in shear rate. This helps placement: once SCC is placed, the viscosity is enhanced because of the association and entanglement of the polymer chains of the VMA at the low shear rate (Khayat, 1999b).

As a result, the consistence loss of VMA-type SCCs is greater than that of powder-type SCCs, which is a disadvantage for application of VMA in SCC. More superplasticiser might be required to compensate for the reduced consistence resulting from the addition of VMAs, and the additional superplasticiser dosage required increased with the increase in the VMA content (Schwartzentruber et al., 2006).

Petersson and Billberg (1999) reported that the slump flow decreased more quickly with an increase in the amount of welan gum; mixes with VMA lost consistence more quickly than those without VMA.

Table 2-7 Variations in superplasticiser dosage due to welan gum added (Khayat, 1995)

Welan gum content (%)	0	0.12	0.20	0.24
A naphthalene-based Superplasticiser (l/m^3)	1.0	3.5	4.0	4.5

The example in Table 2-7 (Khayat, 1995) shows that, to maintain the initial slump of 190±5 mm of a concrete with a W/C ratio of 0.41 and a Type I cement, an increased VMA content requires an increased superplasticiser dosage.

It is also shown in Table 2-7 that a small dosage of welan gum led to a big change of superplasticiser requirement. This may subsequently lead to a bigger change in concrete's performance.

However, VMA does not affect the saturation of a superplasticiser: although an increase of a VMA led to the decrease of spread and the increase of flow time, the saturation value of a superplasticiser remained 0.2% (Schwartzentruber et al., 2006).

Effects on SCC

Adding a VMA to SCC will greatly improve the robustness and reduce the risk of segregation.

Its ability to lower the sensitivity of SCCs to water content was demonstrated by testing the filling ability of SCC (Okamura and Ozawa, 1994): although the water content varied by ± 10 litre/m^3, the U-shaped box (refer to Figure 2-10) values of SCCs with a VMA were still within acceptable ranges. Similar results were reported by Grunewald and Walraven (2005a).

Setting time

In general, adding a VMA can result in delays in setting time because VMA polymer chains adsorb onto cement grains and interfere with the precipitation of various minerals into the solution, thus influencing the hydration rate and setting time (Khayat and Guizani, 1997). Consequently VMAs decrease early strength gain but have no negative influence on later compressive strength (Nehdi et al., 2004).

The effect depends on the type and content of the VMA, as well as the superplasticiser, cement and powder composition, and W/C ratio.

For example, the initial setting time of a paste increased from 11.5 to 20.5 hours after the incorporation of a welan gum at 0.03% by mass of cement; another increase of the welan gum to 0.05% resulted in a further increase in setting time of 2.5 hours. The paste was composed of a Type I cement, a W/C ratio of 0.40 and a naphthalene-based superplasticiser of 0.8% by the mass of cement (Khayat and Yahia, 1997). The retardation was also shown in concretes (Khayat, 1995): the concrete made with a W/C ratio of 0.45, a Type II cement and a superplasticiser of 0.65% by the mass of cement, had a slight delay in setting without a VMA; but the addition of 0.15% welan gum can delay the initial setting by 80 minutes. An increase of 3~6 hours in the initial and final setting time was reported in SCC with welan gum and polysaccharide-based VMAs (Lachemi et al., 2004b).

Comments: Two aspects of VMA must be considered when using in SCC, its characteristics and its interaction with superplasticisers. VMA should not significantly change the consistence of concrete. Therefore the compatibility between VMA and superplasticiser can be assessed by testing the consistence retention.

2.4.1.3 Other admixtures

Superplasticisers and VMAs have been the most commonly used materials in SCC. Anti-foaming agent can be used to overcome the air entrained by VMAs (Petersson, 1999); retarders and slump retaining agents gave longer consistence retention; accelerating agents can be used to improve early strength (Petersson, 1997); thixotropy-enhancing agents reduced the maximum lateral pressure and increased the rate of pressure drop (Khayat and Assaad, 2005); air-entraining (AE) admixtures were used to ensure frost resistance (Khayat, 2000); expansive agents to compensate shrinkage and chemical shrinkage-reducing agents to decrease the shrinkage of SCC. However it is difficult to control the amount of air in concrete when using AE agents. The more admixtures used the more the difficulties of controlling their compatibility and the more trials that may needed to achieve the required fresh properties.

2.4.2 Aggregate

It is believed that a continuous grading of aggregates, which results in a better deformation capacity, is better suited for SCC. In fact, a wide range of aggregate types, sizes and shapes has been used in SCC. Figure 2-26 (Aarre and Domone, 2004) shows that SCC can be produced with significantly different gradings of aggregates.

Depending on the local availability and practice, the dividing line between fine aggregate (sand) and coarse aggregate are different, e.g. 4 mm in Europe

(EFNARC, 2002), 5 mm in Japan (Nawa et al., 1998) and 8 mm in Sweden (Billberg, 1999).

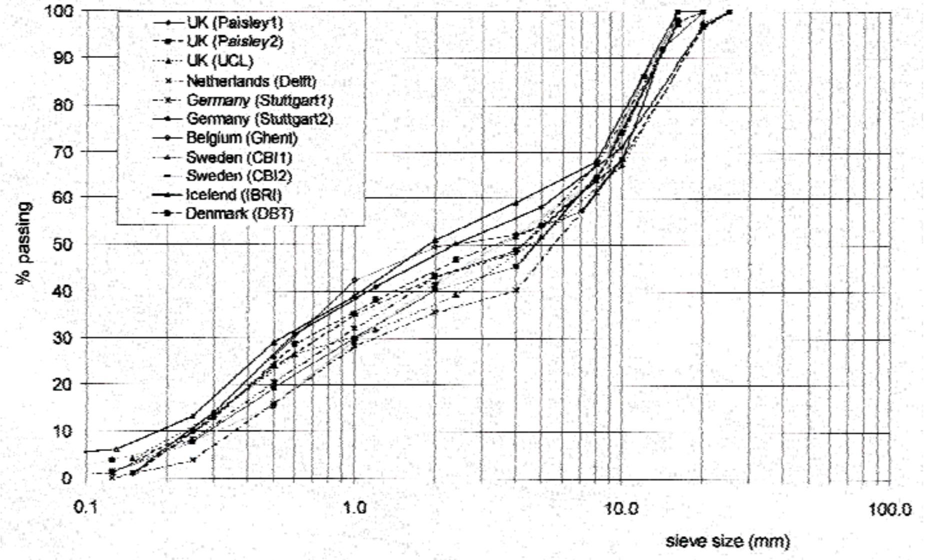


Figure 2-26 Aggregate grading used for successful SCC by Testing-SCC project (Aarre and Domone, 2004)

Although packing does not have much influence on the final strength, it has a major effect on the fresh properties of a concrete (Loedolff and van Zijl, 2005). In fact, realization of a SCC is dependent on aggregate packing. A combination of fine and coarse aggregates and graded aggregates increases the packing density which leads to a reduced superplasticiser dosage and paste volume (Khayat et al., 1999). This also helps segregation resistance because small aggregates can resist the settlement of medium size aggregates which in turn will resist the settlement of large aggregates (Bonen et al., 2007). Better packing enhances strength and durability because of the minimised voids and dense structure. The denser the concrete, the more effective the paste is, which lubricates and fills the voids in concrete to provide consistence and strength.

To minimise the interaction between the aggregates, particle shape is also important. Naturally rounded gravel might be preferable to angular crushed aggregate for SCC. Natural gravels will give a better filling ability because of the smaller inter-particle friction (Billberg, 2002) but crushed aggregate has a beneficial effect on the strength of concrete. According to CBI's model (refer to 2.5.2), using crushed aggregate requires more volume of paste and less aggregate to avoid blocking. It also demands more superplasticiser (Petersson, 1999). Blocking also easily occurs if the shape of aggregate is not spherical.

Therefore, the fineness, shape, distribution, packing density and ratio of sand/coarse aggregates all have influence on fresh properties of SCC.

2.4.2.1 Sand

Sands with well-distributed grading, spherical shape and low absorption are advantageous to SCC. Consequently, the naturally rounded cleaner sand might be preferable to angular crushed sand. In fact, local availability decides its use in SCC (Skarendahl, 2003). Poorly graded and shaped sand was used by increasing the paste volume or the viscosity (Westerholm et al., 2008). Atomized steel slag was successfully used to make SCC (Yoo et al., 2005). This reflects local availability.

Billberg (1999) concluded that the variations in sands did affect the performance of SCC by showing that the influence of aggregate fineness on the slump flow, and the fill height of a U-shaped box varied with different aggregate moisture contents. Similar result was also reported by Embory (2000).

The effect of moisture on the SCC is mainly found in the sand. It is therefore important to control the surface moisture of the sand during SCC production. An error in the calculation of the moisture content of the sand of 0.5% will cause a change in the water content of 8 kg/m^3 in the concrete which could lead to a change in the slump flow of about 45 mm (Bartos, 2005). It is suggested that the minimum moisture content of all aggregates be kept above the saturated surface dry (SSD) level (Bartos, 2005).

The proportion of fine particles in the sand has more pronounced influence on SCC than NVC (Skarendahl, 2003). Fine particles less than 125um in the aggregate increases viscosity (Felekoglu, 2008; Johansen and Busterud, 2001). Fine particles act like clay which increase the W/P ratio, delay cement hydration, have an adverse effect on concrete volume stability (Topcu and Ugurlu, 2003), and lead to an increase in the superplasticiser dosage and decrease the compressive strength (Felekoglu, 2008).

2.4.2.2 Coarse aggregate

Coarse aggregate has an important role when studying the fresh properties; SCC is considered as a two-phase material of mortar and coarse aggregate in many mix design studies.

In fact, an analysis of 63 case studies found that the choice of crushed or gravel aggregates depends on local availability (Domone, 2006b). Lightweight aggregates (Muller et al., 2001; Umehara et al., 1999) and recycled concrete aggregates (Corinaldesi and Moriconi, 2003; Tu et al., 2005) were also used in SCC. Since lightweight aggregate tends to float, higher viscosity may be required to reduce the risk of segregation (Shi and Yang, 2005). The water absorption of recycled concrete used as aggregate could significantly influence filling ability because of the rapid loss of consistence.

Blocking occurs easily if the size of the aggregate is large compared with the reinforcement spacing. Most SCC applications have used coarse aggregate with a maximum size in the range of 16~20 mm depending on local availability and practice (Domone, 2006b). However, in the early development of SCC, it was reported that in the anchorages of the Akashi Kaikyo Bridge connecting Honshu and Shikoku Islands, the maximum size of coarse aggregate in SCC was 40mm (Okamura and Ozawa, 1995).

Okamura and Ouchi (2003b) reported that the decrease in filling ability due to an increase of the coarse aggregate content in concrete occurred regardless of its shape. It is known that blockage is negligible when the coarse aggregate quantity is below 50% of its dry rodded bulk density (typical volume ratio of 32%); for well-graded and well-shaped aggregate, this value could be increased to 60% (Okamura and Ozawa, 1995). Alternatively, the critical coarse aggregate volume ratio is less than 35% (Byun et al., 1998).

2.4.3 Powder

Powder has more pronounced effects on SCC than on NVC due to its larger content. It is important to use the proper powder(s) to achieve the required fresh and hardened properties of concrete. Powders are the smallest solid particles in concrete, and include cement and additions.

The definition of powder size differs, less than 250 or 125 μm in Europe (Billberg, 1999; The SCC European Project Group, 2005) and less than 90 or 75 μm in Japan (Okamura and Ozawa, 1995).

Aggregates in SCC mainly affect blocking, whereas powder particles fill the voids between aggregates and affect the friction and collision between aggregates. The packing of the powder particles themselves is thus important for SCC, which depends on the shape, size and surface characteristics of the particles and their behaviour during mixing.

The amount of particle sizes smaller than 100 μm is an important factor contributing to filling ability and segregation resistance (Noumowe et al., 2006). Tests on pastes with ground granulated blast furnace slag (GGBS) of 8000 cm^2/g or 3200 cm^2/g in Blaine value showed that the paste with the finer powder had a higher segregation resistance than that with the coarser powder (Ozawa et al., 1992a). This is due to the increase in the water retained by the finer powders. Khayat et al. (1999) also reported an increase in the powder content of particle sizes less than 80 μm in SCC led to a greater resistance to surface settlement. However coagulation of very fine particles less than 20 μm led to a higher required superplasticiser dosage to disperse them (Felekoglu, 2008).

The most distinctive features of powder are confining a large amount of water, which can be expressed by the retained water ratio (β_p) and deformation coefficient (E_p) as follows.

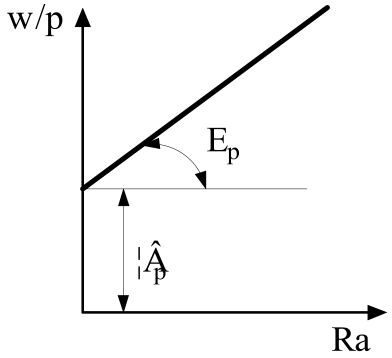


Figure 2-27 Schematic relationship between relative flow area and water to powder ratio

As shown in Figure 2-27, there is a linear relationship between relative flow area Ra (refer to 2.2.2.1) and W/P volume ratio. β_p and E_p are the intercept of the regression line with the W/P axis and the slope respectively.

β_p and E_p has been used to study additions (Domone and Chai, 1997; Takada et al., 1998b): β_p reflects the initial water to commence flow, which includes the water absorbed on the surface of the powder and fills the voids among the powder; the lower the value of β_p, the less water is needed to start flow; β_p depends on the composition and fineness of the powder; E_p reflects the sensitivity of the paste to water change; the larger value of E_p, the more robust the paste.

Table 2-8 The retained water ratio and deformation coefficient of different powders (Domone and Chai, 1997)

	Portland cement	GGBS	Limestone powder	Fly ash
β_p	1.08	1.10	0.77	0.59
E_p	0.061	0.046	0.037	0.024

β_p and E_p depend on the powder's characteristics. Some commonly used powders in SCC are shown in Table 2-8 (Domone and Chai, 1997). Fly ash has the smallest β_p and E_p than others, that is, fly ash starts to flow with the least water required and it is the most sensitive to the variation of W/P ratio. This is due to its spherical particle shape. On the other hand, cement is high in both β_p and E_p. Replacing cement with GGBS, limestone powder and fly ash will therefore lead to a decrease in the water requirement and an increase in the sensitivity to the change of W/P ratio.

2.4.3.1 Cement

SCC has been successfully produced using all kinds of Portland cement such as CEM I, sulphate resisting cement (ASTM C151 type III) and blast furnace slag cement.

The composition of cement affects SCC performance. Because superplasticisers are first adsorbed by the C_3A and C_4AF in cement after mixing, the dispersion efficiency of a superplasticiser depends on the content of C_3A and C_4AF (Nawa et al., 1998). The C_3A and C_4AF content also affect consistence retention due to their initial rapid hydration (Collepardi, 1998). That is why low C_3A and C_4AF cement such as low heat and high belite content Portland cement was preferable in the early development of SCC in Japan.

According to the European guidelines for SCC (The SCC European Project Group, 2005), all cement which conform to EN 197-1 can be used.

2.4.3.2 Additions

SCC usually requires a high powder content. If only cement is used, SCC has a high cost and is susceptible to attack and thermal cracking. It is therefore necessary to replace some of the cement by additions such as fly ash, GGBS or limestone filler.

Additions are ‘finely divided materials used in concrete in order to improve certain properties or to achieve certain properties’ including two types: nearly inert or semi- inert additions (Type I) and pozzolanic or latent hydraulic additions (Type II) (BS EN 206 - 1, 2000). The type II additions are also called pozzolana.

A pozzolana is defined as a “siliceous or siliceous and aluminous material which in itself possesses little or no cementititous value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties" (ASTM C 618, 2003). A typical pozzolanic material used in concrete is characterised by

- a high amorphous silica content, which varies in pozzolanas such as fly ash, GGBS and microsilica.
- a large surface area. In general, fine particles react faster than coarse particles, which lead to higher early strength.
- being X-ray amorphous.

Other factors such as particle shape, Al_2O_3 and CaO content also affect the reactivity of pozzolanas.

The principal chemical ingredients in additions, SiO_2 and Al_2O_3 can react slowly with lime $Ca(OH)_2$ a cement hydration product, leading to the formation of calcium silicate and aluminate hydrates – the pozzolanic reaction. These supplement those produced by the cement hydration and fill the voids in the concrete, improving long term strength and durability by lowering the permeability, reducing shrinkage, creep, chloride ingress and sulphate attack. Pozzolanic reaction also reduces the thickness and porosity of the interfacial zone thus improving the bond strength between paste and aggregate (Kuroda et al., 2000; Wong et al., 1999).

The contributions of additions to the strength significantly vary with their pozzolanic reactivity, which depends on their inherent properties (fineness and vitreous content) and replacement ratios. Fine particles can act as nucleation sites for crystallization of hydration products thus enhancing the strength (Kuroda et al., 2000; Ping and Beaudoin, 1992).

However, at normal temperatures, the reaction between cement and pozzolana is generally slow. To accelerate a pozzolana's reactivity, three methods have been developed: (1) mechanical treatment - pozzolana becomes more active by improving its fineness by grinding; (2) chemical activation - pozzolana's activity can be accelerated by adding chemicals; and (3) thermal treatment – reaction can be promoted by curing in higher temperature or/and higher pressure.

Both types of additions have been used in SCC. Nearly all SCCs included either a binary or ternary blend of cement with Type II additions for the following reasons (Domone, 2006b): to improve rheological or fresh properties, to control strength, to reduce temperature rise and ASR risk and to improve hardened properties.

Although most properties are degraded by including Type I additions in SCC, this is still attractive because of the impact on the environment. Successful incorporation of additions into SCC could turn low-value or waste materials into a valuable resource, thus reducing concrete costs, saving natural resources and reducing CO_2 emission.

Generally speaking, finer additions, which means larger surface area and smaller distance between particles, lead to a higher inter particle friction when concrete is sheared, thus resulting in a higher yield stress and plastic viscosity than those of coarser additions.

The effects of some commonly used additions on the fresh and hardened properties of SCC are summarised as follows:

- Silica fume is an extremely fine powder and very expensive. It increases the shear stress and the plastic viscosity, thus significantly decreasing the slump flow and segregation (Carlsward et al., 2003). Silica fume decreased the ionic strength of the pore solution leading to a reduced consistence loss (Bonen and Sarkar, 1995). The hardened properties and the durability of concrete are also improved. Modest quantities, up to 5%, have been used in SCC (Khayat and Aitcin, 1998).
- Fly ash benefits the rheological properties of concrete because of its spherical particle shape; fly ash improves the filling ability of concrete but leads to low early strength (The Concrete Society and BRE, 2005). Various fineness of fly ash have been used. An ultra pulverised fly ash of Blaine

surface area 500~600 m^2/kg can lead to an increase in the viscosity and a decrease in the risk of segregation, thus producing a SCC with satisfactory properties and with a lower powder content (Xie et al., 2002). Fly ash has no effect on shear thickening (Cyr et al., 2000). Fly ash contributes to the strength at late age due to its pozzolanic nature.

- GGBS increases the viscosity of concrete and higher early strength; as it is latently hydraulic, it can replace up to 70% of the cement by mass; GGBS may extend the setting time (30 minutes) and slightly decrease water demand which may lead to extra bleeding (The Concrete Society and BRE, 2005). Compared with fly ash and limestone powder, concrete with GGBS is more robust to water variation (shown in Table 2-8).

- Limestone powder is a common addition in SCC. Limestone powder increases the yield stress but has little effect on the plastic viscosity and the slump flow (Carlsward et al., 2003).

  Limestone powder is only a filler in the SCC which does not participate in cement hydration (Ye et al., 2007). On the other hand, it has been reported that although limestone is not pozzolanic, it can still contribute to strength (Edamatsu et al., 1999; Pera et al., 1999; Sonebi et al., 2004) because: finely ground limestone particles act as nucleation sites for cement hydration, thus accelerating early age strength development; limestone reacts with cement hydrate products producing a cementitious reactant. Limestone powder may reduce the drying shrinkage of the concrete and decrease the water absorption (Felekoglu, 2008).

Table 2-9 Strength of SCCs with fly ash and limestone powder (Mnahoncakova et al., 2008)

	W/P BY WT.	COMPRESSIVE STRENGTH (MPA)				
		1 day	3 day	7 day	28 day	90 day
SCC with 40% limestone powder	0.28	13.2	36.6	44.4	54.2	63.8
SCC with 40% fly ash	0.24	8.1	21.3	33.4	43.2	63.0

Table 2-9 (Mnahoncakova et al., 2008) shows two SCC mixes incorporating limestone powder and fly ash respectively. Limestone is finer

than fly ash. Particle sizes of both are in the range of 0~300 µm but the cumulative percentages passing 20µm are 62.6% and 31.2% for limestone and fly ash respectively. As shown SCC with limestone has higher strength than that with fly ash up to 28 days and similar results at 90 days; the strength increases from 28 to 90 days are 18% and 46% for SCC with limestone and fly ash respectively. It shows that limestone powder contributes higher early strength and fly ash improves long-term strength.

- Metakaolin is produced by heating china clay. Its quality is more stable than other additions made from industry by-products. Metakaolin increases shear thickening (Cyr et al., 2000). Its normal cement replacement is 5~10% which can decrease the bleeding of the concrete; higher replacement up to 20% in SCC can enhance permeability resistance (The Concrete Society and BRE, 2005).

- A few SCCs incorporating chalk powder in the range of 25~55% of total powder were reported (Zhu and Gibbs, 2005): the SCC mixes with chalk powder required higher superplasticiser than those with limestone powder for the same filling ability; chalk powder may contribute to the strength gain; the compressive strength of the SCCs using two chalk powders showed a strength increase of 67% and 70% at 7 days, 23% and 28% at 28 days and 23% and 18% at 90 days, compared with the NVC of the same W/C ratio.

As well as the common additions as above, SCC was successfully produced with fine sawdust ash with satisfactory slump flow, V-funnel time, U-box and L-box and compressive strength (Elinwa et al., 2008). Crushed tire rubber (Bignozzi and Sandrolini, 2006), quarry fines (Ho et al., 2002) and fines in sand (Felekoglu, 2008) have also been used in SCC with careful attention to mix design. This can reduce costs and provide benefits to concrete producers.

Among the above, fly ash is abundant in most countries as an industrial by-product and has been proven to significantly improve the fresh and hardened properties of concrete (Neville, 1996). Its effects on concrete and SCC are discussed in detail in 2.6. The application of glass in concrete is also reviewed in 2.7 because of its availability, increasing production and potential use in SCC.

Comments: Due to the higher powder content in SCC, the effects of additions on water absorption, filling ability, cement hydration and hardened properties have to be considered. The compatibility between additions and superplasticisers is also an important factor to decide SCC performance. SCC properties could be improved or deteriorated by replacing cement with additions.

2.4.4 Water

Water has profound effects on both the fresh and the hardened properties of SCC. Water decreases both the yield stress and the plastic viscosity. Concrete is much more prone to segregation if only water is added to increase the filling ability. Because of this, SCC could not have been developed until suitable superplasticisers were produced.

Water in the fresh concrete includes freely movable water and the water retained by the powder (additions and cement), sand and VMA. Coarse aggregate does not confine water. It is the free water that controls the performance of SCC. Free water is one of the main factors determining the filling ability and segregation resistance (Ozawa et al., 1992a). This is confirmed by Kasemchaisiri and Tangermsirikul (2008), free water content was used to predict slump flow and T500 with satisfactory accuracy in a deformability model.

The moisture content of the aggregate has a significant effect on free water content. The moisture variation in sand of 3~4% led to a W/C ratio variation of ± 0.1 (Persson, 2000). It is therefore important to correctly estimate aggregate's moisture content. Testing-SCC project recommended that the moisture content of aggregates should be more than the level of SSD (Aarre and Domone, 2004).

The robustness of a mix thus can be tested by its sensitivity to the water variation.

Water content is another important factor to maintain consistence retention besides superplasticiser types; that is, the higher the W/C ratio, the lower the consistence loss for the same initial consistence (Felekoglu and Arikahya, 2008).

2.4.5 Others

Entrapped air increases the slump flow and reduces the plastic viscosity (Carlsward et al., 2003). Since air bubbles confine only a small amount of water and they cannot prevent aggregate particles from coming in contact with each other, they can be regarded simply as filling materials in SCC (Okamura and Ozawa, 1995). However bubbling is a sign of segregation.

To modify the ductility/toughness of the hardened concrete, steel fibre (Barragan et al., 2005; Busterud et al., 2005), carbon fibre (Uebachs and Brameshuber, 2005) and glass fibre (Xu and Li, 2005) have all been used successfully in SCC with careful mix design method. However, they all lead to a reduction in filling ability and an increase in blocking.

2.4.6 Conclusions

SCC could not have been produced without the development of superplasticiser technology. The use of a superplasticiser enhances consistence. The performance of superplasticisers varies significantly with ambient temperature, properties of cement and superplasticiser and their interaction, and characteristics of other ingredients. Superplasticisers' imbibing water, associating and entangling with time and cement hydration are the main cause of consistence loss.

VMA results in a reduction in consistence, which can be reversed by increasing the superplasticiser dosage. A properly combined use of superplasticiser with VMA secures a mix with high filling ability, stability and robustness. However, superplasticisers and VMAs can result in some delay in setting time.

As superplasticisers themselves are developed to achieve the required fresh properties of SCC and the new generations of superplasticisers can provide good segregation resistance, VMA may not be necessary in SCC.

The choice of aggregates and powders in SCC depends on local availability. Because of various shape, fineness and other characteristics, powders have different effects on SCC. Type II additions are commonly used in SCC while Type I is also encouraged to widen its application for environmental reasons. Among those, fly ash and ground glass are presented in more detail later.

It is difficult to predict SCC performance in its fresh and hardened states because of the interactions among the cement, additions, superplasticisers and VMAs. It is therefore essential to do laboratory trials in designing the SCC, as described in the following section.

2.5 Mix design methods

To secure the required balance between the fresh properties of SCC, which are contradictory in nature, the proportion of the constituent materials must be carefully designed. Mix design methods of both SCC and NVC are based on volume composition with subsequent conversion to batch weights for production. There are two main differences in the mix design methods between SCC and NVC.

- Like NVC, the choice of constituent materials of SCC depends on local availability to reduce cost (Skarendahl, 2003) and the characteristics of the materials exert more effects on SCC than on NVC. In consequence, mix design methods have to be made locally, the properties of SCC are more difficult to predict than those of NVC and more testing after design is necessary.
- The design of NVC start from determining the W/C ratio to meet the strength requirement and finishes by calculating the amount of aggregates according to a British method (Building Research Establishment Ltd, 1997). SCC on the other hand is usually designed starting with the required fresh

properties; the principles are adding superplasticisers with/without VMA, limiting the aggregate content and an appropriate W/P ratio to meet the fresh-property requirement. Designs of SCC usually do not consider strength because the W/P ratio of SCC is low (refer to Table 2-1) which ensures high strength, often greater than is required for structural purposes.

SCC is a family of concretes, which contains a broad range of fresh properties. There are no standard methods for SCC mix design. Because of different conceptions and a wide range of possible constituent materials, many methods have been proposed and developed. Among these, the general-purpose method and the CBI method and their extensions, have led to a clearer understanding of SCC performance and wider use and are therefore described in this section. Because it is simple, effective and can be readily applicable to local materials, the UCL method is discussed in detail. A number of other methods are also briefly reviewed.

2.5.1 General purpose mix design method and extensions

The general purpose mix design method was developed in the University of Tokyo by Okamura and Ozawa et al (Okamura et al., 1993; Okamura and Ouchi, 1999; Okamura and Ozawa, 1994; Ozawa et al., 1990). It is based on the use of Japanese materials, e.g. a maximum size of coarse aggregate of 20 mm, a 5 mm division between fine and coarse aggregate, moderate heat Portland cement used and air entrainment agents (AEA) used, which are mixed by a forced mixer, pan type or pug mill type. This method suits powder-type SCC.

It is a step-by-step method in which parameters are set for each stage. It regards SCC as having two parts, mortar and coarse aggregate. Mortar is composed of the powder, including cement and fine particles less than 0.090 mm in the fine aggregate, fine aggregate (particles more than 0.090 mm), water and admixtures. The five parameters including air content, coarse aggregate volume in concrete, fine aggregate volume in mortar, W/P volume ratio and superplasticiser dosage by powder weight are determined as follows.

1. The air content is assumed to be 4~7% of concrete volume for concrete with AEA, 1% for that without AEA.

2. The coarse aggregate volume is 50% of its dry rodded bulk density.

3. The fine aggregate (particles more than 0.090 mm in fine aggregate) to mortar volume ratio is 40%.

4. The W/P volume ratio and superplasticiser dosage are estimated from mortar tests (see 2.2.2). A spread of 250 mm (relative flow area of 5) and a V-funnel time of 9~11 seconds (relative flow velocity of 0.9~1.1) were considered as suitable for producing SCC.

5. The W/P ratio and superplasticiser dosage are subsequently used in the concrete trials and adjusted if necessary until a slump flow of 650 mm and a V-funnel time of 10~20 seconds are achieved.

   A U-box height of larger than 300 mm sometimes is used for adequate passing ability.

According to this method, the mortar is the first step in producing SCC: it has properties that ensure the filling ability, passing ability and segregation resistance of the concrete itself; and possess sufficient viscosity to support the coarse aggregate. This method gives a better analysis and understanding of the behaviour of SCC than others.

In this method, the coarse aggregate volume (about 32%) is in the middle of the range of most for SCC of 28.0%~38.6%; the sand/mortar volume ratio of 40% is lower than the middle of the range of 38.1~52.9% (refer to Table 2-1). It therefore produces more paste and powder content than often required. Since cement is the only powder considered in this method and a low W/P ratio is achieved, the fresh and hardened properties are more than adequate for most requirements (RILEM TC 174 SCC, 2000). In addition, the targets for mortar and concrete produced a SCC with high viscosity (refer to 6.1).

2.5.1.1 Extensions of the general purpose method

Several modifications to the general purpose method have been developed as follows:

- The relationships between relative flow area (Ra) and relative flow velocity (Rv) (refer to 2.2.2.1) were found to be linear for a constant superplasticiser dosage and non-linear for a constant W/P ratio ($Rv = A.Ra^{0.4}$) all passing through the origin (shown in Figure 2-28). There was also a linear relationship between the constant A and the W/P ratio (Ouchi et al., 1998; Ouchi et al., 2001). The relationships were considered to be independent of materials and were used to find the required combination of W/P ratio and superplasticiser dosage for a mortar with a specific spread and V-funnel time. Consequently, the mortar tests are minimised.

  However, it seems that such relationships are not obtained with U.K. materials. Approximately linear relationships between Ra and Rv for both constant W/P ratio (0.28~0.38) and superplasticiser dosages (0.25~1.5%) were reported on a mortar with Glenium 51 (Domone, 2006a). This can be schematically shown in Figure 2-29.

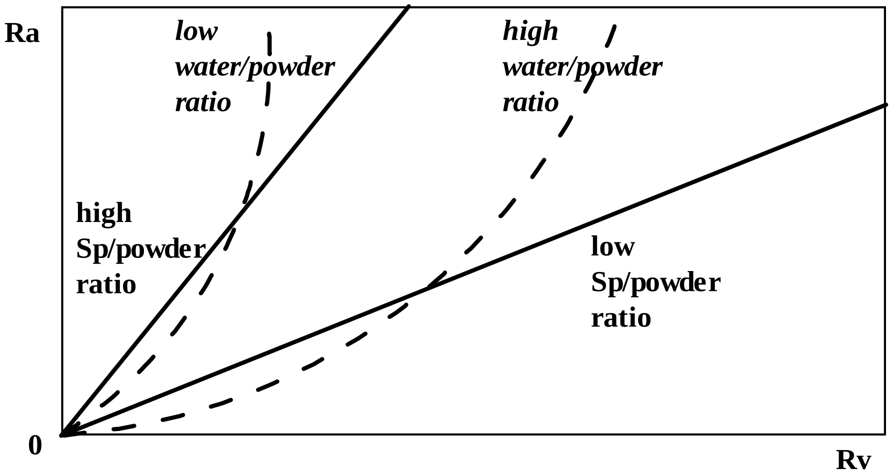


Figure 2-28 Schematic relationships between Ra and Rv for moderate heat cement mortar, sand/mortar=40%

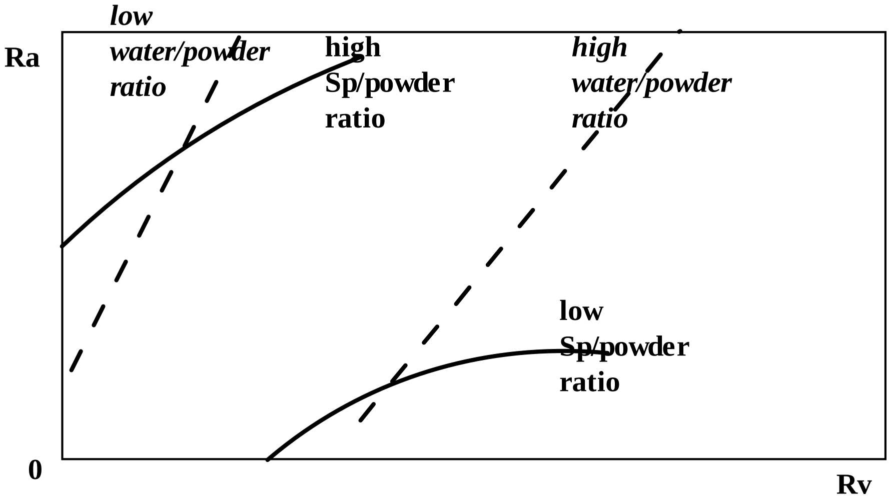


Figure 2-29 Schematic relationships between Ra and Rv for mortars in U.C.L. sand/mortar=45%

- The general purpose method has been successfully applied in the Netherlands (Bennenk, 1999; Pelova et al., 1998; Takada et al., 1998b; Walraven, 1998). By adapting it for Dutch materials with a maximum size of coarse aggregate of 16 mm, the coarse aggregate content was increased to 55~60% of its dry rodded bulk density and the W/P ratio for the concrete was 5% more than the W/P ratio derived from the mortar test. The paste content was therefore 10% less than that in the general purpose method. It was confirmed that this method could be used in SCC with welan gum as a VMA with 0.05% of the water content.

- In a study on the influence of the physical properties of particles in mortar on the fill height of fresh concrete, the interaction between coarse aggregate and mortar was evaluated by using 10 mm glass beads employed as the standard coarse aggregate (Edamatsu et al., 1999). The sand to mortar volume ratio was set at 40%, the same as in the general purpose method. The ratio of the relative flow velocity of mortar with and without 25% glass beads (R_{mb}/R_m) correlated to the fill height of the concrete in the U-box tests, and can be used to design different filling requirements in SCC by testing mortar only. This was also applicable to SCCs incorporating different powders including Portland cement, fly ash, GGBS and limestone powder.

2.5.1.2 Developments at UCL

The mortar experiments in general-purpose method are useful for a quick evaluation of design SCC, and it seems that when the mortar is right, the mixes will achieve the required properties. Based on this principle, research on SCC started at UCL in 1994 with a substantial laboratory investigation by Chai and Jin, and continued in the current research.

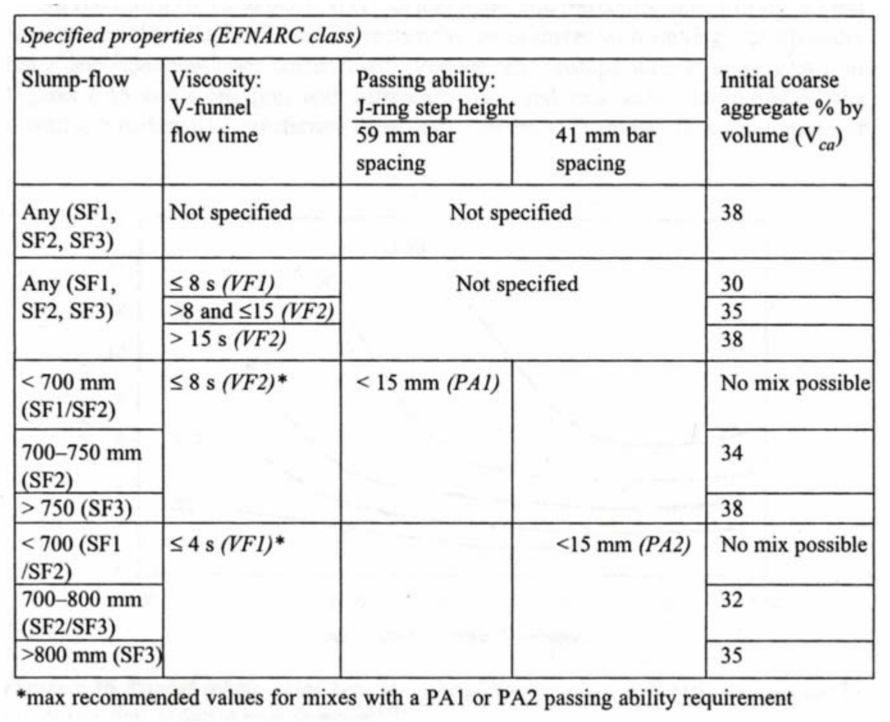
Chai (1998) developed a mix design method of producing SCC with readily available UK materials by optimising the cementitious content for a maximum size of coarse aggregate type and size. This mix design method was adapted for the Testing-SCC project (2005) to develop mixes for the comparison of test methods.

Jin (2002) tested the mortar phase of SCC. The relationships between the properties of the mortar and the derived SCC with coarse aggregate of 50~55% of its dry rodded bulk density were established. Mortar testing was shown to be an efficient and effective method of assessing SCC, e.g. the delayed addition time of superplasticisers, the effect of the powder composite including binary and ternary blends of Portland cement with fly ash, GGBS, silica fume and limestone powder on SCC, the binder/superplasticiser interaction, and the effect of viscosity agents etc.

Based on Jin’s work, the relationships between the properties of the mortar and the derived SCC with a higher coarse aggregate content (55~65% of its dry rodded bulk density) were established in the research and adopted. SCC with a high volume of fly ash and SCC with ground glass (this project), SCC with recycled aggregate and VMA-type SCC (third year projects in UCL) have been successfully produced, which confirm and support this method.

The UCL method described as follows includes the modifications from the above research.

Table 2-10 Initial coarse aggregate content recommended in UCL method (De Schutter et al., 2008)



Specified properties (EFNARC class)				Initial coarse aggregate % by volume (V_{ca})
Slump-flow	Viscosity: V-funnel flow time	Passing ability: J-ring step height		
		59 mm bar spacing	41 mm bar spacing	
Any (SF1, SF2, SF3)	Not specified	Not specified		38
Any (SF1, SF2, SF3)	≤ 8 s *(VF1)*	Not specified		30
	>8 and ≤15 *(VF2)*			35
	> 15 s *(VF2)*			38
< 700 mm (SF1/SF2)	≤ 8 s *(VF2)**	< 15 mm *(PA1)*		No mix possible
700–750 mm (SF2)				34
> 750 (SF3)				38
< 700 (SF1 /SF2)	≤ 4 s *(VF1)**		<15 mm *(PA2)*	No mix possible
700–800 mm (SF2/SF3)				32
>800 mm (SF3)				35

***max recommended values for mixes with a PA1 or PA2 passing ability requirement**

1. Coarse aggregate is estimated from Table 2-10 (De Schutter et al., 2008). The method is applicable to a coarse aggregate of 16 or 20 mm maximum size, crushed or uncrushed; the dividing line between coarse and fine aggregate is 4 or 5 mm.

2. Sand to mortar volume ratio is set at 45% which is a typical value for SCC (Domone, 2006a).

3. Air content is estimated as 1%.

4. Cement content is estimated based on previous experience and the 28-day compressive strength required.

5. Water/powder ratio, admixture dosage and powder composition are determined from mortar tests.

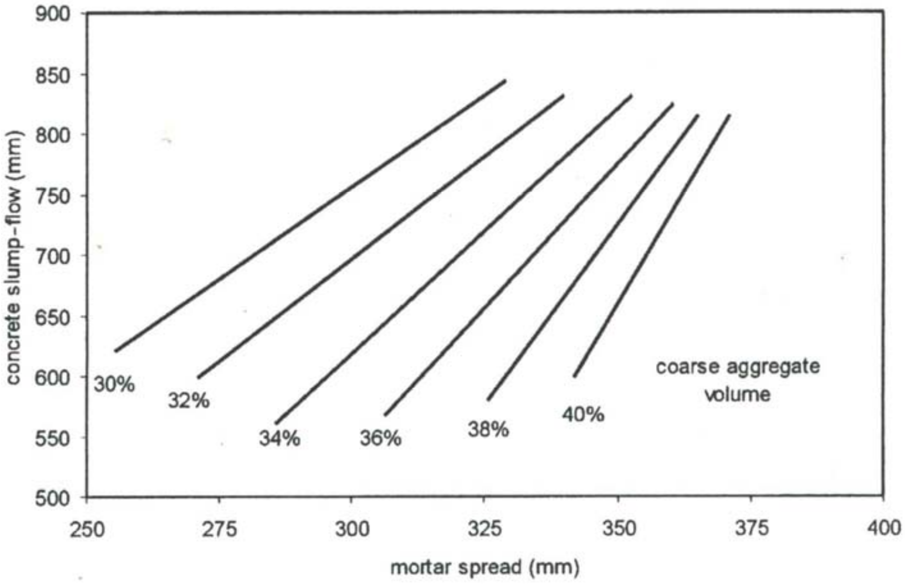


Figure 2-30 Spread of mortar vs slump flow of SCC with various coarse aggregate contents (De Schutter et al., 2008)

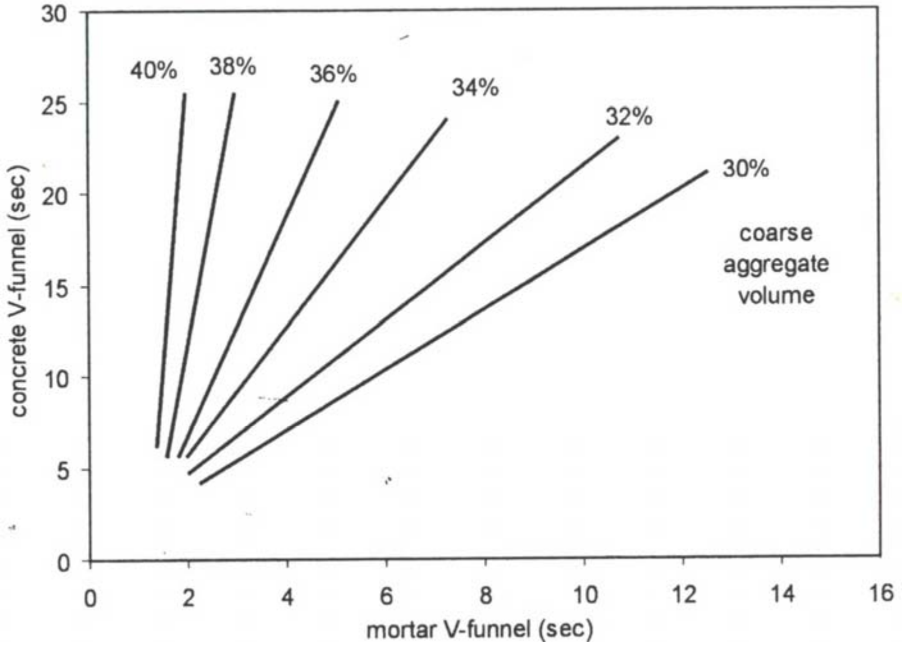


Figure 2-31 V-funnel times of mortar vs SCC with various coarse aggregate contents (De Schutter et al., 2008)

Good correlations have been established between the spread of mortar and the slump flow of concrete (shown in Figure 2-30 (De Schutter et al., 2008)), and between the V-funnel time of mortar and that of concrete when the coarse aggregate volume in concrete is 30~40% (shown in Figure 2-31 (De Schutter et al., 2008)) for UK materials. Using these graphs, the required spread and V-funnel time of mortar are obtained from the specific slump flow and V-funnel time of SCC.

The effect of the W/P ratio and superplasticiser contents on mortar can be shown on the graph of spread vs V-funnel time, which varies with different superplasticisers and powders (refer to 5.4). This is obtained from tests on the specific materials to be used.

For the required spread and V-funnel time, the W/P ratio and superplasticiser dosage are then obtained from the above graphs. The content of additions is also adjusted in the tests to meet the required spread and V-funnel time.

The paste composition for the required SCC, W/P ratio, the admixture dosage and powder composition are therefore determined.

6. Concrete trials are then carried out to test the proportions and if required, adjustments are made until the specific properties are obtained. The slump flow and the V-funnel test, the J-ring test and the sieve stability test are used to confirm the filling ability, passing ability and segregation resistance respectively.

It can be seen from the above that the mortar properties have a significant effect on the performance of SCC. The reason are: SCC contains a higher amount of mortar and lower coarse aggregate than NVC and variations in aggregate are limited; mortar contains all the constituent materials to create SCC, such as superplasticisers, VMA and powder materials; the filling ability of SCC is fully reflected in mortar. Once the mortar properties are established, subsequent concrete tests are minimised. In addition, testing mortar is more efficient and convenient than testing concrete.

The importance of testing mortar in SCC is summarised by Domone (2006a). In fact, assessing the mortar properties becomes an integral part of UCL method. This is also confirmed by Lachemi et al (2007) who revealed that the rheological properties of mortar had better correlations with the flow characteristics of the corresponding SCC thus more relevant to design a SCC.

However, concrete trials are indispensable because of the influence of coarse aggregate and the interactions among the constituent materials (refer to 2.4). Therefore, the actual performance of SCC can only be fully evaluated in concrete tests.

This method is relatively simple and effective. SCC can be designed to have various fresh properties and it is applicable to SCC with a wide range of constituent materials including VMA.

However, the above relationships are based on U.K materials. Validation needs to be confirmed before use.

2.5.2 CBI method and extensions

The CBI mix design method was proposed by the Swedish Cement and Concrete Research Institute (Billberg, 1999; Billberg, 2002; Billberg and Petersson, 1996; Petersson et al., 1996; Petersson et al., 1998; Petersson and Billberg, 1999). It considers SCC as being composed of aggregates and paste that is made up of water, admixture and powders. Powder means all particles less than 0.125 (Billberg, 2002) or 0.25 mm (Billberg, 1999) including cement, additions and fine particles in the fine aggregate. It aims to produce a mix with an optimum aggregate skeleton and hence the minimum but sufficient paste content and is based on the blocking criterion.

This design method consists of three stages, namely, to calculate the minimum paste volume, paste composition and SCC evaluation.

Step 1 The minimum paste volume

The minimum paste volume is derived from the void content and blocking criterion, which are in turn based on the aggregate properties and the structural conditions.

The void content is measured by varying the coarse/fine aggregate ratio, which also affects the total aggregate surface area. The minimum paste volume should fill all voids in the aggregates and envelop all surfaces of the aggregate particles.

The blocking criterion came from a study on the blocking risk of the mortar composed of single-sized sand (Ozawa et al., 1992a). They found that the influence of each single-sized sand on mortar blocking is independent of each other and the blocking risk of a multi-size aggregate is expressed as:

$$\text{Risk of blocking} = \sum_i \left(\frac{n_{ai}}{n_{abi}} \right)$$

where n_{ai} is the volume ratio of a single-sized aggregate group and n_{abi} is the blocking volume ratio.

The concept was then extended to concrete and a relationship between the blocking volume ratio of aggregate (n_{abi}) and the ratio of reinforcement clear spacing to the average diameter of aggregate particle (D_{ca}) was found (Bui, 1994; Ozawa et al., 1992b; Tangermsirikul, 1998; Tangermsirikul and Bui, 1995). This is shown schematically in Figure 2-32.

The parameters are defined as

$$n_{abi} = \frac{V_{abi}}{V_t}$$

$$D_{ca} = \frac{c}{D_{af}}$$

$$D_{af} = M_{i-1} + \frac{3}{4}(M_i - M_{i-1})$$

$$K = \frac{\phi}{D_{\max}}$$

Where n_{abi} is the blocking volume ratio of aggregate group i;

V_{abi} is the blocking volume of aggregate group i;

V_t is the total volume of the concrete mix;

D_{ca} is the ratio of clear spacing (c) to aggregate particle size (D_{af});

M_i and M_{i-1} are the upper and lower sieve dimensions of aggregate group respectively.

K is the ratio between reinforcement diameter (Φ) and maximum size of aggregate (Dmax)

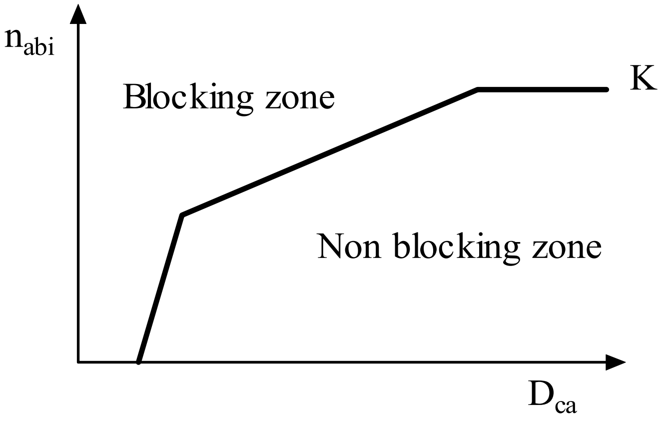


Figure 2-32 A schematic relationship between blocking volume ratio and clear spacing to particle size ratio in CBI mix design method

The above blocking criterion is related to the aggregate properties (e.g. crushed or uncrushed, the size and the overall grading of aggregates) and placing conditions (e.g. diameter and the space of reinforcement bars). This is one of the advantages of this method.

The maximum total aggregate content without blocking occurs when the risk of blocking equals 1 as

$$\text{Blocking criterion} = \sum_{i=1}^{n} \frac{V_{ai}}{V_{abi}} = 1$$

where V_{ai} and V_{abi} are the volume and blocking volume of aggregate group i respectively.

Therefore, this model will lead to a minimum paste volume, which makes a concrete with sufficient filling ability without aggregate blocking.

Step 2 Paste composition

The powder consists of cement and filler, which contribute to the strength and the paste volume respectively. Hardened concrete requirements determine the maximum W/C ratio allowed and cement type. Good correlations between rheological properties of paste and filling ability of concrete were established by performing rheological tests on the fine mortar with a viscometer to determine the powder composition and estimate the superplasticiser dosage (Petersson et al., 1996). This leads to the minimum yield stress and proper viscosity.

It recommended that the Bingham ranges of the paste for SCC should be yield stress of 10~20 Pa and plastic viscosity of 0.5~1.2 Pa.s (Billberg, 1999; Petersson et al., 1996).

Step 3 Self-compacting concrete evaluation

The superplasticiser dosage is adjusted in concrete tests to meet specific recommendations e.g. slump flow more than 700 mm and the blocking ratio of the L-box test higher than 0.80 (refer to 2.2.3.2). The time for the front concrete to reach a distance of 200 mm or 400 mm is sometimes tested but there are no recommendations for appropriate values. The mix proportion of concrete is then finally established.

It can be seen from above that the W/P ratio and powder composition resulted from strength and durability requirement, which is another advantage of this method. Therefore, it is possible to produce SCC with a strength and durability to suit all kinds of situations. However CBI method requires previous knowledge of blocking of each aggregate. The reference curve for the blocking criterion in Figure 2-32 is not general and is not easy to get.

Modifications have been developed as follows.

- The concept of a 'liquid phase criterion' (Bui and Montgomery, 1999b) was developed to provide an additional criterion to calculate the minimum paste volume. The aim is to calculate the minimum spacing between aggregate particles, which varied with the W/P ratio, the maximum size of coarse aggregate and the average aggregate diameter. The targets for SCC are slump flow $\geq$ 650 mm, T500 $\leq$12 seconds and penetration depth $\leq$8 mm. VMA is not considered in this method.

- VMA can be used to reduce paste volume further (Petersson and Billberg, 1999).

- Based on parameters e.g. the free water content, the water retained by powders and aggregates, the minimum free water content to start flow, and the effective surface area of solid particles, models for predicting the key properties of SCC were proposed (Kasemchaisiri and Tangermsirikul, 2008; Kasemsamrarn and Tangtermsirikul, 2005) and verified by the results of the authors and other researchers. By these models, the slump flow, T500, bleeding and risk of blocking can be predicted with satisfactory accuracy. These models are powerful and useful to mix design various SCCs. However, it is not clear how to derive mentioned parameters

2.5.3 JSCE method

This is the only method proposed for the design of a SCC with VMAs. Different constituent material ranges are specified for mixes with or without VMA and with various different VMAs as shown in Table 2-11 (Japan Society of Civil

Engineers, 1998). Consequently, the fine aggregate content can be calculated from the volumes of coarse aggregate, water, powder and air.

Table 2-11 JSCE recommendation (Japan Society of Civil Engineers, 1998)

	SCC without VMA	SCC with VMA
Coarse aggregate content	0.30~0.32 m^3/m^3; maximum size 20 or 25 mm.	
Water content	155~175 kg/m^3	≤ 180 kg/m^3
Water/powder ratio	28~37% by weight	Depends on the type and content of VMA
Powder content	0.16~0.19 m^3/m^3	
Air content	4.5%	

2.5.4 Aggregate packing model

Su et al. proposed an alternative method by determining aggregate content first then filling this with the optimum paste containing fly ash and GGBS (Su et al., 2001; Su and Miao, 2003). It aims to design a medium strength (28~35 MPa) SCC, which is economical due to the large amount of cement replaced by fly ash and GGBS, which are also used to improve consistence. The 28-day compressive strength of the concrete is determined by the W/C ratio and cement content; consistence is determined by the aggregate/paste volume ratio and superplasticiser dosage.

This is a way to design SCC for strength, which is consistent with practice codes. The method leads to less paste, thus saving costs and improving strength, permeability, creep and drying shrinkage. It was successfully applied in the Netherlands (Brouwers and Radix, 2005) and adapted for lightweight SCC in South Korea (Choi et al., 2006).

It should be noted that this method ignores the contribution of GGBS and fly ash to the strength by using the W/C ratio in order to simplify the design. This may lead to a higher long-term strength than required.

2.5.5 LCPC method

This French approach was developed at the Laboratoire Central des Ponts et Caussées (LCPC). Sedran and De Larrard (1999) used a ‘solid suspension’ model to predict void content between the aggregate aiming to optimise the aggregate skeleton thus minimising the water requirement for SCC. The concept of ‘reference relative viscosity’ is used to evaluate the packing state of the constituent materials and an optimised overall particle size distribution is obtained.

This method has reduced concrete trials, however, it required a number of preliminary tests and it does not apply to mixes with VMA.

2.5.6 Rheology designs

Rheology is important to SCC not only as a tool to study and understand it, but also as an important way to design it. Successful production of SCC is based on the premise of paste or mortar having satisfactory rheological values. The requirements for the paste or mortar of a typical SCC are similar to those of SCC itself; that is, a low yield stress to ensure filling ability and a proper viscosity to avoid blocking and segregation. The below mix methods, based on rheological investigations on the corresponding paste or mortar of SCC, are discussed.

A model was developed to explain SCC’s passing ability by using the rheological constants, that is, both the yield stress and the plastic viscosity which increase when SCC passes through narrow spaces due to the reduced excess paste thickness (Noguchi et al., 1999; Oh et al., 1999; Reinhardt and Wustholz, 2006). The excess paste thickness is half the distance between the two neighbouring aggregates on the premise that the distance is independent of aggregate size. The relationships between slump flow, T500, V-funnel time, yield stress and plastic viscosity of SCC and the excess paste thickness can be used to design SCC.

Saak et al (2001) modelled the segregation resistance by using one size spherical particles suspended in the cement paste. Segregation of concrete is dictated by the yield stress, the viscosity and the density of the paste; SCC is designed by controlling the aggregate segregation in both static and dynamic conditions by rheological tests. So far this is the only design method aiming at low segregation. For a given aggregate content, there is a minimum viscosity and yield stress to prevent segregation. This model was then developed by considering the interactions among particles (Bui et al., 2002a).

Other rheological methods for SCC are based on investigations into

- the optimum proportions of constituent materials (Tang et al., 2001; Wallevik and Nielsson, 1998).
- the relationships between paste and concrete (Lachemi et al., 2004a; Pedersen and Smelpass, 2003; Saak et al., 2001).
- measuring the Bingham parameter of mortar (Jacobs and Hunkeler, 1999). The clearer segregation resistance criterion for mortar and SCC is 0.1 Pa and 67 Pa respectively, and no segregation occurred during the tests (Petit et al., 2007).

2.5.7 Factorial design

Since many factors influence SCC properties, factorial design has been used to optimize the constituent materials and minimise testing. Key parameters, such as powder content, powder composition, W/P ratio, coarse aggregate volume ratio, superplasticiser and VMA dosage are selected and a set of mixes with appropriate combinations of these parameters are tested and their respective influence on SCC are described (Khayat et al., 2000; Sonebi, 2004).

This method is useful in examining the effect of key parameters and their interaction on SCC performance during various tests. For example, consistence retention was influenced mostly by the binder content, followed by the water/binder ratio, the VMA content and then the coarse aggregate volume (Ghezal and Khayat, 2002). This method reduces concrete trials. However the conclusion is only valid for a given set of materials tested. For example, 0.38~0.72 W/P ratio, 250~400 kg/m^3 of cement content, up to 120 kg/m^3 limestone filler and 0.12~0.75% of superplasticiser by mass of powder was proposed to achieve a given slump flow, viscosity, passing ability, segregation resistance and 28-day compressive strength (Ghezal and Khayat, 2002).

This method however was not investigated in this research. There are many factors influencing SCC and if the optimum mix proportions could be deduced by factorial design, more tests are required to meet the targets. A major concern is that those tests require some time to perform. If acceptance of a mix proportion is based on such tests, material variations may make constant quality of SCC impractical. For example, $2^5 = 32$ tests are needed if only five factors, e.g. W/P ratio, addition content, superplasticiser dosage, sand to mortar volume ratio and coarse aggregate content, are considered which is far more than the number of the trials needed to find the target mixes by other methods.

2.5.8 Conclusions

The aim of designing a SCC is to find suitable mix proportions to meet the required properties. Due to the wide range of possible constituent materials, many methods, which are based on scientific theories or empirical evidence, have been published. The most common ones are testing the relationships between paste or mortar and concrete, optimising aggregate and powder packing and predicting the required paste or mortar from the voids content of the aggregate.

No comparison of mixes designed by the different methods was carried out due to the difficulty of use of some of these. The general-purpose method, the CBI method and the UCL method are examined further and direct comparisons between them made in Chapter 6.

2.6 Fly ash

Pulverized fuel ash (pfa, but now commonly called fly ash) is a by-product of electricity production in coal-fired power stations. It consists of oxides of silica, alumina, iron, calcium and various minor constituents. Due to the high temperature of formation, these are mainly in a glassy phase and the particles, particularly those less than about 45 µm, are mainly spherical.

Fly ash is readily available. In the UK there are about 250 million tonnes stock-piled and around 5.5 million tonnes are being produced annually[3]. Not all fly ash can be used, and approximately 50%[4] of the annual production is currently landfilled. In 2007, about 58%[5] of fly ash produced was used in construction products, such as cement raw material and blended cement, concrete additions and non-aerated blocks, grouting, aerated blocks manufacture, fill and ground remediation. Considering the following well-known benefits of using fly ash, there is a potential to increase the utilisation rate.

2.6.1 Fly ash in concrete

As shown below, fly ash can be used in concrete as a Type II addition[6] complying to BS EN 450 (2005) or a Type I addition[7] complying to BS EN 12620 (2002) as filler aggregate. BS EN 450 includes two categories with category S fly ash being finer and contributing greater strength.

Table 2-12 Classification of fly ash according to BS EN 450 (2005) and 12620 (2002)

SPECIFICATION	FINENESS	APPLICATION
BS EN 450 2005	Category S: ≤ 12.0 % retained on the 45 µm sieve	type II addition
	Category N: ≤ 40.0 % retained on the 45 µm sieve	
BS EN 12620	70~100% passing the 63µm sieve	type I addition

In addition, fly ash also can be used as lightweight filler aggregate according to BS EN 13055-1 (2002).

Another widely adopted classification is given in Table 2-13 (ASTM C 618, 2003). Fly ash is classified according to the types of coal and the total content of SiO_2, Al_2O_3 and Fe_2O_3 by American Society for Testing and Materials. Compared with Class F, Class C fly ash has higher CaO, MgO and SO_3. Class F

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[3] http://www.ukqaa.org.uk/Environment/Code_of_Practice_January_2003.pdf

[4] http://www.ukqaa.org.uk/Datasheets_PDF/Datasheet_8-1_July_2007.pdf

[5] http://www.ukqaa.org.uk/PowerAndStats/2007Utilisation.pdf

[6] Pozzolanic or latent hydraulic additions (refer to Glossary of Terms)

[7] Inert additions (refer to Glossary of Terms)

fly ash is a pozzolanic material while Class C exhibits direct cementitious activity. Only Class F fly ash is available for use in concrete in the U.K. (Manz, 1999).

Table 2-13 Classification of fly ash according to ASTM C618 (2003)

CLASSIFICATIONS	TYPES OF COAL	$SIO_2 + AL_2O_3 + FE_2O_3$ (%)
Class C fly ash	Lignite or subbituminous coal	≥ 50.0
Class F fly ash	Bituminous or anthracite coal	≥ 70.0

Fly ash is one of the most widely used additions in concrete. It has been extensively investigated over many years and there are numerous publications about its various roles in concrete. The physical and chemical effects on concrete performance are summarised as follows.

2.6.1.1 Physical effects

The relative particle density of fly ash (typically 2.3) is lower than that of cement (3.12). If cement is replaced by fly ash by weight the total volume of cementitious materials will therefore increase, for example by about 10% at 30% replacement.

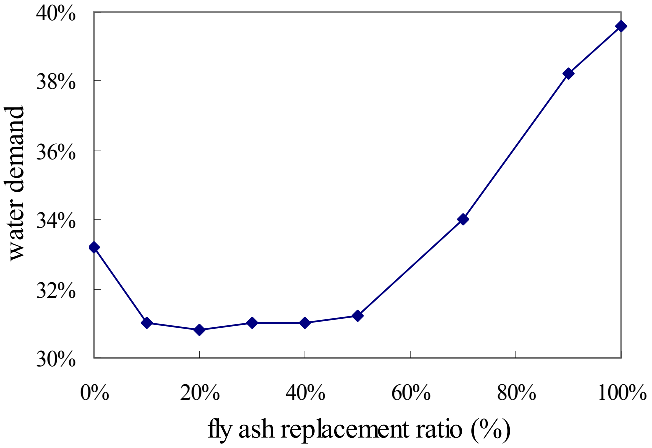

Figure 2-33 The influence of fly ash on water demand of concrete (Dietz and Ma, 2000)

Figure 2-33 (Dietz and Ma, 2000) shows that inclusion of 10~50% fly ash reduces the water demand of paste due to better particle packing; at higher replacement levels, however, water demand increased significantly.

The spherical particle shape leads to a reduction in the water requirement or increases the consistence of the paste or concrete. The concrete thus has lower bleeding and is easier to compact both leading to higher strength and durability. Typically, the water content of a Portland cement concrete can be reduced by 3% for each 10% of fly ash (Building Research Establishment Ltd, 1997). Jiang and Malhotra (2000) found that the water demand of a concrete was reduced by up to 20% with a replacement of 55% of the cement (by weight). It follows that in superplasticised mixes, the addition of fly ash can lead to a reduced superplasticiser requirement to achieve the same consistence.

Fly ash fills the space thus leading to a denser concrete structure. Cao et al (2000) showed that substituting cement with 50% fly ash (with 10.3% retained on the 45 µm sieve) eliminated the harmful pores larger than 100 nm and reduced half of the total pore volume in the concrete. In another study, the sorptivity of a concrete with 40% fly ash was found to be 37% lower than identical strength neat cement concrete cured at a relative humidity of 95±3% (Gopalan, 1996). This filling effect is an important factor contributing to the strength at early ages especially for concrete with large volume of fly ash.

2.6.1.2 Chemical effects

Fly ash consists of 60~90% amorphous glassy materials including silica, alumina, iron oxides and other metallic oxides in the proportions given in

Table 2-14[8].

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[8] http://www.ukqaa.org.uk/Datasheets_PDF/Datasheet_8-0_Aug_2004.pdf

Table 2-14 Typical range of chemical compositions of fly ash[8]

CONSTITUENTS	RANGE	CONSTITUENTS	RANGE
Aluminium (% by wt as Al_2O_3)	20~40	Silicon (% by wt as SiO_2)	38~52
Calcium (% by wt as CaO)	1.8~10	Sodium (% by wt as Na_2O)	0.8~1.8
Chloride (% by wt as Cl)	0.01~0.02	Sulphate (% by wt as SO_3)	0.35~2.5
Free calcium Oxide (% by wt)	<0.1~1.0	Titanium (% by wt as TiO_2)	0.9~1.1
Iron (% by wt as Fe_2O_3)	6~16	Water soluble sulphate (G/L as SO_4)	1.3~4.0
Magnesium (% by wt as MgO)	1.0~3.5	Loss on Ignition (%)	3~20
Potassium (% by wt as K_2O)	2.3~4.5	pH	9~12

Fly ash exhibits very little pozzolanic reaction at the early ages and, rather like filler, mainly serves as nuclei for precipitation of $Ca(OH)_2$ and C-S-H from the cement hydration thus contributing to the strength (Fraay et al., 1989). The rate of pozzolanic reaction compared to that of the Portland cement does however lead to lower strength and other properties at early ages compared to 100% Portland cement mixes.

The contribution of fly ash to the strength is higher in concrete with lower W/P ratio than that with higher W/P ratio (Bijen and van Selst, 1993; Poon et al., 2000). For example, at 28 days, the compressive strength of a mix with 45% fly ash and W/P ratio of 0.50 was about 30% lower than that of the control mix without fly ash; this reduction however was 17% when the W/P ratio reduced to 0.30 (Lam et al., 1998). However further lowering the W/P ratio to 0.19 did not improve the concrete strength. Therefore, for concrete with higher volume of fly ash, high strength is still possible by lowering W/P, which is only realized by using superplasticisers.

Since the pozzolanic reaction consumes some lime, it has been claimed that using fly ash in concrete leads to faster carbonation (Neville, 1996). However, this conclusion was based on accelerated carbonation testing which does not reflect the true performance of fly ash of slow hydration, which lowers the long-term permeability thus reducing the accessibility of CO_2 to the concrete. Sear (2005) listed several concretes incorporating up to 50% fly ash that had been exposed for two years indoors and outdoors showing that fly ash actually reduced ingress of CO_2. Other studies showed that curing period, exposure conditions and concrete strength had greater influences on carbonation than fly ash content (Matthews.J.D., 1995; Thomas and Mattews, 1994).

The rate of the pozzolanic reaction depends on temperature, and so the strength gain of fly ash concrete improves with increasing temperature. Heat curing is therefore favourable.

Apart from the glassy silica and alumina content, the degree of reactivity of fly ash is mainly determined by its fineness (Helmuth, 1987). For example, the pozzolanic activity of silica fume is normally more than that of fly ash. But when finely grounded, a fly ash can give equivalent activity to silica fume (Agarwal, 2006). In this study, the total content of SiO_2 and Al_2O_3 was 91.4 in the silica fume and 85.73 in the fly ash.

The calcium oxide and the smaller amounts of sodium and potassium oxides also have significant effects. In general, the low-calcium fly ash (total CaO less than 10%) contains an aluminosilicate-type glass and no crystalline compounds of calcium; the high-calcium fly ash (total CaO more than 15%) consists of a calcium aluminosilicate glass and crystalline compounds of calcium such as C_3A, C_4A_3S, CS and CaO (Manz, 1999). Due to the higher CaO content, Class C is more reactive than Class F fly ash. It can form cementitious products without the addition of calcium hydroxide.

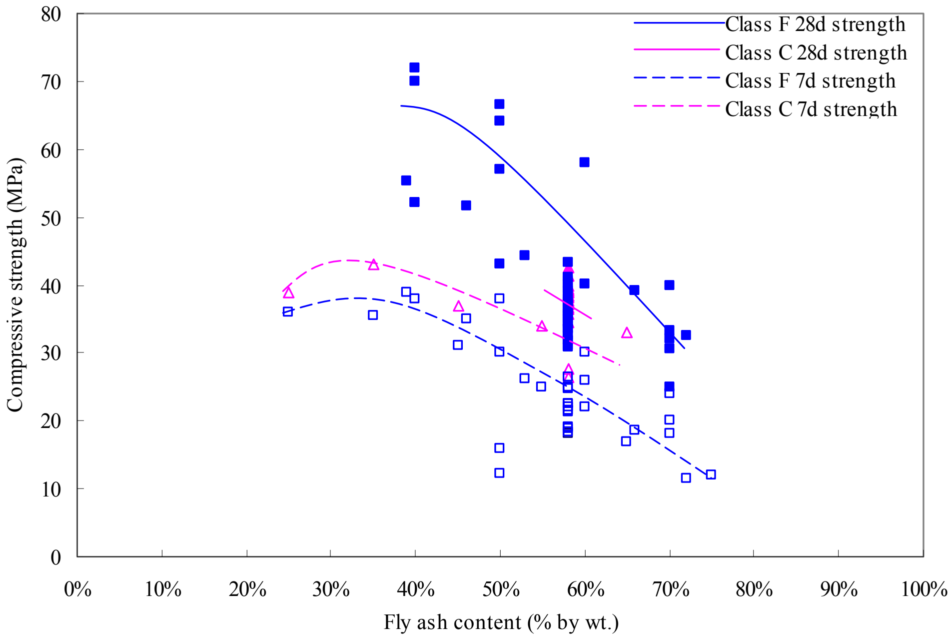

Figure 2-34 Influence of the types and contents of fly ash on concrete strength (Atis, 2003; Berryman et al., 2005; Bilodeau et al., 1994; Cao et al., 2000; Nehdi et al., 2004; Reiner and Rens, 2006)

Some strength data of concrete containing increasing proportions of Class C and Class F fly ash are shown in Figure 2-34; this is based on five studies (Atis, 2003; Berryman et al., 2005; Bilodeau et al., 1994; Cao et al., 2000; Nehdi et al., 2004; Reiner and Rens, 2006). There are many differences among these studies not only in the constituent materials (cement, fly ash, admixtures, aggregate and W/P ratio) but also in the test methods (size and shape of the specimens) which may result in the scatter of the data. However concrete strength decreases with an increase in the content of fly ash of whichever type. The Class C fly ash concrete has a higher strength than Class F at 7 days as anticipated; at 28 day, however, the strength of Class F is higher than that of Class C (although the results for the Class C are limited). Figure 2-34 also shows that the strength increases when replacing less than 30% cement by fly ash; at higher replacements of more than 30% or 40%, compressive strength decreases sharply. This is the reason that for most applications the fly ash content is restricted to 40% (Marsh, 2003). However, concrete incorporating higher fly ash is possible by proper design (see below).

In a specification developed by Canada, fly ash is thus classified into three types based on CaO content, less than 8% for type F, 8~20% for type CI and more than 20% for type CH (Can3-A23.5-M86). Jiang and Malhotra (2000) correlated CaO content of fly ashes with compressive strength of concrete incorporating fly ashes, high strength occurred in the fly ashes with high CaO. This confirms the rationality of classifying fly ash by CaO contents.

Fly ash also reacts with the sodium and potassium alkalis in the concrete. Concrete is thus less prone to ASR if the cementitious materials consist of at least 25% of fly ash[9].

In addition, using fly ash reduces the hydration temperature rise due to the dilution of cement and the slower pozzolanic reaction. Figure 2-35 (Atis, 2002; Bisaillon et al., 1994) clearly shows that replacing cement with fly ash leads to a reduction in the maximum temperature of concrete; the higher the amount of fly ash in concrete, the higher the reduction in temperature rise. It also indicates that normal fly ash content (less than 30%) may not cause a significant reduction in the peak temperature. Only those with high incorporation of fly ash (more than 50%) can.

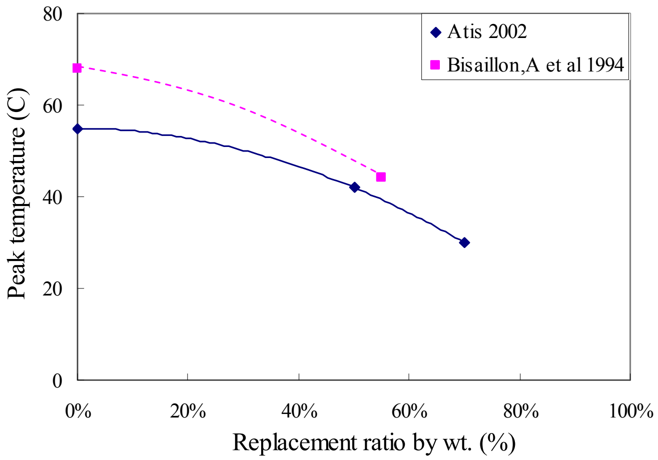

Figure 2-35 Effects of fly ash on the peak temperature of concrete (Atis, 2002; Bisaillon et al., 1994)

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[9] http://www.ukqaa.org.uk/Datasheets_PDF/Datasheet_1-0_Nov_2006.pdf

2.6.1.3 Environmental impacts

Besides the physical and chemical advantages mentioned above, fly ash reduces the total energy demand of concrete by replacing cement. Therefore considerable environmental and sustainability benefits can be achieved by using fly ash.

The environmental impacts of a product is assessed by embodied carbon (ECO_2), which includes the total carbon dioxide, a greenhouse gas, released in a product's life time, from the extraction of raw materials until the product leaves the factory gate, known as cradle to gate.

ECO_2 of cement and fly ash are 0.83 and 0.01 $kgCO_2/kg$ respectively; ECO_2 reduces to 0.62 and 0.42 if 25% and 50% respectively cement is replaced by fly ash (Hammond and Jones, 2008). Higher replacement levels will cause further reduction in the overall greenhouse gas emissions. Use of fly ash in concrete also have environmental effects such as reducing primary energy and saving landfill and quarry material etc (The Concrete Centre, 2007).

2.6.2 High volume fly ash concrete

In the last two decades there has been considerable interest in increasing the content of fly ash in concrete above the accepted or typical levels discussed above for both technical and environmental reasons.

High volume fly ash concrete (HVFA) in which at least 50% cement is replaced by ASTM Class F fly ash by mass, was developed by Canadian Centre for Mineral and Energy Technology (CANMET) in 1985. More recently, concrete containing up to 70% of both class C and class F of fly ash in the total cementitious material has been possible (Atis, 2003; Bilodeau et al., 1994; Reiner and Rens, 2006). HVFA concrete has been realized by lowering the W/P ratio and providing consistence by the use of superplasticiser. The anticipated disadvantages of longer setting time and lower strength gain can then be overcome. HVFA concrete has characteristics of low cement content, adequate early and long-term strength, high elastic modulus and high durability. A strength of over 100MPa was achieved after continuous immersion in water for a year (Marsh, 2003; Sear, 2005).

HVFA concrete is also attractive for environmental and sustainability reasons as described above.

In addition, the superplasticised HVFA concrete is rated as having a high effect on the concrete industry because of the low complexity of the technology, a low initial material cost and low maintenance cost and excellent environmental friendliness. Many applications of HVFA concrete, mainly in Canada and U.S.A., have been realized, and it has been used in highway construction including soil stabilization, pavement base courses, embankments and road shoulders (Mehta, 1999). The number of applications is increasing with the increasing demand for 'greener' concrete and landfill space becomes more limited and expensive.

2.6.2.1 Hydration

Due to the low W/C ratio, high volume of fly ash and low proportion of cement in HVFA concrete, there is insufficient calcium hydroxide for fly ash to react.

The required proportion of fly ash for complete pozzolanic reaction with the cement hydration products is calculated by using a method slightly modified from Helmuth (1987) as follows.

1. In presence of sufficient sulphate, the most important hydration of cement can be represented by the following simplified equations:

   $2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH$ (1)

   $2C_2S + 4H \rightarrow C_3S_2H_3 + CH$ (2)

   where $C = CaO$, $S = SiO_2$, $H = H_2O$.

2. The most important pozzolanic reactions are between reactive silica, reactive alumina in the fly ash and the calcium hydroxide from reaction (1)

and (2) above. These can be represented by the following simplified equations:

$$xCH + yS + zH \rightarrow C_xS_yH_{x+z} \quad (3)$$

$$A + 3CH + C\overline{S}H_2 + 7H \rightarrow C_3AC\overline{S}H_{12} \quad (4)$$

where S and A are the silica and alumina components of the fly ash respectively.

3. In the mix of cement and fly ash, the amount of fly ash required to react completely with the calcium hydroxide produced from cement hydration, can be estimated as follows.

   ○ The average molar lime-silica ratio of the C-S-H in reaction (3) after complete reaction is assumed as 1.0, which is equivalent to a CaO to SiO_2 weight ratio of 0.93.

   ○ The molar lime to silica plus aluminate ratio of the pozzolanic reactions in reaction (3) and (4) is 1.0, which is equivalent to a CaO to Al_2O_3 weight ratio of 0.55.

   The reactive SiO_2 and Al_2O_3 contents of the fly ash (2^{nd} batch) used in the project, are 50% and 25% respectively (refer to Table 5-4). The amount of lime required for complete reaction with the fly ash will therefore be

   $$0.5 \times 0.93 + 0.25 \times 0.55 = 0.60 \text{ kg CaO / kg fly ash}$$

   or 1.66 kg fly ash / kg CaO = 1.26 kg fly ash / kg $Ca(OH)_2$

   At complete hydration, 0.24 kg $Ca(OH)_2$ / kg cement is produced. The amount fly ash required for complete reaction is

   $$1.26 \times 0.24 = 0.30 \text{ kg fly ash / kg cement}$$

   or 23% fly ash by weight in the mix of cement and fly ash.

An alternative way to estimate the required fly ash for complete reaction is:

first to calculate the calcium hydroxide required for cement hydration, which is 30.8 in total according to reaction (1) and (2). The amount of C_3S and C_2S in the cement are 60.3 and 11.3 respectively (refer to Table 5-3)

second to calculate the silica and alumina components of the fly ash required to react completely with the above calcium hydroxide, which is 87.9 according to reaction (3) and (4) and the first assumptions above.

The ratio of fly ash to cement is therefore 30.8/87.9=0.35, this leads to a mix of 26% fly ash and 74% cement.

Although using simple reactions (1) to (4), both calculations lead to a better understanding of HVFA concrete. The estimation of the amount of fly ash required to react completely with the calcium hydroxide produced by cement hydration is of the order of 23% to 26%. Actual values depend on glass content and particle size and may be higher because glass contents vary from 60% to 90% and those reactive components (SiO_2 and Al_2O_3) in large particles may not be available for reaction (Helmuth, 1987).

In any case, the reaction between fly ash and cement in the HVFA concrete will be limited by lack of lime. This was confirmed by Marsh (2003): the morphology of well-cured HVFA concrete is that a high proportion of unreacted fly ash is unevenly distributed in a very dense matrix of insufficient hydration products. On the other hand, low strength of fly ash concrete will be improved by activating the fly ash by a lime solution.

Mechanism

Like it acts in the normal fly ash concrete, fly ash contributes to properties due to its physical and chemical effects (refer to 2.6.1). These become more significant for HVFA concrete.

From the studies by Berry et al (1994), Jiang et al (1999) and Zhang (1995), the hydration of HVFA pastes, in which the cement replacement ratio was up to 70%, is summarized as follows.

- At 7 days, about 5% fly ash reacts with the alkali ions in the pore solution forming AFt. Fly ash particles improve densification through particle packing due to the spherical form and the use of superplasticisers. The paste at early age is porous.

- At 28 days, the degree of the pozzolanic reaction increases to more than 10%. More fly ash particles react with Ca(OH)2. Fly ash particles act as nucleation sites for crystallization of hydration products of cement thus accelerating the reaction. However there is still a large amount of unreacted fly ash acting as filler.

- At the age of 90 days, about 14.8~22.6% fly ash undergoes pozzolanic reaction, gel-like calcium silicate hydrates (CSH) form. Pozzolanic reaction becomes dominant and results in about 20% increase in compressive strength.

- After 180 days continuous water curing the paste becomes denser due to the pozzolanic reaction but there are still large quantities of unreacted fly ash after one year.

The total porosity of the pastes incorporating 40~70% Class F fly ash increased with an increase in fly ash content, and HVFA pastes have more pores less than 20 nm than that of pure cement paste.

Therefore the pozzolanic reaction and the filling effect are important factors in strength and other properties developed; the pozzolanic reaction of fly ash in HVFA paste could not be complete; the main reaction product is CSH.

2.6.2.2 Other properties

Fly ash particles are glassy, harder, denser and have a higher elastic modulus than hydration products; the interfacial zone between fly ash particles and the matrix is relatively weak; therefore cracks generally do not go through fly ash particles; in the matrix of HVFA paste, the incomplete hydration leads to the presence of fly ash particles which act as micro-aggregate which restricts the deformation such as shrinkage and creep (Zhang, 1995). This can explain the characteristics of HVFA concrete of high elastic modulus, low permeability and shrinkage and good resistance to sulphate and chloride compared with concrete without fly ash (Atis, 2003).

Atis (2003) tested concrete prisms (50×50×200 mm) incorporating 50% and 70% fly ash by weight with a W/P ratio of 0.30 by weight (zero slump) and found that the shrinkage decreased as the fly ash replacement ratio increased; that is, 70% fly ash replacement resulted in the lowest shrinkage. His findings support that of Ghosh and Timusk (1981). In another study, dry shrinkage of SCC incorporating 40% to 60% Class F fly ash by weight was similar to that of a control, 100% cement NVC of the same 28-day compressive strength (Bouzoubaa and Lachemi, 2001).

HVFA concrete has higher carbonation rate than control mix but achieving similar depth of carbonation after 90-day curing; the depth of carbonation increases with the increase of fly ash replacement levels (Jiang et al., 2000). Due to low permeability, carbonation depths of HVFA concrete were reported to be low in real concretes (Sear, 2005).

HVFA concretes exhibited excellent performance in freeze-thaw cycling, resistance to chloride-ion penetration, and water permeability tests; however, their performance in de-icing salt-scaling test was unsatisfactory (Bilodeau et al., 1994).

HVFA concretes can cause a significant reduction of peak temperature due to substantial reduction in hydration heat (refer to Figure 2-35).

2.6.3 Improve the activity of fly ash

One clear disadvantage of using high volume fly ash in concrete is the reduction of strength and slow strength development at early age because of the low degree of reaction between $Ca(OH)_2$ and fly ash at room temperature. A practical use of high volume fly ash in concrete has to tackle its adverse effect on the early strength.

The commonly used ways to accelerate the pozzolanic reaction of fly ash include

- mechanical treatment by grinding fly ash, strength of mortar with 15~60% fly ash all increased at ages from 3 to 365 days (Paya et al., 1995; Paya et al., 1996; Paya et al., 1997).
- chemical treatment by adding certain activators and curing at certain temperature.

Work by Shi (1992) and Saraswathy et al (2003) indicated that chemical activation is the most effective method for producing better results than mechanical treatment.

2.6.3.1 Sulphate activation

Sulphate activation uses gypsum ($CaSO_4.2H_2O$), calcium sulphate anhydrite ($CaSO_4$), sodium sulphate (Na_2SO_4) and potassium sulphate (K_2SO_4) to accelerate the pozzolanic reaction in the fly ash - cement system. The sulphate ions will react with aluminate in fly ash to produce ettringite (AFt), which contributes early strength; thus the glass structure of fly ash is broken down (Xu and Sarkar, 1991). These activators led to improvements in the early strength and the pore size distribution and smaller pore size and total porosity; however they did not accelerate the strength at later age (Ma et al., 1995; Poon et al., 2001). Other products are calcium silicate hydrate, tricalcium aluminate hydrate (Ma and Brown, 1997).

2.6.3.2 Alkali activation

Fraay et al (1989) reported that the pozzolanic reaction depends on the alkalinity of the pore solution and high alkaline solutions are more likely to break the glassy structure. Thus it is necessary to provide hydroxyl ion to activate fly ash.

Alkali activation is a complex chemical process, which stimulates the inert or low pozzolanic materials by highly alkaline solutions and then transforms them into cement-like composites, which are characteristics by the elevated mechanical strength and not requiring high energy consumption compared with the manufacture of cement. This is a new type of binder named 'alkaline cement', which has important economical and environmental benefits compared with the traditional manufacture of Portland cement.

In general, the process includes mixing the materials to be activated with the activators followed by curing at a moderate temperature to produce solids. By increasing alkalinity or curing at elevated temperature or pressure, the glass structure of fly ash is broken and hydrates are produced and then strength is improved. These materials usually come from industry by-products, waste or residues, have amorphous structures and contain Si, Ca and Al, such as GGBS, fly ash and metakaolin; activators are high concentration of $Ca(OH)_2$ (Ma and Brown, 1997), NaOH (Katz, 1998), KOH (Palomo et al., 1999), water glass (Xie and Xi, 2001) etc. The main products are amorphous alumino-silicate gel, the nature and composition of which depends on the activator, curing temperature and pressure (Palomo et al., 2004).

The nature of the alkaline solution is a crucial factor in the process. The higher the concentration of the solution the higher is the strength (Fraay et al., 1989).

Temperature is another crucial factor in the process. Higher than 65°C was more favourable for fly ash activated by strong alkali (Palomo et al., 1999). There were hydrate products formed at 100 °C in the system of 90% fly ash and 10% $Ca(OH)_2$ while none was formed at 25 °C; this was due to the increased dissociation of the glass structure at high temperature (Ma et al., 1995).

There are few applications in concrete reported. Vandivort and Ziemkiewicz (2007) reported several projects using up to 100% fly ash concrete in construction applications by using hydroxide and either high temperature or pressure or both to activate the fly ash's reaction.

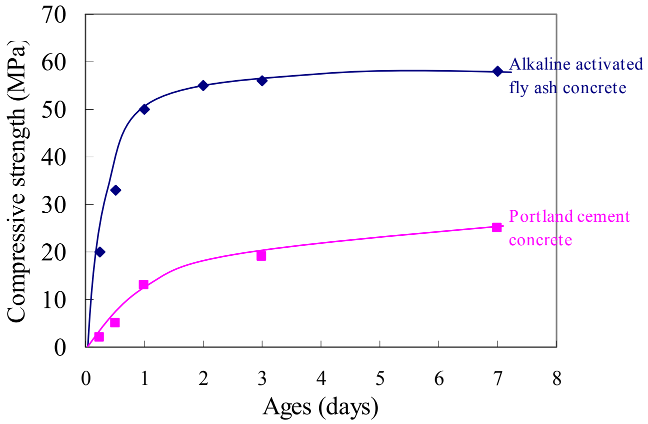

Figure 2-36 Compressive strength developments of alkaline activated fly ash concrete and Portland cement concrete (Ana et al., 2006)

A typical strength development with time is shown in Figure 2-36 (Ana et al., 2006): alkaline activated fly ash concrete develops high compressive strength in a few hours, achieves the maximum strength in a day after activation and then continues to rise more slowly with time.

There is little literature about the effects of admixtures on the properties of the mortar or the concrete made from alkaline-activated fly ash and most superplasticisers are made for cement based concrete and may not work well with alkaline-activated cement (Shi et al., 2006). Puertas et al (2003) studied the effects of the superplasticisers based on vinyl copolymers and polyacrylates on properties of mortar made from alkaline Class F fly ash: the presence of superplasticisers in activated fly ash mortars did not cause substantial change of consistence and strength. Tests on fly ash-cement paste superplasticised by a sulphonated melamine formaldehyde showed that the addition of activators all increased the yield stress and the plastic viscosity of fly ash activated by lime (Grzeszczyk and Front, 2000).

2.6.4 Fly ash in self-compacting concrete

Fly ash has been used in SCC mainly because of hydration heat reduction, water reducing properties and the effect on the thixotropic performance. The physical and chemical effects of fly ash have been also observed in substantial research conducted on SCC incorporating up to 40% fly ash in recent years.

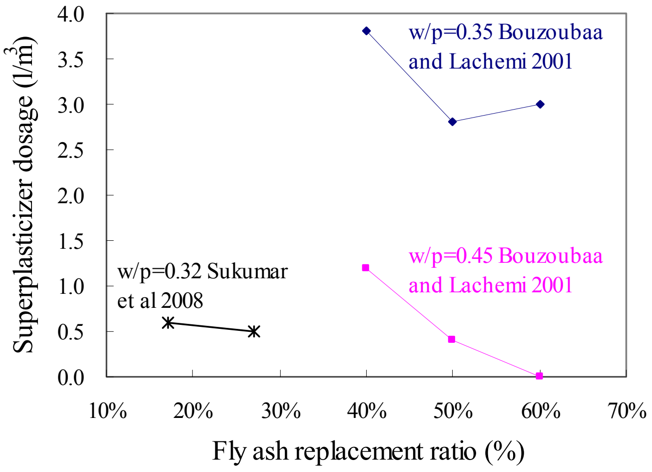

Figure 2-37 Effect of fly ash on superplasticiser dosage of SCC (Bouzoubaa and Lachemi, 2001; Sukumar et al., 2008)

Figure 2-37 (Bouzoubaa and Lachemi, 2001; Sukumar et al., 2008) shows that inclusion of 17~60% fly ash in SCC helps to reduce superplasticiser usage to maintain the same slump flow as that of SCC made with Portland cement only. Such SCC mixes showed better slump retention and segregation resistance.

Sukumar et al. reported the relation between superplasticiser dosage and fly ash content existed in SCC mixes with 8~52% fly ash, slump flow of 742~793 mm, and W/P of 0.31~0.34. The superplasticiser dosage decreased with an increase in fly ash content up to 39%; higher fly ash incorporation however did not change the superplasticiser required.

Fly ash in SCC helps to reduce early-age cracking in SCC which decreases with an increase in strength. Low permeability, good freeze-thaw resistance and low drying shrinkage of SCC were achieved by incorporating 30~40% fly ash (Blaine surface area of 500~600 m^2/kg); the fly ash had a similar effect to VMA on fresh concrete: improving the viscosity of fresh concrete and keeping consistence constant; 28-day compressive strength of such SCC could reach 71 MPa (Xie et al., 2002).

SCC incorporating fly ash has long setting time because of slower reactivity of fly ash and the delaying effects of superplasticiser and VMA (Atis, 2003). Setting time of SCC incorporating 40~60% Class F fly ash by weight was 3~4 hours longer than that of a control, 100% cement NVC of the same 28-day compressive strength (Bouzoubaa and Lachemi, 2001).

An accelerator was used to improve SCC's early strength (Christensen and Ong, 2005), chemical composition of which is unknown. A small quantity of Na_2SO_4 or K_2SO_4 together with $Ca(OH)_2$ or a longer curing time were considered necessary to increase the early strength of HVFA SCC (Poon et al., 2003; Shi and Day, 2000).

Comments: In order to extend the concept of HVFA concrete to SCC, investigations on SCC incorporating higher proportions of fly ash in SCC is necessary despite there are a few published papers on the topic.

2.6.5 Comparisons between concretes with fly ash

Typical mixes and properties of fly ash concrete, HVFA concrete and SCC incorporating fly ash are shown in Table 2-15. This shows that:

- For constant W/P ratio, addition of fly ash in concrete leads to a reduction in the strength.
- For constant fly ash content, using superplasticisers leads to a lower W/P ratio and hence higher strength.
- Compared with HVFA concrete, fly ash concrete can be made in a range of the W/P ratio from 0.3 (when superplasticisers are used) up to 0.5 (when no superplasticisers used). Required consistence is ensured by superplasticiser or high water content. Better strength performance is achieved at lower W/P ratio.
- Low slump HVFA concrete can be produced without the need for superplasticisers; but most HVFA concrete is however produced by using superplasticisers and a narrower range of the W/P ratios of 0.28~0.33;

- Compared with NVC incorporating similar fly ash content, SCC has a higher W/P ratio to ensure its fresh properties and thus has lower strength. Higher superplasticiser doses may also be needed.

Table 2-15 A comparison between fly ash concrete, HVFA concrete and SCC with fly ash

	REFERENCE	FLY ASH		CEMENT (KG/M^3)	WATER (KG/M^3)	W/P BY WT.	ADMIXTURE	SAND (KG/M^3)	COARSE AGGREGATE (KG/M^3)	SLUMP (MM)	SLUMP FLOW (MM)	V-FUNNEL TIME (SECS)	28-DAY STRENGTH (MPA)
		% powder	kg/m^3										
Fly ash concrete	(Lam et al., 1998)	15[1]	75	425	150	0.3	Sp	700	1086 (10mm)	>75			86 (cube)
			61.5	348.5	205	0.5	No	589	1132 (20mm)				49 (cube)
		45[1]	225	275	150	0.3	Sp	650	1086 (10mm)				72 (cube)
			184.5	225.5	205	0.5	No	549	1132 (20mm)				36 (cube)
HVFA concrete	(Atis, 2003)	50[1]	200	200	120	0.30	No	600	1200	0			57~67 (cube)
					132	0.33	Sp			600[2]			
	(Jiang and Malhotra, 2000)	55	220	180	137~ 155	0.34~ 0.39	No	726~ 749	1089~ 1124	57~70			31~56 (cylinder)
	(Bilodeau et al., 1994)	55~60	211	152	119	0.33	Sp&AE	638~ 648	1187~ 1206	150±25			28~42 (cylinder)
	(Marsh, 2003)	50	150	150	111	0.37	No						25
		55~60	215~ 225	155~ 200	115~ 125	0.28~ 0.33	Sp	750±10	1100~ 1210	150~ 200			~50 (cube)
	(Atis, 2003)	70[1]	280	120	116	0.29	No	600	1200	0			30~33

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[1] Class F

[2] Vibrating slump test

					112	0.28	Sp			560[2]			(cube)
	(Reiner and Rens, 2006)	60~70[1]	246~287	123~164	126~128	0.31	Sp	767~778	1068	100~150			24 (cylinder)
SCC with fly ash	(Sonebi, 2004)	34~39[1]	160	250~317	226~262	0.55	Sp	594~746	837		700~790	4.2~5.4	27~29
	(Nehdi et al., 2004)	50[1]	215	215	163	0.38	Sp&AE	925	905		635		20 (cylinder)
	(Christensen and Ong, 2005)	50[1]	177	177	123~133	0.32~0.35	Sp& accelerator				>500		31~41 (cylinder)
	(Bouzoubaa and Lachemi, 2001)	40~60[1]	160~240	161~247	136~190	0.35~0.45	Sp&AE	842~866	842~866		520~650	3~7	26~48 (cylinder)
	(Khatib, 2008)[3]	20~80	100~400[4]	100~400	180	0.36	Sp	751~845	876		>700		10~53 (cube)

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[3] Khatib's study is alleged on SCC but only the slump flow tests were performed.

[4] Khatib did not present the fly ash content correctly. Fly ash of 100~400 kg/m^3 is calculated according to his fly ash to binder (cement + fly ash) mass ratio of 0.36.

2.6.6 Conclusions

The enormous output of fly ash from power plants is an incentive to incorporate it in concrete. The physical and chemical effects of fly ash can also improve the performance of concrete. By using fly ash, SCC can be produced with less need for admixtures. SCC can be made more environmental friendly by incorporating higher replacement ratios of fly ash. Therefore, it is necessary to do further research on SCC with a very wider range of replacement ratios of fly ash.

HVFA concrete, in which generally 50% to 60% cement is replaced by fly ash, can be produced with satisfactory early strength and strength development by lowering the water content and ease of compacting. For an SCC with such a high content of fly ash, more water and/or superplasticiser is needed to ensure its fresh properties, which could lead to a lower strength than HVFA concrete. Most investigations have been carried out on SCC containing up to 60% fly ash. There is a need for research into SCC incorporating a high volume of fly ash. With the use of proper chemical admixtures and mix design methods, SCC incorporating 60% or more of fly ash may become a reality. The influence of such a high replacement ratio of fly ash on the early strength, strength development and durability needs further research.

2.7 Glass

Glass is made from a mix of silica, soda ash and calcium carbonate, which are melted at high temperature then quickly cooled, a process leading to solidification without crystallization. Glass is widely used to make products such as flat glass (windows and windscreens), glass containers (bottles and jars), bulb glass (light bulbs), cathode ray tubes (TV screens, monitors, vacuum tubing etc.) (Byars and Zhu, 2003; Shayan and Xu, 2004). All of these are produced to serve for a limited time and then become waste.

Due to urbanization and industrialization, three million tonnes of waste glass is produced every year in the UK; of which 71% is waste glass containers (Richardson, 2004). The remainder comes from windows, light bulbs and electronic grade glass etc. This increasing trend has raised social and environmental concerns, resulting in a growing interest in the recycling of waste glass.

Theoretically waste glass could be recycled completely and infinitely: glass containers could be collected, washed and reused; glass cullet can be melted with raw material to produce glass containers without changing the chemical properties of glass (Byars and Zhu, 2003; Shayan and Xu, 2004).

However, most waste glass is a mixture of colours, partly broken, mixed with plastics, ceramics and metals, and contaminated with organic matters such as sugars, liquids or mercury, lead etc. (Meyer et al., 2001; Shao et al., 2000). Due to the high cost of cleaning and colour sorting, only a tiny proportion can be recycled by conventional markets like container manufacture (Meyer et al., 2001). Most waste glass is sent to landfill. Since glass is not biodegradable, landfills do not provide an environmental friendly solution.

The construction industry is an ideal home for the economic and safe disposal of glass because of the low quality material requirements and the large amount of consumption. The main applications include paving materials, concrete masonry blocks, glass marbles, glass tiles, glass fibres and abrasives.

Some attempts have been made to crush the glass cullet for use as a raw siliceous material in manufacturing cement (Chen et al., 2002; Xie and Xi, 2002). However this would increase the alkali content in the cement, thus increasing the risks of alkali-silica reaction (ASR) and would lead to flash setting.

Waste glass can be made into a multi-porous structure, foamed glass, which can be used as lightweight aggregate for concrete (Lu and Onitsuka, 2004). Ducman et al (2002) produced a highly reactive and porous lightweight aggregate by firing the finely ground glass (less than 100 μm) with an expanding agent in a rotary kiln at 880 °C; the fired fine glass aggregate formed gels in ASR tests. However there was no expansion because the porous structure of the glass aggregates accommodates a large amount of ASR gels.

For many years, industrial by-products such as fly ash, GGBS, silica fume etc. have been used in concrete as aggregates or additions depending on their chemical composition, particle size and their contribution to concrete strength and durability (Neville, 1996). This provides a good example for the application of waste glass cullet (hereafter referred to as “glass” in this project) in SCC.

Glass can be crushed or ground to produce particle sizes ranging from fine powder to several millimetres and therefore it can be used as aggregates or additions in concrete.

2.7.1 Glass aggregate

Glass aggregate is considerably different from natural aggregate in particle shape and texture. Coarse glass aggregates have a flat shape, angular and sharp edges, a smooth surface and considerable friability; fine glass aggregates, on the other hand, have a more regular shape and reduced friability; particles of sizes of less than 1.5 mm resemble normal sand (Polley et al., 1998). In addition, glass has a lower specific gravity (about 2500 kg/m^3) than natural aggregate (around 2600 kg/m^3). Furthermore, glass does not absorb water.

As a result, glass aggregate exhibits significant effects on concrete, as set out below. The data in the following graphs were chosen from those papers studying concrete with glass and providing clear test methods and results. To make comparisons between them, the graphs do not show the absolute values but the changes based on the control mix without glass.

1. Glass aggregate increases water demand, bleeding and segregation, and decreases consistence of the fresh concrete due to its particle shape and smooth texture (Polley et al., 1998; Taha and Nounu, 2008).

   Figure 2-38 (Chen et al., 2006; Park et al., 2004; Taha and Nounu, 2008; Topcu and Canbaz, 2004) shows the influence of the replacement ratio of glass aggregate on the consistence of concrete. The results indicate that the slump values of concrete after incorporating glass aggregate all reduce with an increase in glass aggregate content. The magnitude of change varied with different size and shape. Due to the cylindrical shape of the glass aggregate used in Chen et al (Chen et al., 2006), slump loss is much higher than other studies.

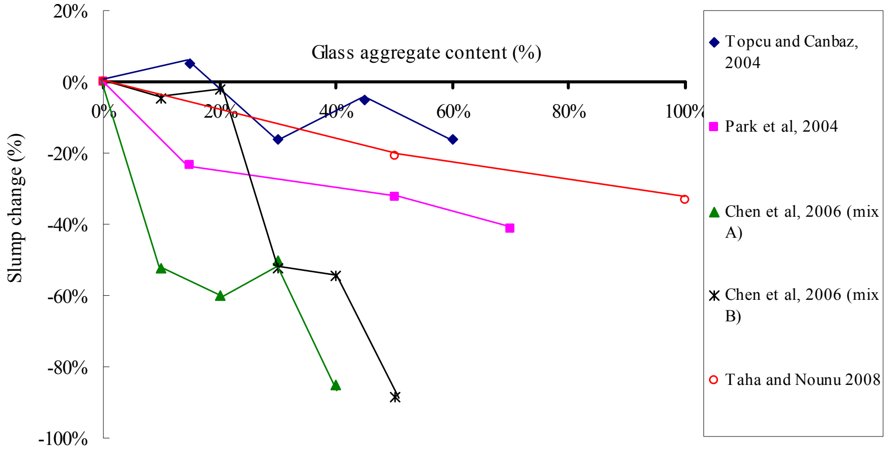

Figure 2-38 Change of slump of concrete after incorporating glass aggregate (Chen et al., 2006; Park et al., 2004; Taha and Nounu, 2008; Topcu and Canbaz, 2004)

2. Replacing natural aggregate with glass aggregate decreases the concrete's density. The density of the concrete in which 60% natural aggregate is replaced with a glass aggregate of 4~16 mm, decreases from 2340 to 2335 kg/m^3 (Topcu and Canbaz, 2004). A reduction of 50 kg/m^3 in the density was reported by Taha and Nounu (2008) when all the sand was replaced with glass aggregate in the concrete.

3. Compared with natural aggregates, the substitution of the coarse aggregates by glass may lead to strength loss and poor strength development of a concrete due to higher water demand and weaker bond strength, high friability of glass and excessive ASR expansion (Polley et al., 1998).

   As shown in Figure 2-39 (Park et al., 2004; Sangha et al., 2004; Shayan and Xu, 2006; Topcu and Canbaz, 2004) and Figure 2-40 (Park et al., 2004; Topcu and Canbaz, 2004), both the compressive strength and indirect tensile strength of concretes with glass aggregate may decrease in proportion to an increase in glass content, which however did not show significant change up to 30% replacement ratio.

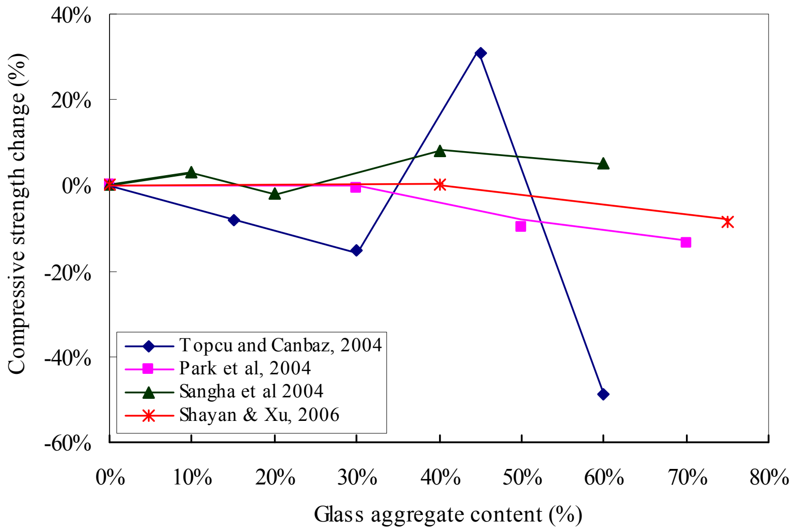

Figure 2-39 Change in concrete compressive strength due to glass aggregate (Park et al., 2004; Sangha et al., 2004; Shayan and Xu, 2006; Topcu and Canbaz, 2004)

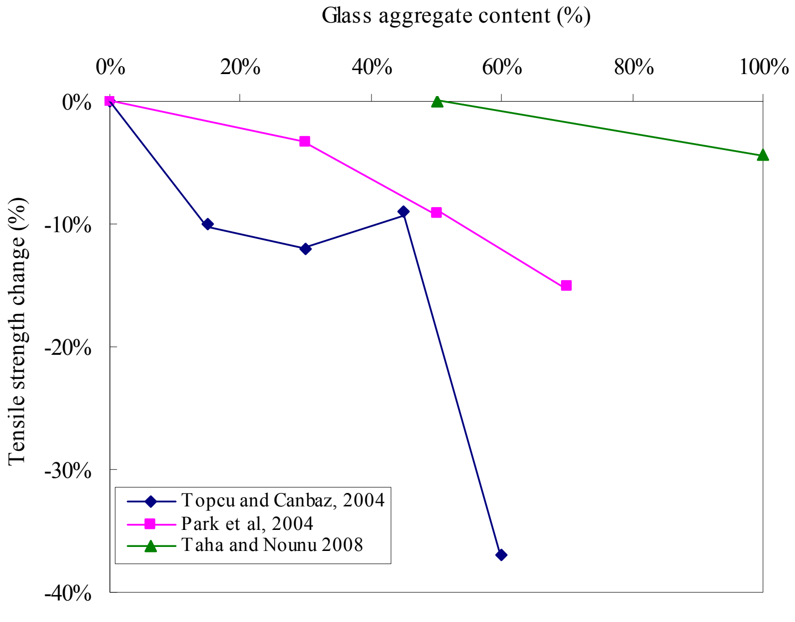

Figure 2-40 Change of concrete tensile strength due to glass aggregate (Park et al., 2004; Topcu and Canbaz, 2004)

The exception is the results displayed by Sangha et al (2004) which show that compressive strength of concrete with the glass aggregate increases with an increase in glass content. Their glass was produced by a special implosion process, resulting in sharp-edge-free particles of size 0~10 mm. The strength gain can be attributed to better bonding between glass aggregate and the surrounding matrix, and lower entrapped air.

Park et al (2004) reported that the strength of concrete with glass aggregate can be increased significantly by adding 10% styrene butadiene rubber latex, which can secure the required consistence of concrete. However, the reason is not clear.

4. Concrete with glass aggregate may exceed the standard expansion criteria for alkali-silica reaction (ASR) (refer to 2.7.3.1). However, by using low-alkali cement and ASR suppressants, this adverse effect can be mitigated.

5. The colour of the glass aggregate does not have a significant effect on the strength of concrete (Park et al., 2004).

6. Compared with natural aggregate, glass aggregate does not absorb water, and it is hard but brittle. Concretes containing glass aggregates are reported as low in water absorption and shrinkage, high in resistance to abrasion and freeze/thaw attack and cracking (Johnston, 1974; Meyer et al., 1996; Meyer et al., 2001).

Comments: It seems that the difference in glass shape, in surface characteristics and in the characteristics of the glass itself have the greatest influence on the performance of concrete. Glass aggregate may lead to the degradation in strength, however, by changing particle size or shape and limiting content, glass concrete may achieve comparable or better properties. Glass aggregate may be prone to ASR, expansion can be suppressed by incorporating appropriate pozzolanic materials. This is one of the most important preconditions for the use of glass aggregate. In addition, since natural aggregates will be depleted in future, research on glass aggregate is practical.

2.7.2 Glass powder

The chemical compositions of soda-lime glass which is the most commonly used in containers are compared with fly ash and cement as shown in Table 2-16. As shown, the chemical compositions of glass do not vary significantly irrespective of different origins. The SiO_2 and (Na_2O+K_2O) of glass are much higher than fly ash and cement. The total reactive component (SiO_2+ Al_2O_3+Fe_2O_3) of glass and fly ash is about the same. Other main constituent contents are in the similar range to those of fly ash and cement.

Table 2-16 The comparisons between soda-lime glass, fly ash and cement

	SODA-LIME GLASS						FLY ASH	CEMENT
	(Chen et al., 2006)	(Schwarz and Neithalath, 2008)	(Shao et al., 2000)	(Shayan and Xu, 2004)	(Shi and Wu, 2005)	(Taha and Nounu, 2008)	UKQAA[1]	(Neville, 1996)
SiO_2	73	72.5	72.8	72.61	72.5	72.3	38~52	17~25
Al_2O_3	1	0.4	1.4	1.38	0.16	1.04	20~40	3~8
Fe_2O_3	0	0.2	0	0.48	0.2	0.17	6~16	0.5~6.0
CaO	12	9.7	4.9	11.70	9.18	8.61	1.8~10	60~67
MgO	0.6	3.3	3.4	0.56	3.65	3.89	1.0~3.5	0.5~4.0
SO_3				0.09	0.39		0.35~2.5	2~3.5
Na_2O	13.5	13.7	16.3	13.12	13.2	13.31	0.8~1.8	0.3~1.2
K_2O		0.1	0.3	0.38	0.12	0.52	2.3~4.5	
LOI				0.22			3~20	
Colour			white					
Density		2490			2470	2510		3150

Moreover, glass is X-ray amorphous. It is therefore reasonable to expect glass may be used as a pozzolana (refer to 2.4.3.2) and subsequently a substitute for cement. This is also a higher value choice than glass aggregate, not only because it makes full use of its physical and chemical properties, but also because cement is more expensive than aggregate, thus offering more economic and environmental advantages (Jin et al., 2000; Shayan and Xu, 2004).

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[1] http://www.ukqaa.org.uk/Datasheets_PDF/Datasheet_8-0_Aug_2004.pdf

2.7.2.1 Effect of particle size

It was found that glass activity was more related to fineness than other factors such as particle shape, composition and colour (Byars et al., 2004). If the glass is fine enough, the SiO_2 in the glass will react with the $Ca(OH)_2$ from the cement hydration to form CSH (Richardson, 2004). Its high alkali content acts as a catalyst.

Some research recommended that the dividing size between cementitious and inert materials for ground glass is 38 μm (Shi et al., 2005; Shi and Wu, 2005). Other research found below 75 μm glass is pozzolanic whereas larger than 75 μm glass have less or no pozzolanic property (Chen et al., 2006), and thus could be used as type II additions in concrete according to BS EN 206-1.

Figure 2-41 (Shao et al., 2000; Shayan and Xu, 2006; Taha and Nounu, 2008) shows that the compressive strength gain of concrete with finer glass, passing a 38 μm sieve, is higher at all ages than that with the same substituted amount of coarser glass, passing a 75 and 150 μm sieve. Shao et al also showed that the finer the glass used the higher the concretes' strength especially at a late age.

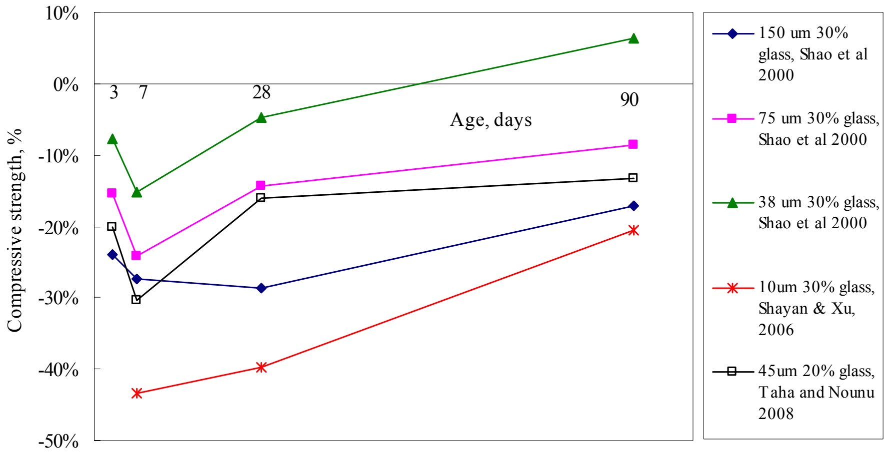


Figure 2-41 Compressive strength development of concrete with glass powder (Shao et al., 2000; Shayan and Xu, 2006; Taha and Nounu, 2008)

Concrete with glass of only 10 μm also produced a fast increase in the compressive strength with curing time. However, its strength development is lower than that with glass of 150 µm as shown in Figure 2-41. This result may be caused by the different glass processed.

Compared with fly ash, the contribution from glass to strength is no less than that from fly ash. Glass of the fineness larger than 300 m^2/kg would reach an activity index equivalent to a BS EN 450 fly ash (Byars et al., 2004). Shao et al (2000) found the concrete with 30% ground glass (particle size of 38 µm), achieved higher compressive strength than that with 30% Class F fly ash. This is also confirmed by Shi and Yang (2005) in concrete with a glass powder of a Blaine fineness of 400 m^2/kg and a Class F fly ash.

2.7.2.2 Effect on consistence

It was reported that the slump of concrete with glass powder from 38 to 300 µm all decreased because of its angular shape (Shao et al., 2000). Superplasticiser therefore had to be used when the glass content was higher than 30% to avoid segregation (Chen et al., 2006).

2.7.2.3 Effect on strength

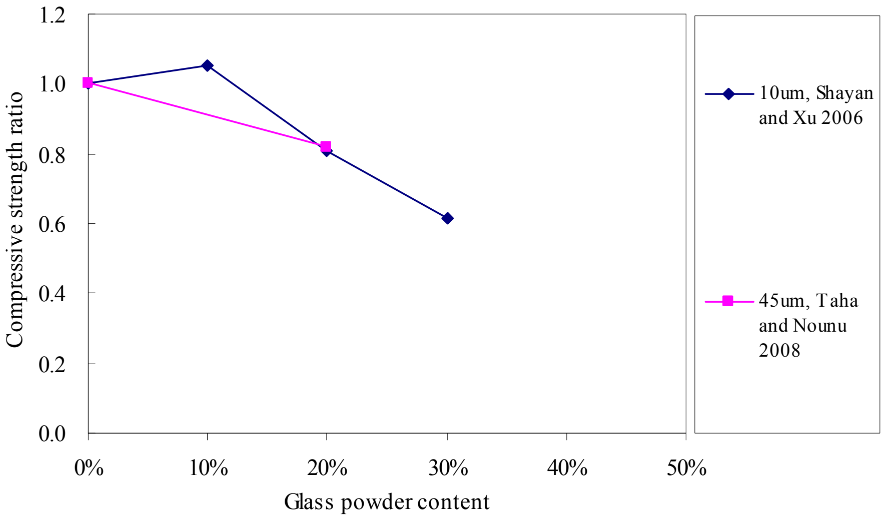


Figure 2-42 The influence of glass powder on the compressive strength of concrete (Shayan and Xu, 2006; Taha and Nounu, 2008)

Like other additions, replacing cement with glass powder in concrete leads to a reduction in strength. Figure 2-42 (Shayan and Xu, 2006; Taha and Nounu, 2008) shows the compressive strength ratio of concrete incorporating glass powder compared to a control mix. No matter what the powder size, the strength decreases in proportion to an increase in glass content.

Figure 2-41 (Shao et al., 2000; Shayan and Xu, 2006; Taha and Nounu, 2008) shows that most concretes with glass powder show lower compressive strength than the control concrete with cement only at all ages; at 7 days, their strengths are far behind the control concrete; at 90 days, the concrete with a very fine glass powder of 38 μm exhibits higher strength than the control concrete. 30% was the maximum replacement ratio recommended for strength reasons and to avoid potential ASR (Shayan and Xu, 2006). Other studies also confirmed that the glass powder hydrates significantly after 7 days at room temperature, promoting concrete early strength development of the concrete (Jawed and Skalny, 1978; Shao et al., 2000; Shi et al., 2005; Shi and Wu, 2005).

Figure 2-41 also shows that the strength increases with age. This change can be attributed to pozzolanic reaction. The addition of glass powder is shown to enhance the cement hydration and strength development.

2.7.2.4 Effects on other properties

Like other additions, using ground glass as an addition will lead to a lower hydration heat of the concrete.

It is reported that the drying shrinkage of concrete with glass powder is higher than that with fly ash due to its low water demand and that the drying shrinkage decreased with an increase in glass fineness (Shi et al., 2005; Shi and Wu, 2005). Shayan and Xu (2006) also reported that drying shrinkage of concretes with 20~30% glass of less than 10 μm was higher than that of a control mix and that it increased with increasing glass content. This accords with the effect of alkali on cement, that is, shrinkage tends to increase with an increase in alkali content (Jawed and Skalny, 1978).

Fine glass powder was reported to contribute to micro structural properties due to its filler effect and pozzolanic reactivity (Corinaldesi et al., 2005); thus sulphate resistance, chloride penetration resistance and freeze/thaw attack of concrete were all improved after incorporating 20~30% glass powder compared to those with fly ash (Chen et al., 2006; Shayan and Xu, 2006; Shi et al., 2005; Shi and Wu, 2005).

2.7.3 Challenge of Alkali-silica reaction in the use of glass

Application of waste glass in concrete is still not common at present because of the concern regarding alkali-silica reaction (ASR).

2.7.3.1 Alkali-silica reaction

ASR is an adverse chemical reaction, which occurs in concrete, between certain aggregates containing a high proportion of reactive silica and alkali coming from cement when there is a supply of water (Neville, 1996); the reactive silica reacts with the hydroxyl ions in concrete pore solutions and produces a gel which imbibes water and swells. This causes expansion and subsequent cracking, weakening the cement-aggregate bond. As a result, the main adverse consequences of ASR are significant reductions in compressive strength (up to 25%), tensile strength (up to 50%), elastic modulus (up to 60%), flexural strength and bond strength; long term durability ultimately degrades due to the network of cracking which substantially increases the permeability to aggressive agents such as carbonation and chloride attack.

The main methods of minimising ASR include limiting the alkali content in the concrete, using non-reactive aggregates and isolating concrete from moisture (BRE Digest 330, 1999).

Alkali contents in cement should be restricted to 0.60% or 2.5 kg/m^3 or less when potentially reactive aggregates are to be used (Freitag et al., 2003). Shi and Zheng (2007) suggested that the pH of the concrete with glass should be below 12 to avoid adverse expansion and cracking.

Replacing cement with fly ash, GGBS, metakaolin, microsilica etc.' which are called ASR suppressants, also limits expansion, as shown in Table 2-17. The usage of ASR suppressants varies depending on their characteristics.

The reasons that ASR suppressants limit expansion are: the pozzolanic reaction consumes Ca^{2+} ions and OH^- ions, lowers the Ca/Si ratio in the pore solution and the CSH gel, thus leading to electrostatic trapping of alkali ions (Duchesne and Berube, 1994a; Duchesne and Berube, 1994b).

Table 2-17 ASR suppressants

ASR suppressants	Cement replacement ratio	Reference
Fly ash	20~30%	(Freitag et al., 2003; McCarthy et al., 2006; Shayan et al., 1996)
GGBS	40~65%	(Freitag et al., 2003; GEOPAVE, 1999)
Metakaolin	10-20%	(Aquino et al., 2001; Ramlochan et al., 2000)
Microsilica	10-20%	(Aquino et al., 2001; Gudmundsson and Olafsson, 1999)
Ground clay brick	< 30%	(Turanli et al., 2003)

However, there is little literature about the correlations of the results between laboratory tests and the field performance of concrete made from the same materials because it takes long time for ASR damage to be displayed (Hobbs, 1993).

2.7.3.2 Glass and alkali silicate reaction

Glass is normally unstable in a high alkali environment due to the cement hydration products in concrete. Silica-rich glass can react with the alkali which, in turn, can lead to damage to the concrete.

The alkali level of cement is the most important factor affecting the reactivity of glass aggregate in concrete (Byars et al., 2004). Alkali originally contained in the glass, which is bound in the paste and pozzolanic products, is not released into the pore solution as suggested by SEM/EDX (Shayan and Xu, 2006).

The composition, colour, contents and particle size of the glass used are also responsible for the ASR of concrete.

Effect of glass composition

The reactivity of glass comes from the amount of amorphous silica it contains. Jin et al (2000) tested three types of glass, (1) fused silica – a pure amorphous silica glass, (2) pyrex – containing 80% silica glass and 20% sodium-borate glass, (3) soda-lime glass – containing 65~80% silica. The expansion with glass (1) and (2) were multiples of that caused by (3); fused silica caused the most expansion among the three. Thus, the most reactive glass will lead to the largest expansion.

As well as amorphous silica, the CaO content also contributes to the reactivity of aggregate; the reactivity of aggregate (Chatterji, 1979; Tang et al., 1986) was defined as

$$K = \frac{CaO + Al_2O_3}{SiO_2 + Na_2O}$$

The higher the SiO_2 and Na_2O content, the higher the reactivity of aggregates, therefore, soda-silicate glass, which contains both silica and sodium, is more susceptible to ASR attack than soda-lime glass (Shayan and Xu, 2006).

Effect of glass colour

The colour of the glass, which results from the oxide added, e.g. Fe_2O_3 for amber colour and Cr_2O_3 for green, has an effect on ASR expansion.

Jin et al (2000) found that clear glass was the most reactive, amber glass was less reactive and green glass was not reactive at all. Finely ground green glass actually suppressed ASR and this suppressing effect increases with the reduction in its particle size. The author explained that the cause was the Cr_2O_3 content and found a correlation between this and expansion, that is, the expansion rate decreases as the Cr_2O_3 content increases. Other results confirmed that a mortar bar with finely ground glass in white, amber and brown glass expanded more than one with green glass; (Dyer and Dhir, 2001; Jin et al., 2000; Meyer, 1999; Meyer and Xi, 1999; Topcu and Canbaz, 2004).

Expansion with green glass aggregate was also less than with brown glass (Park and Lee, 2004). In ASR tests on concretes incorporating green, amber flint and blue glass aggregates, 3~6 mm blue was the most reactive, then 6-12 mm amber and flint (Byars and Zhu, 2003). This can be explained by the double-layer theory that expansion pressure resulting from electrical double-layer repulsion was inversely proportional to the ionic valence (Prezzi et al., 1997).

Effect of glass content

The effect of glass content on the risk of ASR has also been reported by many researchers who have found that the higher the glass content, the higher the expansion rate (Jin et al., 2000; Park and Lee, 2004; Shayan and Xu, 2004; Topcu and Canbaz, 2004).

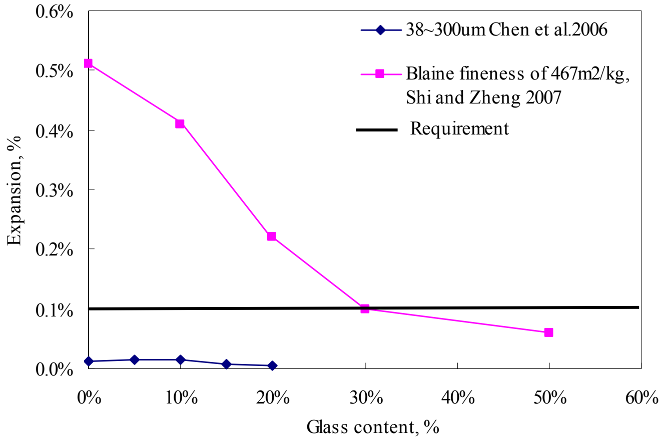


Figure 2-43 The influence of glass powder on the volume changes of mortar in ASR tests at 14 days (Chen et al., 2006; Shi and Zheng, 2007)

Figure 2-43 (Chen et al., 2006; Shi and Zheng, 2007) shows the 14 day expansion of mortar bars according to ASTM 1260. It can be seen that replacing 10~50% cement with ground glass of Blaine fineness of 467 m^2/kg significantly reduces ASR; no expansion happened in concrete incorporating 30~50% glass. Chen et al used an E-glass obtained from electronic grade glass which has lower SiO_2 and (Na_2O+K_2O). This is the reason that it caused much less expansion than container glass.

Effect of glass particle size

The particle size of the glass also has an effect on ASR. For glass aggregate, the viscous gel created from ASR will form on the surface of the aggregate because glass is dense. Confined by the cement paste and aggregate, the gel swells after absorbing water, which generates hydrostatic pressure. The gel can permeate into the surrounding porous cement matrix and aggregate, thus decreasing hydrostatic pressure. But if the hydrostatic pressure exceeds the tensile strength of the system, cracks will form and develop. That is why most concrete with glass aggregate expands more.

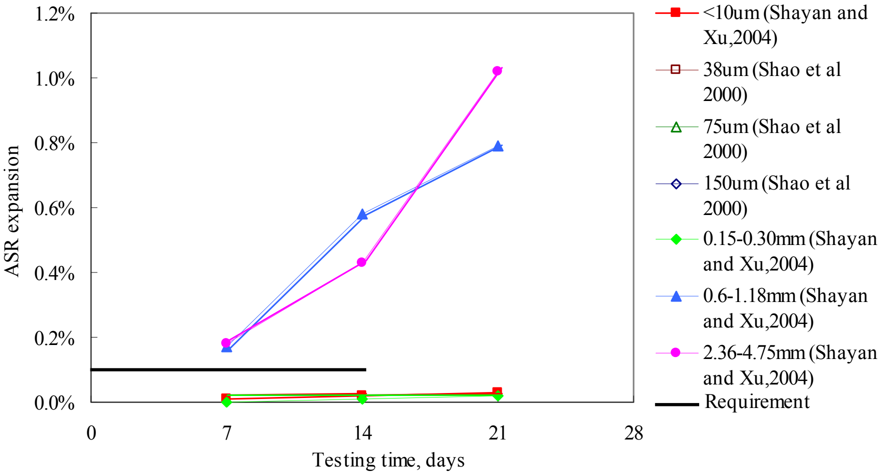


Figure 2-44 Developments of ASR expansion (Shao et al., 2000; Shayan and Xu, 2004)

It has been shown that the finer the glass particles, the less the expansion. It can be seen from Figure 2-44 (Shao et al., 2000; Shayan and Xu, 2004) that glass particle sizes below 0.30 mm give no significant expansion whereas above 0.6 mm causes adverse volume change. This is confirmed by others (Corinaldesi et al., 2005; Meyer et al., 1996; Park et al., 2004; Park and Lee, 2004; Topcu and Canbaz, 2004). The reason may be because the fine glass powder has high pozzolanic activity and reaction products bind alkali, thus making it unavailable for ASR (Shayan and Xu, 2006).

Shayan et al (2006) shows that expansion of concretes with glass up to 2.36 mm are all less than that of a control mix with cement only.

Compared with a control mix without glass, Byars and Zhu (2003) found that glass aggregate with a particle size below the 0.6-1.18 mm range caused less ASR expansion. Jin et al (2000) found that glass particles of 1.18~2.36 mm caused maximum expansion in fine aggregate of less than 4.75 mm.

Therefore, glass powder can also be used as an ASR suppressant. Comparison between mortar with cement and that with a glass powder of Blaine fineness of 467 m^2/kg showed that the expansions of the mortar with 20% glass at all ages up to 21 days are all less than half of that with pure cement (Shi et al., 2005).

However, Diamond and Thaulow (1974) suggested that the size of the reactive aggregate should be no guarantee against ASR because opal aggregate of 20~30 μm expanded in the ASR test. On the other hand, Jin et al.'s study (2000) showed that the more reactive the aggregates the smaller pessimum size. Therefore ASR could be mitigated if the glass particles are fine enough.

2.7.4 Application of glass in self-compacting concrete

In spite of its recognized feasibility in concrete, very limited work has been carried out on the application of ground glass in SCC.

Glass has the potential to be used as a powder in SCC. The preferred fineness of additions for SCC is more than 70% particles passing 0.063 mm (The Concrete Society and BRE, 2005). It is recommended that recycled glass can be used in SCC as long as the particle size is less than 0.1 mm and the specific surface area more than 2500 cm^2/g (EFNARC, 2002).

A few cases of the application of ground glass in SCC have been reported (Shi and Wu, 2005): a glass, of which the fineness was not mentioned but which exhibited higher pozzolanic reactivity than Class F fly ash, was successfully applied in a lightweight SCC, without segregation and visual bleeding; the changes in fresh properties were: a decrease of 25 mm and 23% in slump flow and L-box blocking ratio respectively and an increase of 0.8 seconds in V-funnel time, when 15% cement was replaced by the glass powder.

It is anticipated that more superplasticiser will be necessary to meet the required fresh properties of SCC with glass powder.

2.7.5 Conclusion

Glass is highly reactive with alkali due to its high silica content and amorphous structure and therefore the application of glass in concrete must take its special physical and chemical properties into consideration, e.g. irregular particle shape, smooth surface, aesthetic potential, hard but brittle, no water absorption, pozzolanic if finely ground.

Glass could be used in concrete as coarse and fine aggregates and a substitute for cement. The application of glass, no matter its form, has decreased consistence, strength and strength development. Glass aggregate introduces more risk of ASR than powder. Replacing cement by glass powder seems feasible especially for low replacement ratios.

ASR expansion depends on the chemical composition, content and particle size of the glass and the alkali content of the concrete. Glass particle size has the most significant effect on ASR expansion. Type and colour also affect expansion. Green glass powder can suppress expansion. Glass aggregate could lead to adverse expansion in concrete, whereas glass powder is effective in reducing ASR expansion which depends on its particle size.

Based on the data about concretes incorporating glass powder and one successful application of ground glass in a lightweight SCC, it is probable that glass could be used in SCC provided care is taken with design.

Chapter 3 Aims and Scope of the Project

3.1 Conclusions from literature review

The conclusions from literature review of direct relevance to this project are:

- SCC has gained worldwide acceptance and is still evolving.
- An effective mixing procedure leads to consistent and reliable test results.
- Test combinations can give a complete analysis of fresh properties of SCC.
- The most recent European guidelines (2005) are the first co-ordinated international recommendations.
- SCC can be made from many materials, among which superplasticisers are indispensable. The required fresh properties may be met with new generations of superplasticisers. If not, VMA may be needed to provide proper viscosity.
- The interactions among constituent materials are uncertain and concrete trials are necessary for SCC.
- The UCL mix design method has the advantages of being simple and efficient; it includes use of clear correlations between the properties of mortar and SCC and suits local materials. Testing mortar is also an effective way of selecting the constituent materials because mortar needs far less sample size and simpler to perform than concrete.
- The physical and chemical effects of fly ash can improve concrete performance. By incorporating fly ash, SCC can be produced with lower quantities of admixtures, and there will be environmental advantages if SCC with more than 40% fly ash can be developed.

- Glass could be used as a substitute for cement or aggregate. Limiting glass content or changing particle shape or size, glass concrete can achieve comparable hardened properties. Glass aggregate may introduce ASR expansion while glass powder can suppress the risk. The negative influence on consistence can be compensated by using superplasticizer. This indicates glass may be feasible especially for low replacement ratios in SCC.

3.2 Overall objective

The enormous output of fly ash from power plants is an incentive to incorporate it in concrete. Normally up to 30% fly ash has been incorporated in SCC. The effect of higher volumes of fly ash on SCC is uncertain, and it is therefore necessary to carry out further research on SCC at all levels of replacement ratios of fly ash.

Ground glass is an unconventional material for SCC but it is certainly promising considering its potential environmental benefits. In spite of the risk of ASR, some limited previous studies have shown that glass may be suitable for use in SCC with careful mix designs.

The objective of the present project is therefore to identify the possibility of use of high volumes of fly ash and ground glass in SCC with satisfactory properties, thus widening the quantity and the type of additions available to SCC producers and users.

3.3 Scope of test programme

The stages and scope of the test programme were planned as follows; they are summarised in Table 3-1.

Stage 1 Selection of mix design methods, test methods and procedures, target properties and constituent materials.

Stage 1a Assessment of mix design methods

Mixes were produced by using general-purpose method, CBI method and UCL mix design methods. Comparisons led to the extensions to the UCL method and its subsequent use throughout the subsequent test work.

The UCL method is based on the relationships between spread and the V-funnel times of mortar and SCC with coarse aggregate contents of 50~55% of its dry rodded bulk density. Tests were carried out to confirm the relationships between Bingham parameters and the mortar spread and the V-funnel times, and then the relationships between the spread of mortar and the slump flow of SCC and the V-funnel time of mortar and that of SCC were confirmed by tests on SCC with 100% Portland cement.

The method was then extended by establishing the relationships between mortar and SCC on mixes with coarse aggregate contents of up to 65% of its dry rodded bulk density. The limit of coarse aggregate content in SCC was determined by the J-ring test.

Stage 1b Selection of mixing procedures and test methods.

A fixed mixing procedure was adopted and used throughout for mixing mortar and concrete for maximum superplasticiser efficiency and full dispersion of the powder.

Based on the European guidelines (2005), a combination of tests was selected for assessment of fresh properties of SCC.

Stage 1c Selection of the target properties of self-compacting concrete for the subsequent tests.

A slump flow of 650~750 mm is applicable for many normal applications, e.g. walls, columns; a V-funnel time of 8 seconds has good filling ability even with congested reinforcement; a segregation index less than 20% is generally suitable for thin slab and for vertical applications (The SCC European Project Group, 2005). Because the J-ring test was performed after the slump flow test and the V-funnel test in which some paste may be lost and was not carried out until 35 minutes after mixing, the recommended value of 15 mm is quite severe for the project. A more realistic value, 25 mm was selected as the target. Acceptance ranges were selected according to European guidelines (2005).

Stage 1d Selection of constituent materials.

The choice of aggregate, cement, fly ash and ground glass was based on locality, convenience, availability and consistence of supply.

A series of tests on mortars were used to compare the performance of eight polycarboxylate-based superplasticisers that had been developed and marketed for use in SCC. Sika ViscoCrete 10 was selected due to its greatest consistence retention and the strongest robustness to variations of water and superplasticiser content.

VMAs were also compared by mortar tests. KELCO-CRETE 200 diutan gum leads to the lowest decrease in the yield stress and the highest increase in the plastic viscosity. If the required fresh properties can be obtained by using superplasticisers alone, then VMA may not be necessary.

Stage 2 Production and testing of self-compacting concrete incorporating fly ash at up to 100% cement replacement.

Concrete mixes with the target fresh properties at each fly ash replacement level (0, 20, 40, 60, 80 and 100%) were produced, and all except the 100% level tested for hardened properties.

Tests on mortar (spread and V-funnel time) were first used to establish W/P ratios and superplasticiser dosages for constant mortar properties with increasing amounts of fly ash. These were then used in concrete mixes and, if necessary, the proportion adjusted until the target properties were achieved in each mix.

It was necessary to switch to a second batch of fly ash from a different supplier during this work – comparisons between the batches were made.

The hardened properties of each of the concrete mixes (at up to 80% fly ash) were then measured, including compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), dynamic elastic modulus (Ed) and water absorption at ages of up to 180 days. Then the relationships between compressive strength and splitting strength, UPV and Ed were compared to those of NVC. This can be used to compare the material properties of SCC and NVC and will give indirect information about SCC in situ.

Stage 3 Production of self-compacting concrete incorporating ground glass.

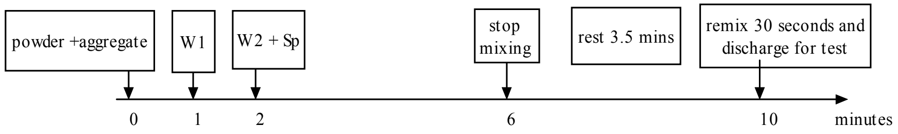
The overall aim was similar to that for fly ash – to establish a set of concrete mixes at varying glass content with the target fresh properties and then evaluate their hardened properties.

The ground glass was first considered as an addition, but due to its coarse size, it was found that it would be more appropriate to consider it as a partial replacement for both cement and fine aggregate. The limiting content for segregation control of the mortar was determined, and a set of mortar mixes leading to a set of concrete mixes with the target properties established.

The hardened properties measured were - compressive strength, splitting tensile strength, UPV, Ed and water absorption at ages of up to 180 days. The relationships between compressive strength and splitting strength, UPV and Ed were compared to those of NVC.

ASR tests were performed on the mortar mixes with the maximum glass content possible.

Table 3-1 Scope of test programme

STAGE	OBJECTIVE	INVESTIGATION	PARAMETERS CHOSEN	REF.
1a	Selection of mix design method	General-purpose method CBI method UCL method	1. Coarse aggregate content is fixed at 55% of its dry rodded bulk density, i.e. 35.5% of concrete volume. 2. Sand to mortar ratio is kept constant at 45% by volume. 3. Air content is estimated as 1%. 4. The W/P ratio and superplasticiser dosage are determined in the mortar tests and then applied to a concrete and adjusted if necessary to meet the required targets of SCC.	Chapter 6
1b	Selection of test procedures and methods	Mixing procedure Mortar tests SCC tests	 W1 = 80% mixing water W2 = 20% mixing water Sp: superplasticizer Spread and the V-funnel tests on mortar Slump flow, V-funnel, J-ring, L-box and sieve stability tests on concrete	Chapter 4
1c	Selection of target properties of SCC	Criteria	● Slump flow of 700 ± 50 mm ● V-funnel time of 8.0 ± 3.0 seconds ● Step height in the J-ring < 25 mm ● Sieve segregation < 15%.	2.3.2
1d	Selection of constituent materials	Selection of aggregate, cement, fly ash and ground glass Spread and the V-funnel tests on mortar with superplasticisers and VMAs.	● Thames Valley aggregates of size 0/4 mm, 4/10 mm and 10/20 mm ● Blue Circle CEM I 42.5 N from Lafarge ● Fly ash, Ratcliffe plant of RMC UK LTD and Drax of CEMEX ● Ground glass powder, green and white ● Tap water ● Sika ViscoCrete 10	Chapter 5

2	Production and testing of SCC with fly ash	Test the fresh properties of SCC incorporating fly ash Evaluate their hardened properties	SCC can be produced with up to 100% fly ash replacement ratio Hardened properties are carried out on mixes with up to 80% fly ash replacement at ages of up to 180 days	Chapter 7
3	Production and testing of SCC with ground glass	Test the fresh properties of SCC incorporating ground glass Evaluate their hardened properties Evaluate ASR risk on mortar mixes	SCC can be produced with glass up to 6.4% concrete volume without VMA Hardened properties at ages of up to 180 days ASTM C1260 ASR test up to 42 days	Chapter 8

Chapter 4 Mixing, Tests and Data Evaluation

To obtain accurate results, it is important that the mixing and testing procedures are as identical as possible throughout the project. This includes: same equipment, procedures, laboratory environment and materials.

In this chapter, the mixing procedures, test methods for the fresh paste, mortar and concrete and hardened concrete are described and methods of data evaluation are demonstrated. All tests were available at UCL at the start of the research apart from the water absorption and ASR mortar expansion tests.

All materials were stored in the laboratory at ambient temperature before use, and mixing and testing were carried out at room temperature which varied from 18 to 28 °C, but was normally between 18 and 23°C.

4.1 Tests on constituent materials

4.1.1 Particle size distribution of powders

The particle size distribution of cement, fly ash and glass were measured by a laser granulometer by Cemex (UK) Ltd.

4.1.2 Superplasticisers

Tests on superplasticisers include relative density and dry material content test.

4.1.2.1 Relative density test

The relative density of the superplasticisers was tested by using a method slightly modified from BS EN 3712-1 (1991). A 10 ml graduated cylinder was filled and weighed and the relative density calculated.

4.1.2.2 Dry material content test

The dry material content of superplasticiser was tested by using a method slightly modified from BS EN 480-8 (1997). A sample in a stainless steel container was evaporated to dryness in an oven at 110°C for 24 hours and the solids content from the weights before and after drying.

4.1.3 Aggregate

Tests on aggregate include water absorption, moisture content, packing density and sieve analysis test.

4.1.3.1 Water absorption test

The water absorption of the aggregate fractions was obtained by using a method slightly modified from BS EN 1097-6 (2000). The aggregate was dried in an oven for 24 hours and weighed (W_0). The dry aggregate was then immersed in water for another 24 hours, after which it was carefully dried by hair drier until only the surface of the aggregate was dry and weighed again (W_1). The water absorbed is calculated as

$$\text{The absorption (\%)} = \frac{(W_1 - W_0)}{W_0} \times 100$$

4.1.3.2 Moisture content test

Accurate control of the water content of the mixes is essential. To avoid changes in consistence of the concrete, the aggregate was kept in a condition greater than saturated surface dry (SSD). Moisture content of aggregates was measured every time before batching the mortar and concrete. About 200 g wet aggregate was weighed (W_1) and dried in the microwave. Fine aggregate of 0/4 mm and coarse aggregate of 4/10 mm and 10/20 mm were dried for 8 minutes and 6 minutes respectively and weighed (W_0). The moisture content is calculated as

$$\text{The moisture content (\%)} = \frac{(W_1 - W_0)}{W_0} \times 100$$

4.1.3.3 Packing density test

The packing density was tested by using a method slightly modified from ASTM C 29/C 29M (1990) in order to investigate the optimum proportions of binary coarse aggregates for mixes. This procedure is simple enough for practical applications and takes the shape, texture and particle grading of the aggregate into account.

Aggregates were dried in an oven for 24 hours and mixed in Liner Cumflow mixer for about 3 minutes. Then a cylinder (240 mm in diameter, 200 mm in height) was filled with aggregate in 6 layers, each layer was uniformly compacted 30 strokes of the tamping rod (16 mm in diameter, 600 mm in length). For the top layer, extra aggregates were struck off and the tamping rod was rolled over the surface. Tests were executed for various proportions of 4/10mm and 10/20mm aggregate and the ratio that gave the lowest void content was taken as the optimized value.

4.1.3.4 Sieve analysis test

Sieve analysis of aggregate was tested by using a method slightly modified from BS EN 933-1 (1997). The aggregate was dried in oven for 24h. Then about 2 kg oven-dry aggregate was weighed and put in the sieves. The fine aggregate of 0/4mm was shaken for 6 minutes in shaking sieves. The coarse aggregate was shaken by hand. The residue on each sieve was measured and the cumulative percent passing was calculated.

4.2 Mixing procedures

For paste, 1 litre batches were mixed in a Silverson mode RBXL mixer. This is a high shear mixer. Water was put in the cup first, the mixer then turned on and powder gradually added during mixing. The total mixing time was about 10 minutes.

For fine mortar or mortar, 1.6 litres batches were mixed at speed 1 in a Hobart Model N-50 mixer with a maximum capacity of 2 litres.

Concrete was mixed in a Liner Cumflow mixer with a maximum capacity of 60 litres. This is a forced action pan mixer which was robust and reliable. Usually 35 litres of concrete were mixed for fresh-property tests only, and 55 litres for fresh-property tests and subsequent casting of specimens for hardened-property tests.

It is shown that the mixing procedures have a significant influence on the fresh properties of the SCC (refer to 2.2.1). Based on Jin's work (2002), a fixed mixing procedure was adopted and carried out throughout this research for mixing mortar and concrete to achieve maximum superplasticiser efficiency and full dispersion of the powder. The constant procedure shown in Figure 4-1 was used to mix mortar and concrete.

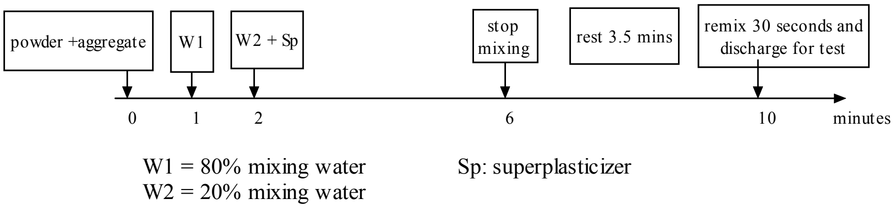


Figure 4-1 The mixing procedure for mortar and concrete

1. Powder (including cement and/or fly ash and/or ground glass) and aggregate were mixed for one minute;
2. The 1st part (80%) of mixing water was added slowly while mixing and mixed for another one minute;
3. The 2nd part (20%) of mixing water with superplasticiser dissolved in it was added slowly while mixing for another 1 minute;
4. Mixing was continued for a further 3 minutes;
5. The mix was allowed to rest for 3.5 minutes;
6. The mix was remixed for 30 seconds and discharged for testing.

4.3 Tests on fresh paste, mortar and self-compacting concrete

In this section, tests on the fresh paste, fine mortar, mortar and concrete are described. These included rheological, spread and the V-funnel tests on paste and mortar. Rheological tests on mortar were performed after V-funnel test and the mortar was remixed by hand for a minute before rheological test. Then the fresh property tests on the concrete which included slump flow, V-funnel, J-ring, L-box and the sieve stability tests are described.

All the tests were carried out by only one operator. The order of testing after mixing usually was one slump flow test, three consecutive V-funnel tests, one sieve stability test and one J-ring test; these were carried at approximately 12, 20, 30 and 35 minutes after adding mixing water respectively. The concrete was sampled for the sieve stability test after the slump flow test. Consistence retention was assessed by a second series of tests, consisting of one slump flow test and three consecutive V-funnel tests at 65 and 70 minutes after adding water respectively.

Between measurements, concrete was stored in the mixer covered with a plastic sheet to avoid moisture loss. Concrete was re-used after the slump flow test to minimise the production of concrete in the lab. To simulate the concrete slowly stirred in the truck-mixer, concrete was dropped back into the mixer after testing and remixed for 1 minute before another test was taken. Great care was taken not to lose paste in the operation.

During handling and testing, concrete was always inspected to ensure the homogeneity. The halo of cement paste or unevenly distributed or clustered aggregates was recorded.

4.3.1 Rheological test

Paste, fine mortar and mortar were all considered as Bingham materials and two-point tests were used to measure the yield stress and plastic viscosity. These tests used at the initial stage of the project to obtain correlations between yield stress and spread and between plastic viscosity and V-funnel time of the mortar to confirm previous data (refer to Figure 2-7).

Figure 4-2 Rheometer 115 with CIO-DAS802/16 recording system

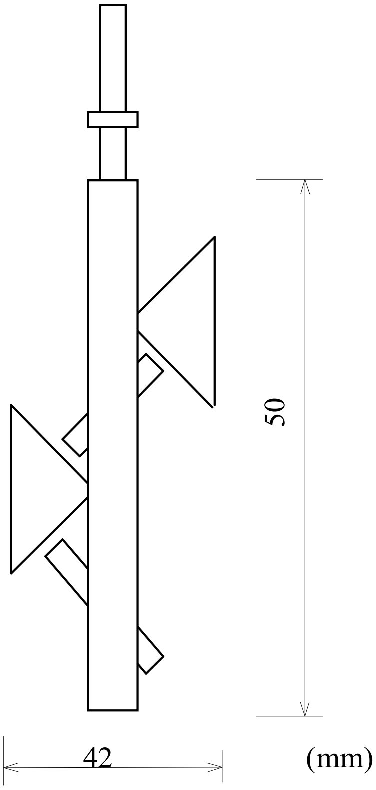
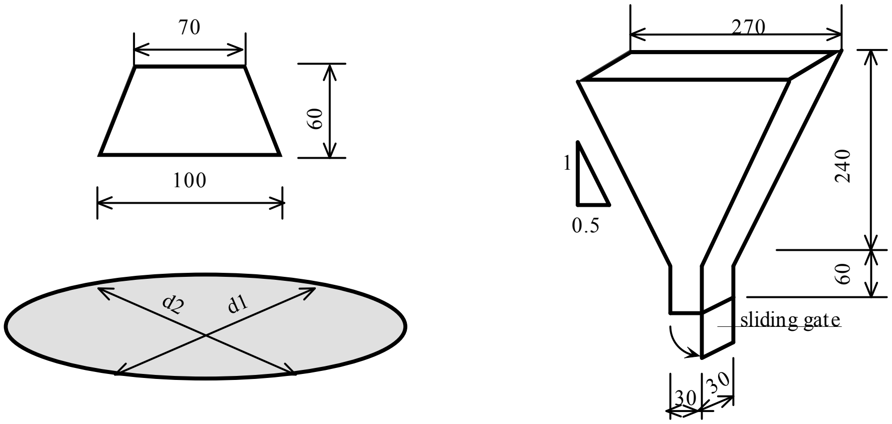


Figure 4-3 Schematic of helical impeller rheometer for mortar

The tests used a Rheometer 115 with CIO-DAS802/16 recording system on a computer with Instacal^{TM} programme (shown in Figure 4-2). It measures the torque produced by rotating an impeller at different speeds in a cup filled with sample. This is a reduced scale version of the two-point test for concrete which was developed by Jin (2002) in the previous project at UCL.

The dimensions of the impeller are shown in Figure 4-3. The speed first increases to its maximum value then gradually decreases to zero. The computer connected to the rheometer records the speed and torque values from which linear results are selected and plotted. An analysis programme then calculates shear stress and shear rate and hence yield stress and plastic viscosity from the intercept and the gradient of the resulting graph respectively. These two fundamental Bingham parameters are more helpful than results from single point tests.

4.3.2 Spread and V-funnel test



Dimensions in mm

(a) Spread test

(b) V-funnel test

Figure 4-4 Dimensions of frustum cone and V-funnel for mortar test

The apparatus for the spread test (shown in Figure 4-4) comprises a frustum cone and a glass plate. All surfaces of the cone and glass plate were clean and just-moist at the start of each test. The cone was placed on the centre of glass plate, filled with the sample without compaction and then lifted vertically. After the sample stopped flowing, the diameters of the deformed sample in two perpendicular directions were measured as d1, d2 (mm). The final spread was the average of d1 and d2 (mm). If a spread with a 'halo' of mortar, the thickness of the halo was measured.

The surface of the V-funnel was clean and just-moist before the first test and was not cleaned between repeat tests. The V-funnel was placed horizontally with the gate closed and was filled with mortar without tamping. Then the gate at the bottom of the orifice was opened to let concrete flow out under gravity and started to time. The time of the first light seen from the top was recorded.

The above operation was carried out three times using the same sample. The surface of V-funnel was saturated with mortar after the first flow. The first reading was discarded and the V-funnel time taken as the average of second and third recording.

To assess the consistence retention, spread and V-funnel time were measured at 30, 60 and 90 minutes after first adding the water to the mix. Between measurements, the mortar was stored in the mixing bowl and covered with a damp cloth to avoid moisture loss. The mortar was remixed before each test for 30 seconds.

4.3.3 Slump flow test

Slump flow test was carried out in accordance with EN 12350-8 (2007), from which slump flow and T500 were obtained, assessing deformation ability and deformation rate (refer to 2.1.2.1) in the absence of obstructions respectively.

The dimensions of mould and base plate are shown in Figure 4-5. The surfaces of all the apparatus were clean and damp before each test. The mould was placed in the centre of the plate and filled with about 6 litres concrete without external compaction. The mould was lifted vertically and the concrete was allowed to flow out freely. The test ended when concrete stopped flowing. Slump flow was the mean diameter of the concrete at two perpendicular directions $S=(d_{max}+d_{perp})/2$ and expressed to the nearest 5 mm.

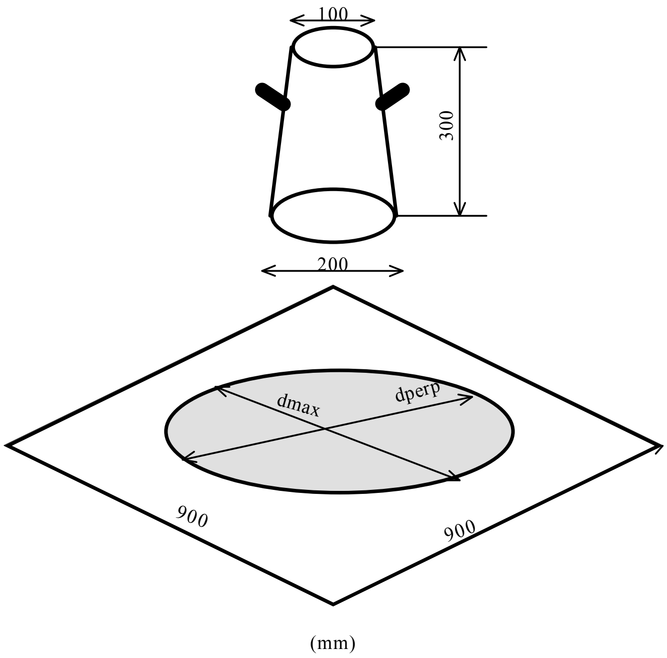


Figure 4-5 Dimensions of a slump cone and a base plate in slump flow test

T500 was the time from lifting the cone to the concrete reaching a diameter of 500 mm. It was measured at the initial stage of this project but not tested later for the following reasons:

- In testing, it is difficult to lift the mould and start the stopwatch for measuring T500 time at the same time for a single operator.
- The time for the concrete to reach the 500 mm circle is difficult to assess reliably.
- There were good correlations between T500 and V-funnel times from the initial stage of testing (shown in Figure 9-3), and the V-funnel test is more convenient for a single operator.

The V-funnel time was therefore selected to evaluate the deformation rate of concrete throughout of project.

Segregation can be evaluated by observing the periphery of the concrete. If there was halo and the coarse aggregate was unevenly distributed in the paste, the mix was evaluated as segregated.

4.3.4 V-funnel test

The V-funnel test, which is used to assess deformability rate of SCC flowing through a restricted area, was carried out in accordance with EN12350-9 (2007).

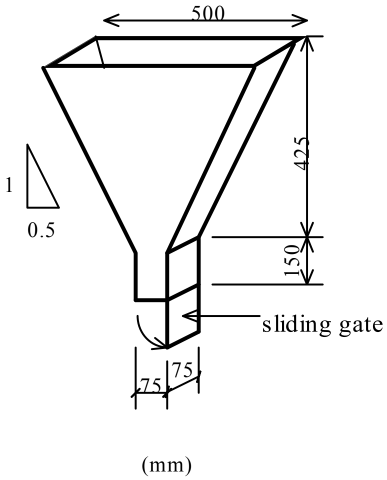


Figure 4-6 Dimensions of the V-funnel for concrete

The dimension of apparatus which has a capacity of about 10 litres, are shown in Figure 4-6. The test procedure was the same as that for mortar. The V-funnel time was the average of the second and third flow time recorded.

4.3.5 J-ring test

From all the passing ability tests described in the literature review, the J-ring test was selected for this project for the following reasons:

1. It has been considered as a standard by European project.

2. It simulates the reinforcement distribution in real construction site.

3. It investigates the blocking behaviour of concrete. Passing ability of concrete can be simply quantified by the height difference between the outside and the inside the J-ring.
4. The same mould as in the slump flow test is used.
5. It requires less amount of concrete than the L-box test.
6. It can be easily performed and cleaned.

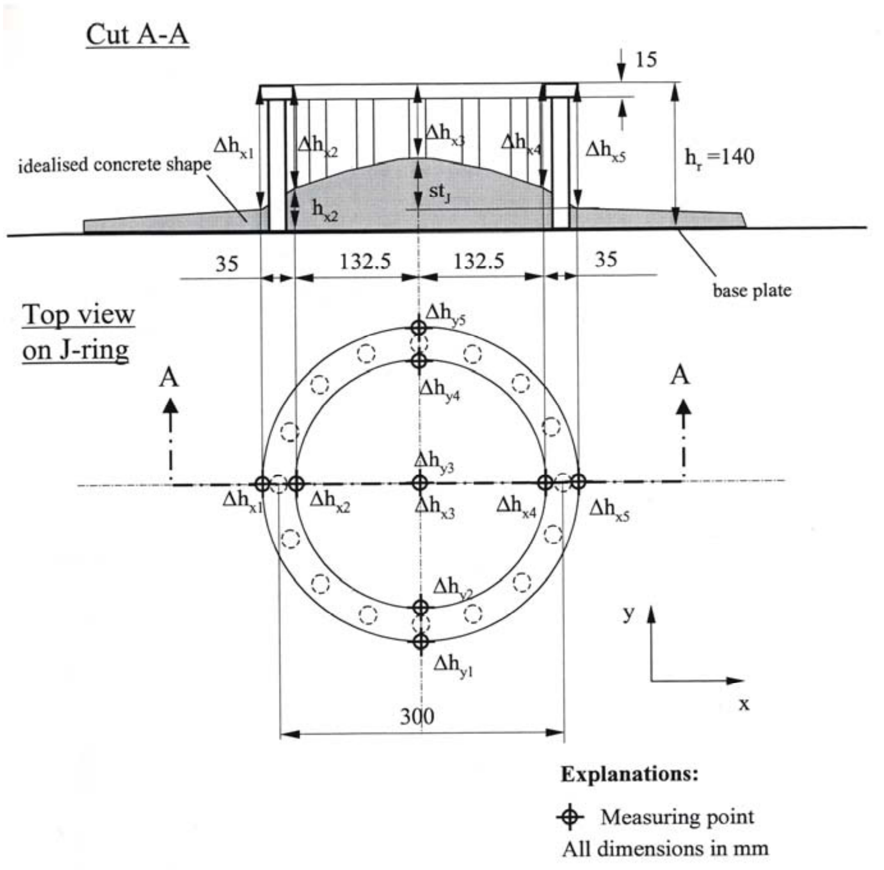


Figure 4-7 Dimensions and measuring points of J-ring in UCL

The J-ring, an open circular steel ring (shown in Figure 4-7) is used for the maximum size of aggregate of 20 mm, 16 smooth steel bars of 18 mm in diameter, 150 mm in height were placed vertically under the ring at even spacing. Abrams cone is placed centrally inside the J-ring.

The J-ring test was carried out in accordance with EN 12350-12 (2007). The surfaces of all the apparatus were clean and damp before each test. The J-ring and mould were placed in the centre of the plate (with the same dimensions as shown in Figure 4-5). The mould filled with about 7 litres concrete without external compaction. After the mould was lifted vertically and concrete stopped flowing, the heights from the concrete surface to the top of the J-ring inside and outside the ring in two directions at right angles were measured. The final result, the step of J-ring (also called the step height), was expressed as the average height difference between the inside and outside the ring, to the nearest 1mm. At the beginning of the project, the spread of the concrete in two perpendicular directions was also measured with the average being taken as the J-ring spread (S_J) to the nearest 5 mm.

$$\text{Step of J-ring } S_J = \frac{1}{6}\left(\sum_{i=2}^{5}\Delta h_{xi} + \sum_{i=2}^{5}\Delta h_{yi}\right) - \frac{1}{4}\left(\sum_{i=1,5}\Delta h_{xi} + \sum_{i=1,5}\Delta h_{yi}\right)$$

$$\text{slump flow of J-ring } SF_J = \frac{d_{1J} + d_{2J}}{2}$$

The concrete was inspected visually to evaluate segregation and blocking. If coarse aggregates are accumulated inside the bars blockage is apparent. If coarse aggregate particles distributed evenly inside and outside the bars, there is no blockage but there is probably a deficiency of filling ability.

4.3.6 L-box test

The L-box test was used to assess the passing ability of SCC at the initial stage of designing SCC (refer to 6.2). The test was carried out in accordance with EN12350-10 (2007). The dimensions of the three-bar L-box used are shown in Figure 4-8.

The vertical part of the box is filled with about 12 litres of concrete without tamping and left to rest for one minute in order to allow any segregation to occur. Then the sliding gate is lifted and the concrete flows out of the vertical part into the horizontal part through the reinforcement bars. The times for the front concrete to reach a distance of 200 mm along the horizontal part, and the heights of concrete at the two ends of the box are measured, H1 and H2, after the concrete has stopped flowing (show in Figure 2-19), were measured in three places each and the average taken. The ratio of H2/H1, called the blocking ratio (BR), is used to evaluate the passing ability.

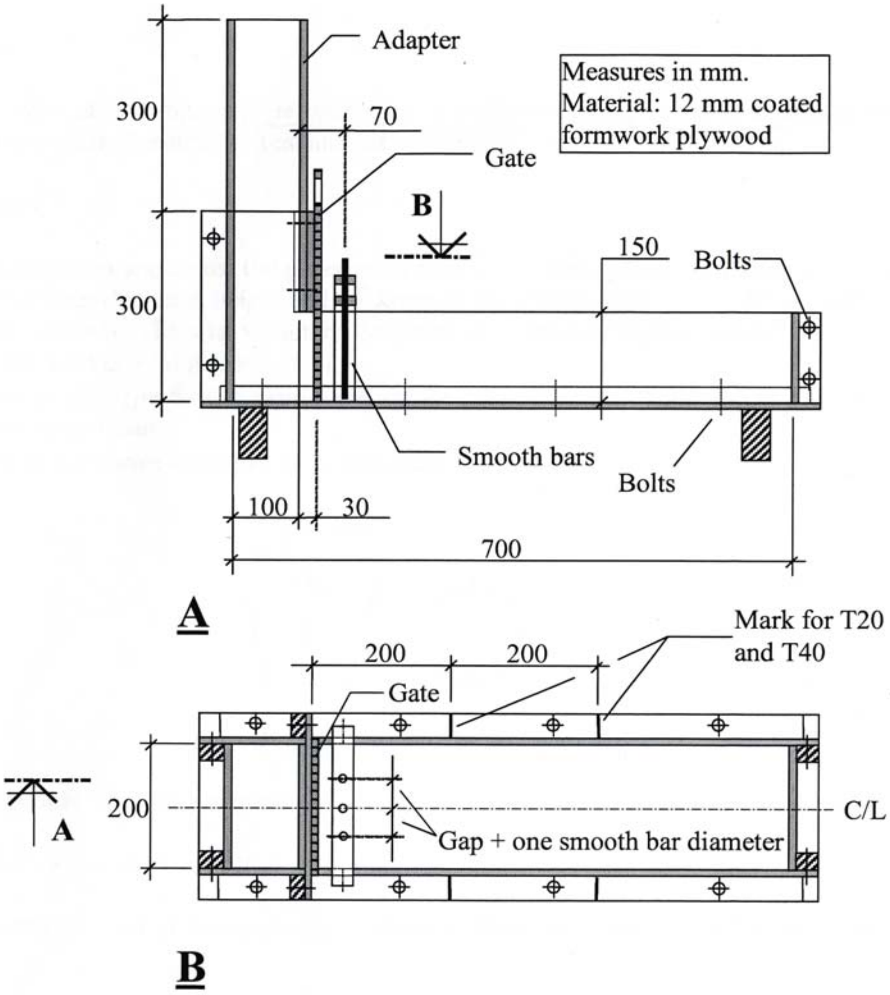


Figure 4-8 Dimensions of L-box in UCL

If coarse aggregates are evenly distributed on the concrete surface or there are no aggregate particles wedged between the bars, the mix can be regarded as having no segregation.

4.3.7 Sieve stability test

The segregation resistance of SCC was evaluated by the sieve stability test as shown in Figure 4-9 in accordance with EN 12350-11 (2007).

Figure 4-9 Sieve stability test in UCL

About 10 litres of concrete in a bucket was allowed to stand for 15 minutes. Then a sample of about 4.8 kg of concrete was poured from the top of this on to a 5 mm sieve from a height of 500 mm. The amount of laitance passing through the sieve after 2 minutes was weighed. The segregation index (SI) is the amount of laitance passing through 5 mm sieve expressed as a percentage of the total weight of the sample to the nearest 1% as

$$SI = \frac{(m_{pl} - m_p) \times 100\%}{m_s}$$

where m_p and m_s are the weight of pan and concrete sample respectively (kg); m_{pl} is the weight of the laitance (kg).

4.4 Tests on hardened mortar and concrete

Concrete properties are a function of time and ambient humidity, and because of this, tests on concrete are performed under specific conditions. SCC is different from other concrete in fresh properties. However, the hardened properties of SCC subjected on the same factors such as cement hydration, W/C ratio and powder types etc (refer to 2.1.2.6). Thus hardened SCC is assessed by the existing testing methods for concrete which are described briefly as follows.

4.4.1 Casting, curing and storage

Casting, curing and storage of concrete was based on BS EN 12390-2 (2000) except there was no compaction during casting.

Hardened tests were carried out only on mixes meeting the target fresh property (refer to 3.3). For each mix 18 cubes (100×100×100 mm^3) for UPV and compressive strength, 6 cylinders (100 mm in diameter and 200 mm in length) for splitting strength and 3 prisms (100×100×505 mm^3) for dynamic elastic modulus were cast without vibration from a single batch. Only slump flow and the V-funnel tests were carried out on these batches before casting.

The cubes, cylinders and prisms were covered with plastic sheets and stored in the lab after casting. After about 24 hours, all the specimens were de-moulded, marked and cured in water at 21°C until the date of testing. The cubes for sorptivity test were stored in the water before transferring to an oven at 55 ± 2°C. All testing was carried out on three samples and the average value reported.

4.4.2 Density test

The density of each specimen (prisms and cubes) was determined by measuring the weight of a specimen in the air and under water according to BS EN 12390-7 (2000). The density was calculated by

$$\rho = \rho_w \frac{M_a}{M_a - M_w}$$

where ρ and ρ_w, are the density of concrete and water respectively (kg/m^3); M_a and M_w are the weights of the concrete specimens in air and water respectively (kg).

When the compressive result was in doubt, for example a low strength with an abnormally low density, the result was discarded.

4.4.3 Strength test

Strength tests include compression on cubes and splitting tests on cylinders.

4.4.3.1 Compressive strength test

Compressive strength test is the most common of all tests on hardened concrete and compressive strength is the most important parameter in structural design. Three standard cubes of 100 mm^3 were produced for each mix. The compressive strength test was carried out according to BS EN 12390-3 (2002) at ages of 7, 28, 90 and 180 days. The testing apparatus is shown in Figure 4-10.

Figure 4-10 Uniaxial compression device in UCL

4.4.3.2 Splitting test

Tensile strength tests are used to assess the cracking resistance of concrete and bond strength to reforcing bars. However direct tests on tensile strength of concrete are difficult to conduct. The most commonly adopted tests for determining the indirect tensile strength are the flexural strength and the splitting test.

The tensile strength was measured by indirect splitting test, according to BS EN 12390-6 (2000). Three cylinders per mix are tested at ages of 28 and 90 days. Plywood strips ($3\times15\times200$ mm^3) were used as bearing strips. The splitting strength was calculated by

$$f_s = \frac{2P}{\pi \times l \times d}$$

where f_s is the splitting strength (MPa), P is the failure load (kN), l is the length of cylinder (mm) and d is the diameter of cylinder (mm).

4.4.4 Non-destructive tests

Non-destructive tests, also known as in-situ tests, have been developed to give indirect information about the concrete in situ. The tests do not damage the concrete thus can be performed repeatedly. It is well known that there are correlations between the non-destructive test results and the strength values in NVC (CEB FIB Model Code 90). It will be also useful to have such information for SCC in situ. As the result, the internal structure of concrete could be non-destructively monitored.

Among the available non-destructive methods, the dynamic elastic modulus and UPV test were carried out on target mixes.

4.4.4.1 Dynamic elastic modulus test

The dynamic elastic modulus test according to BS 1881-209 (1990) was carried out on prisms of 100×100×505 mm. The Erudite apparatus (shown in Figure 4-11) measures the resonant frequency of a concrete prism in longitudinal vibration when supported at its mid-point.

The dynamic elastic modulus was determined using

$E_d = 4\, n^2\, l^2\, \rho$

where Ed, n, l and ρ are the dynamic elastic modulus (GPa), resonant frequency (Hz), length of the beam (mm) and density (kg/m^3) respectively.

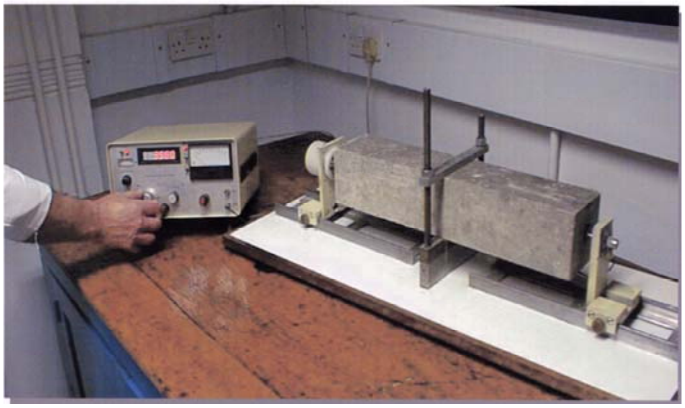


Figure 4-11 Erudite apparatus in UCL

Dynamic elastic modulus tests on concrete were conducted at ages of 7 and 28 days. After initial 28-day tests, dynamic elastic modulus of concrete was tested once per month up to 6 months. Density was measured before this test.

4.4.4.2 Ultrasonic pulse velocity test

Figure 4-12 Pundit apparatus in UCL

The test is described in BS EN 12504-4 (2004). The Pundit apparatus (shown in Figure 4-12) was used to measure the time for a pulse to travel from the transmitting to the receiving transducer on two opposite sides of a cube of 100 mm. Small amount of grease was used to couple between the transducer and the specimen. The velocity is calculated as

$$UPV = \frac{l}{t}$$

where UPV, l and t are the velocity (km/s), the length between two transducers (mm) and the time (micro seconds) respectively.

UPV tests were carried out at ages of 7, 28, 90 and 180 days and before the compression test. UPV could correlate with concrete strength if the parameters (aggregate type, curing conditions etc) are constant.

4.4.5 Water absorption tests

Durability is closely associated to the density of the surface layer of the concrete which can be investigated by measuring the capillary absorption (refer to 2.1.3.7). Many tests have been developed as follows.

4.4.5.1 Complete immersion test

Three specimens of circular discs with diameters of 75 mm are used which are cored from the concrete at the age of 24~38 days. The length of the specimen is the full thickness of the concrete when it is between 32 and 150mm, or 75 mm when it is greater than 150 mm. All specimens are dried in the oven of 105 °C for 3 days, cooled for 1 day, and then completely immersed in the water of 20 °C for 30 min (BS 1881-122, 1983).

This quick test determines the absorption capacity of a dry concrete after initial contact with water, which provides the water permeable pore volume but not the capillary action. The high drying temperature of 105 °C for 72 hours in the oven could produce cracking, thus leading to unrealistic higher absorption.

4.4.5.2 Sorptivity test

Water absorption evaluated by the water uptake from the concrete per unit cross-sectional area with time, is referred to as the sorptivity. The test is conducted on the surface of concrete which is in contact with a thin water layer and capillary suction is considered the dominant invasion mechanism. There are three different ways to perform the test.

- Horizontal in-flow method (Hall, 1989): absorption is influenced by hydrostatic forces, no gravitational effects;

- Ponding method (Neithalath, 2006): absorption is due to capillary suction and gravitational forces; performed on three cylindrical specimens with the bottom sealed and the top in contact with the water for 400 hours.

  The conditioning procedure is at a low temperature of 70 °C for 3 or 7 days to prevent micro cracking, thus avoiding relatively unrealistic values. The total surface area of water ingress was kept constant for all specimens. However this method measured the absorption of water from a pressure head of 200 mm into the concrete from the top surface besides capillary action.

- Capillary rise methods: the effects of capillary and gravity forces are opposed.

  - The test is performed on circular discs with a diameter of 150 mm and a height of 50 mm; the moulded bottom side of the specimen is immersed in water, the other surfaces are sealed and above water. The absorption is determined by weight changes of the specimen weighed and the test stops after water rises and reaches the top surface (RILEM TC 116-PCD, 1999).

    The surface in contact with water absorbs water mainly by capillary action. However drying at 105 °C in the oven could produce cracking, thus increasing absorption.

  - Another version of the test is ASTM C 1585 (2004). This method dries specimens in a low temperature of 50 °C to prevent micro cracking, thus leading to relatively realistic values. This test is performed on cylinders of 100 mm in diameter and 50 mm in length, which are supported by rods immersed in water of 1~3 mm.

Sorptivity test determines the rate of capillary absorption by concrete over time. There is a linear relationship between water intake per unit (kg/m^2) over the first four hours immersed in water shown as follows (Neithalath, 2006; Zhu and Bartos, 2003).

$$\frac{M}{A} = St^{\frac{1}{2}} + \overline{S}$$

where M is the water intake through a surface area A; S is sorptivity; t is the time from the start of the water absorption test and $\overline{S}$ is a correction term.

The absorption as a function of longer period of time is expressed as exponential (Neithalath, 2006). This is a comprehensive sorption and diffusion model.

$$\frac{M}{A} = B\left[1 - \exp\left(\frac{-St^{\frac{1}{2}}}{B}\right)\right] + S_g t^{\frac{1}{2}}$$

where M, A, S and t are the same as the above equation, B is a constant and S_g is the sorptivity of smaller pores.

Sorptivity test by capillary rise method is relatively simple and convenient, and was therefore chosen for this project. It can be seen from above that the initial water content varies in different tests; the influence on sorptivity such as size and moisture content of specimens, drying and curing conditions, ambient relative humidity and temperature should be kept constant; drying temperature should be low to prevent micro cracking.

Therefore, a slightly modified version of the RILEM TC 116-PCD test was used, as follows:

1. The size and moisture content of specimens, drying and curing conditions, ambient relative humidity and temperature were kept constant.

2. A set of three cubes were selected for water absorption tests after 7 or 90 days curing under water.

3. After the specimens were removed from the water, they were kept in an oven at 55 °C for 21 days.

   This temperature was chosen to prevent micro-cracking and, thus prevent unrealistically high sorption results. Based on preliminary testing, approximately half of the weight loss occurred within 4 days and the weight of specimens was found to be stable after 20 days.

4. After their removal from the oven, the specimens were allowed to cool to room temperature for 24 hours.

5. Only one surface of the cube was in contact with water. A side surface was chosen in order to eliminate any surface finishing effects which lead to abnormally high sorption results. The opposite surface was exposed to air and the other four surfaces were sealed by an epoxy resin, with two coats applied within one hour. Then the specimens were stored in the conditioning room at 19 °C and 90% relative humidity for another 24 hours to achieve the same degree of saturation.

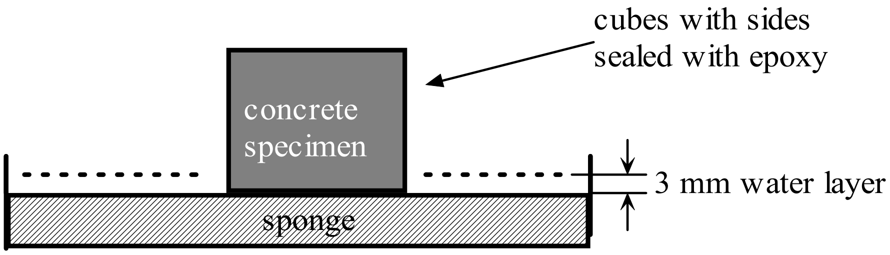


Figure 4-13 Schematic of sorptivity test

6. All specimens were placed on a sponge, which was completely immersed in water (as shown in Figure 4-13). Water layer of about 3 mm was maintained throughout the test, additional water was added if necessary. All the specimens were placed in a tray which was covered with a plastic sheet

and kept in the conditioning room at 19 °C and 90% relative humidity during the test.

The above procedure allowed water movement only through the surfaces in contact with the sponge. The epoxy resin obstructed water ingress from other surfaces.

7. The initial weight of the specimen was measured before contacting water. Specimens were removed from the sponge and weighed every 10 minutes in the first four hours and then every day for 20 days.

4.4.6 Alkali-silica reaction tests

ASTM 227, ASTM C 1293 and BS 812-123 test concrete prisms at normal temperature for a year. They have better correlations with in-situ concrete performance than results from accelerated tests. However they were not selected due to their long testing period.

Since ASR takes 5 to 8 years for ASR damage to display, accelerated test has been developed to study the potential reactivity of aggregates. ASTM C 1260 (2003) is considered to be one of the most commonly used methods because of its quickness to detect potential reactivity of aggregate (Byars and Zhu, 2003; Chen et al., 2006; Jin et al., 2000; Park and Lee, 2004; Shao et al., 2000; Shi and Wu, 2005; Topcu and Canbaz, 2004). Curing conditions, water at 80°C for 24 hours, then 1 N NaOH solution at 80°C for 14 days, are severe, which are impossible for concrete structures in real life. However it is selected because of the advantage of getting results quickly.

The aggregate is regarded as innocuous if the expansion is less than 0.1% at 14 days, potentially deleterious if 0.1~0.2% and reactive aggregate if more than 0.2%.

In addition, the above tests are performed on suspicious aggregates to detect the potential ASR. No specific tests are designed to evaluate the effect of the alkali in additions.

As a result, ASR test was performed by using a method slightly modified from ASTM C 1260 (2003).

- Nine mortar bars, 50×50×150 mm in size, were cast. The moulds were covered with plastic sheets and placed in the lab at 22 °C for 24 hours.
- All mortar bars were then demoulded and stored in water at 80°C for another 24 hours. The lengths of mortar bars were measured as initial lengths, and then the bars were immediately immersed in 1 N NaOH solution at 80°C for 14 days. The testing was extended for four weeks to find the development of volume change with time.
- Length of mortar bars was measured every week. The length change was an average of three identical mortar bars at the same age. The period of reading was less than 10 seconds according to ASTM C1260.
- After a gauge with calibrated dial and calibration bar failed to provide consistent readings, length changes were measured by a vernier scale with accuracy of 0.02 mm.

4.5 Accuracy evaluation

As in all studies on mortar and concrete, in this project there were inevitable variations in raw materials, weighing, mixing, sampling and environmental conditions such as temperature, moisture content of aggregate and so on. It was therefore impossible to reproduce identical fresh mortar and concrete with successive batches of nominally identical mix proportions. Since a large number of experiments needed to be carried out in a limited time, it was impossible to perform each test several times to determine an average value. Therefore it was necessary to evaluate the accuracy of a single measurement by finding the typical scatter of the test.

Since fresh properties of mortar and concrete change with time, and their constituent materials are variable, it is impossible to rigorously determine the repeatability and reproducibility (refer to 2.2.4). Furthermore, all the tests were performed by a single operator in the same laboratory and similar environment using same apparatus in this project. The most reproducibility conditions therefore could not be fulfilled but most of the repeatability conditions could.

Accuracy of SCC tests was therefore taken from Testing-SCC (2005) as shown in Table 2-5 Precision of SCC tests as it was not possible for a single operator to perform many concrete tests within a limited period of time.

A modified repeatability, acceptance range and variation ratio are used to evaluate mortar results as follows.

4.5.1 Accuracy of tests on mortar

A slightly modified definition of repeatability (Rm) was used to evaluate mortar test results in this project. Rm derives from testing on the identical mix proportion composed of different batches of constituent materials on different testing dates. Other conditions, testing method, operator, apparatus, and laboratory are maintained the same.

Therefore, Rm shows the variations in the mixing, testing and different batches of materials. Rm can be obtained by multiplying their standard deviation (SD) with a factor of 2.8[1] with a probability of 95%.

$$Rm = 2.8\ SD$$

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(y_i - \overline{y})^2}$$

$$\overline{y} = \sum_{i=1}^{n} y_i$$

where y_i are the measured values; n is the number of measured values.

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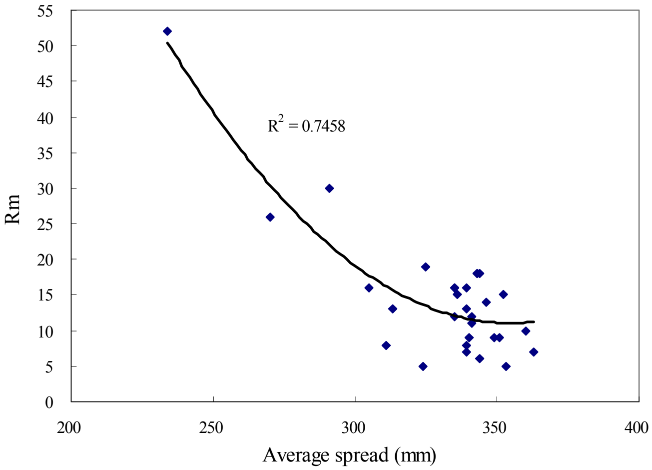
[1] $2.8 \approx 1.96\sqrt{2}$, the factor 1.96 for 95% probability and $\sqrt{2}$ for two test results

The variation ratio used in the Testing-SCC project to evaluate the test method thus is adopted here. The typical scatter of a single measurement is also evaluated by the acceptance range (AR) as follows.

$$AR = \frac{2SD}{\sqrt{n}}$$

$$VR = \frac{AR}{\overline{y}}$$



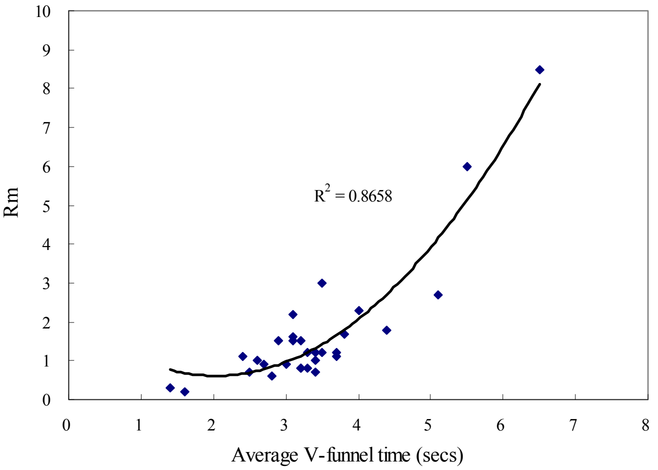


Figure 4-14 Modified repeatability of spread and V-funnel time of mortar

Figure 4-14 shows the relationships between average spread and V-funnel time and Rm. The x-axis is the average of the test results and y-axis is Rm. The data are taken from the mortar mixes in the project. The complete results are shown in Appendix 2.

Take the mid range for example, Rm is 20 for spread of 300 mm and Rm is 2 for V-funnel time of 4 seconds, variation is 7% and 50% for spread and the V-funnel test respectively. Spread test is more accurate than the V-funnel test.

Figure 4-14 also shows that Rm increases with the decrease in spread values and the increase in V-funnel time; the increase extent is more significant when spread is less than 310 mm and when V-funnel time is longer than 4 seconds.

Table 4-1 Accuracy of spread and V-funnel time of mortar tests

Time after adding water (min.)	11.3	15.3	19.5	24.2	28.2	AR	VR	Rm
Spread (mm)	339	338	338	333	335	337±2	0.6%	7
Time after adding water (min.)	14. 8	15.8	16.6	17.5	18.5	AR	VR	Rm
V-funnel time (secs)	3.9	3.5	3.5	3.3	4.1	3.7±0.2	5.4%	0.9

To find the AR of mortar tests, successive spread and the V-funnel tests were performed on the mortar mix, W/C of 0.33 by wt, ADVA Flow 410 of 2.3% of cement mass. The glass plate in spread test was cleaned each time after testing but V-funnel was not cleaned between tests. Results are shown in Table 4-1.

Acceptance range (AR) of spread and the V-funnel test are 2 mm and 0.2 seconds respectively. Variation ratio (VA) of spread and V-funnel test are 0.6% and 5.4% respectively, which also shows spread test is more accurate than V-funnel test.

Table 4-2 Summary of accuracy of the tests

Tests	AR	VR	R_m
Spread	± 2 mm	0.6%	5~50 for spread of 235~365 mm
V-funnel time	± 0.2 seconds	5.4%	0.3~8.5 for V-funnel time of 1.5~6.5 seconds

The accuracy of mortar tests is summarized in Table 4-2. A single measurement is reliable enough for analysis.

4.6 Conclusions

The sequence of performing the tests on fresh SCC was designed to complete tests quickly, thus minimising any change in the properties of the concrete with time.

Hardened tests on concrete, such as strength tests and non-destructive tests were applied to SCC in order to establish the relationships between strength and non-destructive test results for SCC’s practical use. Sorptivity tests were selected to evaluate durability. ASTM C 1260 is used to detect the expansion due to ASR.

Acceptance range, variation ratio and a modified repeatability are used to access the accuracy of spread and the V-funnel test. A single measurement is reliable and spread test is more accurate than V-funnel test.

Chapter 5 Constituent Materials

In this chapter, the constituent materials used in the research are described and discussed. Aggregate, cement, ground glass, superplasticiser and VMA were obtained from the same source throughout, and so different batches received at different times were considered nominally the same. Fly ash was obtained from two different plants, and so some tests were repeated on the two batches.

It is difficult to predict the interaction between cement, additions and admixtures with any certainty and so a series of tests to compare the performance of eight superplasticisers, all recommended by manufacturers as suitable for SCC, was carried out from which a single superplasticiser was chosen for the remainder of the research. The performance of four superplasticiser/VMA combinations was also assessed to determine the potential benefits. These tests are also described in this chapter.

5.1 Aggregate

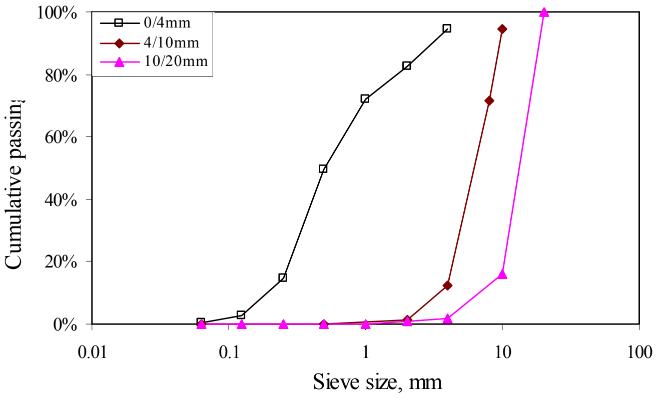


Figure 5-1 Grading curves of aggregates

Thames Valley uncrushed aggregates, supplied from Northfleet by Cemex UK[1], were used. The specific gravity was measured as 2.6 in the oven dry state. A

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[1] http://www.cemex.co.uk/aa/aa_lp.asp

maximum size of aggregate of 20 mm was used to minimise cement content in SCC. The fineness modulus of the 0/4mm (fine) aggregate was 2.78.

The grading curves of the fine and two single-size coarse aggregate fractions are shown in Figure 5-1.

Water absorptions of 0/4mm, 4/10mm and 10/20mm aggregate were measured as 1.2%, 1.1% and 1.0% respectively, and the dry-rodded bulk density of 0/4mm, 4/10mm, 10/20mm aggregate were measured as 1766 kg/m^3, 1520 kg/m^3 and 1605 kg/m^3 respectively.

5.1.1 Bulk density of coarse aggregate

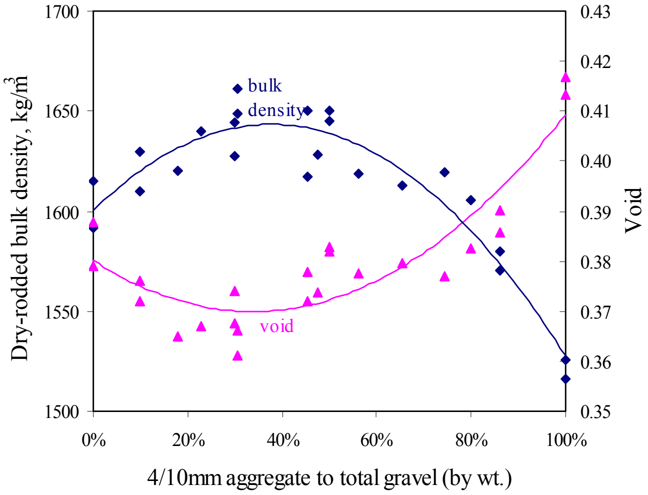

Figure 5-2 Dry-rodded bulk density and void of coarse aggregate

The coarse aggregate used was a mix of 4/10 mm and 10/20 mm gravel. The relative proportion was chosen to be that which gives the maximum bulk density (or minimum voids content). The results of the tests carried out on a series of mixes are shown in Figure 5-2. Despite the scatter of the data, which may be due to the testing being carried out in several sessions, the best fit curves show that the region of maximum bulk density is rather broad. The maximum value is around 1650 kg/m^3 when the weight ratio of 10/20 mm to 4/10mm aggregate is 2:1; this was used throughout the project.

5.1.2 The influence of aggregate on filling ability

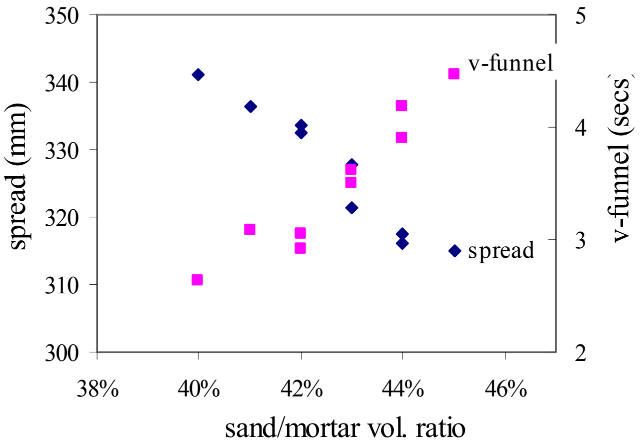

Figure 5-3 Influence of sand/mortar ratio on mortar

The influence of the sand/mortar volume ratio is shown in mortar mixes with constant W/P ratio and superplasticiser dosage as shown in Table 5-1 and Figure 5-3. The experimental results derived from 8.1.

It clearly shows that an increase of sand volumes in mortar leads to a decrease in spread and an increase in V-funnel time. As there are correlations between the spread and the yield stress and between the V-funnel time and the viscosity (refer to 2.2.2.1), when the mortar mix proportions are kept constant, the increase of sand volume results in an increase in both the yield stress and the viscosity.

Table 5-1 Influence of sand/mortar vol. ratio on mortar

W/P by wt	Sp (% powder wt.)	sand/mortar by vol.	Spread (mm)	V-funnel time (secs)
0.33	1.40%	40%	341	2.6
0.33	1.40%	41%	337	3.1
0.33	1.40%	42%	333	2.9
0.33	1.40%	42%	334	3.0
0.33	1.40%	43%	322	3.6
0.33	1.40%	43%	328	3.5
0.33	1.40%	44%	316	4.2
0.33	1.40%	44%	318	3.9
0.33	1.40%	45%	315	4.5

The influence of coarse aggregate on filling ability of SCC is shown in Table 5-2 and Figure 5-4. Three pure cement SCC mixes with constant W/C ratio and superplasticiser dosage. The results come from 6.3.

Table 5-2 The influence of coarse aggregate on filling ability of SCC

COARSE AGGREGATE (% CONCRETE VOL.)	W/C BY WT.	SP (% CEMENT WT.)	SLUMP FLOW (MM)	V-FUNNEL TIME (SECS)
32.3%	0.30	1.10%	735	9.0
35.5%	0.30	1.10%	662	14.2
38.8%	0.30	1.10%	423	23.7

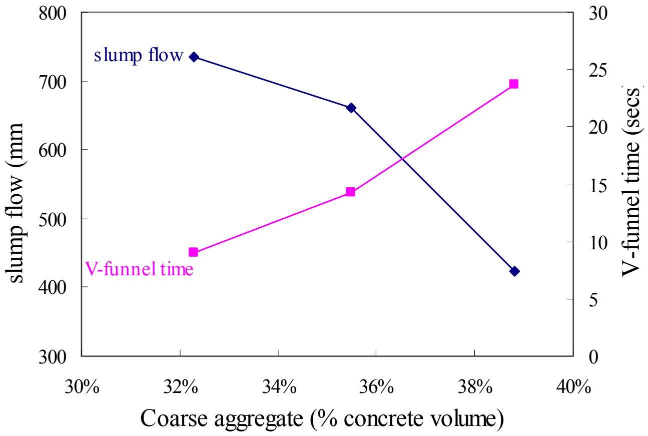

Figure 5-4 The influence of coarse aggregate content on filling ability of SCC

It clearly shows that an increase of coarse volumes leads to a decrease in slump flow and an increase in V-funnel time, i.e. degradation of filling ability. The extent of decrease is higher with more than 35.5% coarse aggregate in concrete. As the correlations between slump flow and yield stress and between V-funnel time and viscosity (Testing-SCC, 2005), the increase of coarse aggregate volume results in an increase in both the yield stress and the viscosity. The reason is because a high aggregate content decreases the inter particle distance (Khayat et al., 1999).

5.2 Powders

5.2.1 Supply and composition

CEM I is the most common type cement in the UK, and this was obtained from Northfleet plant of Lafarge[2] throughout the project. Cement from a total of twenty one batches[3] was used in two years, all complying with BS EN 197–1 CEM I 42.5N and from the same plant.

Table 5-3 Composition and physical properties of cement

Batch number	13/09/06	29/03/07	28/06/07		
SiO_2	18.96	20.47	19.69		
Al_2O_3	4.73	5.08	5.42		
Fe_2O_3	3.33	2.88	3.31		
CaO	63.97	64.41	62.28		
MgO	2.47	1.09	2.54		
SO_3	3.76	3.28	3.44		
K_2O	0.54	0.69	1.3		
Na_2O	0.31	0.18	0.13		
Eq_{Na2O}	0.67	0.63	0.98		
LOI	2.63	1.12	2.44		
F_{CaO}	1.64	1.12	1.27		
Cl	0.02	0.012	0.01		
Passing 45um	4.5		10.7		
Compound composition (Bogue)				AR[4]	VR[4]
C_3S	69.0	59.0 (54.48)	52.9	60.3 ± 4.7	7.8%
C_2S	2.7	14.5 (17.59)	16.9	11.3 ± 4.4	38.9%
C_3A	6.9	8.6 (8.59)	8.8	8.1 ± 0.6	7.4%
C_4AF	10.1	8.8 (8.76)	10.1	9.6 ± 0.4	4.2%

Note: Values given in parenthesis are provided by the manufacturers.

The compositions of three batches are shown in Table 5-3, from which the compound compositions can be calculated. It shows that the chemicals of cement do not vary very much and thus different batches of cement are considered as nominally similar.

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[2] http://www.lafarge.co.uk/wps/portal/

[3] Usually ten bags per batch were ordered and used for all projects in the laboratory.

[4] Refer to 4.5.1.

The fly ash was obtained from two different sources, referred as fly ash 1 and fly ash 2 respectively. Fly ash 1 was obtained from the Ratcliffe plant[5] of RMC UK LTD and complied with BS 3892 Part 1: 1997. Two batches of fly ash 1 were used, date sampled of 05/12/05 (1a) and 29/09/06 (1b) respectively. Fly ash 2 was from the Drax plant of CEMEX[6] and complied with BS EN 450-1. The physical and chemical properties of the two batches, provided by the supplier, are demonstrated in Table 5-4.

Table 5-4 Physical ad chemical properties of fly ashes

	FLY ASH 1	FLY ASH 2
Al_2O_3 (%)	-	25.0
CaO (%)	3.6	3.9
Cl (%)	0.01	0.01
Free lime	-	0.1
Fe_2O_3 (%)	-	7.2
MgO (%)	-	1.9
SiO_2 (%)	-	50.5
Na_2O equivalent	2.69	2.3
SO_3 (%)	0.8	0.9
TiO_2 (%)	-	1.1
Loss on ignition (%)	5.7	6.1
Moisture (%)	0.1	-
Fineness (%)	9.8	-
Density (kg/m^3)	2220	2300
Colour index	4	-

Glass came from the screening of crushed colour-sorted waste glass[7] by Fosroc[8]. The powder product consisted of angular and flaky particle shapes. Two colours were obtained, green and white.

5.2.2 Particle size of powders

Figure 5-5 shows the particle size distribution of all the powders used in the project.

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[5] It is now part of CEMEX UK.
[6] http://www.cemex.co.uk/ce/ce_bp_pf.asp
[7] This information sourced from its provider
[8] http://www.fosroc.com/GlobalHome.aspx

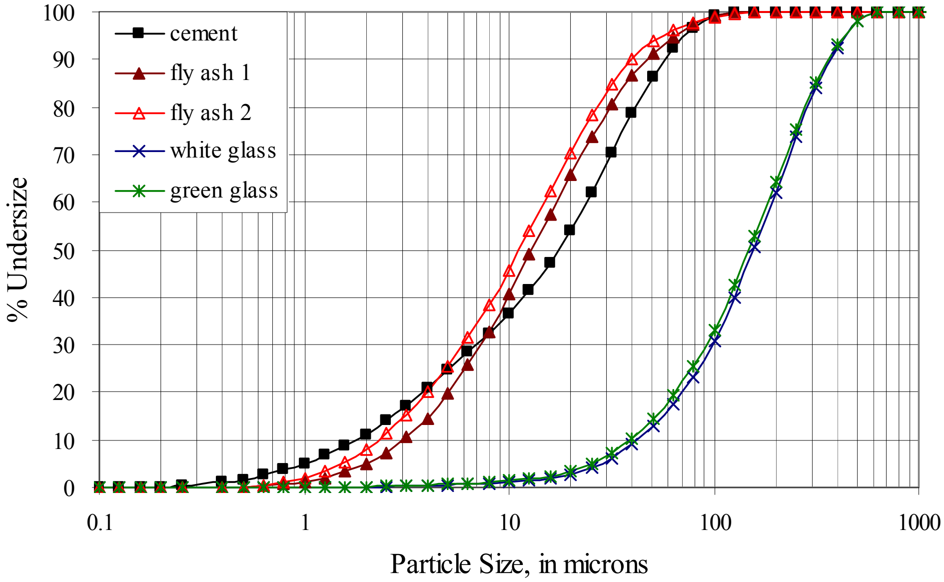

Figure 5-5 Particle sizes of powders used in the project

The particle size distributions of the two batches of fly ashes (fly ash 1 and fly ash 2) are very similar and both are slightly finer than that of cement especially in the portion of particles smaller than 80 µm. The fly ash therefore is anticipated to improve the particle packing and reduce porosity when used as an addition.

Glass contains particles from 5 to 600 µm. There is only a marginal difference in particle size distribution between green and white glass, with the green glass being slightly finer. Approximately 82% particles of the green or the white glass are less than 300 µm.

It can be seen from Figure 5-5 that the glass is much coarser than cement and fly ash. Cement, fly ash 1, fly ash 2, white glass and green glass contains 83%, 89%, 92%, 11% and 12% respectively of particles smaller than 45 µm. Glass contains particles larger than 150 µm, whereas cement and fly ash do not.

5.2.3 Retained water ratio and deformation coefficient of the powders

It is known that replacing cement with fly ash will inevitably lead to a decrease in the water requirement and an increase in the sensitivity to the change of W/P ratio due to smaller retained water ratio (β_p) and deformation coefficient (E_p) (refer to 2.4.3).

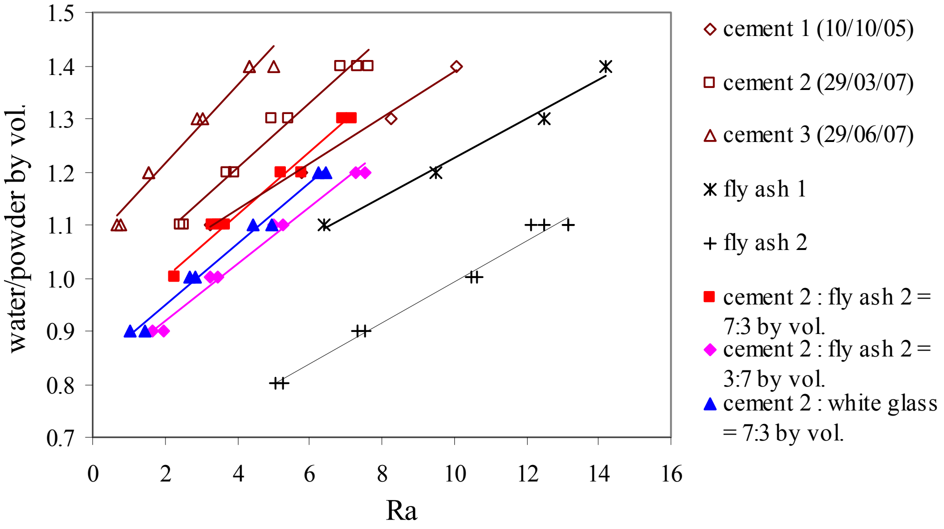

Figure 5-6 Relative flow area vs water/powder ratio of paste by volume

Table 5-5 Retained water ratio and deformation coefficient of the powders

POWDER COMPOSITION	EP	BP
Cement 1 (10/10/05)	0.0432	0.9546
Cement 2 (29/03/07)	0.0608	0.9642
Cement 3 (29/06/07)	0.0736	1.0686
Fly ash 1	0.0372	0.8535
Fly ash 2	0.0385	0.6055
Cement 2 : fly ash 2 = 7:3 by vol.	0.0593	0.8817
Cement 2 : fly ash 2 = 3:7 by vol.	0.0531	0.8145
Cement 2 : white glass = 7:3 by vol.	0.0568	0.8424

It can be seen from Figure 5-6 and Table 5-5 (complete results are in Appendix 3) that fly ash 1 has a larger β_p and smaller E_p than fly ash 2, that is, fly ash 1 needs more water to start flow and it is more sensitive to water content variation.

Fly ash has a smaller β_p and E_p than the cement, which is in agreement with other results (Domone and Chai, 1997; Pelova et al., 1998).

It also shows that both β_p and E_p of cement-fly ash mixes are influenced by the fly ash content. The more cement replaced by fly ash in the paste, the lower β_p and E_p are. This could be attributed to the spherical particle shape of the fly ash, which decreases interparticle friction (Ferraris et al., 2001; Nawa et al., 1998). Therefore incorporation of fly ash will decrease the water needed to start flow or it will increase the filling ability of concrete. It also means that the replacement by fly ash will lead to an increase in the sensitivity to water change. The difference however is not significant.

β_p and E_p depend on the characteristics of the powder itself. β_p and E_p of the paste in which 30% cement is replaced by glass are smaller than those of the paste with 30% fly ash and those of corresponding cement. Considering the particle shape and the size of glass, this is not anticipated. However, it is impossible to measure β_p and E_p of glass powder alone because the coarse particles always sank to the bottom of the mixing cup.

For cement, $\beta_p = 0.9958\pm0.0365$ and $E_p = 0.0592\pm0.0088$. The variations of β_p and E_p are thus 4% and 15% respectively, which are small. Different batches of cement are also nominally similar in water demand and sensitivity to water variation.

5.3 Water

Ordinary tap water was used as the mixing water throughout. In summer, the water was stored in a plastic container in an air-conditioned room overnight to ensure constant temperature.

5.4 Superplasticisers

Eight polycarboxylate-based superplasticisers, listed in Table 5-6, all commercially available in UK and recommended by manufacturers as suitable for SCC, were evaluated by the use of tests on mortar, which have been shown to be efficient and effective for this (Domone, 2006a). The spread and the V-funnel tests as described in 4.3.2 were used. The superplasticizer dosage is expressed as the percentage of the cement weight.

Table 5-6 Dry material content and relative density of superplasticisers

Superplasticisers[9]	Company	Dry material content (%)	Relative density
ADVA Flow 410	Grace[10]	20	1.03
Glenium 27	BASF[11]	22	1.04
Glenium c315		35	1.09
Glenium sky 544		29	1.07
Glenium sky 545		30	1.08
Sika ViscoCrete 10	Sika[12]	30	1.06
Sika ViscoCrete Premier		40	1.08
Structuro 11180	Fosroc[13]	36	1.11

5.4.1 The influence of superplasticizers on mortar

Table 5-7 The influence of superplasticisers on mortar

SP TYPE	W/C BY WT.	SP DOSAGE (% CEM. WT.)	SPREAD (MM)	V-FUNNEL TIME (SECS)
Sika ViscoCrete Premier	0.30	0.5%	249	5.8
	0.30	0.6%	301	5.4
	0.30	0.7%	335	4.5
	0.30	0.8%	350	4.2
	0.30	0.9%	350	4.2
	0.30	1.0%	349	4.3
Glenium c315	0.30	0.7%	245	5.5
	0.30	0.8%	292	5.0
	0.30	0.9%	319	4.6
	0.30	1.0%	330	4.2
	0.30	1.1%	342	4.2
	0.30	1.2%	341	4.1
Structuro 11180	0.30	0.6%	205	6.5
	0.30	0.8%	305	5.1
	0.30	1.0%	359	3.7
	0.30	1.1%	360	3.6
	0.30	1.2%	369	3.3
	0.30	1.3%	370	3.3

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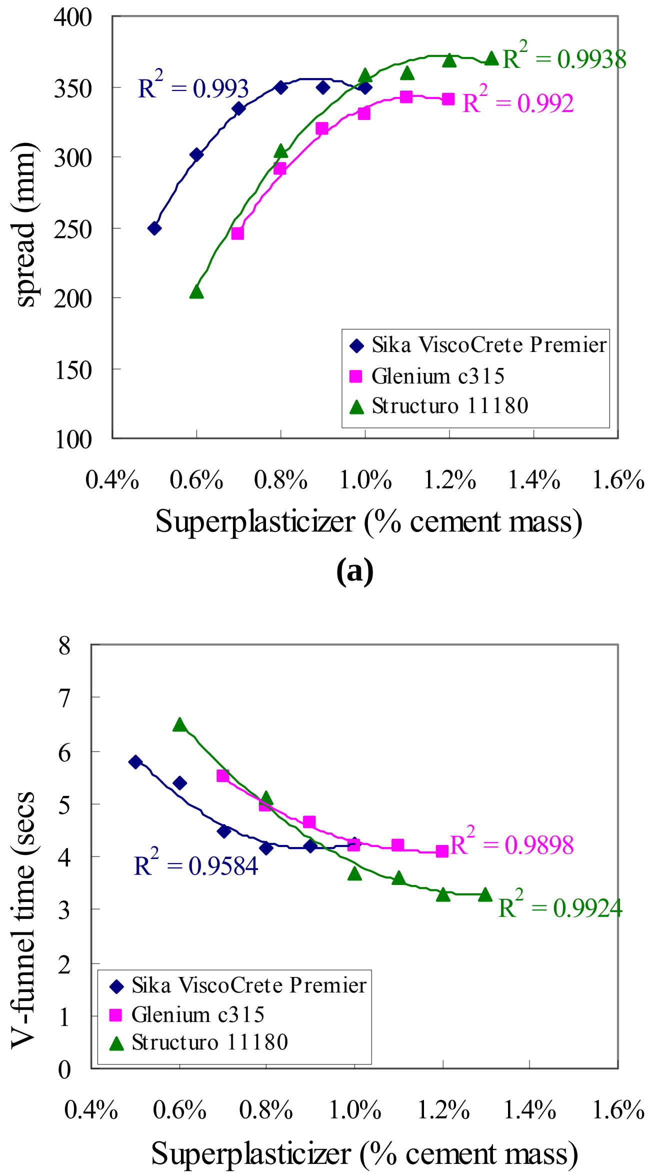
[9] Data sheets are all included in Appendix 4.
[10] http://www.na.graceconstruction.com/
[11] http://www2.basf.us/corporate/index.html
[12] http://www.sika.co.uk/
[13] http://www.fosroc.com/GlobalHome.aspx



(a)

(b)

Figure 5-7 Saturation point and effects of superplasticisers on the (a) spread and the (b) V-funnel time of mortar

The influence of three superplasticisers on spread and V-funnel time is shown in Table 5-7 and Figure 5-7. All the mortars were made at a constant W/C ratio of 0.30. Figure 5-7 shows the spread and the V-funnel time curves as a function of the superplasticiser dosage.

It is clear that as the superplasticiser dosages increase, the spreads of mortar all increase and the V-funnel time decrease; spreads reach the maximum value and V-funnel time reduces to the minimum at a specific superplasticiser content, which is referred as the saturation point. Beyond this value, spread and V-funnel time do not change significantly even more superplasticiser is added and the mortar tends to segregate.

The slopes of all the curves are different, and the saturation point of a specific superplasticiser varies, which reflects the different characteristics of the admixtures. For Sika ViscoCrete Premier, Glenium c315 and Structuro 11180 (refer to 5.4.2.2) as shown in Figure 5-7 the saturation points are about 0.8%, 1.1% and 1.3% respectively.

In addition, the decrease in the spread due to the addition of superplasticiser is more significant than the decrease in the V-funnel time.

Because of the close relationship between the spread and the yield stress, and between the V-funnel time and the plastic viscosity, it can be anticipated that the incorporation of superplasticisers reduces the yield stress approaching zero, and causes a limited decrease in the plastic viscosity. This is different from the general effects of superplasticisers as shown in Figure 2-5. However various superplasticisers affect the rheological properties differently depending on their dispersing action.

5.4.2 Superplasticizer selection

According to the relationships between mortar and SCC (refer to Figure 2-30 and Figure 2-31), the target value of the spread and the V-funnel time were chosen as 310 mm and 4 seconds respectively for the mortar; these would produce a SCC with a slump flow of 700 mm and V-funnel time of 8 seconds for coarse aggregate of 32% concrete volume. For each admixture:

- The combination of W/C ratio and superplasticiser dosage to achieve the target mortar properties was obtained.

- The sensitivity of the target mortar to variations in W/C ratio and supeplasticiser dosage was calculated from the slopes of the W/C and superplasticiser trend lines.

- The consistence retention was assessed by the change of spread and V-funnel time of the target mix for up to 90 minutes after mixing.

The results obtained during the evaluation of the Sika ViscoCrete 10 are now shown and discussed in detail to illustrate the process, and then the results given for the other admixtures for comparison.

5.4.2.1 Sika ViscoCrete 10

The influence of admixture[14] on the spread and V-funnel time of mortar with a constant W/C of 0.32 by weight are shown in Figure 5-8 and Figure 5-9 respectively. The spread tends to a maximum value and the V-funnel time a minimum.

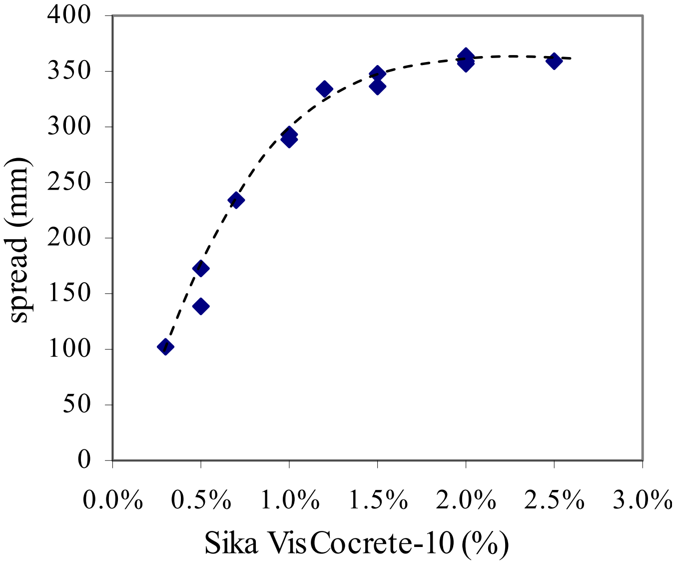


Figure 5-8 Influence of Sika ViscoCrete 10 on the spread of mortar

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[14] Dosage of superplasticiser is based on the weight of cement.

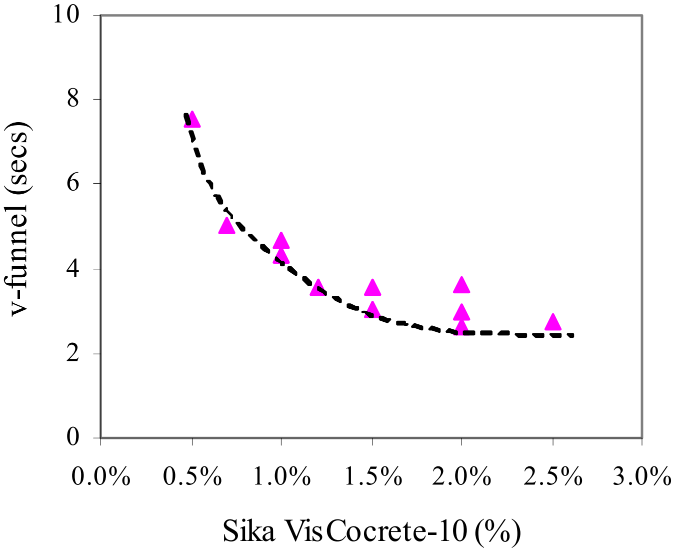

Figure 5-9 Influence of Sika ViscoCrete 10 on the V-funnel time of mortar

Bleeding indicating segregation started at a superplasticiser dosage of about 1.5%.

Since the maximum spread and the minimum V-funnel time were reached at a dosage of 2.0% of cement mass, and bleeding was then extensive, this is the saturation (refer to 2.4.1.1) dosage for this W/C.

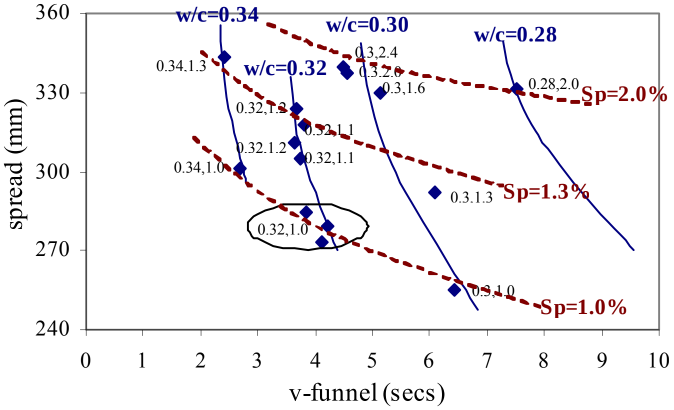

Figure 5-10 Spread and V-funnel time of mortar with Sika VisCocrete 10

Figure 5-10 shows the results of a series of tests to establish the combined influence of W/P ratios and admixture contents up to the saturation dosage on the spread and the V-funnel time: It can be seen from the slopes of trend lines that the admixture influences the spread more than the V-funnel time, which is consistent with the typical effect of superplasticisers on yield stress and plastic viscosity (Tattersall and Banfill, 1983) as shown in Figure 2-7, there are good correlations between the spread and the yield stress and between the V-funnel time and the plastic viscosity. On the other hand, the W/P ratio has a greater influence on spread than that on the V-funnel time.

The target spread and the V-funnel time of 310 mm of 4 seconds respectively are achieved at a W/C ratio of 0.32 and a superplasticiser dosage of 1.2% of cement by weight. This is then a performance characteristic of this cement/admixture combination.

The estimation is based on the relationships between the spread and the V-funnel time. This may not be very precise due to the variations in environment, materials and tests. This method however reduces the amount of experiments to find the target mix and indicate the robustness of the target mix.

Further tests later showed this mix indeed achieved the targets of spread and V-funnel time (test results are shown in brackets in Table 5-8), which indicated the effectiveness of the procedure.

The sensitivity of the mix to variations in W/P ratio and superplasticiser dosage can be calculated from the slopes of the W/C and superplasticiser trend lines at this combination. From Figure 5-10: an increase in 0.01 W/C ratio results in an increase in spread of 9 mm and an decrease in V-funnel time of 0.7 seconds; an increase in the superplasticiser dose of 0.1% of cement by weight results in an increase in spread of 14 mm and an decrease in V-funnel time of 0.1 seconds.

These are the “characteristics” that can be used to evaluate the robustness of the cement/admixture combination.

From above, estimations of the admixture characteristics with sufficient accuracy can be obtained from a relatively limited number of tests.

Consistence retention, a third important characteristic, was assessed by repeating the spread and the V-funnel tests on the target mix.

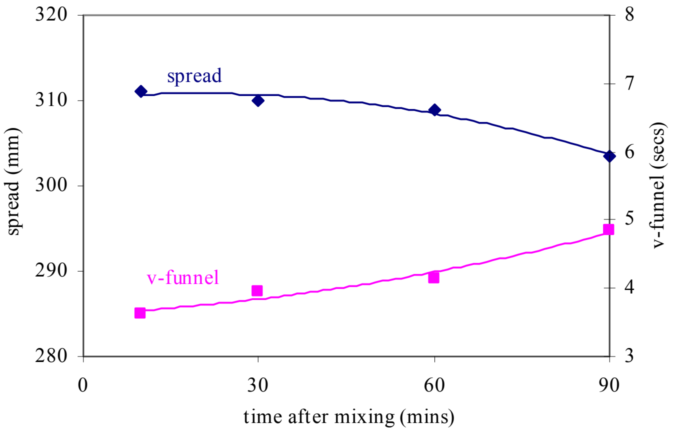

Figure 5-11 Consistence retention of mortar with Sika VisCocrete 10

The results (Figure 5-11) show that after 90 minutes the spread decreased from 311 mm to 304 mm and the V-funnel time increased from 3.6 to 4.8 seconds.

5.4.2.2 Other superplasticisers

The spread vs the V-funnel time diagrams and the consistence retention of mortar with other superplasticisers are shown in Figure 5-12 Spread, V-funnel time and consistence retention of mortar with ADVA Flow 410, Figure 5-13 Spread, V-funnel time and consistence retention of mortar with Glenium c315, Figure 5-14 Spread, V-funnel time and consistence retention of mortar with Glenium sky 544, Figure 5-15 Spread, V-funnel time and consistence retention of mortar with Structuro 11180, Figure 5-16 Spread, V-funnel flow time and consistence retention of mortar with Glenium sky 545, Figure 5-17 Spread, V-funnel flow time and consistence retention of mortar with Sika ViscoCrete Premier and Figure 5-18 Spread and V-funnel time of mortar with Glenium 27.

Except Glenium 545 and Glenium 27, other superplasticisers produced similar patterns as Sika ViscoCrete 10, from which the characteristic values can be derived. Similar consistence retention patterns are produced that the spread decreases and the V-funnel time increases during the period tested.

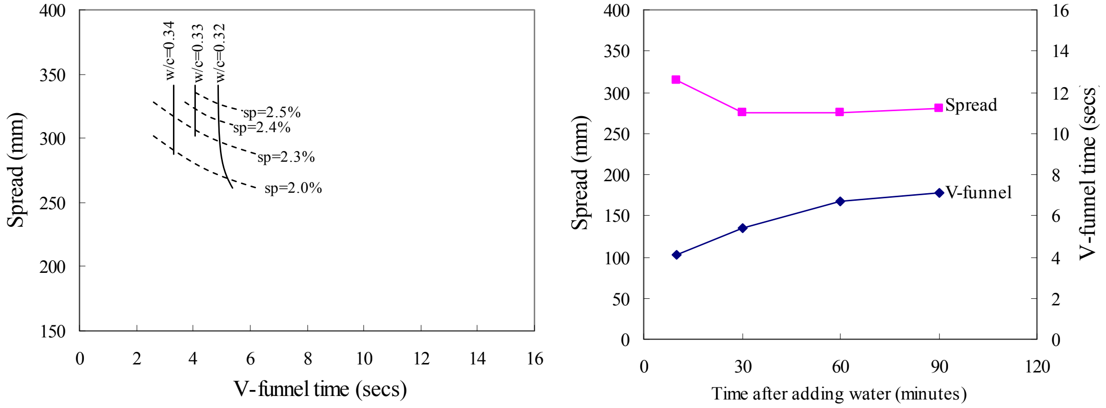

Figure 5-12 Spread, V-funnel time and consistence retention of mortar with ADVA Flow 410

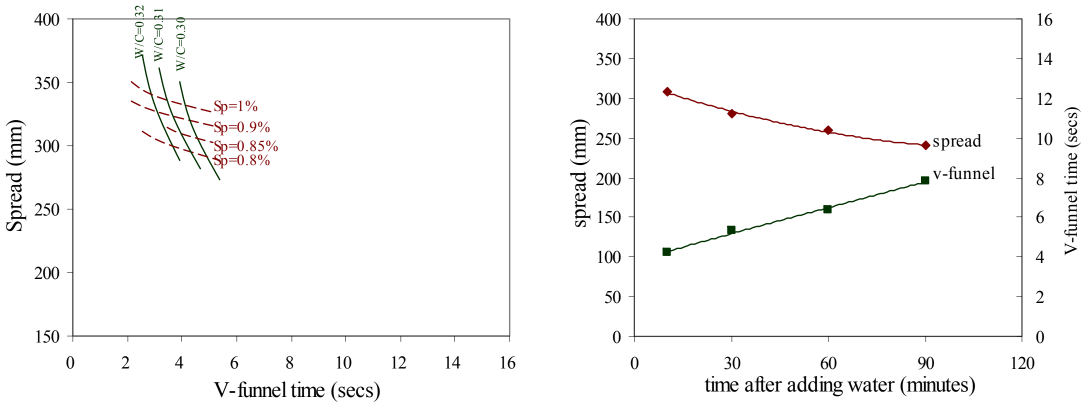

Figure 5-13 Spread, V-funnel time and consistence retention of mortar with Glenium c315

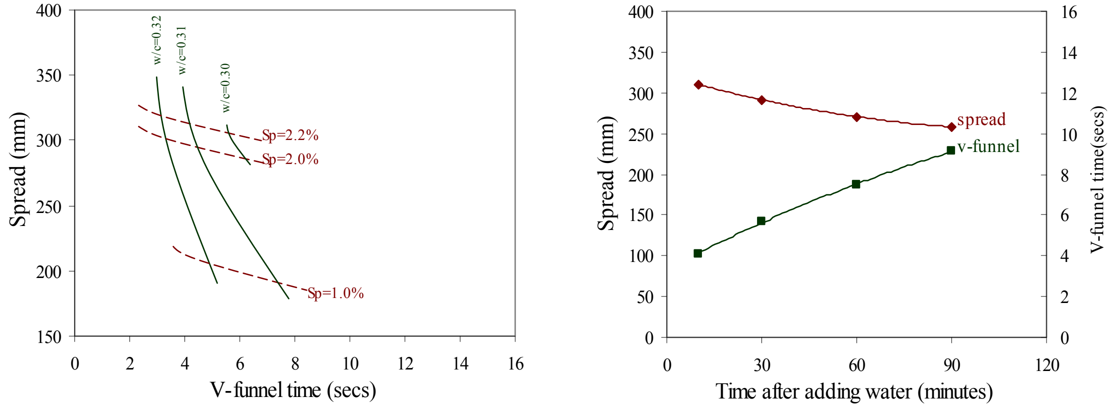

Figure 5-14 Spread, V-funnel time and consistence retention of mortar with Glenium sky 544

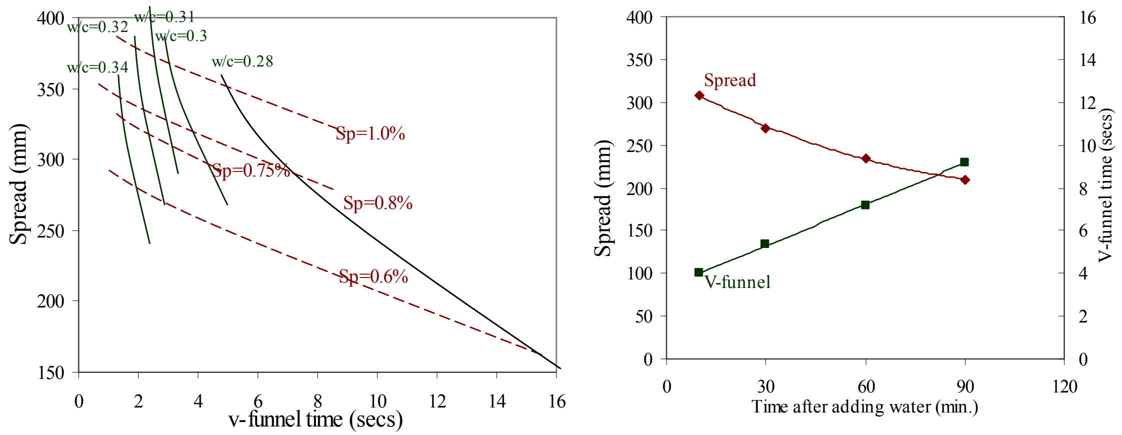

Figure 5-15 Spread, V-funnel time and consistence retention of mortar with Structuro 11180

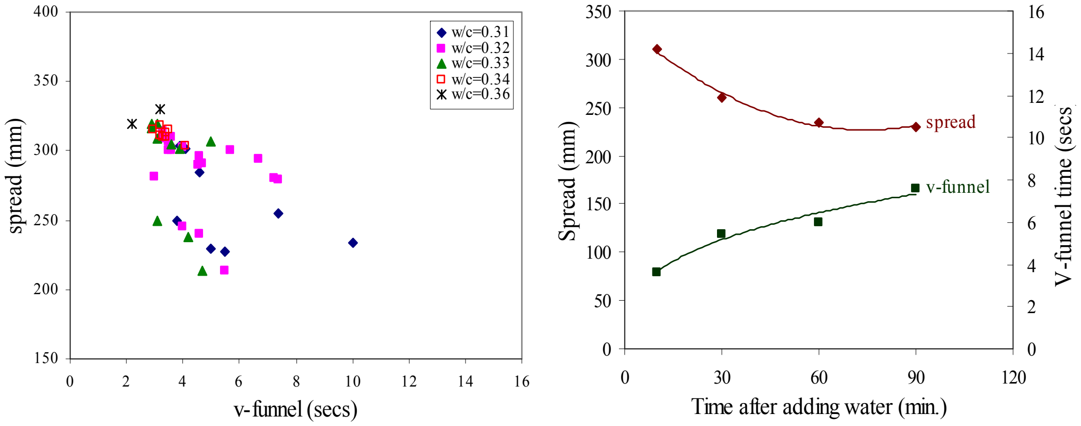

Figure 5-16 Spread, V-funnel flow time and consistence retention of mortar with Glenium sky 545

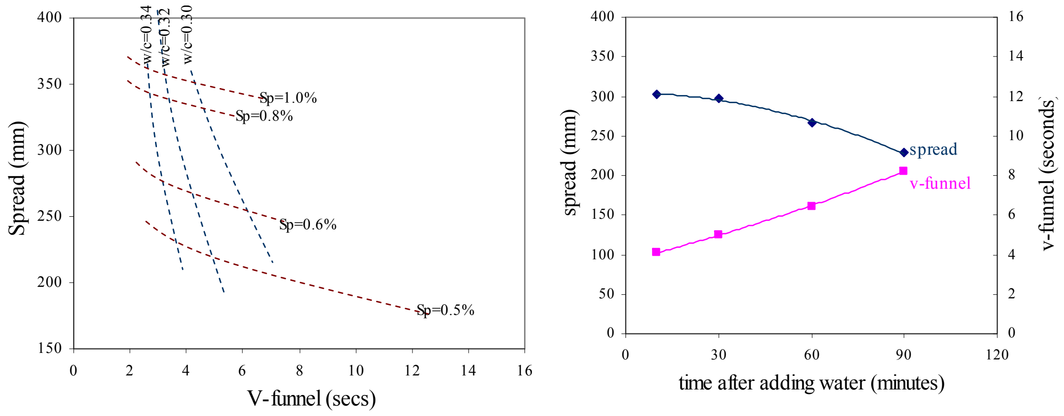

Figure 5-17 Spread, V-funnel flow time and consistence retention of mortar with Sika ViscoCrete Premier

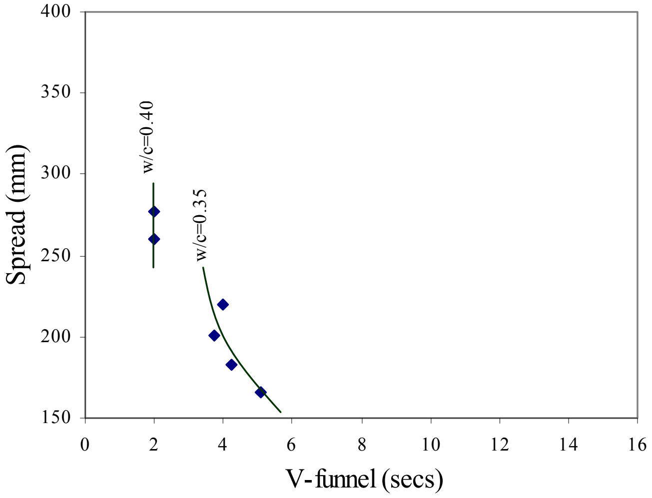

Figure 5-18 Spread and V-funnel time of mortar with Glenium 27

It can be seen from Figure 5-16 that there are different combinations of W/C ratios and Glenium sky 545 dosages that can achieve the target properties. The overlapping data suggested that the fresh properties cannot be determined separately by W/C and superplasticiser dosage. Glenium sky 545 was therefore not considered. Figure 5-18 shows that the mortar with W/C ratio of 0.33 to 0.40 and dosage of Glenium 27 from 2% to 10% of weight of cement failed to achieve the target properties. The target may be achievable at the dosage of more than 10% of cement weight for Glenium 27, which is however unreasonable for the project. Therefore, Glenium 27 was not considered further.

All the above superplasticisers are modified carboxylic polymer (see data sheets in Appendix 4). Although they are all said to be suitable for SCC, their performance will depend on their reactions with cement and their molecular structure (refer to 2.4.1.1), which are not available from the manufacturers. The reason why two of them failed to provide a satisfied mortar is not clear. The superplasticisers' performances also rely on other factors such as mixing and temperature. Thus it is not 100% certain that a specific designed superplasticiser will work without testing with specific cement proposed for use.

The characteristic values obtained from the above tests for each cement/superplasticiser combination (except Glenium 27 and Glenium Sky 545) are shown in Table 5-8. Significant variation in superplasticiser dosage to achieve the target spread and the V-funnel time were obtained, but at approximately similar W/C ratios. The sensitivity values, indicating the robustness of the mix, and the consistence retention show wide variation. It also shows that experimental results of sensitivity given in parenthesis are similar to the predicted ones. Among the superplasticisers tested, Sika ViscoCrete 10 shows the greatest consistence retention and the strongest robustness to variations of water and superplasticiser content. As the result, it was therefore selected to use in the subsequent tests on mixes incorporating fly ash (Chapter 7) and ground glass (Chapter 8).

Table 5-8 Experimental and estimated robustness and consistence retention of mortars with different superplasticisers

Sp	Target mixes		Sensitivity				Changes after 90 minutes	
	W/C	Sp (% cem. by wt.)	to W/C		to Sp dosage		loss of spread (mm)	increase in t_v (secs)
			Spread (mm/ 0.01 w/c)	t_v (secs/ 0.01 w/c)	Spread (mm/ 0.1% Sp)	t_v (secs/ 0.1% Sp)		
ADVA Flow 410	0.33	2.24	14 (11)	0.8 (0.7)	9 (6)	0 (0.1)	34	3
Structuro 11180	0.31	0.78	11 (6.5)	1.2 (0.7)	31 (26.5)	0.6 (0.6)	98.5	5.2
Glenium c315	0.31	0.85	7	0.7	24	0.6	68.5	3.6
Glenium sky 544	0.31	2.20	7	1.1	7	0.1	52	5
Sika ViscoCrete 10	0.32	1.25	9	0.7	10	0.1	7	1.2
Sika ViscoCrete Premier	0.32	0.71	7	1.0	36	0.6	74	4.1

Note: Values given in parenthesis are experimental results.

5.5 Viscosity Modifying Agents

In case a superplasticiser alone could not produce satisfactory SCC, mortar tests were also carried out to evaluate the effects of combinations of superplasticisers and VMAs on the spread, the V-funnel time, yield stress and plastic viscosity.

The aims were to confirm one of the VMAs' functions by studying the effect of VMA on segregated mortar, and to choose one VMA for the subsequent research if needed.

Four VMAs, Glenium Stream 5, Glenium Stream 2006L, V-Mar 10L and KELCO-CRETE 200 diutan gum, shown in Table 5-9, were studied due to their availability in U.K and their manufacturers' recommendations that they are suitable for SCC.

Both Grace and BASF claim that their VMAs are compatible with their superplasticisers. As a result, Glenium Stream 5 and Glenium Stream 2006L were tested with Glenium sky 544, and V-Mar 10L with ADVA Flow 410. The manufacturer claims that KELCO-CRETE 200 diutan gum is compatible with any superplasticisers. It was tested in combination with Sika ViscoCrete 10.

Table 5-9 VMAs tested

VMAs[1]	Company	Dry material content (%)	Relative density
V-Mar 10L	Grace	12	1.16
Glenium Stream 5	BASF	3	1.01
Glenium Stream 2006L		3	1.01
KELCO-CRETE 200 diutan gum	CP Kelco[2]	Dry powder	

V-Mar 10L is said to be a non-adsorptive VMA[3] which reduces the amount of free water available for fluidity and would therefore increase the yield stress and plastic viscosity of mortar as well as the segregation resistance.

Glenium Stream 5 and Glenium Stream 2006L are all adsorptive VMAs (refer to 2.4.1.2) and the manufacturers claim that they are compatible both with each other and with Glenium Sky 544. The VMAs do not compete with Glenium sky 544 for the same water and so they then can be added together.

KELCO-CRETE 200 diutan gum is a new version of welan gum, which the manufacturers[4] claim in many cases is more efficient than welan gum.

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[1] Data sheets are all included in Appendix 5.
[2] http://www.cpkelco.com/
[3] Email of Ernie, a technician in Grace.

5.5.1 Mix procedures

It is recommended by the manufacturers that the VMA should be added before the superplasticiser or together with superplasticiser. However, in previous tests at UCL on welan gum with two superplasticisers, Conplast 430 (a sulfonated naphthalene polymer) and Glenium 51 (a modified polycarboxylic ether), both superplasticisers were added 1 minute after the start of mixing, with the Welan gum added 1 minute later (Jin, 2002).

The mixing procedure described in chapter 4.2 was thus modified as follows.

- Sequence I: VMA was added with superplasticiser and 20% mixing water.

  This was found to be appropriate for Glenium Stream 5 and Glenium Stream 2006L which dissolved well by this sequence.

- Sequence II: After a minute of mixing with 70% of the mix water, 15% mixing water along with the superplasticiser was added, and then the VMA dissolved with the remaining 15% of the mix water was introduced after a further minute.

  Sequence I was found not to be ideal for V-Mar 10L; according to its data sheet, it should be added directly to the concrete in the mixer which should already contain some volume of mixing water. However, it proved to be very difficult to add V-Mar 10L directly to mortar with precise measurement (generally low dosage) because much of it adhered to the bottom of the measuring cup. Therefore, sequence II was designed and results from the two sequences compared I as follows.

  A segregating mix (ADVA Flow 410 dosage of 1.6% by weight of cement, the W/C ratio of 0.4) was chosen, and the effects of V-Mar 10L, dosages of which was 0.05%, 0.09% and 0.14%[5] of cement by weight, on spread, V-

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[4] Alain Phyfferoen ALAIN.PHYFFEROEN@cpkelco.com

[5] Calculated from its recommended dosage (refer to Appendix 5) and specific gravity.

funnel time, yield stress and plastic viscosity were measured with each mixing sequence.

The results are shown in Figure 5-19. Although a higher spread and lower yield stress were achieved with mixing sequence I, the V-Mar 10L dissolved better in sequence II. This maybe due to the dispersing mechanism, in which the VMA absorbs water and then produces a thick layer on the cement surface, thus generating effective steric repulsion. It seems that ADVA Flow 410 and V-Mar 10L might be competing for the same water if they are mixed together in sequence I. Therefore, sequence II was chosen for subsequent tests with this VMA.

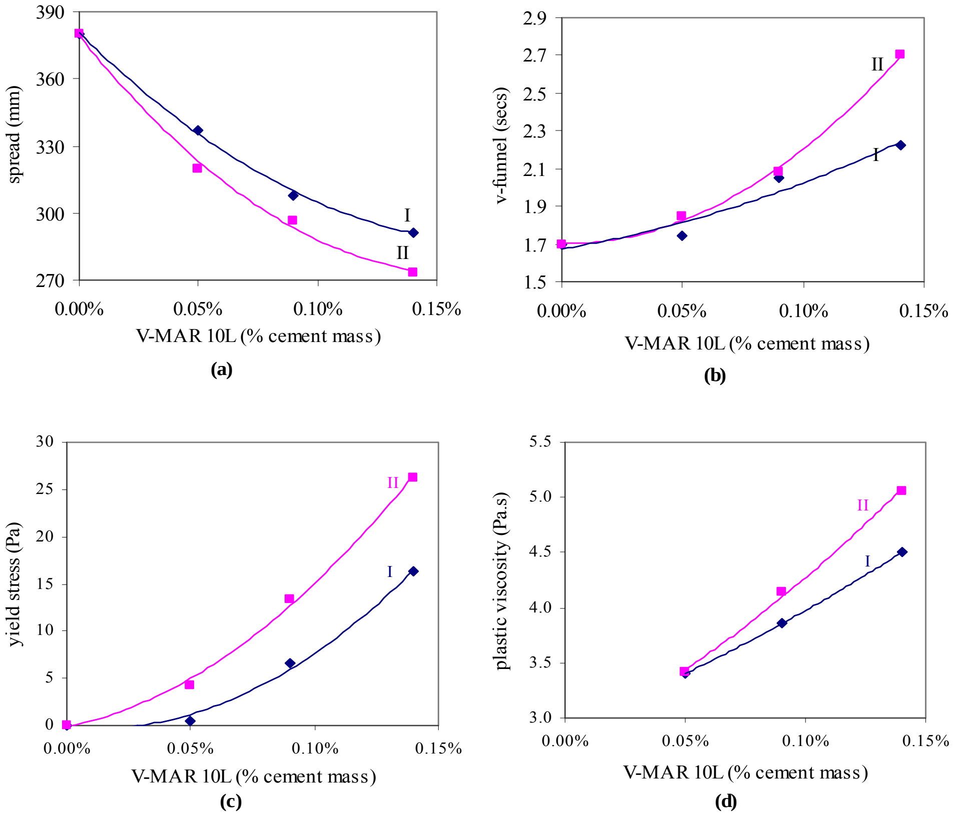

Figure 5-19 The influences of sequence I and II on (a) spread, (b) V-funnel time, (c) yield stress and (d) plastic viscosity of the mortar with V-Mar 10L

- Sequence III: VMA was added with powder and aggregate.

KELCO-CRETE 200 diutan gum was dispersed directly into the cement and was therefore mixed with this sequence.

5.5.2 Effects of viscosity modifying agents on mortar

The effect of a VMA on segregation is confirmed in Table 5-10. The VMA and superplasticiser used were KELCO-CRETE 200 diutan gum (refer to 5.5) and Sika ViscoCrete 10 (refer to 5.4.2.1) respectively. As it is shown in Table 5-10, the width of the paste rim of a segregated mortar was 35 mm in the spread test but was reduced to 0 mm with VMA of just 0.05% by the weight of cement mass.

Table 5-10 The influence of a diutan gum on mortar

W/C BY WT.	SP (% CEMENT WT.)	VMA (% CEMENT WT.)	SPREAD (MM)	V-FUNNEL TIME (SECS)	HALO (MM)
0.4	1.2%	0.00%	358	1.3	Yes, 35
0.4	1.2%	0.05%	231	4.3	No

This may be the reason as Khayat (1998) stated that VMAs can imbibe some free water and increase the viscosity, thus reducing the risk of segregation and bleeding. Similar results are also reported by Khayat and Guizani (1997).

Figure 5-20 shows that the influence of VMAs on the segregated mortar mixes. Four combinations of superplasticiser and VMA, ADVA Flow 410 & V-Mar 10L, Glenium Sky 544 & Glenium 5, Glenium Sky 544 & Glenium Stream 2006L and Sika ViscoCrete 10 & KELCO-CRETE 200 diutan gum were tested (complete results are in Appendix 6).

From previous tests, a mix with a W/C ratio of 0.33 by weight and ADVA Flow 410 dosage of 1.6% by weight of cement, met the target properties. When the W/C ratio was increased to 0.4, severe segregation occurred, and the aggregates were distributed unevenly, sank to the bottom of the mixing pot and a 4.5 mm rim of paste without aggregates occurred on the glass plate during spread test.

This mix was therefore chosen to assess the effectiveness of V-MAR 10L. Other segregated mix proportions are shown in Appendix 6.

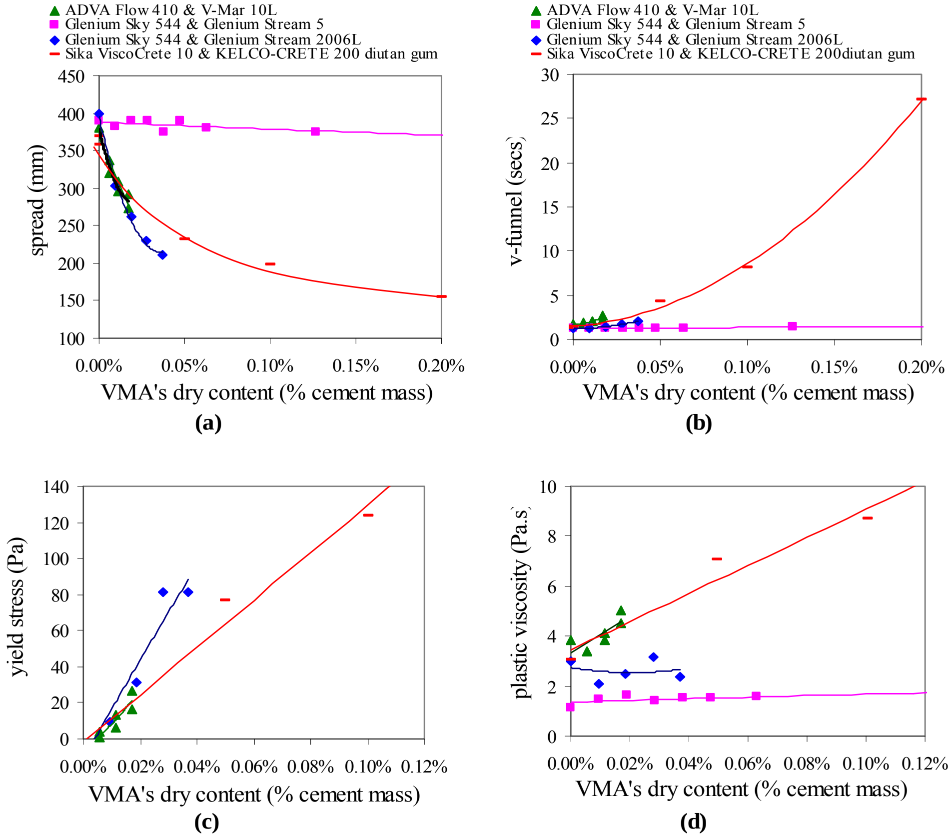

Figure 5-20 Effects of four Sp-VMA combinations on (a) spread (b) V-funnel flow time (c) yield stress (d) plastic viscosity of mortar

It shows that Stream 5 has little or no effect on the fresh properties of mortar in the range of 0~0.32% of cement mass. This was later confirmed by results from a third year undergraduate project (Appleby and Thomson, 2004). The rim of paste without aggregates in the spread test did not change after addition of Glenium Stream 5 even up to 10% of cement mass.

Although V-Mar 10L is said to be a non-adsorptive VMA while Glenium Stream 2006L is adsorptive one, it can be seen from Figure 5-20 that three combinations of superplasticiser and VMA, ADVA Flow 410 & V-Mar 10L, Glenium Sky 544 & Glenium Stream 2006L, Sika ViscoCrete 10 & KELCO-CRETE 200 diutan gum, actually affect the fresh properties of the mortar in a similar way: a sharp decrease in the spread and an increase in the yield stress, and a lesser slight increase in the V-funnel time and the plastic viscosity in all cases. They all completely eliminated the visual segregation as their dosage (in dry content) increased to 0.01% of cement mass, thus confirming that the VMA can eliminate segregation.

In summary, combinations of ADVA Flow 410 & V-Mar 10L, Glenium Sky 544 & Glenium Stream 2006L, Sika ViscoCrete 10 & KELCO-CRETE 200 diutan gum efficiently eliminate segregation of mortar and have similar effect on spread, V-funnel time, yield stress and plastic viscosity of mortar. Glenium Stream 5 has no influence on segregation of mortar.

The spread vs V-funnel time of mortar however did not show clear pattern to select appropriate VMA.

5.6 Conclusion

The spread and the V-funnel tests on mortar are convenient and reliable for selecting appropriate combination of W/C ratio and superplasticiser in advance of tests on concrete.

Although many materials could be used in SCC, the following were selected because of their locality, convenience, availability and consistent supply.

- Thames Valley aggregates of 0/4 mm, 4/10 mm and 10/20 mm
- Blue Circle CEM I 42.5 N by Lafarge
- Fly ash, Ratcliffe and CEMEX
- Glass powder, green and white
- Tap water

Sika ViscoCrete 10 was selected due to its greatest consistence retention and the strongest robustness to variations of water and superplasticiser content.

V-Mar 10L, Glenium Stream 2006L and KELCO-CRETE 200 diutan gum are effective to eliminate segregation.

Chapter 6 Mix Design Methods

In this chapter the use of the General-purpose and CBI mix design methods as a starting point for the practice of designing, producing and testing SCC is first described. The experience gained was then used to extend the UCL method, which was not fully developed at the time of starting the research. This has the advantages of being simple and efficient; it includes use of clearer correlations between the properties of mortar and SCC and it suits local materials.

The test methods and the materials for mortar and concrete that are used in these procedures have been described in 4.3 and Chapter 5 respectively.

6.1 General-purpose mix design method

The steps in the General-purpose method (refer to 2.5.1) and their resulting output for target properties of slump flow of 650±50 mm and V-funnel time of 10~20 seconds are shown in Table 6-1 below. This is followed by analysis of the mortar and concrete tests which have lead to the output and then by a discussion in the subsequent section.

6.1.1 Mix design steps

Table 6-1 General-purpose mix design procedure

Step No.	Description	Output	
		By volume	By weight (kg/m^3)
1	Air content "A" For non air-entrained mix, A=1% of the concrete volume	1% (0.01)	
2	Coarse aggregate volume ratio "G" G=50% of its solid volume except air content.	822/2.6=316 litres/m^3 31.6%	Dry rodded bulk density of aggregate is 1660 0.5×1660×(1-0.01) =822
			Gravel 4/10mm agg.=822×30%=247 10/20mm agg. =822×70%=575
3	Fine aggregate volume ratio "S" Fine aggregate (particles larger than	Fines<0.125mm ratio =2.84% Fines volume =0.40×(1-0.01-0.316) /(1-0.0284)	0.277×2600=721

<table>
<tr><td></td><td>0.125 mm) is set as 40% of the mortar by volume.</td><td colspan="2">=277 litres/m^3 27.7%</td><td colspan="3"></td></tr>
<tr><td>4</td><td>Water to cement volume ratio “W/C”</td><td colspan="2"></td><td colspan="3"></td></tr>
<tr><td>4a</td><td>Retained water to cement ratio (β_p)</td><td colspan="2">From spread tests on paste, β_p=0.902.</td><td colspan="3"></td></tr>
<tr><td>4b</td><td>W/C and a superplasticiser dosage “Sp”</td><td colspan="2">From Spread and V-funnel tests on mortar, W/P was 0.77 for Ra=5 and Rv=0.9~1.1.</td><td colspan="3">W/C=0.25
Sp=0.95%</td></tr>
<tr><td>4c</td><td>Water content</td><td colspan="2">(1-0.01-0.316-0.277)/ (1+1/0.77)=0.173 (173 litres/m^3)</td><td colspan="3">173</td></tr>
<tr><td>4d</td><td>Cement content</td><td colspan="2">Powder content =173/ 0.77=224 litres/m^3
Cement content=224-277×2.84%=216 litres/m^3</td><td colspan="3">216×3.12=674</td></tr>
<tr><td rowspan="3">4e</td><td rowspan="3">Mix proportion (SSD based) of 1m^3 concrete (mix 1)</td><td rowspan="2">Cement (kg)</td><td rowspan="2">Water (kg)</td><td rowspan="2">Sand (kg)</td><td colspan="2">Gravel (kg)</td></tr>
<tr><td>4/10mm</td><td>10/20mm</td></tr>
<tr><td>674</td><td>173</td><td>721</td><td>247</td><td>575</td></tr>
<tr><td>5</td><td>Determination of superplasticiser dosage ”Sp”</td><td colspan="5">From concrete tests for slump flow of 650±50 mm and relative V-funnel time of 10~20 seconds, Sp=2.6%</td></tr>
</table>

Note: 1.Particles larger than 0.090 mm in fine aggregate needs to be determined experimentally when its is ratio more than 2% according to this method. Since 0.090 mm sieve is not available in my laboratory, powder including cement and fine particles in the fine aggregate, is defined as particle size less than 0.125 mm. Cumulative passing percentage of 0.125 mm sieve in this test is 2.84%.

2.Glenium sky 544 was the superplasticiser used for these tests.

6.1.1.1 Retained water to cement ratio

The retained water to cement ratio (β_p) was determined by spread tests on paste with W/C volume ratios of 1.1, 1.2, 1.3 and 1.4.

The results in Figure 6-1 show that, as anticipated, a linear relationship exists between relative flow area ratio and W/C by volume; β_p, the intercept of the regression line with the W/C axis, is 0.9023.

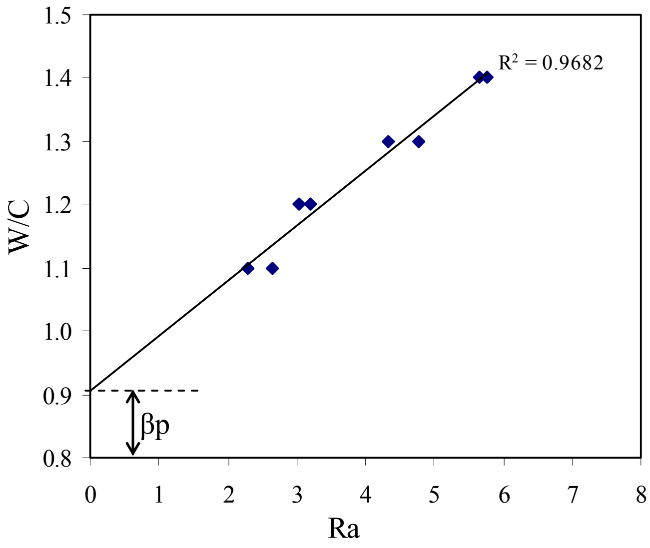

Figure 6-1 Retained water to cement ratio by general purpose method

6.1.1.2 Water/cement ratio by volume

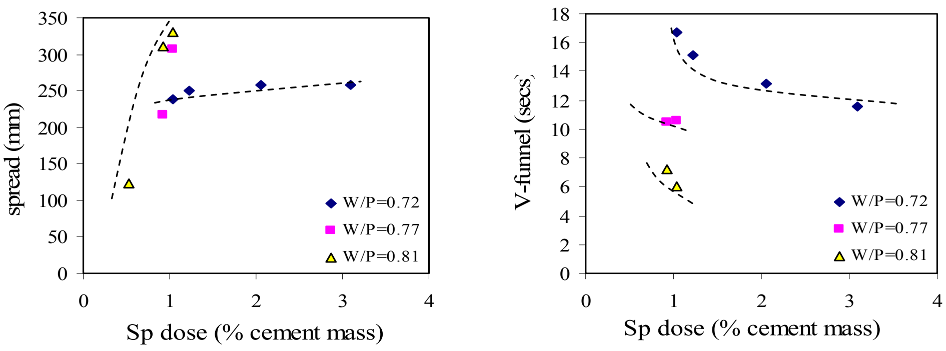

Figure 6-2 Mortar tests by general purpose mix design method

Spread and the V-funnel tests were then carried out on the mortar at W/C volume ratios of 0.8β_p, 0.85β_p and 0.9β_p, i.e. 0.72, 0.77 and 0.81 with increasing superplasticiser doses.

The results are shown in Figure 6-2. The patterns of behaviour for spread are not entirely consistent or logical, but those for the V-funnel time, although limited, are satisfactory. Increase of W/P ratio and superplasticiser dosage all lead to a decrease in V-funnel time.

Although this is not entirely convincing, a W/C ratio of 0.77 by volume and a superplasticiser dose of 0.95% cement were found to give the required combination of Ra = 5 (spread of 250 mm) and Rv = 0.9~1.1 (V-funnel time of 9~11 seconds).

6.1.1.3 Determination of superplasticiser dosage

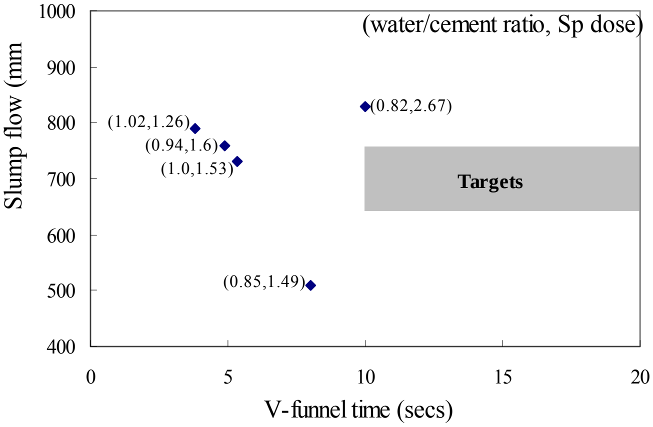

Figure 6-3 Slump flow and V-funnel time of concrete designed by general purpose mix design method

Table 6-2 Slump flow and V-funnel time of concrete designed by general purpose mix design method

Mix No.	2	3	4	5	6
W/P by weight	0.33	0.27	0.26	0.30	0.32
W/P by volume	1.02	0.85	0.82	0.94	1.00
Sp/P by weight	1.26%	1.49%	2.67%	1.60%	1.53%
slump flow (mm)	790	510	830	760	730
V-funnel (secs)	3.8	8.0	10.0	4.9	5.3

Concrete trial mixes were then carried out. The first trial mix with the W/P ratio of 0.77 by volume (0.25 by weight) showed that the concrete was too viscous and difficult to handle. Therefore, the W/P ratio was increased for subsequent mixes. To achieve the targets, the mix had to be adjusted for various W/P ratio and superplasticiser doses five times. The results are given in Figure 6-3 and Table 6-2.

The above results are not very consistent mainly due to inexperience; and clear conclusion of mix to achieve the target properties was not obtained. However, it seems that mix 4 could achieve the target if Sp/P weight ratio was decreased to 2.2%. Therefore, the possible mix proportions with a W/P ratio of 0.82 by volume (0.26 by weight) are shown in Table 6-3.

Table 6-3 A recommended mix proportion of target SCC designed by general purpose mix design method

Mix proportions	By wt, kg/m^3	By volume, litre
Gravel 4/20 mm	822	316
Fine aggregate 0/4 mm	721	277
Cement	655	210
Water	179	179
Glenium sky 544 (2.2% wt powder)	14.86	13
Total	2394	995
slump flow (estimation), mm	650	
V-funnel (estimation), secs	> 10	

The coarse aggregate volume and the sand/mortar volume ratio of this mix are 32% and 41% respectively, which is in the low range of most SCC, the cement content is in the high range. This is a consequence of the target values of a relatively low spread and high viscosity which were typical of Japanese mixes at the time.

This first experience showed that concrete properties were drastically influenced by adding a small dosage of superplasticiser. For example, concrete became highly flowable (slump flow changed from 465mm to 760mm) by adding only 0.58% more into the mix.

6.1.2 Discussion

The advantages of General-purpose mix design method are obvious: most parameters are achieved by assumption or paste or mortar tests, which are comparatively easily performed.

The disadvantages are also obvious: the fixed fresh properties may limit SCC's applications. The W/P ratio and the superplasticiser dosage derived from mortar tests needs to be adjusted by concrete tests, which are laborious and time-consuming. After six mixes, concrete still failed to achieve the targets of slump flow of 650 mm and V-funnel time of 10~20 seconds. This was partly due to inexperience, but it may also show that the method is not effective with materials available in UK.

However, the aims of this trial of gaining experience of producing SCC with local materials and of mastering test methods of SCC, were nearly achieved.

6.2 CBI method

The CBI method (refer to 2.5.2) was then used to design a SCC of slump flow of 650±50 mm and V-funnel time of 10~20 seconds as before; in addition, the blocking ratio of L-box, H2/H1, should be higher than 0.8.

6.2.1 Mix design steps

The four steps are shown as follows.

Step 1 Minimum paste volume calculation

To calculate the minimum paste volume, the packing density (refer to 4.1.3.3) of different combinations of coarse and fine aggregate was first measured. The aggregate void content was then calculated and the results are shown in Figure 6-4. The corresponding minimum paste volume for different N_{ca} was calculated as shown in Figure 6-4 (calculations are in Appendix 7).

The parameters for this are:

- reinforcement spacing (C) was chosen to be 34 mm in order to compare with General-purpose mix design method of SCC

- reinforcement diameter of the L-box was 12 mm

- the maximum size of gravel was 20 mm

K (refer to 2.5.2) was thus calculated as 0.6. The blocking risk of local aggregate is too cumbersome to obtain. The relationship between aggregate blocking volume ratio and the ratio between reinforcement clear spacing and fraction diameter of particle for K=0.6 (river coarse aggregate) is therefore assumed[1] from the trends of other lines in Figure 6-5.

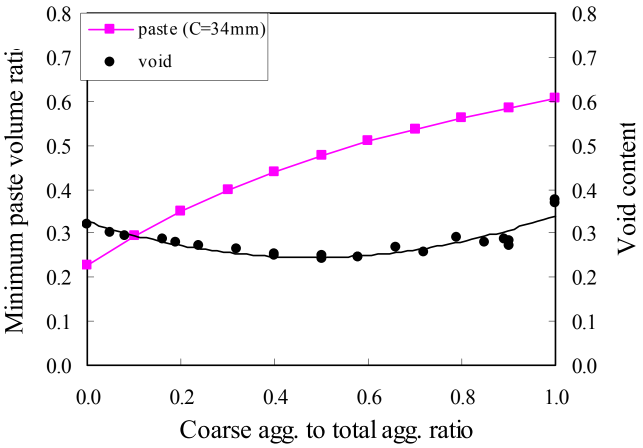

Figure 6-4 Relationship between coarse aggregate ratio, void content and minimum paste volume (Tangermsirikul and Bui, 1995)

As shown in Figure 6-4, the optimum coarse to total aggregate ratio (N_{ca}) which corresponds to the highest packing density is about 50%. The minimum paste volume for this is 0.48 which is very high for SCC.

However, following the same calculation but changing the aggregate size to 0/8mm and 8/16mm and using the relationship of K=1.05 (shown in Figure 6-5 (Tangermsirikul and Bui, 1995)), the minimum paste volume decreased to 0.43

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[1] This assumption may be the reason for a very high paste volume, 0.48 correponding to N_{ca} of 0.5.

when N_{ca} of 0.5 (shown in Appendix 7); while Billberg (1999) produced a paste volume of only 0.415. Therefore, the reason of above higher paste volume calculated is due to the different aggregate size and the blocking criteria guessed for local aggregate. This indicates that the blocking criteria in the CBI reference to predict the minimum paste volume cannot be directly applied to local aggregates.

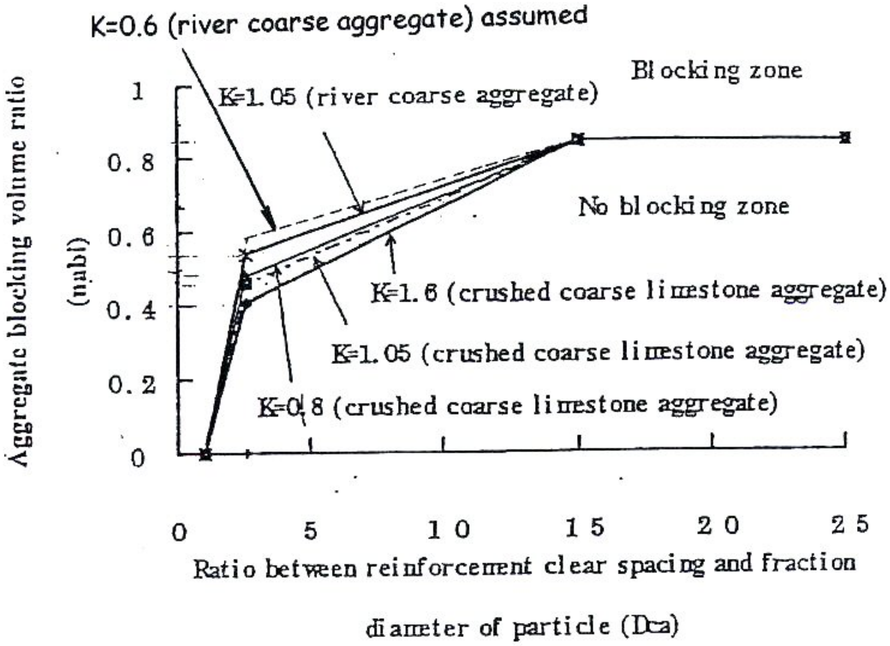

Figure 6-5 Relationship between n_{abi} and D_{ca} in CBI mix design method (Tangermsirikul and Bui, 1995)

The following concrete test further shows this high paste volume led to a much higher filling ability than the target.

Step 2 Rheological tests on fine mortar

The dosage of superplasticiser[2] was estimated by testing the rheological properties of the fine mortar (refer to Glossary of Terms). The air content and the W/P ratio were chosen as 1% by volume and 0.30 by weight (0.93 by volume) respectively.

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[2] Glenium sky 544 (refer to 5.4.2.2) was the superplasticiser used.

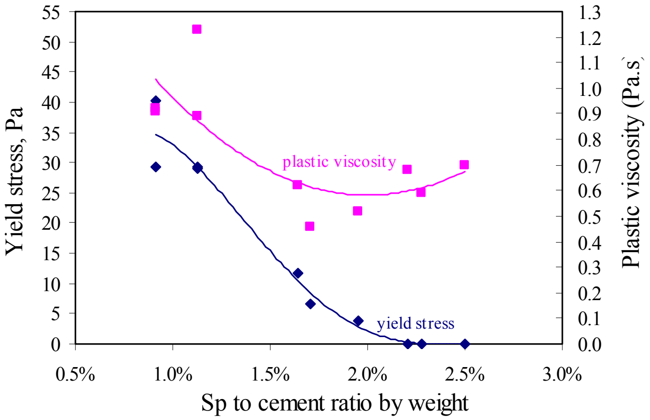


Figure 6-6 The influence of Glenium sky 544 on the rheological properties of fine mortar

It can be seen from Figure 6-6 that the superplasticiser saturation of 2.2% leads to approximately zero yield stress and minimum plastic viscosity. Beyond this value, Bingham parameters do not change significantly with an increase in superplasticiser dosage.

Step 3 SCC evaluation

The mix proportions of the concrete (shown in Table 6-4) were therefore totally determined from above experiments and then evaluated by slump flow test, V-funnel test and L-box test.

Table 6-4 Concrete mix proportions (C=34mm) by CBI method

Test 1		By weight	By volume
Coarse aggregate 4/20 mm		676 kg/m^3	23.6%
Fine aggregate 0/4mm		676 kg/m^3	27.7%
Cement		753 kg/m^3	25.2%
Water		231 kg/m^3	23.5%
Coarse aggregate to total aggregate ratio		0.50	0.50
Paste		1003	0.48
W/P		0.30	0.93
Glenium sky 544 (2.2% powder)		16.99 kg/m^3	
slump flow, mm		> 900[3]	
L-box	H2/H1	1	

---

[3] The concrete flew outside the slump flow testing plate, which is 900×900 mm^2.

It can be seen from Table 6-4 that the H2/H1 met the requirements. However the slump flow is much higher than the target. This maybe the reason of the high paste volume determined in step 1.

Step 4 Revision of concrete proportion

In order to achieve the same targets as in General-purpose method, the paste volume had to be decreased while the superplasticiser dosage and W/C ratios were kept constant. The test results are shown in Table 6-5.

Table 6-5 Test results of SCC designed by CBI method

Mix No.	2	3	4	5
paste volume	0.410	0.410	0.400	0.390
Sand/mortar by vol.	0.42	0.42	0.43	0.45
Coarse agg. to concrete by vol.	0.295	0.295	0.300	0.305
slump flow (mm)	760	735	655	680
V-funnel time (seconds)	7.2	8.8	11.2	14.5

After the paste volume was decreased to 0.40 (mix 4) and 0.39 (mix 5), the targets of slump flow of 650±50 mm and V-funnel time of 10~20 seconds were achieved. The aim to produce a target mix (mix 4) was thus achieved.

6.2.2 Discussion

The superplasticiser dosage and the W/C ratio are determined by rheological tests in the CBI method which is comparatively less laborious than General-purpose method.

However, the method cannot be directly applied to local materials because the reference curve for blocking criterion is not general and it is cumbersome to obtain for each type of aggregate. Moreover, the rheological results of fine mortar do not readily correlate with the slump flow and the V-funnel time of SCC.

6.3 UCL method

The UCL method (refer to 2.5.1.2), not fully developed when the project started, was mainly based on two sets of relationships:

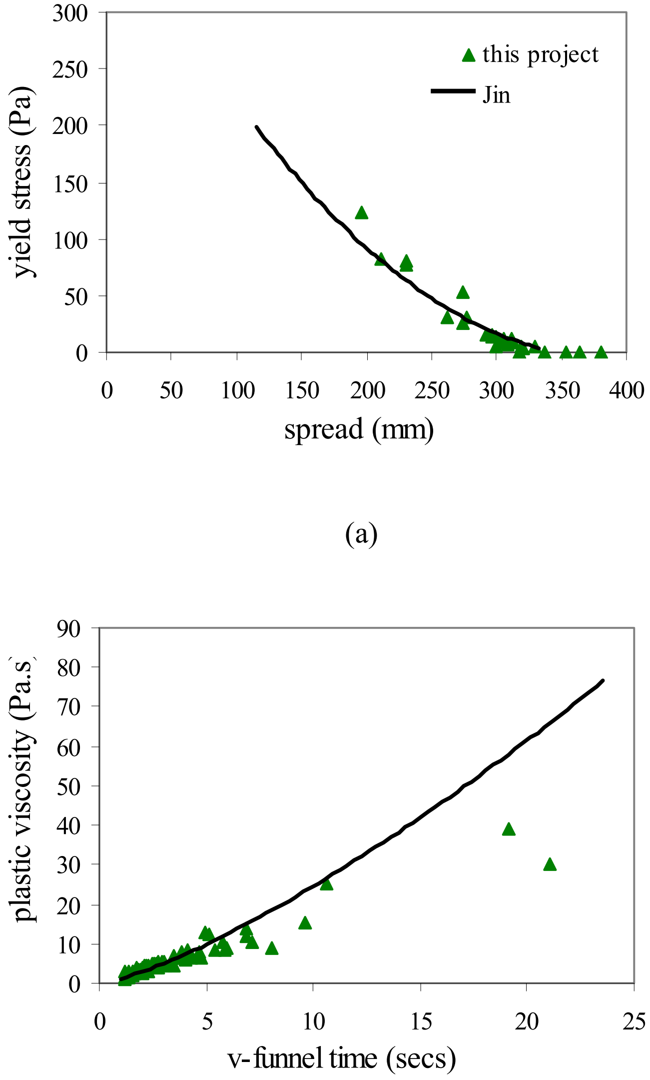
- those between the Bingham parameters and the mortar spread and the V-funnel test results (refer to Figure 2-7)
- those between the mortar and concrete spread and V-funnel values which had been obtained for a sand/mortar volume ratio of 45% and a coarse aggregate of 50~55% of its dry rodded bulk density (Jin and Domone, 2002) (shown by the solid lines in Figure 6-8).

Tests were carried out to confirm these relationships (complete results are in Appendix 8). The method was then extended by establishing the relationships between mortar and concrete on mixes with coarse aggregate contents of up to 65% of its dry rodded bulk density (results have been included by De Schutter et al. (2008)). The limit of coarse aggregate content in the concrete was determined by the J-ring test.

6.3.1 Relationships verified

It can be seen from Figure 6-7 that the results from the project are close to Jin's (Jin and Domone, 2002). The correlations between spread and yield stress and between V-funnel time and plastic viscosity were therefore confirmed. High yield stress and plastic viscosity corresponds to low spread and long V-funnel time. Therefore, Bingham constants can be predicted from mortar tests and rheology tests are not essential as the spread and the V-funnel tests have a sound theoretical basis.

There are several yield stress values near zero and sometimes negative values were obtained, which have no physical meaning. It is reported that the calculation method or the error in the extrapolation process can lead to the negative values (Ferraris et al., 2000).

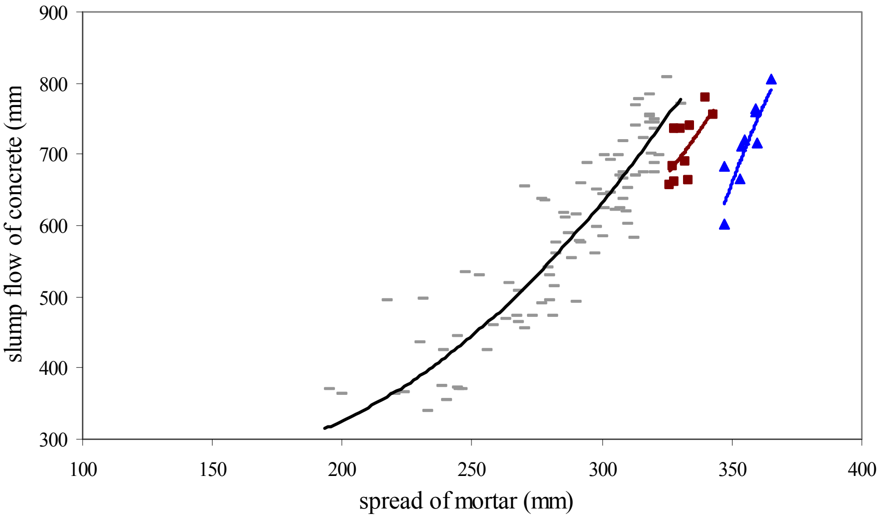


(a)

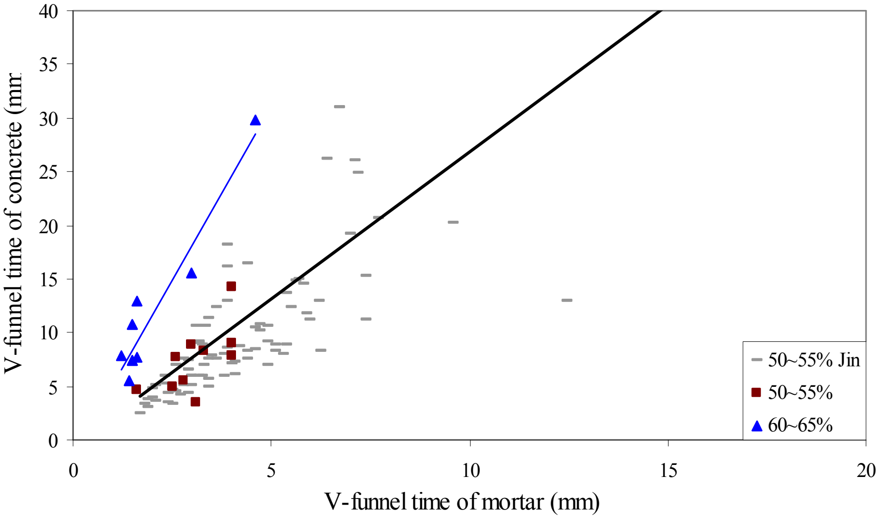
(b)

Figure 6-7 The relationships between (a) yield stress and spread and (b) between plastic viscosity and V-funnel time in mortar tests

The relationships between mortar and SCC with the sand/mortar volume ratio of 45% and the coarse aggregate of 50~55% of its dry-rodded bulk density previously established is shown in Figure 6-8.



(a)



(b)

Figure 6-8 Relationships between (a) spread of mortar and slump flow of concrete and (b) V-funnel times of mortar and concrete

As it shows, the relationships between mortar and SCC mixes (the sand/mortar volume ratio of 45%, the coarse aggregate of 50~55% of its dry-rodded bulk density, cement only and without VMAs) were in the range of Jin's results[4].

For example, according to Figure 6-8, the anticipated filling ability targets of a slump flow of 650 mm and V-funnel time of 10.0 seconds, correspond to mortar properties of a spread of 304 mm and V-funnel time of 3.9 seconds. Then mortar was tested by varying the W/P ratio and superplasticiser dosage normally less than 10 times. From the performance characteristic of a specific superplasticiser (refer to 5.4.2.1), the W/P and superplasticiser dosage to realize the target spread and V-funnel time was estimated as shown in Figure 6-9.

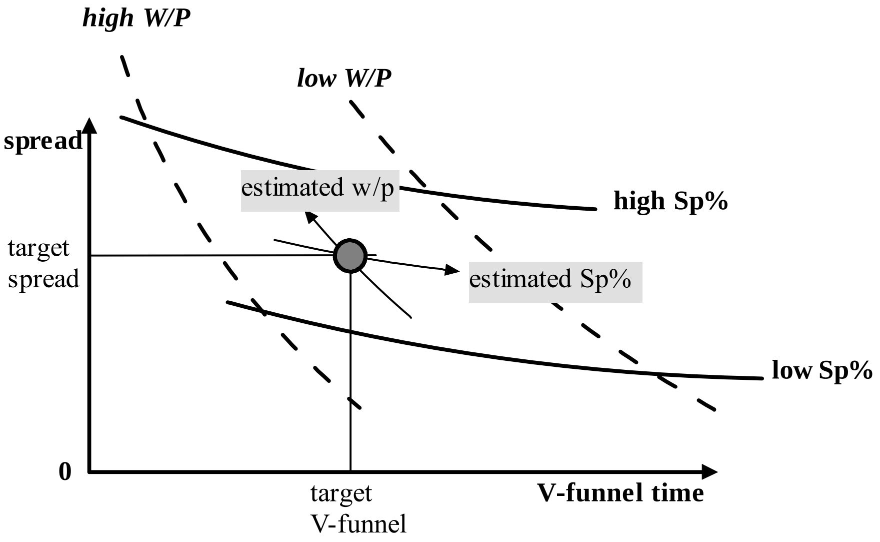


Figure 6-9 Schematic of estimation for proper water to powder ratio and superplasticiser dosage based on spread and V-funnel time

Then the W/P ratio and superplasticiser dosage were estimated and applied to produce concrete, slump flow and V-funnel time of which were measured. These results have developed and further supported UCL method.

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[4] Sika ViscoCrete 10 was the superplasticiser.

6.3.2 Discussion

Table 6-6 Target mix produced by UCL method

	BY WEIGHT	BY VOLUME (%)
Coarse aggregate 4/20 mm	840 kg/m^3	32.3
Fine aggregate 0/4mm	780 kg/m^3	30.0
Cement	585 kg/m^3	18.6
Water	181 kg/m^3	18.1
Glenium sky 544 (% powder)	12.87 kg/m^3	
W/C	0.30	0.98
Sp/C	2.2%	
slump flow	680 mm	
V-funnel time	13.0 seconds	

Follow above procedures, the mix as shown in Table 6-6 with coarse aggregates content of 50% of its dry rodded bulk density achieved the targets.

Then the target mixes designed by the above three methods are compared in Table 6-7.

Table 6-7 Comparisons of three mix design methods

	GENERAL PURPOSE METHOD (REFER TO TABLE 6-3)	CBI METHOD (TEST 4 REFER TO TABLE 6-5	UCL METHOD (REFER TO TABLE 6-6)
Paste vol %	40	40	36.7
Sand/mortar vol. %	41	43	45
Coarse agg. vol. %	32	30	32.3
Cement kg/m^3	655	653	585
W/C by vol.	0.85	0.93	0.98
Sp[5]/C by wt.	2.3%	2.2%	2.2%

For the targets of the slump flow of 650 mm and the V-funnel time of 10~20 seconds, the mix proportions produced by the general purpose method and CBI method are similar. Both produce a paste content of 40% by volume, which is in the higher range for most SCC (refer to Table 2-1) and is thus not efficient. The mix produced by General-purpose method contains higher coarse aggregate and less sand than that by CBI method.

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[5] Glenium sky 544 was the superplasticiser.

For the same targets, the mix produced by UCL method is the most efficient as it has the least paste volume, least cement content and highest sand/mortar ratio and coarse aggregate content. It suits local materials the most and it saves time and materials by testing concrete only once, which is unusual for a beginner.

6.3.3 Developments of UCL method

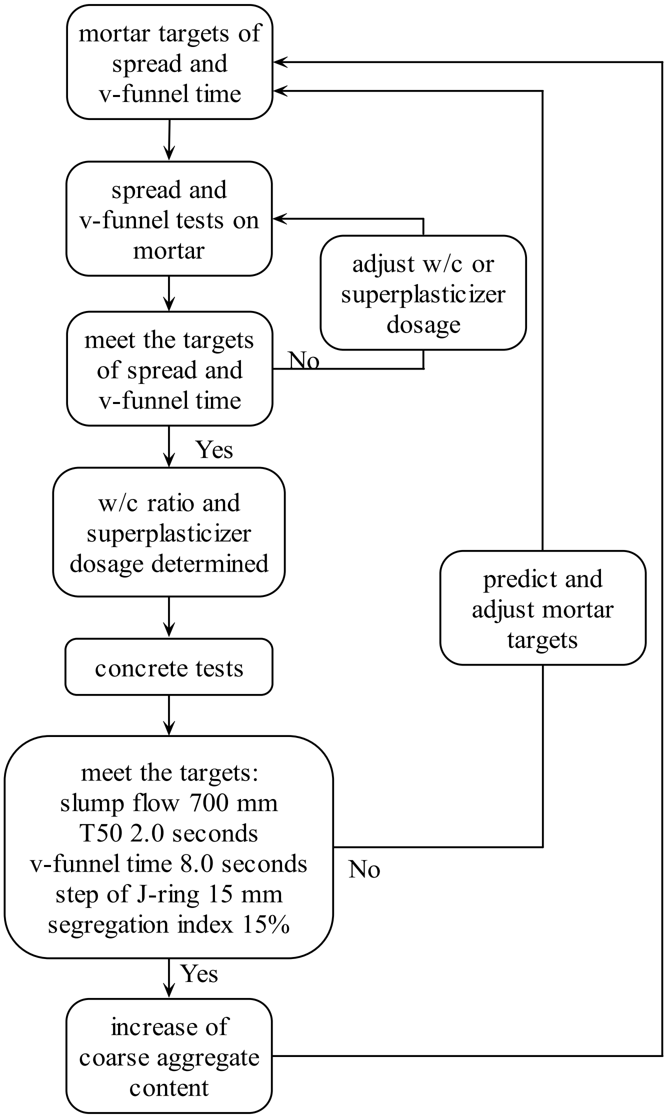

Figure 6-10 Experimental procedure for concrete production

After the UCL method was selected, an experimental programme shown in Figure 6-10 was designed to test if the relationship between mortar and concrete properties exists in concrete with higher coarse aggregate contents. Because aggregates are much less expensive and more stable than cement paste, concrete should contain as much aggregate and less cement paste as possible. Therefore, coarse aggregate contents should be the maximum without causing blockage[6].

The test results also in Figure 6-8 shows that correlations also exist between mortar and concrete when the coarse aggregate content increases to 60% of the dry rodded bulk density. However, the trend line with the coarse aggregate content of 60~65% dry rodded bulk density deviates from that previously established (50~55% dry rodded bulk density). Its slope becomes steeper, which means for the same filling ability, the concrete with more coarse aggregate requires a mortar with higher spread and less V-funnel time. These relationships are reliable for local materials and subsequently used to produce mixes incorporating fly ash and ground glass in the later parts of the research.

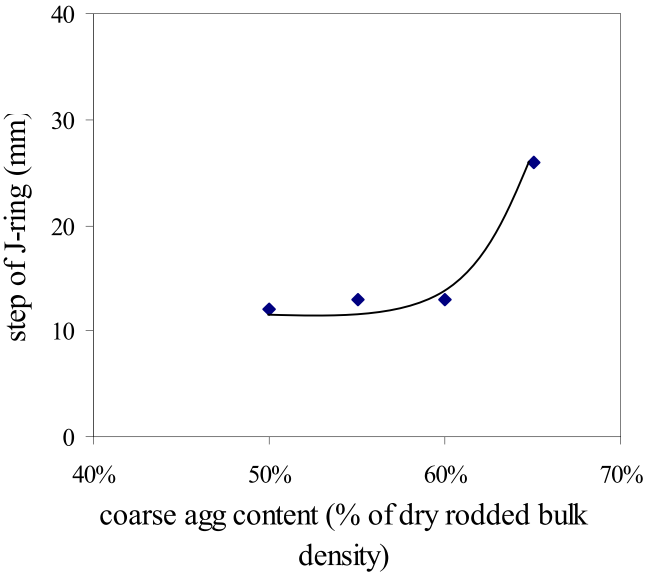

Figure 6-11 Relationship between coarse aggregate and step of J-ring

Figure 6-11 shows that the risk of blockage (as assessed by the J-ring test) rises sharply due to the collision of the aggregate particles when the coarse aggregate

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[6] Assessed by the J-ring test

content is more than 60% dry rodded bulk density, which is about 38.8% of concrete volume. At this content blockage also occurred in the V-funnel test and the mix segregated. Therefore coarse aggregate of below 55% is safe to produce SCC when using the mix of 4/10 mm and 10/20mm coarse aggregate.

6.3.4 Mix design summary

In summarising, the parameters chosen and mix design procedures that were used for the remainder of the research are as follows.

- The coarse aggregate content was fixed at 55% of its dry rodded bulk density i.e. 35.5% of concrete volume.
- The sand to mortar ratio was kept constant at 45% by volume throughout all mortar and concrete tests.
- The air content was assumed to be 1%.
- The W/P ratio and superplasticiser dosage were determined in the mortar tests.
- The W/P ratio and superplasticiser dosage are then applied to a concrete and adjusted if necessary to meet the required targets of SCC.

If the slump flow does not reach the desired value, superplasticiser should be added; if the V-funnel time is inadequate, the W/C ratio should be increased; if the slump flow and V-funnel time are both inadequate, superplasticiser and W/C ratio should be increased. For decreased passing ability, the mortar composition was kept constant and the superplasticiser slightly decreased to ensure the required slump flow.

6.3.4.1 Concrete mix parameters

In the process of confirming the established relationships between mortar and SCC with the sand/mortar volume ratio of 45% and the coarse aggregate of 50~55% of its dry-rodded bulk density previously as shown in Figure 6-8, Sika ViscoCrete 10 produced satisfactory SCC without the use of a VMA. Powder-type SCC (refer to 2.1.1) was therefore used to investigate the influence of high volume fly ash and ground glass in SCC. In each case, pure cement SCC was first produced then modified to have the same target properties with the additions. The addition contents should be the maximum without causing blockage.

Fine aggregate and coarse aggregate contents were 743 kg/m^3 and 924 kg/m^3 respectively, i.e. 28.6% and 35.5% of concrete volume respectively.

6.3.4.2 Assessment tests and targets

In the subsequent parts of the research programme, filling ability was assessed by slump flow and the V-funnel tests. Passing ability and segregation resistance were tested with the J-ring and the sieve stability tests respectively. A visual inspection also gave an indication of the segregation. The consistence retention was evaluated by slump flow and the V-funnel tests about 1 hour after mixing.

The targets are slump flow of 700 ± 50 mm, V-funnel time of 8.0 ± 3.0 seconds, step height in the J-ring of less than 25 mm and sieve segregation of less than 15%.

6.4 Conclusion

For the same targets, the mix proportions produced by the general purpose method, CBI method and UCL method are compared. The mix produced by the UCL method is the most efficient, which has the least paste volume, least cement content and highest sand/mortar ratio and coarse aggregate content. It suits local materials the most and it saves time and materials by minimizing the number of concrete mixes.

In addition, this method has the advantage of being simple and efficient. It includes clearer correlations between mortar and SCC and is the only method can be used to design SCC with various fresh properties, which can be used in wider applications. UCL mix design method is therefore chosen for the project.

In the process, UCL method of mix design was extended. The relationships in fresh properties between fresh mortar and concrete with coarse aggregate content up to 65% dry rodded bulk density, which is about 42% of concrete volume were estabilish.

The risk of blockage increases significantly when the coarse aggregate content is more than 60% dry rodded bulk density, which is about 38.8% of concrete volume. SCC has less risk of blockage when the coarse aggregate of below 55% dry rodded bulk density when using the mix of 4/10 mm and 10/20mm coarse aggregate.

Chapter 7 Self-compacting Concrete with Different Levels of Fly Ash

In this chapter, the results of the tests on SCC with increasing levels of fly ash are presented and discussed. Tests on mortar were first carried out to differentiate the effects of W/P ratio by weight from those by volume and to assess the effects of fly ash on spread and V-funnel time of increasing fly ash levels. The mix proportions were then adjusted so that the target properties (spread 335±2 mm and V-funnel time 3.1±0.2 seconds) were obtained at each fly ash level, and then these proportions were used in concrete and, if necessary, adjusted again until the target properties of the concrete (slump flow 700±50 mm, V-funnel time 8.0±3.0 seconds, step height in the J-ring less than 25 mm and sieve segregation less than 15%) were achieved at each fly ash level. As outlined in Chapter 3 concrete with fly ash levels of up to 80% replacement of the cement by volume were examined (with the fresh properties of mixes tested at 100% fly ash); the aggregate proportions of fine aggregate as 45% by volume of the mortar and the coarse aggregate as 35.5% by volume of the concrete were maintained constant. These mixes were then tested for compressive strength, splitting tensile strength, UPV, Ed and water absorption at ages from 7 to 180 days.

Table 7-1 Tests on mortar and concrete with fly ash

TESTS	AIMS	FLY ASH 1A	FLY ASH 1B	FLY ASH 2
Spread and V-funnel time tests on mortar	To assess the influence of fly ash on mortar	Figure 7-1 Table 7-2	Figure 7-2 Table 7-3	Figure 7-3 Table 7-5
slump flow, V-funnel, J-ring and sieve stability tests on fresh concrete	To assess the influence of fly ash on filling ability, passing ability, segregation and consistence retention	×	Table 7-4	Table 7-6
compressive strength, splitting tensile strength, UPV, Ed and water absorption tests on hardened SCC	To assess the influence of fly ash on mechanical properties and durability	×	×	Table 7-7

As a result of the tests described in 5.4, the superplasticiser used throughout was Sika ViscoCrete 10. The fly ash was obtained from two different sources (refer to 5.2.1). Since both batches of fly ash 1 weer used up during the fresh tests on SCC, there were no hardened test results obtained with these. The fresh tests were repeated with fly ash 2 as well as the hardened concrete tests. The complete tests carried out are shown in Table 7-1.

7.1 Effects of fly ash 1 on fresh mortar and self-compacting concrete

To keep the paste volume constant, fly ash usually replaces cement by volume. To study the influence of fly ash on mortar, the W/P ratio and superplasticiser dosage would be kept constant. The superplasticiser dosage is usually expressed as the percentage of powder weight. There are two ways to calculate the W/P ratios, by weight or by volume, both have been used in the literature published.

For the control mix without fly ash, the W/C ratio of 0.30 by weight or 0.945 by volume and the superplasticiser dosage of 1.3% cement weight had successfully produced a target SCC. These parameters were thus chosen for the first set of mortar tests. Results are shown in Table 7-2 and Figure 7-1.

For the same fly ash replacement ratio, the mixes with constant W/P weight ratio showed smaller spread and longer V-funnel time in the tests than those with constant W/P volume ratio. Since the mortar volume and sand/mortar volume ratio are constant, the difference may be because the former has higher powder (cement and fly ash) content and less water content than the latter. The former was thus more viscous than the latter.

The mix made of 100% fly ash replacement had the least spread and the highest V-funnel time and was too viscous to flow. This may be because fly ash is finer than cement thus the total surface area increases when cement is replaced with fly ash. Another reason may be because the superplasticiser, which is designed for cement systems, may not act on fly ash so effectively as on cement.

The W/P weight ratio was chosen to be constant to examine the influence of fly ash 1b and fly ash 2 on mortar as follows.

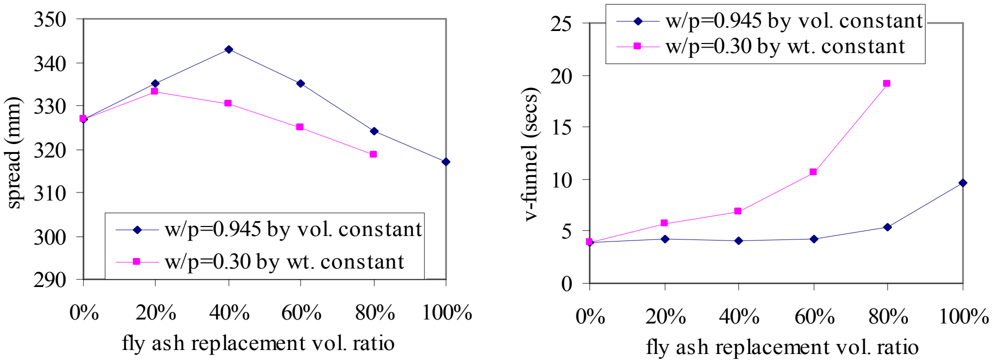


Figure 7-1 Influence of fly ash 1a content on fresh properties of mortar (constant superplasticiser dosage)

Table 7-2 Influence of fly ash 1a on mortar

FLY ASH (VOL. %)	W/P BY WT	W/P BY VOL.	SP (%POWDER WT./WT.)	POWDER VOL.	WATER VOL.	SPREAD (MM)	V-FUNNEL TIME (SECS)
0%	0.300	0.945	1.30%	28.3%	26.7%	327	3.9
20%	0.317	0.945	1.30%	28.3%	26.7%	335	4.2
40%	0.336	0.945	1.30%	28.3%	26.7%	343	4.1
60%	0.358	0.945	1.30%	28.3%	26.7%	335	4.3
80%	0.383	0.945	1.30%	28.3%	26.7%	324	5.4
100%	0.411	0.945	1.30%	28.3%	26.7%	317	9.6
0%	0.30	0.945	1.30%	28.3%	26.7%	327	3.9
20%	0.30	0.894	1.30%	29.0%	26.0%	333	5.8
40%	0.30	0.843	1.30%	29.8%	25.2%	331	6.9
60%	0.30	0.792	1.30%	30.7%	24.3%	325	10.6
80%	0.30	0.741	1.30%	31.6%	23.4%	319	19.2
100%	0.30	0.690	1.30%	32.5%	22.5%		

Since fly ash 1a was used up, the influence of fly ash 1b on the spread and V-funnel time of mortars were repeated. Results are shown in Table 7-3 and Figure 7-2. These were carried out with a constant dosage of superplasticiser 1.3% by weight of powder, and with a W/P ratio of 0.32. These were used because the control mortar (without fly ash) was able to produce a target SCC (refer to mix F_0 in Table 7-4).

It can be seen from Figure 7-2 that the results are nearly identical to those in Figure 7-1 at constant W/P ratio by weight. The V-funnel time increases with an increase in the fly ash content, with significant increases above 60% fly ash replacement. The V-funnel time has a good correlation with plastic viscosity (refer to Figure 2-7) and so it seems therefore that the inclusion of fly ash leads to an increase in the viscosity.

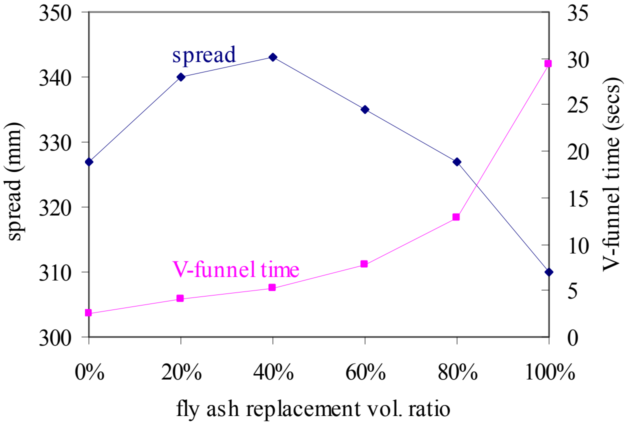


Figure 7-2 Effects of fly ash 1b on mortar

Table 7-3 Influence of fly ash 1b on mortar properties

Fly ash vol.(%)	W/P by wt	W/P by vol.	Sp (%powder wt./wt.)	Spread (mm)	V-funnel time (secs)	Halo (mm)
0	0.32	1.00	1.3%	327	2.6	No
20	0.32	0.95	1.3%	340	4.1	Yes, 2
40	0.32	0.90	1.3%	343	5.2	Yes, 5
60	0.32	0.84	1.3%	335	7.8	Yes, 6
80	0.32	0.79	1.3%	327	12.9	Yes, 9
100	0.32	0.74	1.3%	310	29.3	Yes, 13

Figure 7-2 also shows that the spread of mortar increases with an increase in fly ash content up to 40%, reaches the maximum value at 40% and then decreases with the continued increase in fly ash content.

Table 7-3 also shows that replacement of cement by fly ash leads to increased segregation. The halo of bleeding water at the edge of the mortar in the spread test increased from 0 to 13 mm when the replacement ratio of fly ash 1 increased from 0 to 100%. As described in 5.2.3, fly ash has a smaller retained water ratio than cement. Replacing cement with fly ash will lead to a less water demand or higher flowability or bleeding if excess water cannot be held by the particles. This maybe the reason that the mixes with increasing fly ash contents had increasing halo in the spread test.

Table 7-4 Mix proportion of mortar and corresponding concrete with fly ash 1b

MIX NO.		F0	F20	F40	F60	F60(2)
Mix ratio	W/P by wt.	0.32	0.35	0.36	0.38	0.38
	Fly ash vol.%	0	20	40	60	60
	Sp wt.% by powder wt	1.3	1.0	0.8	0.7	0.8
Mortar	Water (kg/m^3)	276	281	277	275	275
	Cement (kg/m^3)	863	678	517	346	346
	Fly ash (kg/m^3)	0	124	252	379	379
	Fine aggregate (kg/m^3)	1190	1190	1190	1190	1190
	Sika ViscoCrete 10 (kg/m^3)	11.19	8.00	6.13	5.06	5.81
	Spread (mm)	327	331	332	333	343
	V-funnel time (secs)	2.6	3.3	3.7	3.3	2.8
SCC	Water (kg/m^3)	175	178	176	175	175
	Cement (kg/m^3)	548	431	328	220	220
	Fly ash (kg/m^3)	0	79	160	240	240
	Fine aggregate (kg/m^3)	743	743	743	743	743
	Coarse aggregate (kg/m^3)	924	924	924	924	924
	Sika ViscoCrete 10 (kg/m^3)	7.12	5.09	3.90	3.22	3.68
	slump flow (mm)	685	740	700	580	725
	V-funnel time (secs)	7.7	7.1	8.2	8.9	6.6
	Step height in the J-ring (mm)	14	13	19	35	20
	Spread in the J-ring test (mm)	648	620	500	365	560
	Sieve segregation (%)	10	11	7	2	13
	slump flow 1 hour (mm)	610	555	420	335	385
	V-funnel time 1 hour (secs)	8.9	10.0	16.7	36.6	13.1

The adjusted mix proportions to achieve the target properties of the mortar and concrete at each fly ash level, and the measured properties, are given in Table 7-4.

Table 7-4 shows that to achieve the target spread and V-funnel time, the increase in fly ash replacement level leads to an increase in W/P ratio and a decrease in superplasticiser dosage. Using the mortars with properties within the target range produced satisfactory concrete properties for mixes F_0, F_{20} and F_{40}, but not for mix F_{60}, which was very sticky with a slump flow lower than the target. More superplasticiser was thus added to produce the mix $F_{60}(2)$ to meet the target.

The target concrete mixes, which have similar slump flow and V-funnel time indicating similar filling ability, also show an increase in W/P ratio and a reduction in superplasticiser dosage due to an increase in fly ash content. The inclusion of fly ash leads to an obvious increase in the step height of J-ring, a decrease in the slump flow and an increase in the V-funnel time after an hour. For mixes with 0, 20%, 40% and 60% fly ash, the reduction in slump flow and the increase in the V-funnel time are 70 mm and 1.2 seconds (F0), 185 mm and 2.9 seconds (F20), 280 mm and 8.5 seconds (F40) and 340 mm and 6.5 seconds (F60(2)) respectively. This indicates degradation in passing ability and consistence retention because of fly ash. The inclusion of fly ash does not significantly affect segregation. These result from the changes in water, superplasticiser, cement and fly ash content and their interactions and actions with aggregate because the aggregate content and paste volume are both constant.

7.2 Effects of fly ash 2 on fresh mortar and self-compacting concrete

The influence of fly ash 2 on the spread and V-funnel time of mortars is shown in Table 7-5 and Figure 7-3. These were carried out with the same dosage of superplasticiser and the same W/P ratio as fly ash 1b to test if their effects are the same.

Table 7-5 Effect of fly ash 2 on mortar

Fly ash vol.(%)	W/C by wt	W/P by vol.	Sp (% powder wt./wt.)	Spread (mm)	V-funnel time (secs)	Halo (mm)
0	0.32	1.00	1.30%	337	3.0	No
20	0.32	0.95	1.30%	342	3.6	Yes, 6
40	0.32	0.90	1.30%	350	4.1	Yes, 10
60	0.32	0.84	1.30%	350	6.0	Yes, 14
80	0.32	0.79	1.30%	343	7.6	Yes, 19
100	0.32	0.74	1.30%	341	10.0	Yes, 24

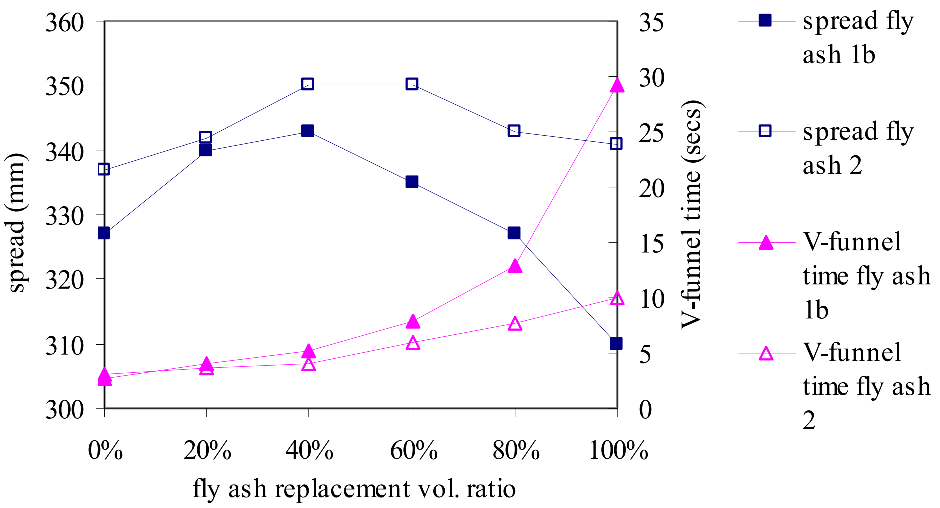


Figure 7-3 Effects of fly ash 2 on mortar

It can be seen from Figure 7-3 that the V-funnel time increases with an increase in the fly ash content, but the magnitude of the increase of fly ash 2 is not as great as that of fly ash 1b. As the fly ash replacement level increases from 0 to 100%, an increase of 26.7 and 7.0 seconds in the V-funnel time for fly ash 1b and fly ash 2 respectively.

In short, inclusion of fly ash leads to an increase in the viscosity. This is in agreement with Poon and Ho (2004) and Xie et al (2002). Helmuth (1987) also showed that plastic viscosity increased with an increase in fly ash contents by testing the paste of the W/C ratios ranged from 0.45 to 0.75 and the fly ash contents from 0 to 100%. This does however contradict previous findings of Ferraris et al (2001), Newman and Choo (2003), and Tattersall and Banfill (1983). The different conclusions may be due to different type and sources of fly ash and particularly the superplasticiser.

Figure 7-3 also shows that, as with fly ash 2, the spread increases up to 40% fly ash replacement, reaches a maximum value at 40% to 60% and decrease above 60%, again the changes are not as great as for fly ash 1. The difference between the maximum and the minimum spread value is 33 and 13 mm for fly ash 1b and fly ash 2 respectively. Different from the results of fly ash 1b, the spread of the pure fly ash 2 mortar is a little higher than that of the pure cement mortar.

In summary, inclusion of a low fly ash content benefits consistence. This can be attributed to the spherical particle shape reducing the inter-particle friction (Helmuth, 1987; Nehdi et al., 2004) and is consistent with the lower retained water ratio of fly ash 2 compared to the cement (refer to 5.2.3), i.e. less water is required to start the flow for fly ash paste.

Table 7-5 also shows that replacement of cement by fly ash 2 led to increased segregation. The reason could be the lower retained water ratio and particle shape of fly ash (Domone and Chai, 1997; Helmuth, 1987) or no action between superplasticiser and fly ash (Wattanalamlerd and Ouchi, 2005). Therefore, for the mortars with the same W/P ratio and superplasticiser dosage, there is more ‘free’ water and un-contributing superplasticiser in the mixes with fly ash than those without fly ash, which lead to bleeding. An increase in total bleeding water from 0.117 ml/cm^2 to 0.127 ml/cm^2 was also observed in SCCs with fly ash content increased from 40% to 60% (Bouzoubaa and Lachemi, 2001). In addition, there was more bleeding in mortar with fly ash 2 than fly ash 1.

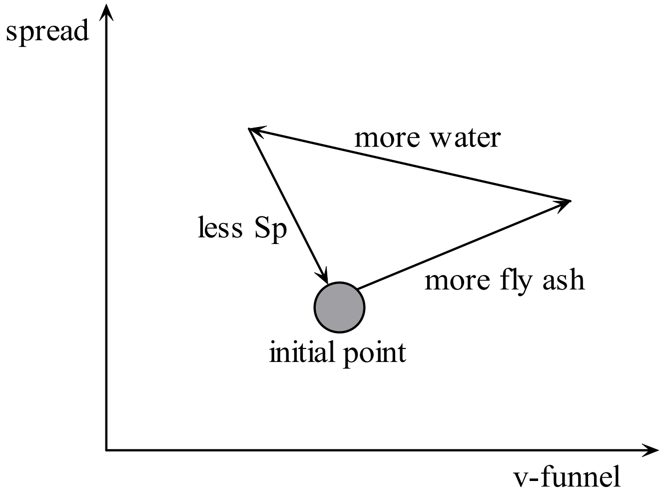


Figure 7-4 The influence of water, superplasticiser and fly ash on mortar

As shown in 5.4.2.1, increased Sika ViscoCrete 10 reduces the yield stress and slightly decreases the viscosity, thus making the flow easier to initiate; we also know that increasing the water content reduces both yield stress and plastic viscosity (refer to Figure 2-5). In these tests the fly ash increased the viscosity and therefore, the effects of water, superplasticiser and fly ash on the spread and V-funnel time can be illustrated schematically in Figure 7-4. To maintain the spread and V-funnel time of the initial mix, i.e. the starting point, replacement of cement with fly ash would require an increase in W/P ratio and a reduction in superplasticiser dosage.

Table 7-6 Mix proportion of mortar and corresponding concrete with fly ash 2

		F0	F20	F40	F60	F80	F100	F80 (2)	F100 (2)
Mix ratio	W/P	0.33	0.34	0.35	0.36	0.38	0.385	0.37	0.36
	Fly ash vol.%	0	20	40	60	80	100	80	100
	Sp wt.% by powder wt	1.10	0.90	0.75	0.68	0.59	0.40	0.65	0.45
Mortar	Water (kg/m^3)	280	277	273	268	266	258	263	249
	Cement (kg/m^3)	850	688	524	355	179	0	181	0
	Fly ash (kg/m^3)	0	126	255	389	522	671	529	692
	Fine agg. (kg/m^3)	1190	1190	1190	1190	1190	1190	1190	1190
	Sp (kg/m^3)	9.34	7.33	5.84	5.06	4.14	2.68	4.61	3.11
	Spread (mm)	335	337	333	333	334	336	346	342
	V-funnel time (secs)	3.1	3.1	3.1	3.1	3.0	3.3	3.7	5.3
SCC	Water (kg/m^3)	178	176	173	170	169	164	167	158
	Cement (kg/m^3)	539	437	333	225	113	0	115	0
	Fly ash (kg/m^3)	0	80	162	247	331	426	336	439
	Fine agg. (kg/m^3)	743	743	743	743	743	743	743	743
	Coarse agg. (kg/m^3)	924	924	924	924	924	924	924	924
	Sp (kg/m^3)	5.93	4.65	3.71	3.21	2.62	1.70	2.93	1.98
	slump flow (mm)	720	700	705	715	650	580	730	715
	V-funnel time (secs)	8.1	8.1	6.1	6.3	5.8	5.7	7.2	9.1
	Step height of J-ring (mm)	11	16	15	20	30	30	23	22
	J-ring spread (mm)	665	620	610	550	405	445	485	500
	Segregation index (%)	11	13	13	13	5	6	5	7
	slump flow 1h (mm)	505	495	495	435	350	395	395	370
	V-funnel time 1h (secs)	11.1	9.6	8.4	9.8	9.8	7.3	11.8	15.8

The adjusted mix proportions and the fresh properties of the mortars and resulting concretes are given in Table 7-6.

Satisfactory concrete properties were achieved with mortars in the target range for the F_0, F_{20} and F_{40} and F_{60} mixes, but the 80% and 100% replacement ratios required increased superplasticiser content.

These results reflect the interactions between particles in the mortar and coarse aggregate through three aspects, filling ability, passing ability and segregation resistance discussed as follows.

7.2.1 Filling ability

Due to its spherical shape, fly ash can disperse agglomeration of cement particles (Nehdi et al., 2004). When cement is replaced by fly ash, a lower dosage of superplasticiser and an increased quantity of water is therefore required to maintain the same filling ability which confirmed the deduction in Figure 7-4 and is in line with other research (Bouzoubaa and Lachemi, 2001).

Slump flow is more related to superplasticiser dosage than to fly ash content or W/P ratio. For example, fly ash content of SCC $F_{80}(2)$ and F_{80} are the same; compared with $F_{80}(2)$, higher W/P ratio and lower superplasticiser dosage of F_{80} are used in F_{80}; the resulting slump flow of F_{80} is lower than that of $F_{80}(2)$. Another example is F_{100} and $F_{100}(2)$.

V-funnel time decreases a little bit with an increase in fly ash content of the concretes. The two concretes, F_{80} and F_{100} were more viscous than other mixes produced from the same mortars. This may be due to the high volume of fly ash used leading to higher viscosity.

7.2.2 Passing ability

Passing ability is dependent on coarse aggregate content and viscosity. The step height of the J-ring test, which gives an indication of the passing ability increased from 11 mm (F_0) to 22 mm ($F_{100}(2)$) for SCC with cement only and with fly ash only respectively as shown in Table 7-6. The difference of 11 mm is higher than the typical within-test variation of 8 mm reported by Bartos (2005). If the difference does not come from variation of the test method itself, it should result from the difference between two mixes.

F_{100}(2) has a higher W/P ratio and a lower superplasticiser dosage than F_0. Mortar tests showed that viscosity increases with the increase in the fly ash content. All the combined influences of an increase in fly ash content and W/P ratio and a decrease in superplasticiser dosage lead to the increased viscosity and hence the increase in step height as the coarse aggregate content is constant.

7.2.3 Segregation resistance

There is an improvement in segregation resistance for the SCC mixes incorporating 80% and 100% fly ash shown in Table 7-6. The segregation index of these mixes is only 5~7% which is low. This is in line with the results from Bouzoubaa and Lachemi (2001) that for SCCs with fly ash, segregation index decreased with an increase in fly ash which accompanied an increase in the superplasticiser content and a decrease in the W/P ratio. The other study showed that segregation resistance was related to the passing ability and viscosity of SCC (Lachemi et al., 2007). As stated above, these mixes have higher viscosity than those incorporating up to 60% fly ash. This can result in lower segregation.

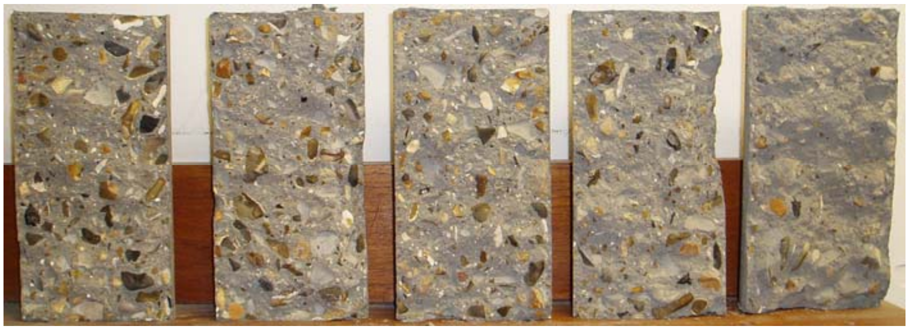


Figure 7-5 Cross section of SCC incorporating 0, 20%, 40%, 60% and 80% fly ash 2 by vol. (from left) at 28 days

The homogeneity of the target mixes can also be checked from the cross sections of cylinders at 28 days after splitting tensile tests as shown in Figure 7-5.

There is no sedimentation and the coarse aggregate distributes evenly but there is increased visible porosity of concrete with fly ash compared with that of the control mix. Visible air voids were only observed at the interface between paste and aggregate on the sample with 80% fly ash replacement ratio; this is discussed further when considering the sorptivity results in 7.3.5.

7.2.4 Consistence retention

To assess the consistence retention, the slump flow and the V-funnel time were also measured at 65±5 minutes after addition of the water. As anticipated Table 7-6 shows that after about an hour, slump flow decreases and V-funnel time increases, which means that the filling ability decreases with time.

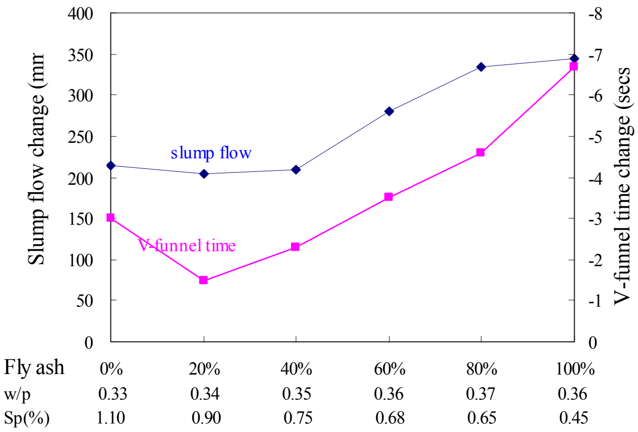


Figure 7-6 Consistence retention of target SCC

Consistence of concrete decreasing with time could be the result of the hydration of cement (Shi et al., 2005) or the inclusion of fly ash in concrete (Dietz and Ma, 2000). Another reason could be because the performance of superplasticiser lapses with time.

The changes in the slump flow and V-funnel time of the target mixes are plotted in Figure 7-6. The magnitude of the decrease in slump flow and the increase in V-funnel time of mixes with up to 40% fly ash F_0, F_{20} and F_{40} is much lower than those mixes with 60~100% fly ash. These changes reflect the combined effects of increased fly ash content and W/P ratio and decreased superplasticiser dosage. These results are similar to those from another study (Dietz and Ma, 2000).

7.2.5 Relation between fly ash and superplasticiser contents

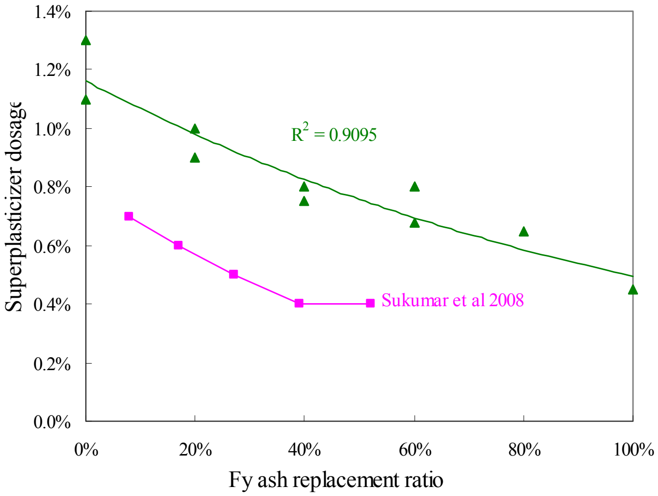


Figure 7-7 Correlation between fly ash vol. ratio and superplasticiser dosage

For the target SCCs (refer to Table 7-4 and Table 7-6), the required superplasticiser dosage and the fly ash content are related as shown in Figure 7-7. The reason could be that fly ash acts as a lubricant material; it does not react with superplasticisers and produce a repulsive force (Wattanalamlerd and Ouchi, 2005) and the superplasticiser may only act on the cement. As a result, the larger amount of fly ash contained, the less superplasticiser needed.

Sukumar et al. also reported a relationship between superplasticiser dosage and fly ash content existed in SCC mixes; higher than 52% fly ash incorporation however did not change the superplasticiser required.

7.3 Hardened properties of self-compacting concrete with fly ash 2

The hardened property results including compressive strength, splitting tensile strength, UPV, Ed and water absorption of the target SCC's are demonstrated in Table 7-7. All the values are the average of three measurements. Complete data are shown in Appendix 9.

Table 7-7 Hardened properties of target SCC with fly ash

MIX NO.		F0	F20	F40	F60	F80(2)
Compressive strength (MPa)	7d	63.4	53.1	43.3	24.5	8.4
	28d	73.3	69.7	58.5	37.2	16.0
	90d	79.0	78.0	63.0	49.3	26.1
	180d	84.1	83.2	68.0	56.4	37.2
Splitting strength (MPa)	28d	5.5	5.5	4.2	3.3	1.8
	90d	5.9	6.0	5.6	4.2	2.3
UPV (km/sec)	7d	4.71	4.63	4.53	4.37	4.20
	28d	4.91	4.89	4.71	4.56	4.35
	90d	4.93	4.93	4.75	4.65	4.43
	180d	4.97	4.94	4.86	4.72	4.55
Dynamic modulus (GPa)	7d	47	45	41	36	26
	28d	48	47	44	39	31
	60d	49	49	46	41	33
	90d	49	49	46	42	34
	120d	50	50	47	43	35
	150d	50	50	47	43	35
	180d	50	50	47	43	37
Sorptivity ($kg/m^2h^{0.5}$)	7d	0.51	0.44	0.35	0.83	1.17
	90d	0.24	0.26	0.18	0.37	0.63

7.3.1 The influence of fly ash

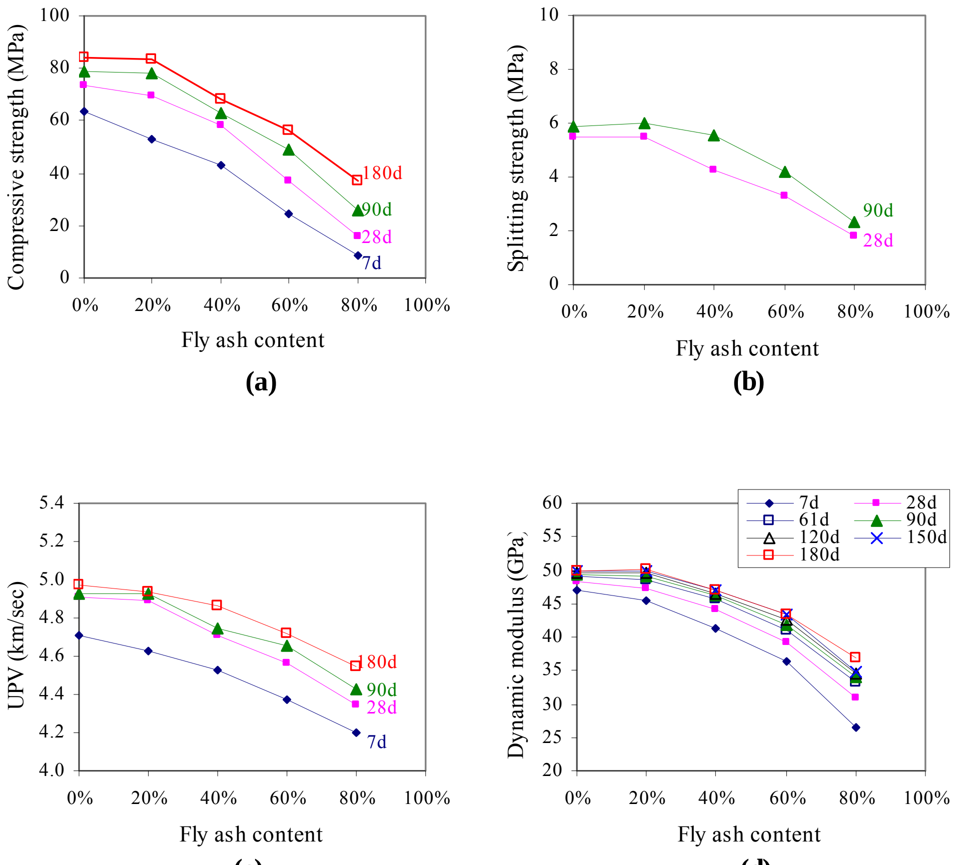
As anticipated, the hardened properties were influenced by W/P ratio and fly ash content.

It is clearly shown in Figure 7-8 that the compressive strength, splitting tensile strength, UPV and Ed of the SCCs with the same fresh properties all decreased with an increase in the fly ash content. For example, at 28 days, the compressive strength decreased from 69.7 MPa (F_0) to 16.0 MPa (F_{80}(2)), a reduction of 77%, whereas the tensile strength decreased from 5.5 to 1.8 MPa, a reduction of 67%.

Due to its inherent slow hydration rate the higher replacement level of fly ash, the higher reduction in the hardened properties. As shown in Table 7-7, these trends also include the influence of the increase in the W/P ratios (not plotted).

There is little difference in the compressive strength, splitting strength, UPV and Ed between the control (F_0) and 20% replacement (F_{20}) mixes, which shows that the use of 20% fly ash did not significantly change the hardened properties. However, there is a significant decrease in strength at all ages when the cement replacement ratio is more than 40%.

The influence of fly ash on strength was more significant at higher contents. The value of SCC with 80% fly ash was only one quarter of that with 20%.



(a) (b)

(c) (d)

Figure 7-8 Hardened properties (a) compressive strength, (b) splitting strength, (c) UPV and (d) dynamic modulus of target SCCs with fly ash

This is attributed to the slower pozzolanic reaction of the fly ash with the $Ca(OH)_2$ of the hydrated cement. Thus the higher the replacement level of fly ash in concrete, the higher the reduction in the hardened properties since not enough cement hydration products react with fly ash (refer to 2.6.2.1). The higher W/P ratios by weight also contribute to the reduction. These results are found to be in line with published data (Atis, 2002).

The level of fly ash affects the interfacial properties. In a study on the bond strength, Wong et al (1999) found that a 15% fly ash replacement increased the interfacial bond strength whereas 45~55% reduced it. The reduction however recovered at 90 days. The reason was given by the pozzolanic action which reduces the thickness and porosity of the interfacial zone after curing thus contributing to strength. Therefore a much lower bond strength is anticipated for cement replacement ratio of 60~80%. Inferior interfacial properties of high volume fly ash mixes also contribute to higher strength reduction.

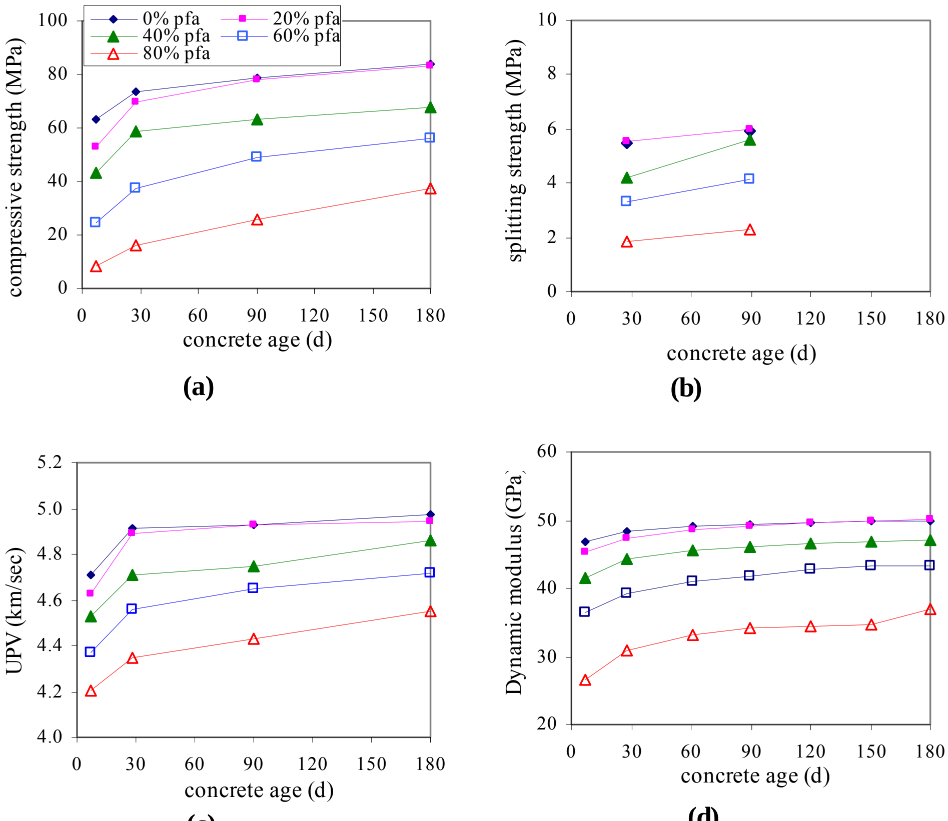
HVFA SCC with 80% fly ash has the lowest values of all hardened properties. It however gained enough strength to be demoulded after placed at room temperature for 24 hours after mixing. Although its compressive strength is only 13% of the control SCC at 7 days, significantly lagging the control, it gained strength at later ages, achieving 22% and 33% of the control mix at 28 days and 90 days respectively. This SCC can be used in non-structural applications, where early strength is not required and ultimate strengths are in the range of 25 to 35 MPa, such as mass concrete.

Table 7-8 Comparison between HVFA concrete and HVFA SCC

	HVFA CONCRETE (MARSH, 2003)	HVFA SCC (MIX F60(2))
Fly ash	55~60%	60% by vol. (52% by wt.)
Powder (kg/m^3)	370~380	472
Water/powder ratio	0.33	0.36
Sand/mortar ratio by vol.	52~53%	45%
28-day compressive strength (MPa)	37.5	37.2

Table 7-8 shows a typical mix proportion for a medium strength HVFA concrete and a HVFA SCC. For similar 28 day compressive strength, HVFA SCC has a higher W/P ratio, a higher powder content and a lower sand/mortar volume ratio in order to achieve its required fresh properties.

7.3.2 Development of hardened properties with time



(a) **(b)**

(c) **(d)**

Figure 7-9 Development of the hardened properties with time

The developments of compressive strength, splitting tensile strength, UPV and Ed of the target SCC mixes with time are shown in Figure 7-9. The gradual improvement with time is apparent: the steep rise from 7 to 28 days; after 28 days, the improvement is marginal for low fly ash content mixes (up to 40%) but significant for strength of the 60% and 80% fly ash mixes. This may indicate that the cement hydration is almost complete during the initial 28 days curing period. This is in agreement with Dehn et al (2000) and Holschemacher and Klug (2002).

It is seen that the difference in the compressive strength between the mixes with and without fly ash becomes less as the age increases. For example, compressive strength at 7 days was reduced from 63.4 MPa (0% fly ash) to 8.4 MPa (80%), a reduction of 86%; at 90 days, the reduction decreased to 68%. The mix containing 20% fly ash attained comparable compressive and splitting strength to the corresponding control SCC at 90 days and beyond.

7.3.3 Cementing efficiency factor

The influence of fly ash on strength can be expressed as the cementing efficiency factor (k) (refer to 2.1.3.3). This was calculated as follows:

Compressive strength vs water to cement ratio for SCC with neat cement

The compressive strength vs W/C ratio relationships for SCC with neat cement at different ages was obtained by shifting typical relationships for NVC (obtained from Illston and Domone (2001)) to pass through the measured compressive strength of neat cement SCC.

Equivalent water to cement ratio

From these, the W/C ratio corresponding to the measured strength of the SCC in which cement was replaced by fly ash (referred as the equivalent W/C ratio) was then obtained.

Equivalent amount of cement

The equivalent amount of cement was calculated by dividing the actual amount of water used by the equivalent W/C ratio.

Cementing efficiency factor

The difference between the equivalent and actual amount of cement divided by the actual amount of fly ash is k .

The values of k for each fly ash replacement level and test age are shown in Table 7-9[1] and Figure 7-10.

Table 7-9 Cementing efficiency factor

fly ash by vol.	W/P	$(w/c)_{equivalent}$			Cement efficiency (k)		
		7d	28d	90d	7d	28d	90d
0%	0.33						
20%	0.34	0.39	0.35	0.33	0.18	0.86	1.16
40%	0.35	0.45	0.42	0.43	0.34[2]	0.46	0.49
60%	0.36	0.63	0.58	0.52	0.18	0.28	0.43
80%	0.37	0.98	0.91	0.80	0.16	0.20	0.28

The value of k is very sensitive to the accuracy of the compressive strength value, e.g. a decrease from 43.3 to 39 MPa (10% change) leads to a change of k from 0.34 to 0.18, that is 47%.

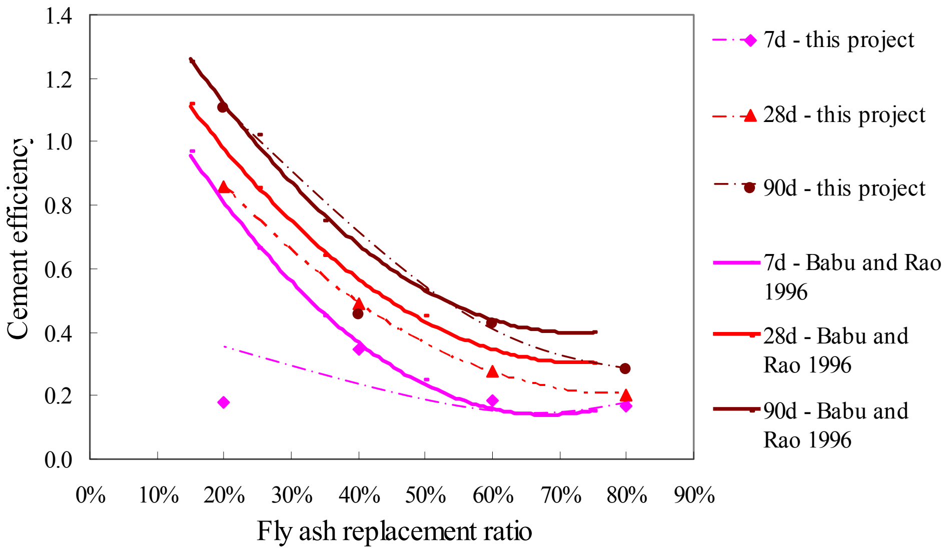


Figure 7-10 The relation between cement efficiency and fly ash replacement ratio

Figure 7-10 clearly shows that the curing time and the replacement level influence cement efficiency factor. k is low, 0.16~0.18, at 7 days but shows increases at 28 days and again at 90 days. The increasing trend as the curing

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[1] The 180 day values are not included because there is not a relationship for NVC available.
[2] This value looks odd in accordance with the regularity displayed.

time increases, which results from the slower pozzolanic reaction of fly ash at early age. Thus curing is an important factor for concrete with a high volume of fly ash. k decreases with an increase in fly ash replacement ratio at all ages.

Figure 7-10 also shows that the k values are in line with that of NVC (Babu and Rao, 1996). Babu and Rao's results are for fly ash replacement ratio of 15~75% and without superplasticiser. This shows the material properties of SCC are similar to those of NVC. The k values are a little lower than the value 0.56 for SCC with 20~60% fly ash (Domone, 2007).

The relationship between the W/C ratio and the compressive strength is well known for concrete. There is also a good correlation between compressive strength and equivalent water to cement ratio for SCC with additions as shown in Figure 7-11. A lower equivalent water to cement ratio leads to an increase in the compressive strength. In this way, the strength of those mixes with higher fly ash content can be predicted. In addition, most data are within the range for SCC (Domone, 2007).

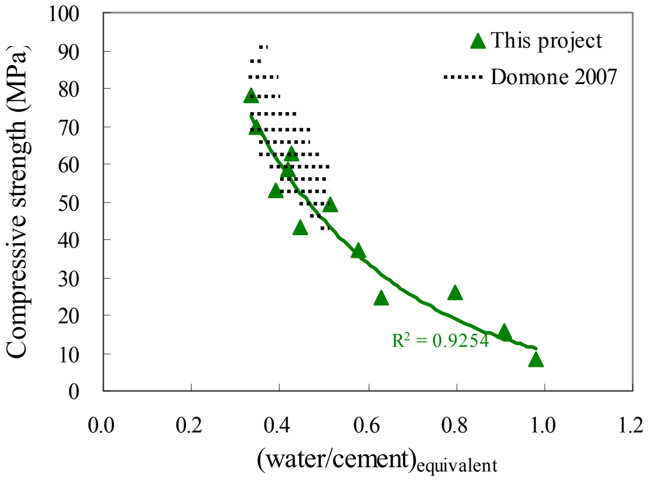

Figure 7-11 The relationship between compressive strength and equivalent water to cement ratio

7.3.4 Correlations among hardened properties

From Figure 7-12, Figure 7-13 and Figure 7-14, good correlations were obtained between compressive strength and splitting strength, UPV and Ed respectively for the results taken as a whole (shown in Table 7-7). All are not dependent on fly ash content.

The best fit equations are:

$f_{cu} = 8.3\ f_s^{1.26}$

$f_{cu} = 0.003\ e^{2.5\ UPV}$

$f_{cu} = 0.0002\ Ed^{\ 3.4}$

where f_{cu}, f_t, UPV and Ed are compressive strength, UPV and dynamic modulus respectively. The correlation coefficient (R^2) is 0.98, 0.98 and 0.97 respectively.

Some other investigations that have measured these properties for SCC with fly ash (Dehn et al., 2000; Holschemacher and Klug, 2002; Khatib, 2008; Leemann and Hoffmann, 2005; Sukumar et al., 2008) are compared as follows. Results from these and the relations given in the CEB-FIB Model Code 90 for NVC are also shown in Figure 7-12 and Figure 7-14. The relation between compressive strength and UPV is compared with test results of NVC in UCL (Illston and Domone, 2001) as shown in Figure 7-13.

Figure 7-12 shows that most splitting tensile strength values of SCC are in the range of CEB-FIB Model Code 90 for NVC with the same compressive strength.

There are some higher splitting tensile strengths reported (Holschemacher and Klug, 2002). The reason for this was given as the better microstructure (smaller total porosity and more even pore size distribution) and denser paste matrix due to the addition of powder.

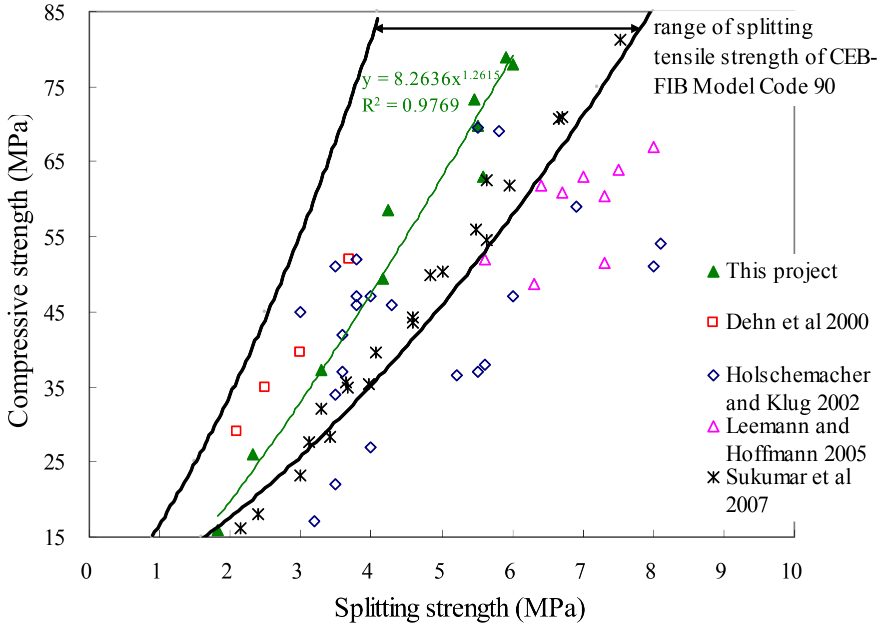

Figure 7-12 The compressive strength vs splitting strength of SCC with fly ash and in comparison to CEB-FIB Model Code 90

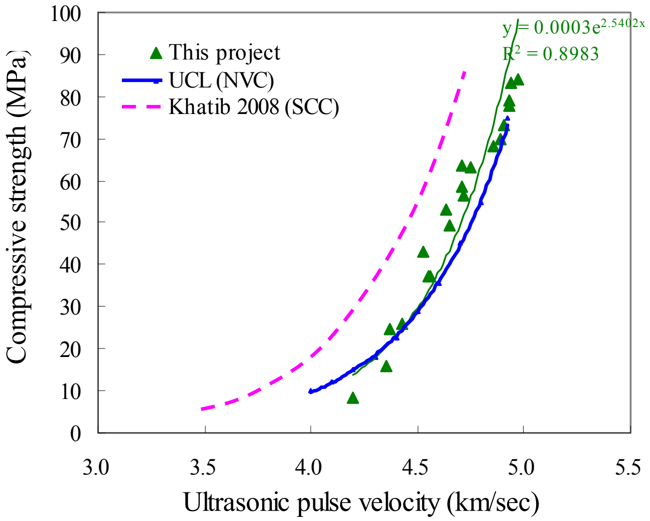

Figure 7-13 The UPV vs compressive strength for SCC and in comparison to NVC

The UPV value is related to the density and elastic modulus of constituent materials and can be used to assess strength of concrete for a given aggregate and a given moisture condition (Neville, 1996). Figure 7-13 shows that most

UPV values of SCC are similar to those of NVC from UCL (Illston and Domone, 2001).

Khatib (2008) also reported a close relationship between UPV and compressive strength. For the same strength, his UPV values are lower than those from the project and other results from UCL. The reason may be due to different materials, test methods and instruments used.

Although SCC has a lower coarse aggregate content and a higher paste volume than NVC, Figure 7-14 shows that most elastic modulus values of SCC are still in the range of CEB-FIB Model Code 90 for NVC with the same compressive strength but at the upper end. This maybe because of the different methods of determination in dynamic and static elastic modulus tests, dynamic elastic modulus is higher than elastic values (refer to 2.1.3.4).

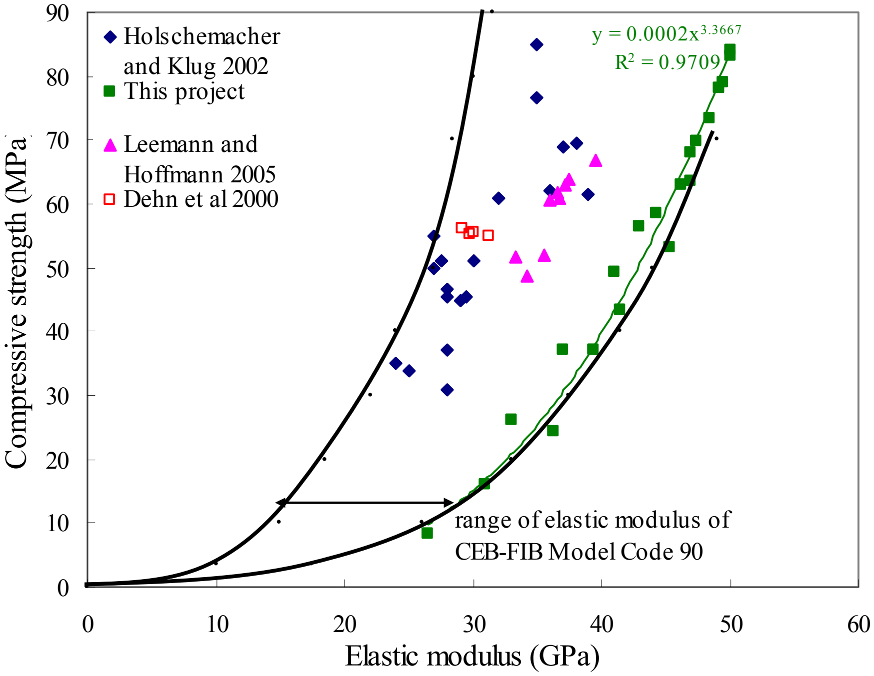

Figure 7-14 The compressive strength vs elastic modulus for SCC with fly ash and in comparison to CEB-FIB Model Code 90

7.3.5 Water absorption

7.3.5.1 Sorptivity

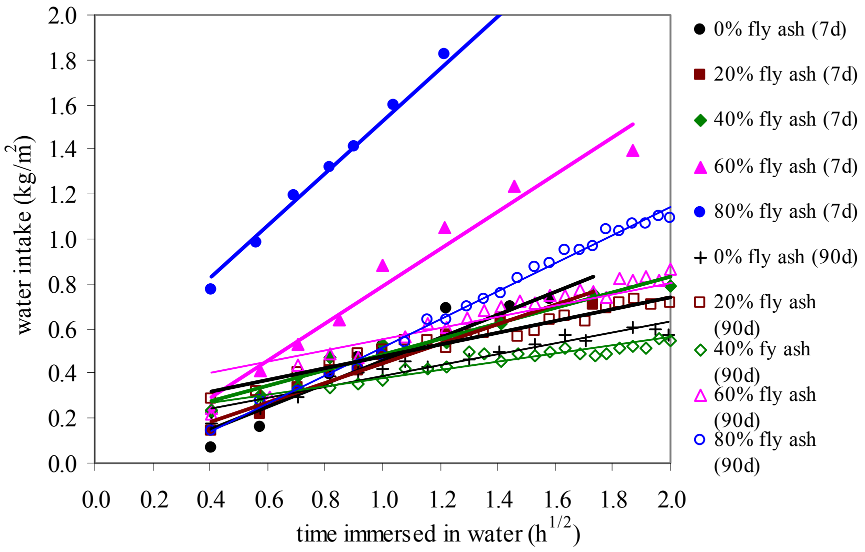

Figure 7-15 Short-term water intake of target mixes with fly ash

Table 7-10 Sorptivity of target mixes with fly ash

	FLY ASH VOL.	W/P WT.	SORPTION EQUATION	SORPTIVITY (KG/M^{2}H$^{0.5}$)	R^2
7 day water curing	0%	0.33	M/A=0.51t$^{0.5}$-0.05	0.51	0.90
	20%	0.34	M/A=0.44t$^{0.5}$+0.01	0.44	0.96
	40%	0.35	M/A=0.35t$^{0.5}$+0.13	0.35	0.96
	60%	0.36	M/A=0.83t$^{0.5}$ -0.04	0.83	0.97
	80%	0.37	M/A=1.17t$^{0.5}$+0.35	1.17	1.00
90 day water curing	0%	0.33	M/A=0.24t$^{0.5}$+0.14	0.24	0.93
	20%	0.34	M/A=0.26t$^{0.5}$+0.21	0.26	0.96
	40%	0.35	M/A=0.18t$^{0.5}$+0.19	0.18	0.91
	60%	0.36	M/A=0.37t$^{0.5}$+0.14	0.37	0.96
	80%	0.37	M/A=0.63t$^{0.5}$ -0.11	0.63	0.99

In water absorption tests the water intake per unit area over the first four hours immersed in water is shown in Figure 7-15[3]. Each plot is the average of the three samples tested from each mix (complete test results are shown in

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[3] The absorption data is offset from zero when t=0.

Appendix 10). Figure 7-15 shows that the water absorption is proportional to $t^{1/2}$ over four hours in accord with the well-established equation (refer to 4.4.5.2). The derived expressions are demonstrated in Table 7-10. The slope of the trend lines, referred as the rate of water absorbed into the concrete pores by capillary suction, is called sorptivity (refer to 2.1.3.7).

The relationship between sorptivity and fly ash content is plotted in Figure 7-16. Water/powder ratio is also included as it varied with the fly ash content. The sorptivity values of the mixes incorporating up to 40% fly ash slightly decrease with the fly ash content although W/P ratio increased from 0.33 (0% fly ash) to 0.35 (40% fly ash). The mix with 40% fly ash reached a minimum sorptivity. This could be because the fly ash is finer than the cement and it therefore fills the voids leading to lower porosity. The sorptivity of HVFA mixes (60% and 80%) increases significantly. This could because fly ash dilates the voids between cement particles, and the higher replacement ratio the voids between the fly ash particles leads to higher porosity.

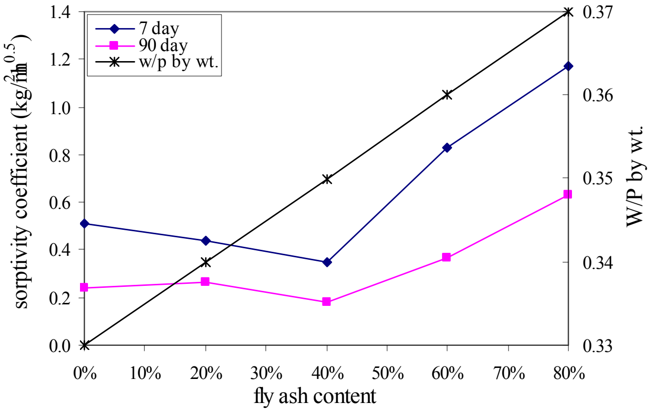

Figure 7-16 Influence of fly ash on the sorptivity coefficient

The sorptivity values decrease from 7 to 90 days. The sorptivity of the mixes with 60% and 80% fly ash are considerably higher at 7 days due to the low amounts of hydration products produced. Assie et al (2006) reported that absorption was inversely related to concrete pore size, the capillary suction increased as the pore radius decreases. As a result, the mix of 40% fly ash in SCC may have the smallest pore size. Clearly the longer the curing time, the finer the pore structure and the less interconnection between the capillary pores and in particular, the porous paste/aggregate interface zone formed at early ages is densified by continuous curing in water (Marsh, 2003). As more hydration products are produced at 90 days, the sorptivity of SCCs at 90 days is only about half of that at 7 days. This is similar to some results on NVC (Martys and Ferraris, 1997).

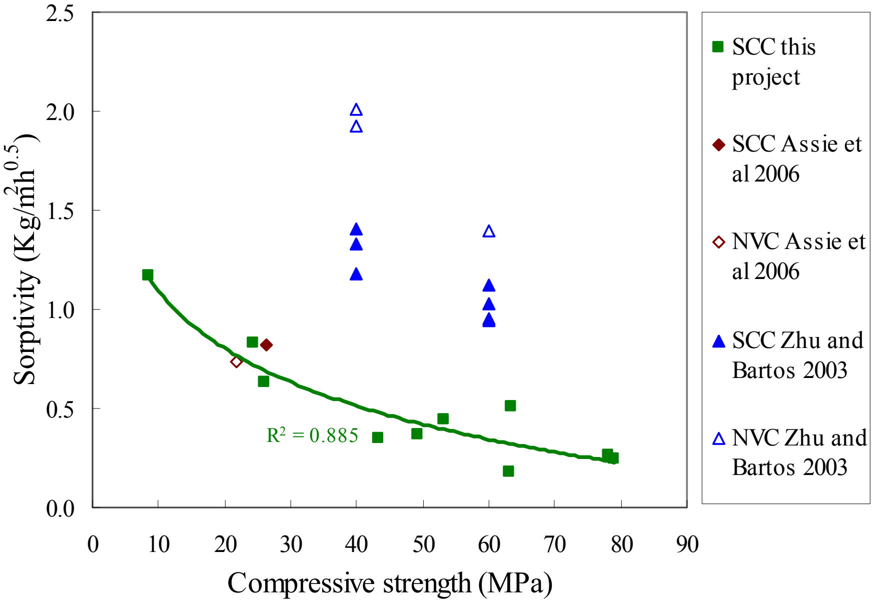

Figure 7-17 Sorptivity vs compressive strength for NVC and SCC with fly ash

As shown in Figure 7-17, there is a good correlation between compressive strength and sorptivity at the ages of 7 and 90 days in the present project. This is compared with other studies (Assie et al., 2006; Zhu and Bartos, 2003). The higher the compressive strength, the lower the sorptivity. Assie's data are similar to this project. For the same strength, the sorptivity from Zhu and Bartos are higher than other. This may be due to different curing, storage and testing conditions and calculating methods used.

It is generally accepted that sorptivity relates to durability thus is useful to predict the service life of concrete. For example, sorptivity can be an important factor to determine the concrete deterioration under the freezing/thawing cycling and wet/dry cycles (Martys and Ferraris, 1997) and carbonation (Assie et al., 2006). From the sorptivity results, use of 60~80% fly ash in SCC may incur lower durability than low usage.

7.3.5.2 Long-term water absorption

The cumulative water intake per unit over the full test time is plotted in Figure 7-18 and Figure 7-19. It shows that all SCC mixes follow a similar trend irrespective of fly ash replacement levels. Sorptivity (slope of the curves) decreased over longer time, which shows the capillary suction rate reduces, and the absorption tends to be stable after some time.

The absorption increases sharply up to a certain time, 10 hours, 2 days and 10 days for fly ash replacement up to 40%, 60% and 80% respectively. Then it increases at a slower rate. The absorption rate slows due to (Martys and Ferraris, 1997): the equilibrium of water with the air before full saturation, the capillary pores being refined with time because of hydration process and the gel pores dominating the ingress. The visual inspection of the cross sections of the crushed samples at the end of tests showed that the waterfront was far from the top, the depth being less than half of the specimens.

Sorption is the dominating process at early ages. At later ages, water ingress is controlled by sorption and diffusion together (Martys and Ferraris, 1997; Neithalath, 2006). Inclusion of fly ash leads to a higher water intake than the control mix and a longer time for the absorption to be stable. SCC containing 80% fly ash has the highest absorption in the test throughout. The water intake of the mix with the 80% fly ash was still increasing significantly at the end of the test. Fly ash therefore seems to improve the pore structure of concrete at lower replacement ratios but imparts increased porosity at higher contents- this may due to the similar fineness of the particles.

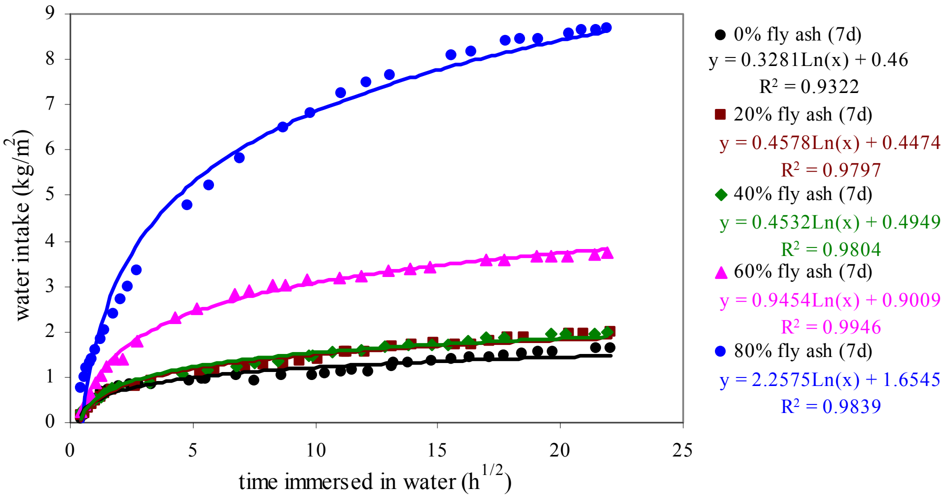

Figure 7-18 Water intake with time after 7 days curing in water of target mixes with fly ash

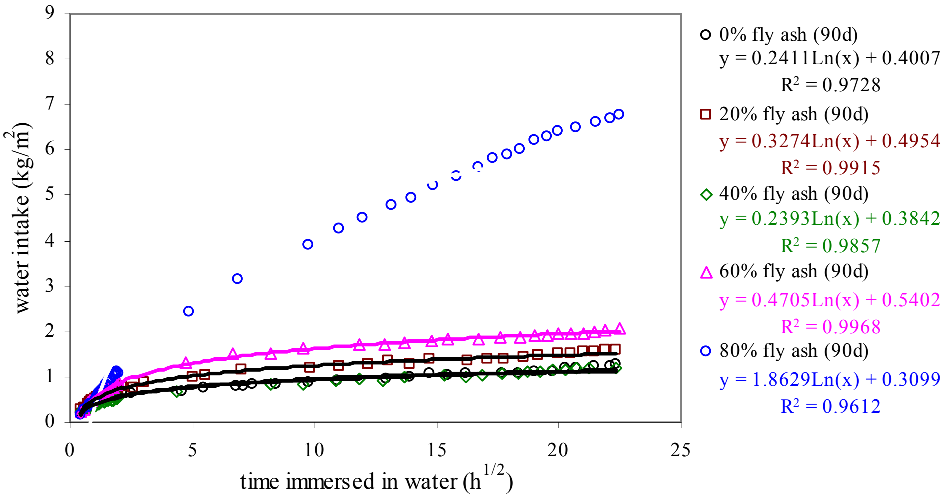

Figure 7-19 Water intake over time after 90 days curing in water of target mixes with fly ash

Curing time is the other important factor. After curing for 7 days there was negligible difference in the water intake between the mixes incorporating 20% and 40% fly ash and the control mix. After curing for 90 days, however, it was found that with the exception of SCC with 80% fly ash, the differences in the rate of absorption between SCC with and without fly ash is not significant. Thus the replacement ratio of up to 60% fly ash does not have much influence on absorption in the long run.

There have been exponential equations reported to model the long-term moisture movement in mortar or concrete by which the relative contributions between sorption and diffusion can be distinguished (refer to 4.4.5.2).

However, it can be seen from Figure 7-18 and Figure 7-19 that the absorption data over about 21 days are consistent with a $t^{1/2}$ behaviour of a logarithmic regression with a high degree of accuracy expressed as follows.

$$\frac{M}{A} = SLn(t^{\frac{1}{2}}) + \overline{S}$$

where M is the water intake through a surface of area A, t is the time from the start of the water absorption test, and $\overline{S}$ is a correction term. S is defined as the total absorption coefficient, which relates to the total moisture movement in the long term contributed by sorption and diffusion.

7.4 Conclusions

The fresh and hardened properties of SCCs with different levels of fly ash have been investigated.

1. Tests on the mortar fractions of the SCC with replacement of the cement by fly ash by volume showed that:

    - The V-funnel time increases with an increase in the fly ash content, with significant increase at high replacement ratio; the spread achieves a maximum value at 40% replacement (for fly ash 1) and 40~60% (for fly ash 2). The magnitude of changes in spread and V-funnel time of fly ash 1 are greater than those of fly ash 2. The maximum changes in spread and V-funnel time are 33 mm and 26.7 seconds for fly ash 1 and 13 mm and 7.0 seconds for fly ash 2. Both inclusions of fly ash led to increased bleeding.

- To keep spread and V-funnel time constant, replacement of cement with fly ash requires an increase in W/P ratio and a reduction in superplasticiser dosage. This was subsequently confirmed in SCC mixes with the constant fresh properties.

2. Tests on the fresh properties of SCC showed that satisfactory properties can be obtained with up to 80% fly ash.

   - To keep the filling ability constant, the combined effects of an increase in fly ash and W/P ratio and a reduction in superplasticizer dosage led to a reduction in passing ability and consistence retention but did not significantly affect segregation.

     However, the magnitude of these effects varied between the two batches of fly ash. Compared with the control mix, the mix with 60% fly ash 1 had a 6 mm greater J-ring step height, 4.5 and 5.4 times higher the change of slump flow and V-funnel time respectively and an increase in the segregation index of 3 mm; the mix with 60% fly ash 2 had a 9 mm greater J-ring step height, 1.3 and 1.2 times higher change of slump flow and V-funnel time respectively and a decrease in segregation index of 4 mm. This reflects the difference in materials.

   - A good correlation exists between the required superplasticiser dosage and fly ash content for the target mixes.

3. Tests on the hardened properties of the target mixes showed that:

   - Replacing cement with 20% fly ash has no significant effects on hardened properties. Higher replacement levels led to a reduction in the compressive strength, splitting strength, UPV and Ed.

     Depending on the W/P ratio and the replacement ratio, the compressive strength varied from 16 to 73 MPa, the splitting strength from 1.8 to 5.5 MPa, the UPV from 4.35 to 4.91 km/second and Ed from 31 to 47 GPa at the age of 28 days. Although there is clearly a strength reduction in the high volume fly ash SCCs, potential use of this low-cost material for applications with low-strength requirements and cement savings is practical.

- The higher the replacement level of fly ash, the higher the reduction in strength, which is greater at early ages but decreases at later ages. The mix with 80% fly ash achieved 22% and 33% of the control mix at 28 and 90 days respectively.

- Compared with HVFA NVC with 55~60% fly ash, HVFA SCC has a higher W/P ratio, a higher powder content and a lower sand/mortar volume ratio but similar 28 day compressive strength.

- The cementing efficiency factor decreases as the cement replacement ratio increases, but increases with concrete age. This is in line with behaviour in NVC.

- Good correlations between compressive strength, splitting strength, UPV and Ed are obtained, and they are also in the range of equivalent correlations for NVC.

- The sorptivity of mixes with up to 40% fly ash are similar but increase significantly high in mixes with 60~80% fly ash. The sorptivity at 90 days is only half of that at 7 days. Curing has a positive effect on all mixes.

- The water absorption is proportional to $t^{1/2}$ over four hours, but the absorption over longer times (up to 21 days) showed a logarithmic relation. Further study is needed to confirm this.

Chapter 8 Self-compacting Concrete Incorporating Ground Glass

This chapter is concerned with the challenges of using ground glass in SCC without the need for VMAs. As outlined in Chapter 3 the ground glass was first used as a partial replacement for cement and then for both cement and fine aggregate due to its coarse size. In both cases a similar approach was used to that for fly ash replacement described in the previous chapter. A set of mortar mixes were first carried out to assess the effects on spread and V-funnel time which then led to a set of concrete mixes with similar target fresh properties (slump flow 700 ± 50 mm, V-funnel time 8.0 ± 3.0 seconds, step height in the J-ring less than 25 mm and sieve segregation less than 15%). These mixes were then tested for compressive strength, splitting tensile strength, ultrasonic pulse velocity (UPV), dynamic elastic modulus (Ed) and water absorption at ages from 7 to 180 days. ASR tests were performed on the mortar mixes. The limiting content for using of glass without segregation was determined.

As a result of the tests described in 5.4, the superplasticiser used throughout was Sika ViscoCrete 10. The materials and tests used have been described in Chapter 5 and Chapter 4 respectively.

8.1 Ground glass as a replacement for cement

Because of the potential convenience, the glass was first considered as a replacement material for cement.

Table 8-1 and Figure 8-1 shows the influence of increasing glass content on the spread and V-funnel time of mortars which had the control values of a constant W/P ratio of 0.32 and the dosage of superplasticiser of 1.45% by weight of powder leading to mix W0 in Table 8-2).

It can be seen from Figure 8-1 that the inclusion of glass leads to a decrease in the spread and an increase in the V-funnel time, and both significantly change as the glass content increases above 20% of powder weight. The glass particles are sharper and more angular which could result in less fluidity. In rheology terms, the inclusion of ground glass leads to an increase in both the yield stress and the plastic viscosity. This corresponds well to the effect of sand on the Bingham parameters (Ferraris et al., 2001) and indicates that large glass particles would have been better considered as fine aggregate.

Table 8-1 White glass as cement replacement materials in mortar test

White glass (powder vol.)	W/P by wt	Sp (powder wt.) by wt.	Spread (mm)	V-funnel (secs)	segregate, halo(mm)
0	0.32	1.45%	333	3.5	No
10	0.32	1.45%	330	3.7	Yes, 2
20	0.32	1.45%	325	4.1	Yes, 5
30	0.32	1.45%	309	8.0	Yes, 15

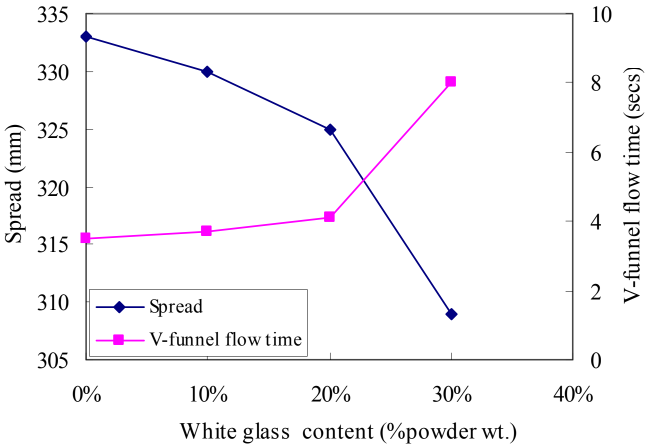

Figure 8-1 Influence of white glass on mortar

Table 8-1 also shows that replacement of cement by ground glass led to increasing segregation. The halo of bleeding water at the edge of the mortar in the spread test increased from 0 to 15 mm when the replacement ratio of glass increased from 0 to 30%. The glass was coarser than cement and the total surface area of all particles reduced after cement was replaced by glass. The water retained by particles was therefore less and more bleeding appeared.

The mortar mixes adjusted for constant spread (333 ± 2 mm) and V-funnel time (3.3 ± 0.2 seconds) are shown in Table 8-2. In order to achieve the similar spread and V-funnel times, the sand/mortar volume ratio had to be decreased. This also indicates that part of glass acts as fine aggregate.

The mortar mixes with 0% to 30% glass were then applied to concrete as shown Table 8-2.

Table 8-2 Concrete made from mortar of the similar fresh properties

		W0	W10	W20	W30
Mix ratio	W/P	0.32	0.325	0.33	0.33
	Sp wt.% by powder wt	1.40	1.35	1.40	1.40
	Sand/ mortar vol.	45%	45%	42%	40%
	White glass (%powder vol.)	0	10	20	30
Mortar	Water (kg/m^3)	276	275	289	295
	Cement (kg/m^3)	863	780	735	673
	White glass (kg/m^3)	0	66	140	220
	Fine aggregate (kg/m^3)	1190	1190	1111	1058
	Sp	12.1	11.4	12.3	12.5
	Spread (mm)	333	333	334	332
	V-funnel time (secs)	3.5	3.5	3.1	3.3
	Segregation, halo (mm)	No	Yes, 1	Yes, 5	Yes, 35
Concrete	Water (kg/m^3)	175	174	183	187
	Cement (kg/m^3)	548	495	466	427
	White glass (kg/m^3)	0	42	89	140
	Fine aggregate (kg/m^3)	743	743	693	660
	Coarse aggregate (kg/m^3)	924	924	924	924
	Sp (kg/m^3)	7.7	7.2	7.8	7.9
	Slump flow (mm)	710	750	755	790
	V-funnel time (secs)	7.7	8.7	8.2	
	Step height of J-ring (mm)	11	14	14	
	J-ring spread (mm)	585	630	655	
	Sieve segregation (%)	14	17	19	25
	Slump flow at 1h (mm)	615	615	645	
	V-funnel time at 1h (secs)	8.7	11.3	9.6	

Note: *1 W0 stands for no white glass replacement in the concrete.*
2 W10 means the white glass replaces 10% cement in the concrete.
3 W20 means the white glass replaces 20% cement in the concrete.
4 W30 means the white glass replaces 30% cement in the concrete.

After adding glass, the concrete mixes became unstable. A thin layer of water appeared on the surface of the mix after the mixer stopped thus it was too difficult to take a sample for test. The concrete mix W30 was the worst to handle. Aggregates rapidly sank in the slump flow test so severely that only the slump flow and the sieve stability tests could be performed. A halo of 75mm appeared in the slump flow test. This shows that the mixes containing glass are not homogeneous. This confirmed Paulou’s discussion (2003) that the use of glass filler in concrete has the problems of segregation.

The sieve segregations of mixes with 10% and 20% glass were 21% and 36% respectively higher than the control mix (W0). Although this is not much different from the control mix, the paste passed through the sieve was as thin as water during the testing. This indeed indicates segregation of the mix. The reason may be due to the low W/P ratio, 0.325 and 0.33 for mixes with 10% and 20% glass respectively, which are in the low range for SCC. It seems the sieve stability test cannot detect segregation of the mixes with low W/P ratio.

The maximum acceptable replacement ratio of glass in SCC was only 10% at a W/P ratio of 0.33 which is in the low range of SCCs.

The segregation could not be overcome by adjusting superplasticiser dosage, W/P ratio and sand/mortar volume ratio only. This led to adjusting the approach as follows.

8.2 Ground glass as a replacement for both cement and sand

The particle size distribution of the glass (refer to 5.2.2) is from 0 to 600 μm; and 62% white glass or 60% green glass is retained on the 120 μm sieve. The glass is therefore better considered as a substitute for both the sand and cement.

The size limit of powder in SCC has been defined variously in different countries (refer to 2.4.3). From these 120 μm was selected because it is similar to the powder size used in Europe. Therefore those particles less than 120μm were regarded as powder which replaced the cement while those larger than 120μm were regarded as sand which replaced the 0/4mm aggregate. In addition, the glass replacement ratio was expressed as the volume of concrete. The sand/mortar volume ratio was still kept constant at 45%, with the sand including both the 0/4mm fine aggregate and the particles larger than 120 μm in the glass.

The mix proportion was consequently adjusted. For example, according to the adjustment, the W/P ratio and superplasticiser dosage of W30 (refer to Table 8-2) was recalculated as 0.39 and 1.7% respectively. This high W/P ratio and high superplasticiser dosage may lead to the segregation. In addition, the sand/mortar volume ratio of W10, W20 and W30 became 46.3%, 45.2% and 45.3% respectively. This maybe the reason that the mixes of W20 and W30 have higher slump flow than W10 although these mixes have similar W/P ratios and superplasticiser dosages.

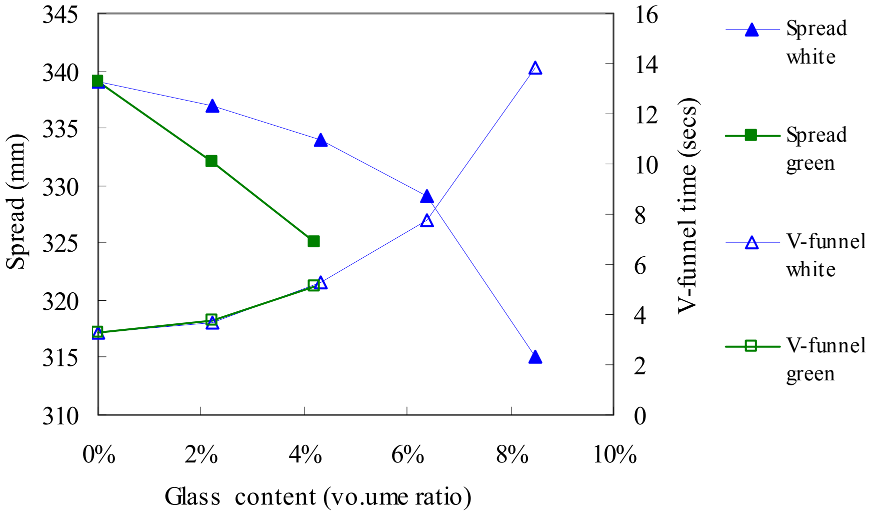

Figure 8-2 Influence of glass on mortar

Table 8-3 Influence of glass on mortar

GLASS TYPE	SAND/ MORTAR VOL.	GLASS VOL.	HALO (MM)	WATER/ POWDER	SP DOSE	SPREAD (MM)	V-FUNNEL TIME (SECS)
green	45%	0.0%	No	0.33	1.15%	339	3.3
	45%	2.2%	No	0.33	1.15%	332	3.7
	45%	4.2%	No	0.33	1.15%	325	5.1
white	45%	0.0%	No	0.33	1.15%	339	3.3
	45%	2.2%	No	0.33	1.15%	337	3.7
	45%	4.3%	No	0.33	1.15%	334	5.3
	45%	6.4%	No	0.33	1.15%	329	7.7
	45%	8.5%	No	0.33	1.15%	315	13.8

After these adjustments, the influence of increasing green glass content on the spread and V-funnel time of mortar was tested on the mixes which had a constant W/P ratio of 0.33 and the dosage of superplasticiser of 1.15% by weight of powder (mix G0 in Table 8-4). These parameters were then used to design mortar mixes with white glass in order to compare their influence. Results in Figure 8-2 and Table 8-3 show that both inclusions lead to a decrease in the spread and an increase in the V-funnel time due to the sharper and more angular particle shape than cement. In rheology terms, these mean an increase in both the yield stress and the plastic viscosity.

Table 8-4 Target SCCs with glass and their corresponding mortars

			W0	W2.2	W4.3	W6.4	G0	G2.2	G4.2
Mix ratio	W/P		0.345	0.354	0.37	0.383	0.33	0.335	0.35
	Sp wt.% by powder wt		1.00	0.88	0.80	0.83	1.15	1.10	1.10
Mortar	Water (kg/m^3)		286	288	293	296	280	281	285
	Cement (kg/m^3)		830	783	729	681	850	806	751
	Glass (kg/m^3)		0	83	164	243	0	80	158
	Fine aggregate (kg/m^3)		1190	1133	1078	1024	1190	1138	1086
	Sp (kg/m^3)		8.3	7.2	6.3	6.4	9.8	9.2	9.0
	Spread (mm)		337	338	337	335	339	338	335
	V-funnel time (secs)		3.3	3.4	3.3	3.5	3.3	3.2	3.4
SCC	Water (kg/m^3)		182	183	186	188	178	178	181
	Cement (kg/m^3)		527	497	463	432	539	511	477
	Glass	Vol.%	0	2.2	4.3	6.4	0	2.2	4.2
		(kg/m^3)	0	53	104	154	0	51	100
	Fine aggregate (kg/m^3)		755	719	684	650	755	722	689
	Coarse agg. (kg/m^3)		924	924	924	924	924	924	924
	Sp (kg/m^3)		5.27	4.55	4.02	4.07	6.20	5.85	5.69
	Slump flow (mm)		715	740	685	710	730	715	700
	V-funnel time (secs)		9.8	9.7	8.8	9.5	8.1	8.2	10.9
	Step height of J-ring (mm)		17	20	22	29	21	24	24
	J-ring spread (mm)		585	540	495	465	635	595	590
	Sieve segregation (%)		6	6	3	3	7	8	5
	Slump flow at 1h (mm)		450	375	340	340	495	465	485
	V-funnel time at 1h (secs)		16.4	31.3	block	block	11.9	11.1	13.8

Note: *1 W and G stands for white glass and green glass respectively.*
2 W2.2 means the white glass volume ratio of 2.2% in concrete, which replaces 5% cement and 5% sand.
3 W4.3 means the white glass volume ratio of 4.3% in concrete, which replaces 10% cement and 10% sand.
4 W6.4 means the white glass volume ratio of 6.4% in concrete, which replaces 15% cement and 14% sand.
5 G2.2 means the green glass volume ratio of 2.2% in concrete, which replaces 5% cement and 4% sand.
6 G4.2 means the green glass volume ratio of 4.2% in concrete, which replaces 10%

cement and 9% sand.

Green glass is slightly finer than white (refer to 5.2.2). This difference did not have much influence on the V-funnel time but led to very different spread values. Up to volume ratio of 4.2%, the decrease in the spread of green glass is higher than that of white glass. The reason is not clear.

By applying the mortars with a spread of 337 ± 2 mm and a V-funnel time of 3.3 ± 0.2 seconds to concrete, SCCs of similar fresh properties were produced. The results of the tests on these mortar and concrete mixes are demonstrated in Table 8-4. The hardened properties of the target SCCs are given in Table 8-5.

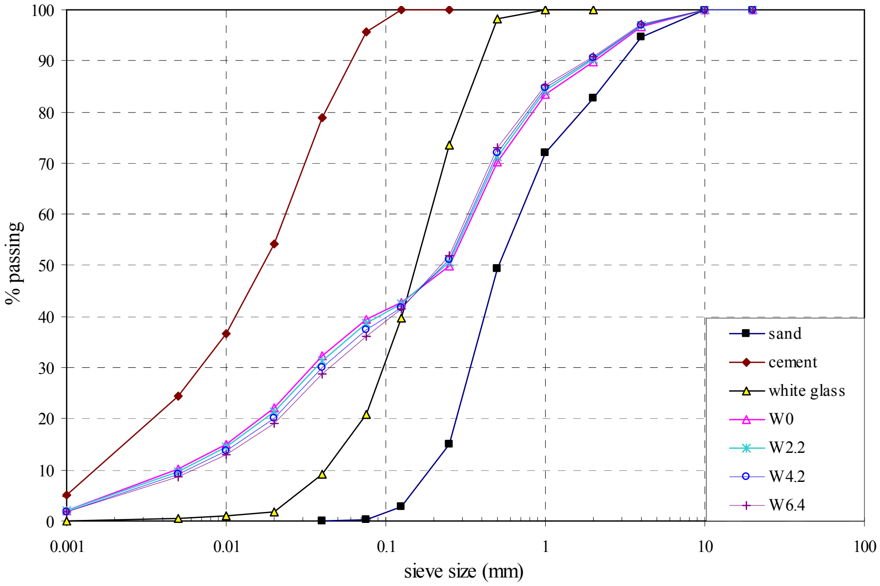

Figure 8-3 Overall particle size distributions of mortar mixes with white glass

The overall particle size distributions of the mortar mixes (in Table 8-4) which lead to target SCC with white glass are shown in Figure 8-3. They are all similar irrespective of glass content – the intended outcome.

8.2.1 Influence on fresh properties

Table 8-4 shows that the mortar mixes with similar spread and V-funnel time produced concrete with similar slump flow and V-funnel time. With an increase in glass content, the concrete mixes required a relatively small increase in W/P ratio and decrease in superplasticiser dosage.

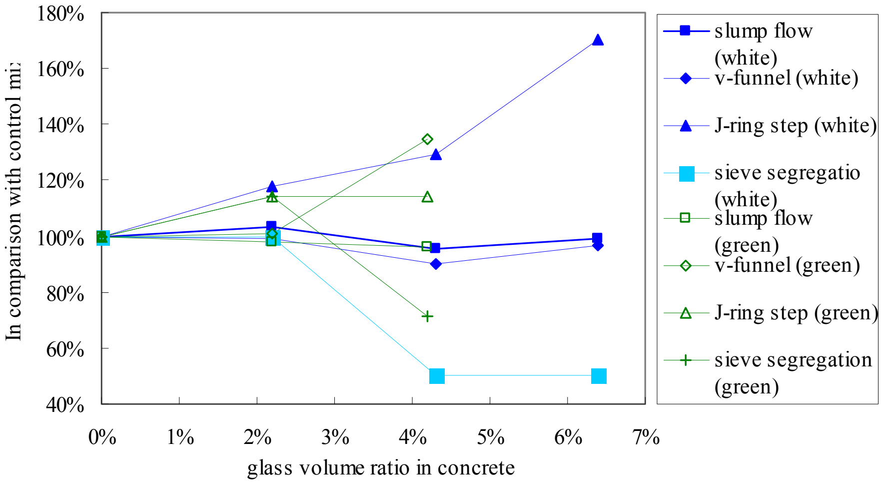

Figure 8-4 Comparisons between fresh properties of SCC with glass and control mix

Figure 8-4 shows the comparison between mixes with and without glass having similar filling ability. As an increase in the glass content, the step heights in the J-ring of the mixes with glass increase and sieve segregation decrease, which indicates higher risks of blocking and lower risks of segregation. White glass shows higher increase in the step height of J-ring and higher decrease in the sieve segregation. These differences result from different W/P ratio, superplasticiser dosage, particle characteristics. There is no clear evidence that the colour difference contributes to the differences.

8.2.2 Influence on hardened properties

Table 8-5 shows that the addition of glass as both cement and sand's substitute in SCCs led to the decrease in all hardened properties from early to late ages, with greater reductions for the higher replacement ratios (compressive strength, splitting strength, UPV, Ed shown in Figure 8-5, Figure 8-6, Figure 8-8 and Figure 8-10 respectively). Colour effects were not obvious. It seems glass performance in concrete is more related to its physical characteristics than the slight difference in chemical compositions (refer to Table 2-16).

Table 8-5 Hardened properties of target SCCs with ground glass

		W0	W2.2	W4.3	W6.4	G0	G2.2	G4.2
Compressive strength (MPa)	7d	63.0	62.0	59.5	57.6	62.6	56.0	51.2
	28d	70.5	68.2	65.2	62.1	74.9	68.3	58.5
	90d	75.0	69.3	66.5	64.4	79.1	77.7	60.9
	180d	79.3	76.5	71.7	71.1	85.1	81.3	69.7
Splitting strength (MPa)	28d	4.2	4.1	3.8	3.6	4.7	4.6	4.2
	90d	5.4	4.9	4.7	4.5	5.9	5.2	5.1
UPV (km/sec)	7d	4.82	4.82	4.80	4.78	4.88	4.85	4.84
	28d	4.90	4.89	4.88	4.87	4.89	4.93	4.92
	90d	4.96	4.97	4.91	4.90	4.98	4.95	4.93
	180d	5.00	4.99	4.96	4.93	4.99	4.99	4.97
Ed (GPa)	7d	47	45	43	43	47	46	45
	28d	49	46	45	45	48	48	47
	60d	49	47	46	46	49	49	48
	90d	50	48	46	46	49	49	48
	120d	50	48	46	46	49	49	48
	150d	50	48	47	46	50	49	49
	180d	50	48	47	46	50	50	49
Sorptivity	7d	0.21	0.24	0.26	0.27	0.19	0.25	0.26
	90d	0.11	0.14	0.17	0.18	0.11	0.16	0.21

8.2.2.1 Compressive strength and cementing efficiency factor

The 28-day compressive strength obtained varies from 51 to 81 MPa depending on the W/P ratio and the glass replacement ratio.

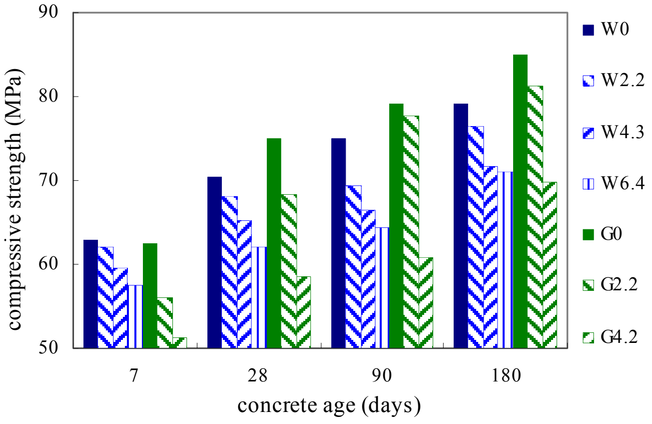

Figure 8-5 The compressive strength development of mixes with glass

Figure 8-5 shows the compressive strength development of target mixes. Using glass as cement and sand substitute leads to a decrease in strength at all ages. At all days, green glass mixes show higher decrease in the strength with an increase in the glass content than those incorporating white glass. This may be due to the lower W/P ratio used in mixes with green glass.

A similar approach (described in 7.3.3) was used to calculate the cementing efficiency factor. For this analysis only the particles less than 120 μm in the glass were considered as part of binder which contributes to strength. Those coarse particles were assumed to be inert.

Table 8-6 Cementing efficiency factor of target mixes with glass

Mix No.	Cement replacement ratio	W/B[1]	$(w/c)_{equivalent}$			Cement efficiency (k)		
			7d	28d	90d	7d	28d	90d
W0	0%	0.345						
W2.2	5%	0.354	0.352	0.352	0.380	1.13	1.11	-0.75
W4.3	10%	0.370	0.367	0.368	0.400	1.12	1.10	0.07
W6.4	15%	0.383	0.379	0.381	0.413	1.11	1.07	0.39
G0	0%	0.33						
G2.2	5%	0.335	0.367	0.344	0.341	-1.22	0.35	0.57
G4.2	10%	0.350	0.400	0.427	0.442	-0.61	-1.34	-1.69

As shown in Table 8-6 that the cementing efficiency factors for glass are not as consistent as those for fly ash (refer to Table 7-9). The negative values are meaningless. Those higher than 1 are interesting, which indicate that glass may be more active than cement or that coarse glass particles do contribute to strength. Some studies reported that the glass powder hydrates significantly after 7 days at room temperature, promoting concrete early strength development (Jawed and Skalny, 1978; Shao et al., 2000; Shi et al., 2005; Shi and Wu, 2005).

Apart from the assumption that only fine glass particles react, the typical relationships for NVC (obtained from Illston and Domone (2001)) may not be suitable for reference. For example, when the compressive strength of W2.2 increases from 63.0 to 65.7 MPa, the cementing efficiency factor changes from

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[1] W/B stands for water to binder ratio (refer to Glossary of Terms).

1.13 to -1.69. The cementing efficiency factors derived are sensitive to strength values.

8.2.2.2 Splitting strength

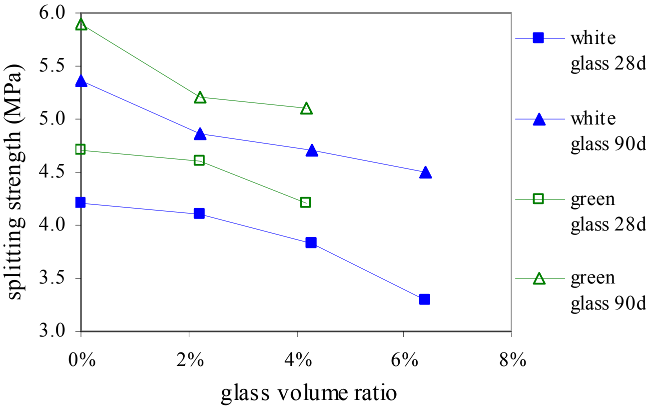

Figure 8-6 The splitting strength of target mixes with glass

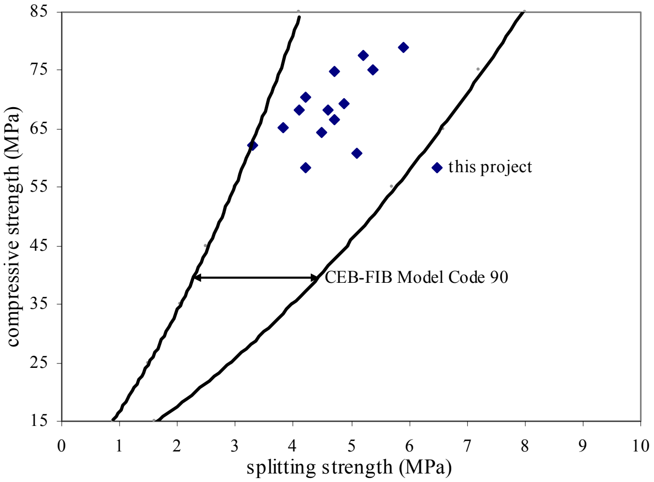

Figure 8-7 The compressive strength vs splitting strength of SCC with glass and in comparison to CEB-FIB Model Code 90

It is shown in Figure 8-6 that the use of glass led to a decrease in the splitting strength at the age of 28 and 90 days. Curing has an important effect: the increase in splitting strength due to curing leads to 36% and 21% increase for W6.4 and G4.2 respectively.

It is also seen from Figure 8-7 that the relationship between the compressive strength and the splitting strength in SCC with glass does not correlate well but all data are in the range of CEB-FIB Model Code for NVC.

8.2.2.3 Ultrasonic pulse velocity

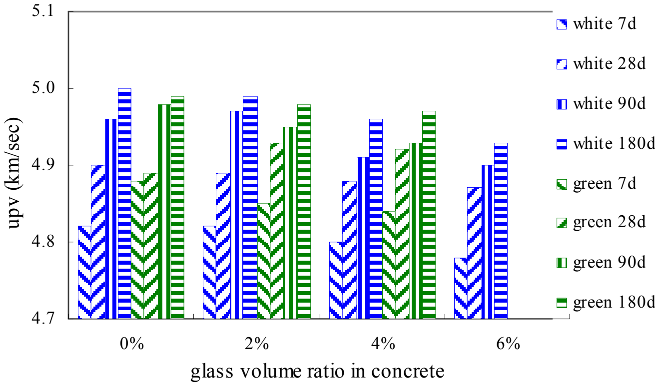

Figure 8-8 UPV of mixes with glass

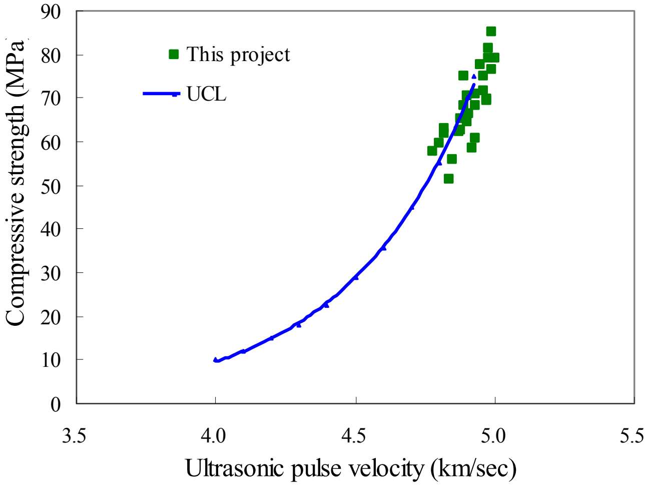

Figure 8-9 The UPV vs compressive strength for SCC with glass and in comparison to NVC

Figure 8-8 shows the influence of inclusion of glass on the UPV that an increase in the glass content leads to a decrease in UPV irrespective of its colour.

Figure 8-9 shows that the UPV values of SCC with glass are similar to those of NVC from UCL (Illston and Domone, 2001). This shows the material properties of SCC are similar to those of NVC.

8.2.2.4 Dynamic elastic modulus

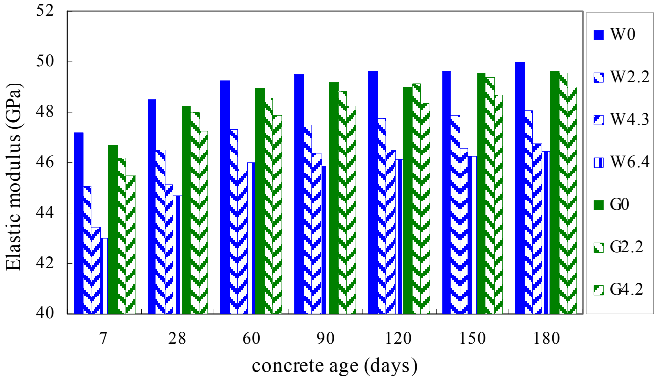

Figure 8-10 Elastic modulus of target SCC

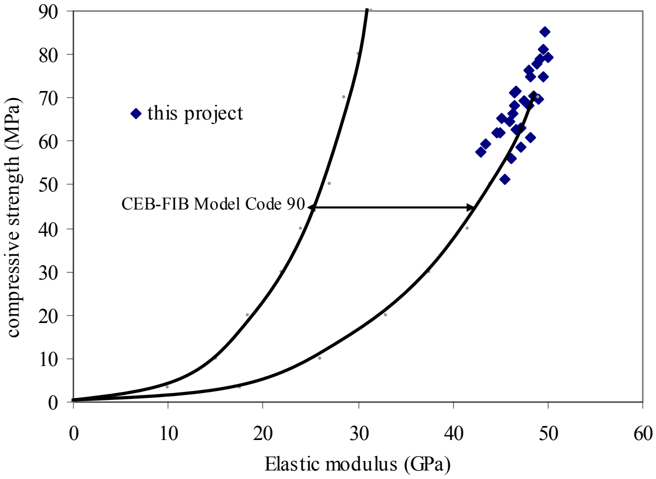

Figure 8-11 The compressive strength vs elastic modulus for SCC with glass and in comparison to CEB-FIB Model Code 90

The dynamic elastic modulus for target mixes varies between 43 and 50 GPa depending on the W/P ratio, glass types and glass content. As shown in Figure 8-10 that the addition of 53~154 kg/m^3 white glass affected the elastic modulus more significantly than that of 51~100 kg/m^3 green glass.

As shown in Figure 8-11 relationship between Ed and compression strength for SCC with glass is still in the range of CEB-FIB Model Code of NVC but at the upper end. As mentioned in 7.3.4, this maybe because of the different methods of determination in dynamic and static elastic modulus tests.

The test results of glass mixes are not as consistent as those of SCC with fly ash because the relationships of SCC with glass (between compressive strength and splitting strength, UPV and elastic modulus shown in Figure 8-7, Figure 8-9 and Figure 8-11 respectively) have been approached as lower correlation coefficients (R^2 below 0.7) than those of SCC with fly ash. This may be because the range of particle size of glass is wider than that of fly ash, thus mixing homogeneously is more difficult.

8.2.2.5 Water absorption

The water intake per unit area over the first four hours immersed in water is shown in Figure 8-12[2].

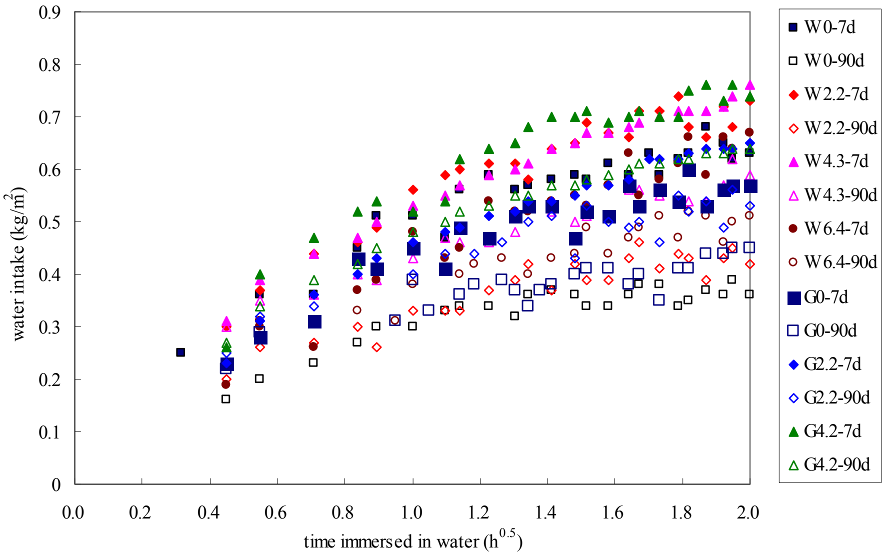

Figure 8-12 Short-term water absorption of SCC with ground glass

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[2] The absorption data is offset from zero when t=0.

The water absorption is proportional to $t^{1/2}$ over four hours. The derived expressions from the trend lines (not shown) are demonstrated in Table 8-7 (complete results are shown in Appendix 12).

Table 8-7 Sorptivity of SCC with ground glass

CURING	GLASS	GLASS VOL.	SORPTION EQUATION	SORPTIVITY ($KG/M^2H^{0.5}$)	R^2
7 day	white glass	0%	$S=0.21t^{0.5}+0.26$	0.21	0.86
		2.2%	$S=0.24t^{0.5}+0.28$	0.24	0.89
		4.3%	$S=0.26t^{0.5}+0.25$	0.26	0.97
		6.4%	$S=0.27t^{0.5}+0.14$	0.27	0.92
	green glass	0%	$S=0.19t^{0.5}+0.22$	0.19	0.85
		2.2%	$S=0.25t^{0.5}+0.19$	0.25	0.97
		4.2%	$S=0.26t^{0.5}+0.28$	0.26	0.89
90 day	white glass	0%	$S=0.11t^{0.5}+0.18$	0.11	0.78
		2.2%	$S=0.14t^{0.5}+0.18$	0.14	0.86
		4.3%	$S=0.17t^{0.5}+0.25$	0.17	0.94
		6.4%	$S=0.18t^{0.5}+0.17$	0.18	0.89
	green glass	0%	$S=0.11t^{0.5}+0.22$	0.11	0.77
		2.2%	$S=0.16t^{0.5}+0.24$	0.16	0.84
		4.2%	$S=0.21t^{0.5}+0.25$	0.21	0.95

Table 8-7 shows that the sorptivities of mixes with glass are all higher than those of control mix, which is due to the combined effects of the increase in the W/P ratio, the decrease in the superplasticiser dosage and the increase in the glass content. At each age, the sorptivity values are similar, which shows that the current glass content does not significantly increase the water absorption. Curing from 7 to 90 days leads to a decrease in the sorptivity as hydration products densify the concrete. From the sorptivity results, use of glass in SCC may not incur severe durability problems.

Figure 8-13 shows a good correlation between compressive strength (7 and 90 days) and sorptivity. As anticipated, the higher strength, the lower sorptivity.

The cumulative water intake per unit area over the full test time is plotted in Figure 8-14 (complete results shown in Appendix 12).

The absorption data over about 21 days are consistent with a $t^{1/2}$ behaviour of a logarithmic regression with a high degree of accuracy expressed shown in Table 8-8.

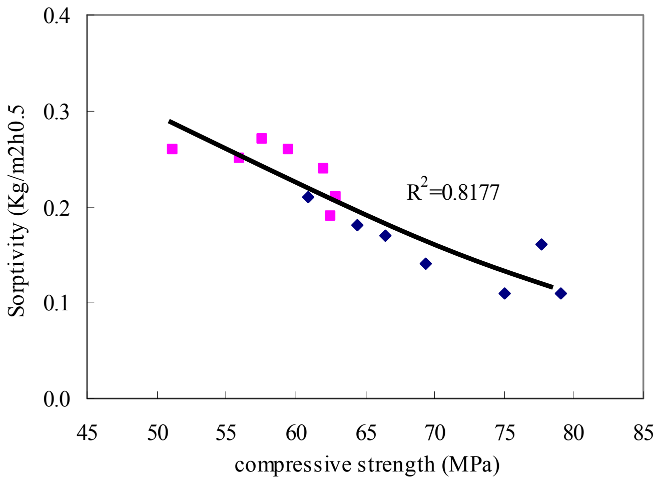


Figure 8-13 Sorptivity vs compressive strength for mixes with glass

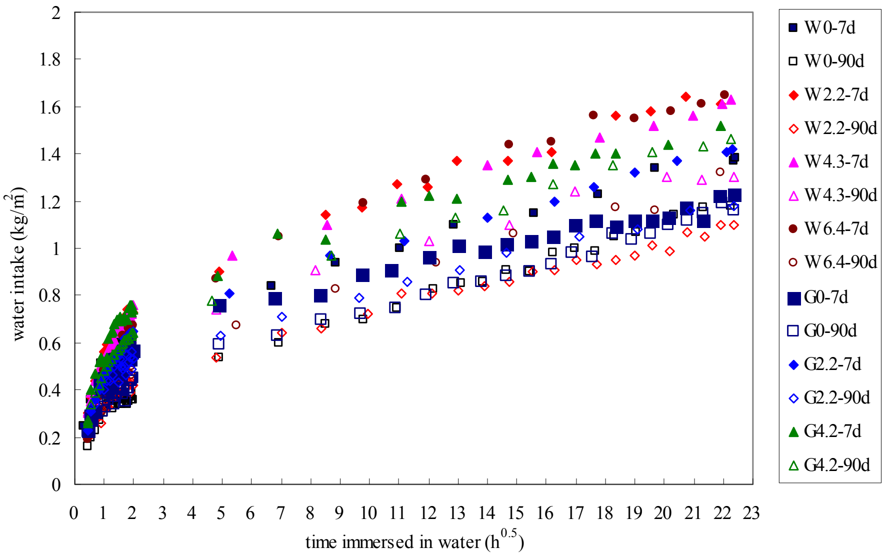


Figure 8-14 Long-term water absorption for mixes with glass

The water intake of SCC with fly ash over 21 days follows similar trends that absorption rate significantly reduces after 4 hours. Inclusion of glass leads to a higher water intake than the control mix. The difference is higher at 7 days but not significant at 90 days. The water absorption between mixes with 2.2% glass and control mixes is similar at 90 days. It seems that the glass content may not have much influence on absorption in the long run.

Table 8-8 Long-term absorption coefficient

	MIX NO.	SORPTION EQUATION	ABSORPTION COEFFICIENCY (KG/M^{2}H$^{0.5}$)	R^2
7-day curing	W0	M/A=0.25Ln ($t^{0.5}$)+0.49	0.25	0.97
	W2.2	M/A=0.33Ln ($t^{0.5}$)+0.52	0.33	0.98
	W4.3	M/A=0.32Ln ($t^{0.5}$)+0.53	0.32	0.99
	W6.4	M/A=0.37Ln ($t^{0.5}$)+0.42	0.37	0.99
	G0	M/A=0.23Ln ($t^{0.5}$)+0.42	0.23	0.98
	G2.2	M/A=0.28Ln ($t^{0.5}$)+0.45	0.28	0.98
	G4.2	M/A=0.28Ln ($t^{0.5}$)+0.56	0.28	0.98
90-day curing	W0	M/A=0.23Ln ($t^{0.5}$)+0.40	0.23	0.95
	W2.2	M/A=0.22Ln ($t^{0.5}$)+0.31	0.22	0.97
	W4.3	M/A=0.26Ln ($t^{0.5}$)+0.42	0.26	0.98
	W6.4	M/A=0.26Ln ($t^{0.5}$)+0.35	0.26	0.96
	G0	M/A=0.23Ln ($t^{0.5}$)+0.30	0.23	0.95
	G2.2	M/A=0.21Ln ($t^{0.5}$)+0.40	0.21	0.96
	G4.2	M/A=0.28Ln ($t^{0.5}$)+0.46	0.28	0.98

8.2.2.6 Alkali-silica reaction tests

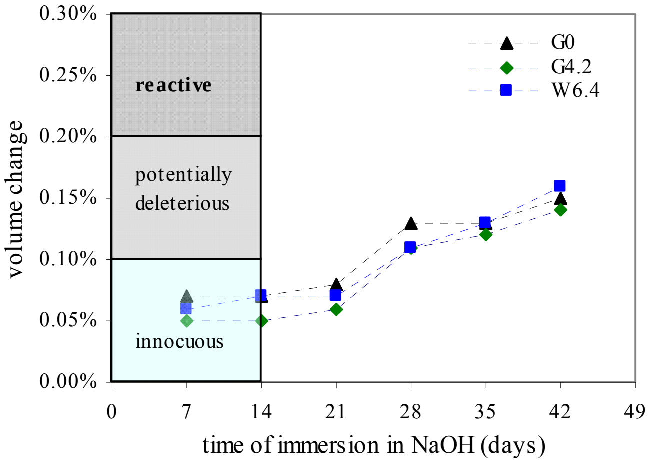


Figure 8-15 ASR test results of mortar with glass

Table 8-9 Volume change of mortar in ASR tests

	7d	14d	21d	28d	35d	42d
G0	0.07%	0.07%	0.08%	0.13%	0.13%	0.15%
W6.4	0.06%	0.07%	0.07%	0.11%	0.13%	0.16%
G4.2	0.05%	0.05%	0.06%	0.11%	0.12%	0.14%

As ASR expansion increases with an increase in glass content (refer to 2.7.3.2), the mixes with the maximum white and green glass volume ratio are chosen. ASR tests were performed on three mortar mixes, G0, W6.4 and G4.2 (mix proportions are shown in Table 8-4). Table 8-9 and Figure 8-15 show the volume changes of mortar in ASR test. No cracks were found on the surface of the bars during testing.

Figure 8-15 shows that glass did not induce more expansions than cement. At 14 days, the expansions of all mortar bars are well below the ‘innocuous’ requirement according to ASTM C 1260 (2003). Since W6.4 and G4.2 contain the maximum glass used, other target mixes (shown in Table 8-4) will induce less expansions in ASR tests.

There is an increase in expansion, which are however all less than 0.20% at the end of tests. The addition of the green and white glass does not aggravate ASR expansion in the testing period.

It can be observed that the mix with green glass has the least expansion, which may be because the content of green glass is less than that of white glass. This could be another reason that green glass is less active than white glass. As the result of this, the expansion is less than that of white glass.

The accelerated ASR test results may not guarantee satisfactory in-situ performance, but it indicates that using glass has the same risk of ASR expansion as cement in concrete.

8.3 Conclusions

The ground glass was first investigated as a partial replacement for the cement in SCC and then for both the cement and fine aggregate. It was found that SCC with satisfactory fresh properties can be produced by incorporating up to 154 kg/m^3 ground glass, replacing about 15% cement and 14% sand, without the need for VMA.

1. Initial tests on the mortar fraction showed that increasing glass contents led to a decrease in the spread and an increase in the V-funnel time. The difference between mixes with green and white glass is negligible.

2. Tests on concrete with the glass as a partial replacement for sand and cement showed that both the fresh and hardened properties were influenced as follows.

    - To keep the filling ability constant, the inclusion of glass led to a small increase in W/P ratio and a slight decrease in superplasticiser dosage, which resulted in some blocking in the V-funnel test, an increase in J-ring step height and consistence retention and an improvement in the sieve segregation.

    - Using glass led to some reduction in the strength, UPV and Ed from early to late ages due to the higher W/P ratio and the brittle nature of glass. Depending on the W/P ratio and the replacement ratio, the compressive strength ranged from 58 to 75 MPa, the splitting strength from 3.6 to 4.7 MPa, the UPV from 4.87 to 4.92 km/second and Ed from 45 to 49 GPa at 28 days.

    - The cementing efficiency factor for the glass showed irregular behaviour.

    - The correlations between the compressive strength and the splitting strength, the UPV and the Ed are all in the range of those for NVC. This shows that the material properties of SCC and NVC are similar.

    - The sorptivities of glass mixes are all higher than those of the control mixes due to the combined effects of an increase in glass content and W/P ratio and a reduction in superplasticizer dosage. The sorptivity decreased by curing from 7 to 90 days.

    - The expansions in the ASR mortar bar tests of the mixes with and without glass are similar to those of the control mix and all can be considered innocuous. This indicates glass incurs no more ASR risks than the cement in concrete.

- No colour effects were obvious.

Chapter 9 Overall Discussion

In this chapter, the whole set of test results are combined and analysed. Some correlations found throughout the project are presented and discussed.

9.1 Discussion

The targets for the SCC were a slump flow of 700 ± 50 mm, a V-funnel time of 8.0 ± 3.0 seconds, a step height in the J-ring of less than 25 mm and a sieve segregation of less than 15%. That is, all target SCC mixes should behave the same in all fresh properties. However, the results of step height in the J-ring test, the sieve segregation, and the slump flow and the V-funnel time 65 minutes after mixing clearly showed that target SCCs did not have the same passing ability, segregation resistance and consistence retention.

9.1.1 Assessment of the test results

As well as the mixes shown in Table 7-4, Table 7-6, Table 8-2 and Table 8-4, a total of 33 mixes achieved the target fresh properties for the project; the results for these mixes are shown in Table 9-1 . To compare the effectiveness of the tests, which were all performed by an individual operator in the same laboratory and in similar environment conditions using the same apparatus, standard deviation (SD), acceptance range (AR) and variation ratio (VR) were calculated from the results for all target mixes, as described in 4.5.1; the results are included in Table 9-1.

The average values and their acceptance ranges are: slump flow of 706 ± 9 mm, V-funnel time (t_v) of 8.2 ± 0.4 seconds, T500 time of 2.1 ± 0.2 seconds, step height of 18 ± 1 mm and segregation index (SI) of 8 ± 1%; the slump flow and V-funnel time 65 minutes after mixing are 474 ± 33 mm and 14.0 ± 1.9 seconds respective.

The ranking of the accuracy according to the variation ratio is the slump flow test, the V-funnel test, the J-ring test, the T500 test and the sieve stability test.

The T500 time is less accurate than the V-funnel time since it involves co operations between two people and depends more on individual judgements. This is in agreement with the findings of the Testing-SCC project (2005).

Table 9-1 All target SCC mixes achieved in the project

Target SCC	Slump flow (mm)	SF at 65min (mm)	T500 (secs)	T500 at 65min (secs)	V-funnel time (secs)	t_v at 65 min. (secs)	J-ring test		SI (%)
							Step (mm)	Spread (mm)	
With cement only	735	518	3.0		9.0	12.8	12	673	8%
	740	631	2.0	3.0	7.9	13.7	12	712	13%
	663	658	1.8	2.1	8.3	10.4	10		10%
	683	609	2.5	2.9	7.7	8.9	14	648	10%
	735		1.3		6.0		14	670	6%
	683	490			10.0	15.1	19	566	6%
	709	613			7.7	8.7	11		14%
	677				10.8		22	552	7%
	715	450			9.8	16.4	17	584	6%
	712	615	2.0	2.8	7.4	10.0	13	610	9%
With fly ash	668	417	3.3		9.9	24.0	22	556	3%
	739	556	2.2	3.9	7.1	10.0	13	620	11%
	700	496			8.1	9.6	16	620	12%
	737	637	2.0	2.1	8.7	17.8	13	710	16%
	715	441	2.2		8.1	17.3	20	512	8%
	683	443	2.1		7.1	9.9	17	586	5%
	700	419	2.3		8.2	16.7	19	500	7%
	661	420			6.8	10.1	21	485	5%
	700	453	1.8		6.1	9.4	17	545	9%
	705	493			6.1	8.4	15	610	13%
	700	377	2.4		8.5	17.0	25	475	4%
	725	385	1.9		6.6	13.1	20	560	13%
	715	433			6.3	9.8	20	548	13%
	705	415	2.0		9.4	18.9	22	553	5%
	729	395			7.2	11.8	24	483	5%
	728	395	1.8		9.3	20.7	18	540	9%
	713	370			9.1	15.8	23	501	7%
With ground glass	652	516			9.7	12.3	19	528	7%
	740	373			9.7	31.3	20	540	6%
	685	338			8.8		22	495	3%
	691	390			9.3	16.1	23	539	2%
	730	495			8.1	11.9	21	634	7%
	715	465			8.2	11.1	24	595	8%
Average	706	474	2.1	2.8	8.2	14.0	18	573	8%
SD	24.9	91	0.5	0.7	1.3	5.1	4.3	65.5	0.0
AR	9	33	0.2	0.5	0.4	1.9	1	24	1%
VR (%)	1.2	6.9	10.8	19.2	5.5	13.4	8.2	4.1	15.1

9.1.2 Fresh self-compacting concrete

An overview over the relationships among the fresh concrete parameters is demonstrated below. Data came from all mixes shown in Table 9-1 and Appendix 8 during the project in order to achieve the targets.

9.1.2.1 The relation between self-compacting concrete and mortar

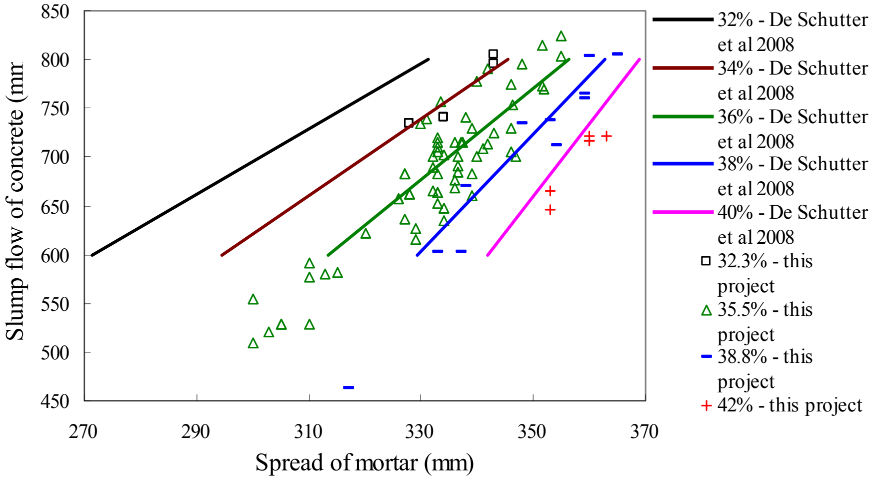


Figure 9-1 Spread of mortar vs. slump flow of SCC

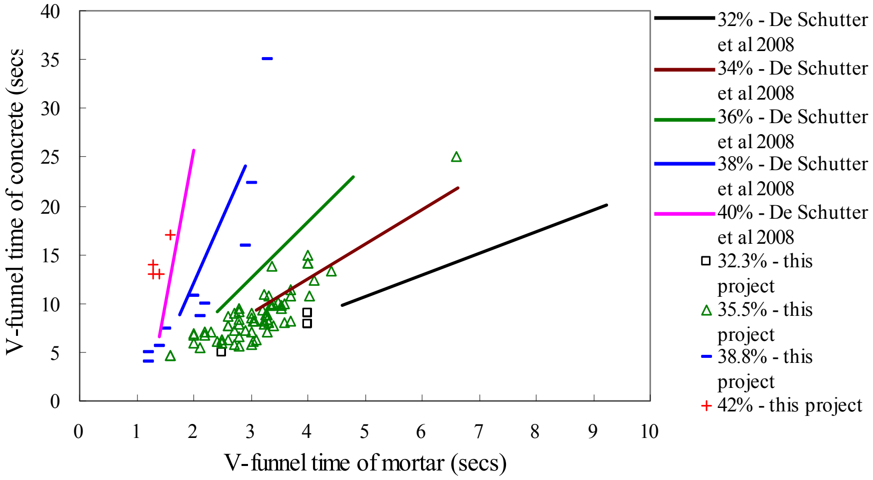


Figure 9-2 V-funnel time of mortar vs. V-funnel time of SCC

Figure 9-1 and Figure 9-2 all the relationships between mortar and concrete established during the application of the UCL mix design method. The solid lines are adapted from De Schutter et al (2008). The black solid line referring to coarse aggregate volume ratio of 32% came from Jin (2002). Other solid lines came from this project. The solid lines with coarse aggregate volume ratio of 34~40%, adapted from De Schutter et al (2008) came from several mixes with a binder of 100% Portland cement tested in the early stages of the project; the data points are from all the mixes tested in the project.

In the relationships between the spread of mortar and the slump flow of SCC shown in Figure 9-1, there is a considerable difference between Jin's results with a coarse aggregate volume ratio of about 32% and those from this project with a coarse aggregate volume ratio of 32.3%. This is mainly due to differences between operators and materials.

The relationships between the spread of mortar and the slump flow of SCC with coarse aggregate of 35.5% and 38.8% are similar to those with coarse aggregate of 36% and 38% respectively. This indicates that replacing cement with fly ash or glass does not change the established correlations between mortar and SCC. The relationships with coarse aggregate volume ratio of 42% are close to those with 40% coarse aggregate.

However in the relationships of the V-funnel time between mortar and SCC (Figure 9-2), there is good correlation between Jin's results with a coarse aggregate volume ratio of about 32% and those from this project with a coarse aggregate volume ratio of 32.3%. This may indicate that different operators and material changes do not influence the V-funnel test as much as the slump flow test.

The relationship of the V-funnel time between mortar and SCC with coarse aggregate of 38.8% is similar to that with coarse aggregate of 38%. This indicates that replacing cement with fly ash or glass does not change the established correlations between mortar and SCC. The relationship of the V-funnel time between mortar and SCC with coarse aggregate of 35.5% is different from that of 36% and the relationship of the V-funnel time between mortar and SCC with coarse aggregate of 42% are close to the results with 40%.

9.1.2.2 T500 time vs V-funnel time

It was shown in 2.2.3.1 that T500 and V-funnel time are both related to viscosity. There might therefore be a relationship between them and Figure 9-3 confirms this.

Because the measurement of T500 is more operator dependent than that of V-funnel time, T500 was only used at the beginning of the project.

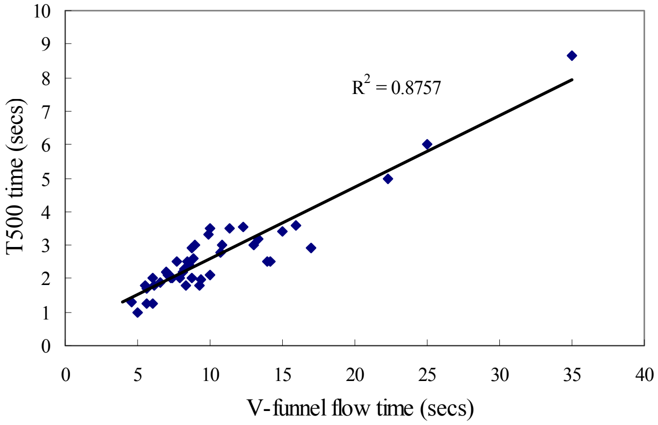


Figure 9-3 Relationships between T500 and V-funnel time

9.1.2.3 Filling ability vs. passing ability

Figure 9-4 shows the relations between filling ability and passing ability test results.

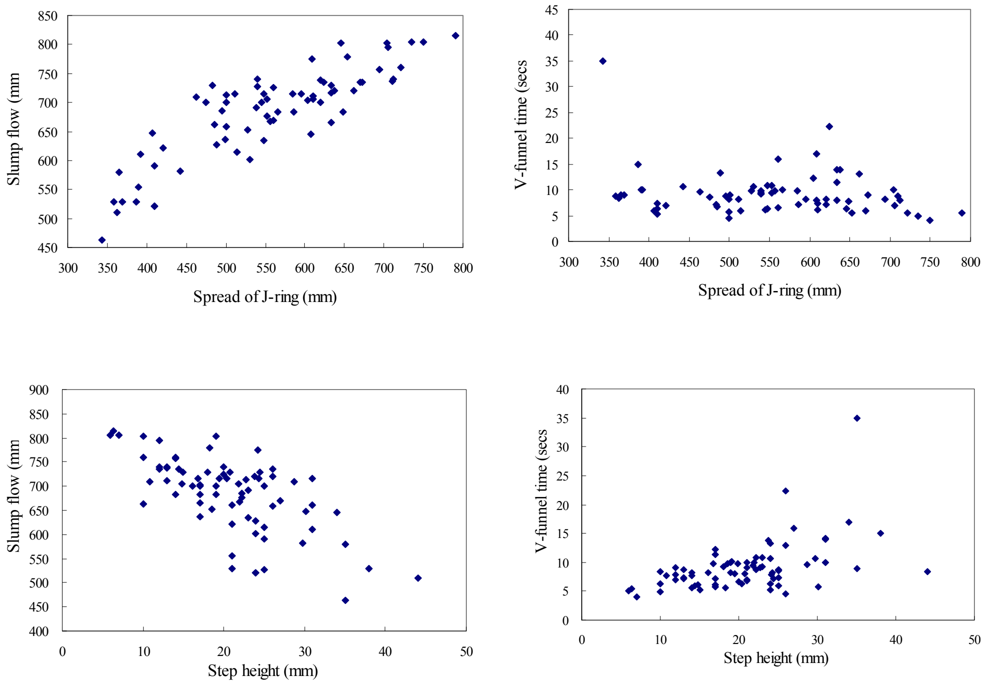


Figure 9-4 Slump flow and V-funnel time vs. J-ring results

Both the spread and the step height of J-ring are more related to slump flow than V-funnel time. The higher slump flow the lower chance of blocking. Because of the correlations between slump flow and yield stress and between V-funnel time and viscosity, it seems yield stress is the main influence on passing ability. This confirms the conclusion from Billberg et al. (2004).

9.1.2.4 Segregation

Figure 9-5 shows that segregation also relates to filling ability: the higher V-funnel time, the lower chance of segregation; the threshold V-funnel is about 10 seconds below which mixes tend to segregate; slump flow larger than 700mm, the segregation index increased sharply. There is a reverse relationship between filling ability and segregation resistance.

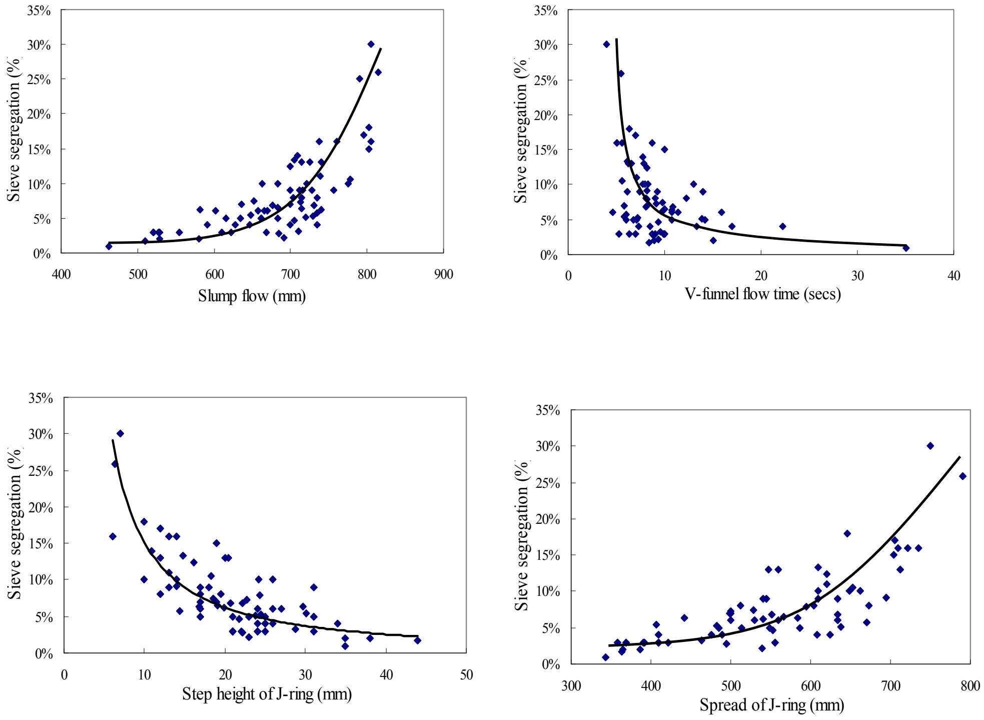


Figure 9-5 Segregation vs. slump flow, V-funnel time, step height and spread of J-ring

Segregation resistance is also related to the passing ability: segregation index decreases with an increase in the step height of J-ring; concrete has low segregation risk while blocking may occur in the J-ring test.

Therefore, filling ability, passing ability and segregation resistance are inter dependent, which confirms 2.1.2. However, due to the interrelations among the tests for filling ability, passing ability and segregation resistance, it is not clear which characteristics control segregation resistance.

9.1.3 Hardened properties of self-compacting concrete

The relationships between compressive strength and splitting strength, UPV and Ed were established and compared to those which are well established for NVC and given in Codes of Practice, guides for the use of non-destructive tests etc. The data of the following table and graphs come from Table 7-7 and Table 8-5.

9.1.3.1 Strength ratio

The strength ratios of mixes with additions to the control mix at the same age are compared and shown in Table 9-2. Fly ash and glass are both expressed as the volume ratio in concrete.

Table 9-2 The strength ratio of mixes with additions and control mix

ADDITION	VOL. RATIO IN CONCRETE	W/P BY WT.	COMPRESSIVE STRENGTH RATIO			
			7d	28d	90d	180d
Fly ash	0.0%	0.330	1.0	1.0	1.0	1.0
	3.5%	0.340	0.8	1.0	1.0	1.0
	7.0%	0.350	0.7	0.8	0.8	0.8
	10.7%	0.360	0.4	0.5	0.6	0.7
	14.6%	0.370	0.1	0.2	0.3	0.4
White glass	0.0%	0.345	1.0	1.0	1.0	1.0
	2.2%	0.354	1.0	1.0	0.9	1.0
	4.3%	0.370	0.9	0.9	0.9	0.9
	6.4%	0.383	0.9	0.9	0.9	0.9
Green glass	0.0%	0.330	1.0	1.0	1.0	1.0
	2.2%	0.335	0.9	0.9	1.0	1.0
	4.2%	0.350	0.8	0.8	0.8	0.8

This clearly shows that replacing cement with additions leads to a reduction in compressive strength. The higher the replacement ratio, the more the reduction. It is particularly interesting to learn that mixes with glass achieve strengths no less than those with similar amount of fly ash. In terms of strength, glass could be a promising addition in SCC.

9.1.3.2 Compressive vs. splitting strength

Figure 9-6 shows the relationship between cube compressive strength and cylinder splitting strength from current project and from more than 70 studies of the mechanical properties of SCC (Domone, 2006b). It shows that nearly all data of current project fall in the ranges for SCC.

9.1.3.3 Compressive strength vs. ultrasonic pulse velocity

Figure 9-7 shows the relationship between compressive strength and UPV from current project and data from NVC (Illston and Domone, 2001; Qasrawi, 2000). The majority of data are close to the relationship given by Illston and Domone which was obtained with the same instrument used but deviate from that given by Qasrawi, in which the instrument and concrete production are not mentioned. On the other hand, the strength of concrete and UPV are related.

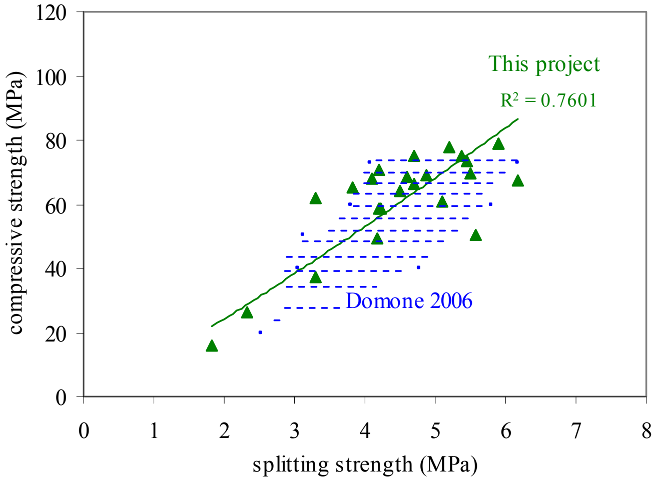


Figure 9-6 Cube compressive strength vs. cylinder splitting strength in SCC

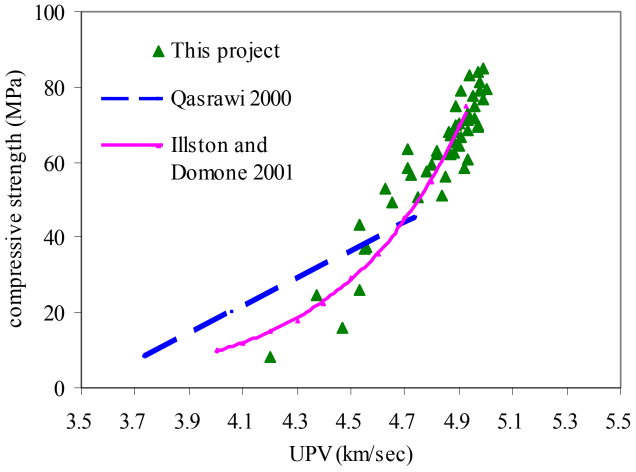


Figure 9-7 The relationship between compressive strength and UPV

9.1.3.4 Compressive strength vs. elastic modulus

Figure 9-8 shows the relationship between compressive strength and elastic modulus from current project and from more than 70 studies of the mechanical properties of SCC (Domone, 2006b).

The data show good relationship between compressive strength and dynamic elastic modulus, which is different from those between compressive strength and static elastic modulus.

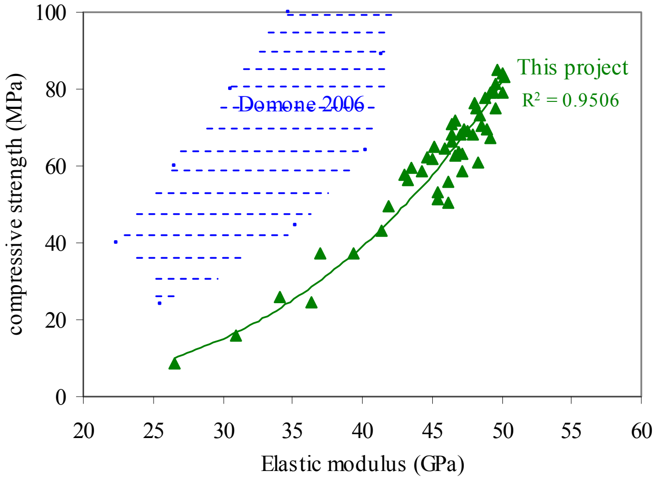


Figure 9-8 The relationship between compressive strength and elastic modulus

9.1.3.5 Sorptivity

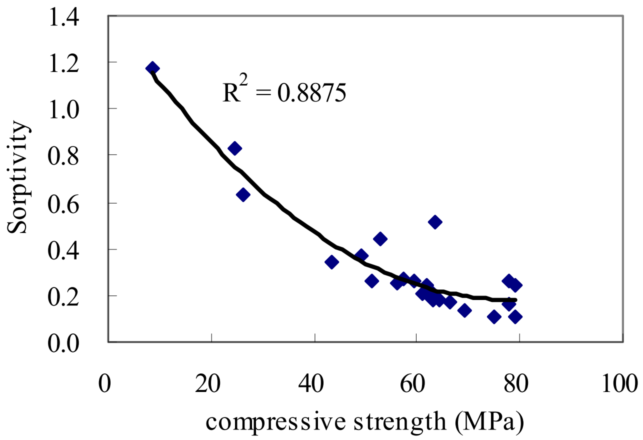


Figure 9-9 The relationship between sorptivity and compressive strength

Figure 9-9 shows the relationship between sorptivity and compressive strength. As anticipated, the higher the sorptivity, the lower the strength. Sorptivity changes significantly below 60 MPa but not so much at higher strength. This shows the denser structure of high strength concrete.

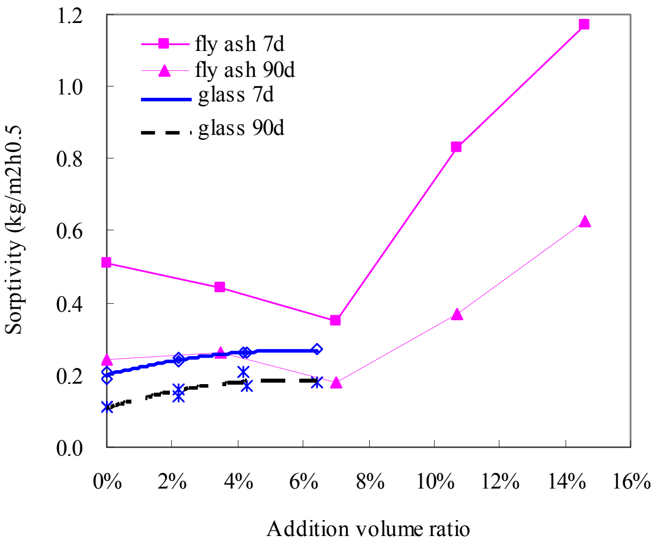


Figure 9-10 The relationship between addition content and sorptivity

The influences of glass and fly ash on sorptivity are compared in Figure 9-10. The different W/P ratio and superplasticiser dosage used in these mixes however are not shown in the graph.

It shows that curing has a more positive influence on mixes with fly ash than those with glass. While the sorptivity of those with fly ash at 90 days is about half of that at 7 days, the reduction of sorptivity for glass mixes is only 36% on average.

It also shows that the sorptivity values of SCC with glass are slightly increase with an increase in glass content while for those with fly ash, sorptivity slightly decreases up to 7% fly ash but significantly increases in mixes with 10.7% and 14.6% fly ash. This may be because glass has a wider range of particle size and may improve packing density by replacing both cement and fine aggregate.

9.2 Conclusions

From the mixes achieved the target fresh properties for the project, it was found that:

- the accuracy ranking of the tests is, in decreasing order, the slump flow test, the V-funnel test, the J-ring test, the T500 test and the sieve stability test.

- the relationships between fresh mortar and concrete with coarse aggregate content up to 65% dry rodded bulk density, which is about 42% of concrete volume, were established These relationships all apply to SCC incorporating fly ash or glass, thus extending the UCL method of mix design.

- there is a good relationship between T500 and V-funnel time.

- filling ability, passing ability and segregation resistance are inter dependent,

- from the current project, good relationships between compressive strength and UPV, dynamic elastic modulus and sorptivity have been obtained. The mixes with glass achieve strengths no less than those with similar amount of fly ash. These confirm that the hardened properties of the SCC's investigated are similar to those of NVC of equivalent strength.

Chapter 10 Conclusions and Future Work

The research started with the establishment of appropriate mixes by comparing the output of three mix design methods, the selection of target fresh properties for the SCCs and the selection of admixtures by carrying out tests on the mortar fractions of the prospective concrete. This was followed by investigating SCCs with two additions:

- levels of up to 80% cement replacement by fly ash with mixes adjusted to give the target fresh properties;

- the feasibility of using ground glass in SCC again in mixes adjusted to give the target fresh properties.

Finally tests were carried out to determine the hardened properties of the resulting concretes, and the relationships between hardened properties investigated.

This chapter summarizes the conclusions from the project and gives suggestions for future work.

10.1 Conclusions

10.1.1 Fly ash and ground glass in SCC

SCC with the target fresh properties can be successfully produced with up 80% of cement replaced by fly ash or with a glass/concrete volume ratio of up to 6.4%, i.e. a replacement of to 15% cement and 14% sand, without the need for a viscosity modifying agent (VMA). The quantity and the type of additions available to SCC producers and users are thus widened.

The results confirm previous work that replacing cement with 20% fly ash has no significant effects on both fresh and hardened properties. However, replacement levels of 40%~80% with fly ash and the incorporaton of glass have greater effects on these properties but not to an unacceptable extent.

More specifically:

- To keep the filling ability constant, replacement of cement with fly ash requires an increase in water/powder (W/P) ratio and a reduction in superplasticiser dosage. Inclusion of ground glass also leads to a required increase in W/P ratio and a slight reduction in superplasticiser dosage. The difference between mixes with green and white glass is negligible.

  Compared with the control mix, the mix with 40% fly ash 2 (a volume ratio in concrete of 7.0%) had a 6% increase in the W/P ratio and 32% decrease in the superplasticizer dosage; while the mix with white glass of 6.4% concrete volume had a 11% increase in the W/P ratio and 17% decrease in the superplasticizer dosage.

- The inclusion of fly ash and glass leads to some reduction in the consistence retention and passing ability; both result in a slight increase in the segregation.

  Compared with the control mix, the mix with 60% fly ash 2 had a 9 mm greater J-ring step height, 1.3 and 1.2 times higher change of slump flow and V-funnel time respectively and a decrease in segregation index of 4 mm; while the mix with white glass of 6.4% concrete volume had a 12 mm greater J-ring step height, and 1.4 times higher change of slump flow and a decrease in segregation index of 3 mm

- A good correlation exists between the required superplasticiser dosage and the fly ash content for the target SCC mixes.

- The cementing efficiency factor for SCC for fly ash in the SCC mixes decreases as the replacement ratio increases but increases with concrete age. The factors for glass are not consistent.

- The fly ash and glass lead to similar reductions in the compressive strength, splitting strength, ultrasonic pulse velocity (UPV) and dynamic elastic modulus (Ed). The higher the replacement level, the higher reduction. The reduction is higher at early stages but reduces with increasing age.

  Compared with the control mix at 28 days, the mix with 40% fly ash 2 had reductions of 20% in compressive strength, 24% in tensile strength, 4% in UPV and 8% in Ed; while the mix with 80% fly ash 2 had reductions of 78% in compressive strength, 67% in tensile strength, 11% in UPV and 35% in Ed.

  At 90 days, the mix with 40% fly ash 2 had reductions of 20% in compressive strength, 5% in tensile strength, 4% in UPV and 6% in Ed; while the mix with 80% fly ash 2 had reductions of 67% in compressive strength, 61% in tensile strength, 10% in UPV and 31% in Ed. However potential use of this high fly ash and therefore low-cost and low energy material for applications with low-strength requirements is practical.

  Compared with the control mix at 28 days, the mix with white glass of 6.4% concrete volume had reductions of 12% in compressive strength, 14% in tensile strength, 1% in UPV and 8% in Ed; while at 90 days, it had reductions of 14% in compressive strength, 17% in tensile strength, 1% in UPV and 8% in Ed.

- The sorptivity of SCCs with up to 40% fly ash were unchanged but were significantly higher in mixes with 60% and 80% fly ash. The sorptivity of SCCs with glass increases slightly with an increase in the glass content. On the whole, SCC with glass has lower sorptivity than that with fly ash. Water curing has a more positive effect on concrete with fly ash: the sorptivity at 90 days is only half of that at 7 days. The reduction due to curing in SCCs with glass is lower than that with fly ash. Logarithmic empirical equations fit the long term water absorption data.

- The expansions in the ASR mortar bar tests of the mixes with and without ground glass are similar to those of the control mix and all can be considered innocuous. This indicates that the ground glass incurs no more ASR risk than the cement in concrete.

10.1.2 Comparison of properties of the SCC's with NVC

Compared with HVFA NVC, HVFA SCC has a higher W/P ratio, a higher powder content and a lower sand/mortar volume ratio but similar 28-day compressive strength.

The results confirm that the hardened properties of the SCC's investigated are similar to those of NVC of equivalent strength.

Good correlations between compressive strength and splitting strength, UPV and Ed were obtained in target SCC mixes with both fly ash and ground glass and they are all in the range of those for NVC.

10.1.3 The UCL method of mix design

This was extended to higher coarse aggregate contents and different additions.

The relationships between the fresh properties of mortar and concrete with coarse aggregate content up to 65% dry rodded bulk density, which is about 42% of concrete volume, were established. These all apply to SCC incorporating fly ash or glass, thus extending the UCL method of mix design.

Using this enables SCC with a wider range of fresh properties and mix proportions to be produced.

10.1.4 Relationships between property measurements of SCC

For the whole range of mixes tested:

- T500 and V-funnel times are closely related. The T500 test is less accurate than V-funnel test.

- Filling ability, passing ability and segregation resistance are interrelated and interdependent. An increase in filling ability can lead to higher risks of segregation but lower risks of blocking.

- The yield stress and the plastic viscosity of mortar have good correlations with the spread and the V-funnel time. Mortar tests therefore have a sound rheological basis.

- The water absorption was proportional to square root of time over the first four hours of testing.

- There is good correlation between sorptivity and compressive strength. This indicates that compressive strength can be a reasonable indicator of durability.

10.2 Recommendations for future work

The use of greater quantities of powder in SCC compared to NVC provides a chance to replace cements by more types or more amounts of additions. Higher volumes of well-known additions and use of alternative additions can have economic effects, help the waste disposal problem, save natural resources and reduce CO_2 emissions. Further research is therefore worthwhile, and the following areas are recommended for future study:

- Other aspects of the durability of high-volume fly ash SCC and SCC with ground glass than were assessed in this project in order to obtain a more complete understanding of these concretes

- The use of different types of additions in SCC, - both for economical and rheological reasons, and the investigation of higher cement replacement levels with other additions such as GGBS.

- The correlation between sorptivity and other durability test results and hence the classification of sorptivity.

- As discussed in 7.3.5 and 8.2.2.5, water absorption over about 21 days is consistent with a $t^{1/2}$ behaviour of a logarithmic regression with a high degree of accuracy. It will be useful to further investigate this relationship and define the parameters.

- As discussed in 2.4.1.1, designing superplastiziers for concrete includes tests performed on cement paste. Superplasticizers may function differently in a system in which a large amount of cement is replaced by additions, and so the interactions between superplastizers and additions will be a pressing topic considering the environmental pressure to incorporate large amounts of additions in concrete.

- The function of VMA was studied in mortar but in this project was not used in concrete. It will be very useful if mortar tests can be used to select VMA type and dosage, thus further extending the UCL mix design method. Also studies of VMA-type SCC may make it possible to incorporate higher volume of glass in SCC.

The project has provided a good example of the application of higher contents of additions and use of an unconventional addition, ground glass, in SCC, - firstly by selecting appropriate tests, mix design methods, target properties and constituent materials, secondly by producing SCC without additions with selected fresh properties, then investigating SCCs with the two additions, and finally by testing the hardened concrete and the relationships between hardened properties. This research procedure is appropopriate for the study of the use of other additions in SCC and thus can lead to increasing economic and environmental advantages.

Appendix 1 Mix Design Procedures of a Normally Vibrated Concrete

The following is the calculations of the mix proportion shown in Table 2-1 of a NVC based on (Building Research Establishment Ltd, 1997).

Step	Item	Reference/ calculation	Values
1	1.4 Target mean strength	C2	(40) N/mm2
	1.5 Cement strength class	Specified	(42.5)
	1.6 Aggregate type: coarse Aggregate type: fine		(uncrushed) (Uncrushed)
	1.7 Free-W/C ratio	Table 2 Fig 4	0.52
	1.8 Maximum free-water/ cement ratio	Specified	
2	2.1 Slump	Specified	Slump (75) mm
	2.2 Maximum aggregate size	Specified	20 mm
	2.3 Free-water content	Table 3	(195) kg/m3
3	3.1 Cement content	C3	195 ÷ 0.52 = (375) kg/m3
	3.2 Maximum cement content	Specified	kg/m^3
	3.3 Minimum cement content	specified	kg/m^3
	3.4 Modified free-water/ cement ratio		
4	4.1 Relative density of aggregate (SSD)		(2.6) assumed
	4.2 Concrete density	Fig 5	(2355) kg/m3
	4.3 Total aggregate content	C4	(2355) – (375) – (195) = (1785) kg/m3
5	5.1 Grading of fine aggregate	Percentage passing 600 μm Sieve	59.2 %
	5.2 Proportion of fine aggregate	Fig 6	37.5 %
	5.3 Fine aggregate content	C5	17850 × 37.5 = (670) kg/m3
	5.4 Coarse aggregate content		1785 - 670 = (1115) kg/m3

The mix proportions are calculated as follows:

Quantities (SSD)	Cement (kg)	Water (kg)	Fine aggregate (kg)	Coarse aggregate (kg)	
				10 mm	20 mm
Per m^3	375	195	670	370	745
Per trial mix of 0.02m^3	7.5	3.9	13.4	7.4	14.9

The slump measured was 30 mm. 0.2 kg of water was then added and the slump reached 70 mm.

The final mix proportion is

- Coarse aggregate 1115 kg/m^3
- Sand 670 kg/m^3
- Water 205 kg/m^3
- Cement 375 kg/m^3
- Coarse aggregate volume ratio 42.4% concrete
- W/C ratio 0.55 by weight
- Paste volume ratio 32.1% concrete
- Sand to mortar volume ratio 44.3%

Appendix 2 Modified Repeatability of Mortar Tests

Mix proportions of the mixes and calculations about standard deviation (SD) and modified repeatability (Rm) of mortar tests (shown in Figure 4-14 Modified repeatability of spread and V-funnel time of mortar) are demonstrated in the following table.

Mix	Addition (powder vol.)	W/P by wt	Sp (powder wt.) by wt.	Spread (mm)	V-funnel time (secs)	SD		Rm		Average	
						Spread	V-funnel	Spread	V-funnel	Spread (mm)	V-funnel (secs)
Cement only, ADVA Flow 410	0%	0.32	2.0%	275	3.2	9	0.4	26	1.1	270	3.7
				275	3.8						
				259	4.0						
Cement only, Glenium c315	0%	0.31	0.9%	321.5	7.8	2	2.1	5	6.0	324	5.5
				325	5.2						
				324.5	3.6						
	0%	0.31	1.0%	330	4.0	4	0.4	12	1.2	335	3.5
				338	3.2						
				336.5	3.4						
Cement only, Glenium sky 545	0%	0.32	3.0%	294	4.0	11	0.8	30	2.2	291	3.1
				300	2.7						
				279	2.6						
	0%	0.324	3.5%	308.5	3.2	3	0.2	8	0.7	311	3.5
				314.5	3.7						
				311	3.5						
	0%	0.327	2.5%	250	3.1	19	0.8	52	2.3	234	4.0
				213.5	4.7						
				238	4.2						
	0%	0.34	3.1%	318	3.9	5	0.6	13	1.7	313	3.8
				310	4.3						

				310	3.1						
cement only; Sika ViscoCrete 10	0%	0.30	1.3%	311	2.9	6	0.3	16	0.8	305	4.1
				304	3.2						
				300	3.5						
	0%	0.32	1.3%	350	6.1	7	1.0	18	2.7	343	5.1
				346	5.5						
				337	4.9						
				337	3.9						
	0%	0.32	2.0%	360	3.0	4	0.5	10	1.5	360	3.1
				364	2.6						
				357	3.7						
	0%	0.33	1.0%	330	2.6	7	0.5	19	1.5	325	2.9
				317	3.6						
				327	2.7						
	0%	0.33	1.05%	340	2.6	6	0.3	16	0.9	335	2.7
				337	2.5						
				329	3.1						
	0%	0.33	1.1%	343	2.8	5	0.6	14	1.5	346	3.2
				343	3.8						
				352	3.0						
	0%	0.33	1.15%	338	2.6	6	0.2	16	0.6	335	2.8
				330	3.1						
				332	3.0						
				343	2.7						
	0%	0.345	1.0%	342	1.5	6	0.1	18	0.3	343	1.4
				350	1.4						
				337	1.3						
	0%	0.36	1.6%	356	1.6	5	0.1	15	0.2	352	1.6
				344	1.5						
				354	1.5						
				353	1.6						

Fly ash, Sika ViscoCrete 10	20%	0.32	1.3%	338	3.9	6	0.4	16	1.2	339	3.7
				345	3.3						
				334	4.1						
	20%	0.32	2.0%	360	3.4	3	0.4	7	1.0	363	3.4
				365	3.1						
				363	3.8						
	40%	0.36	1.0%	343	2.9	3	0.4	9	1.2	340	3.3
				337	3.2						
				339	3.8						
	60%	0.36	0.7%	340	2.9	3	0.3	8	0.8	339	3.2
				336	3.5						
				342	3.1						
	60%	0.37	0.8%	348	2.1	4	0.4	12	1.0	341	2.6
				345	2.6						
				340	2.7						
				337	3.0						
				340	2.6						
				337	2.7						
	60%	0.38	0.8%	347	10.0	2	3.1	6	8.5	344	6.5
				344	4.7						
				343	4.8						
	60%	0.40	0.8%	350	2.1	7	0.4	18	1.1	344	2.4
				337	2.8						
				345	2.2						
	60%	0.41	0.7%	341	2.4	3	1.1	7	3.0	339	3.5
				336	3.5						
				340	4.6						
	80%	0.375	0.6%	339	2.9	5	0.4	13	1.2	339	3.4
				343	3.7						
				334	3.6						
	100%	0.36	0.5%	347	2.4	3	0.4	9	1.2	349	4.6

				347	2.4						
				351	2.7						
				346	2.6						
				353	2.7						
	100%	0.365	0.5%	355	3.1	2	0.3	5	0.9	353	3.0
				352	3.2						
				352	2.6						
	100%	0.37	0.4%	346	3.7	4	0.6	11	1.6	341	3.1
				345	3.8						
				340	2.8						
				339	2.7						
				338	2.6						
	100%	0.37	0.5%	346	3.5	3	0.7	9	1.8	351	4.4
				352	5.4						
				355	4.1						
				352	4.6						
				351	4.6						
Glass, Sika ViscoCrete 10	20%	0.33	1.4%	333	3.4	5	0.3	15	0.8	336	3.3
				342	3.0						
				334	3.5						

Appendix 3 Retained Water Ratio

The complete results of retained water ratio shown as in Figure 5-6 Relative flow area vs water/powder ratio of paste by volume are demonstrated in the following table.

POWDER COMPOSITION	W/P BY VOL.	CEMENT (G)	ADDITION (G)	WATER (G)	SPREAD (MM)	RA	EP	BP
Cement 1 (10/10/05)	1.1	1500.0		523.8	206	3.2	0.0432	0.9546
	1.2	1431.8		545.5	260	5.8		
	1.3	1369.6		565.2	304	8.2		
	1.4	1312.5		583.3	333	10.1		
Cement 2 (29/03/07)	1.1	1500.0		523.8	188	2.5	0.0608	0.9642
	1.1	1500.0		523.8	185	2.4		
	1.2	1431.8		545.5	217	3.7		
	1.2	1431.8		545.5	222	3.9		
	1.3	1369.6		565.2	253	5.4		
	1.3	1369.6		565.2	245	5.0		
	1.4	1312.5		583.3	280	6.8		
	1.4	1312.5		583.3	294	7.6		
	1.4	1312.5		583.3	289	7.4		
Cement 3 (29/06/07)	1.1	1500.0		523.8	129	0.7	0.0736	1.0686
	1.1	1500.0		523.8	133	0.8		
	1.2	1431.8		545.5	160	1.6		
	1.2	1431.8		545.5	160	1.6		
	1.3	1369.6		565.2	198	2.9		
	1.3	1369.6		565.2	202	3.1		
	1.4	1312.5		583.3	245	5.0		
	1.4	1312.5		583.3	231	4.3		
	1.4	1312.5		583.3	232	4.4		
Fly ash 1	1.1		920.0	400.0	272	6.4	0.0372	0.8535
	1.2		1035.0	450.0	324	9.5		
	1.3		1150.0	500.0	368	12.5		
	1.4		1095.2	523.8	390	14.2		
Fly ash 2	0.8		920.0	400.0	250	5.3	0.0385	0.6055
	0.8		920.0	400.0	247	5.1		
	0.9		1035.0	450.0	289	7.4		
	0.9		1035.0	450.0	292	7.5		
	1.0		1150.0	500.0	341	10.6		
	1.0		1150.0	500.0	339	10.5		
	1.1		1095.2	523.8	363	12.1		
	1.1		1095.2	523.8	368	12.5		
	1.1		1095.2	523.8	376	13.1		
	1.1		1095.2	523.8	377	13.2		
Cement 2 : fly ash 2 = 7:3 by vol.	1.0	1102.5	345.0	500.0	181	2.3	0.0593	0.8817
	1.0	1102.5	345.0	500.0	181	2.3		
	1.1	1050.0	328.6	523.8	211	3.5		
	1.1	1050.0	328.6	523.8	208	3.3		

	1.1	1050.0	328.6	523.8	216	3.6		
	1.1	1050.0	328.6	523.8	213	3.5		
	1.2	1002.3	313.6	545.5	261	5.8		
	1.2	1002.3	313.6	545.5	250	5.2		
	1.3	958.7	300.0	565.2	286	7.2		
	1.3	958.7	300.0	565.2	281	6.9		
Cement 2 : fly ash 2 = 3:7 by vol.	0.9	497.4	847.4	473.7	173	2.0	0.0531	0.8145
	0.9	497.4	847.4	473.7	163	1.6		
	1.0	472.5	805.0	500.0	207	3.3		
	1.0	472.5	805.0	500.0	211	3.5		
	1.1	450.0	766.7	523.8	246	5.0		
	1.1	450.0	766.7	523.8	251	5.3		
	1.2	429.5	731.8	545.5	293	7.6		
	1.2	429.5	731.8	545.5	288	7.3		
Cement 2 : white glass = 7:3 by vol.	0.9	1160.5	378.9	473.7	143	1.0	0.0568	0.8424
	0.9	1160.5	378.9	473.7	156	1.4		
	1.0	1102.5	360.0	500.0	192	2.7		
	1.0	1102.5	360.0	500.0	196	2.8		
	1.1	1050.0	342.9	523.8	244	4.9		
	1.1	1050.0	342.9	523.8	233	4.4		
	1.2	1002.3	327.3	545.5	273	6.5		
	1.2	1002.3	327.3	545.5	269	6.2		

Appendix 4 Superplasticisers' Data Sheets

Eight superplasticisers' data sheets are demonstrated as follows.

ADVA Flow 410 is produced by Grace, which is a leading global supplier of catalysts, silica products, specialty construction chemicals, building materials and container sealants.

ADVA® Flow 410

Self-Compacting Concrete Admixture

Description

ADVA® Flow 410 is a high efficiency, new generation admixture designed to impart extremely high workability and enable the production of self-compacting concrete having exceptional workability retention.

ADVA Flow 410 is based on a modified synthetic carboxylated polymer and is manufactured under closely controlled conditions to give a consistent product.

ADVA Flow 410 conforms to EN 934-2, BS 5075 Part 3 and ASTM C494, Type A and Type F Admixtures.

Benefits and Advantages

- ADVA Flow 410 allows the production of very high flow, self-compacting concrete at 'normal' water contents.
- Concrete cohesion and rheology are improved, such that SCC can usually be produced without the need for a separate viscosity control admixture.
- Using suitable mix designs, Self Compacting Concrete produced with ADVA Flow 410 flows and compacts around reinforcement without blocking or segregation.
- ADVA Flow 410 can produce Self-compacting concrete which retains the required workability for 60-90 minutes.
- Self Compacting Concrete produced with ADVA Flow 410 is especially suitable for large-scale civil engineering applications as it has near-neutral setting time and high early strength, allowing rapid progress to be achieved.
- Concrete produced using ADVA Flow 410 is tolerant of variations in water content and aggregate grading, thus minimising problems in the field.

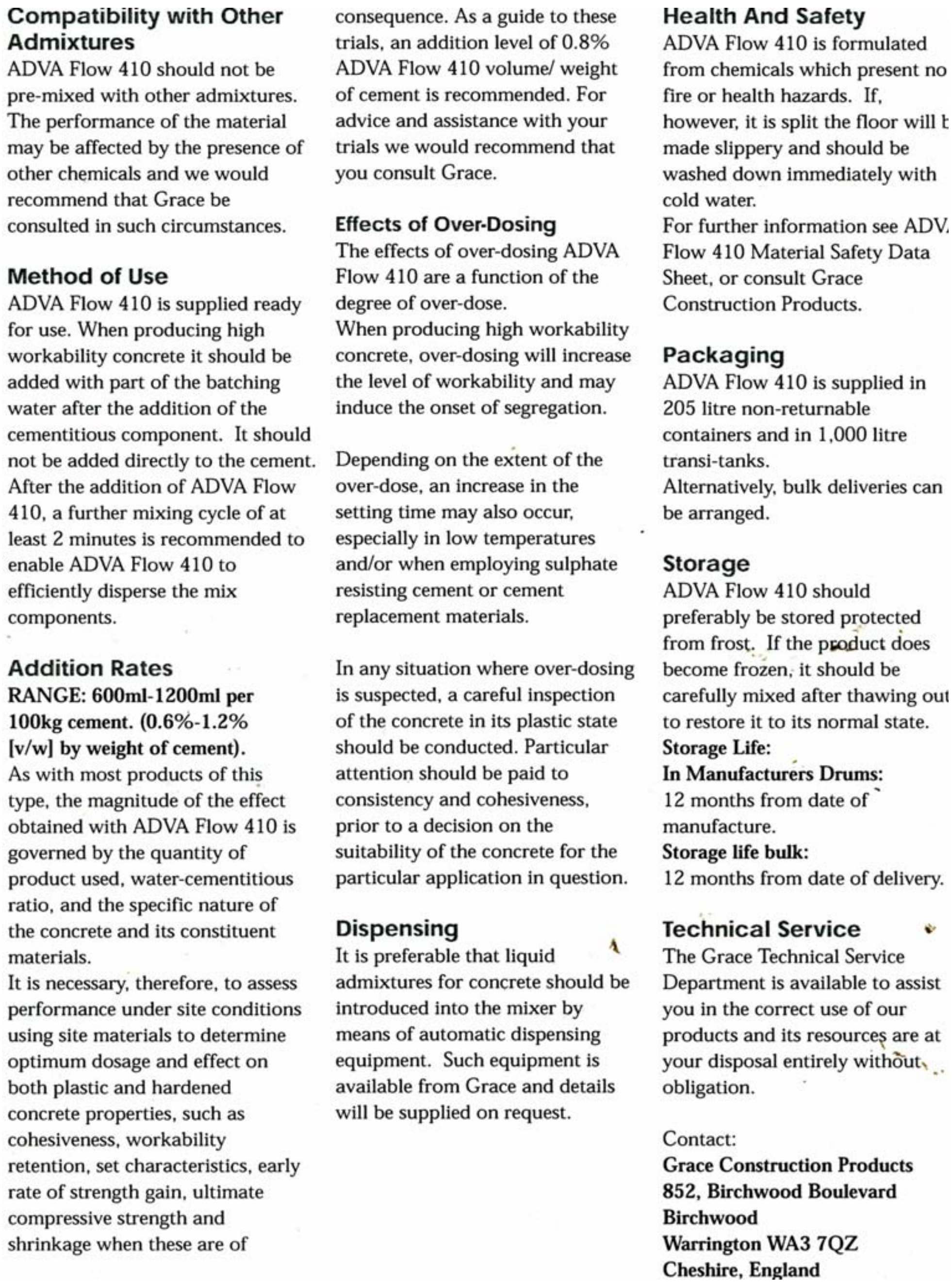
Typical Properties

Appearance: Brown liquid.
Air Entrainment: 1.5% approx.
Chloride Content: Nil.

Compatibility with Cements

410 can be used with all type of Portland Cements, including Sulphate Resisting Cements. It is effective in concretes containing pulverised fuel ash or ground granulated blast furnace slag. It is particularly effective in SCC mix designs containing ground limestone powder as a filler.

For use with special cements we recommend that you consult Grace.



Compatibility with Other Admixtures

ADVA Flow 410 should not be pre-mixed with other admixtures. The performance of the material may be affected by the presence of other chemicals and we would recommend that Grace be consulted in such circumstances.

Method of Use

ADVA Flow 410 is supplied ready for use. When producing high workability concrete it should be added with part of the batching water after the addition of the cementitious component. It should not be added directly to the cement. After the addition of ADVA Flow 410, a further mixing cycle of at least 2 minutes is recommended to enable ADVA Flow 410 to efficiently disperse the mix components.

Addition Rates

RANGE: 600ml-1200ml per 100kg cement. (0.6%-1.2% [v/w] by weight of cement).
As with most products of this type, the magnitude of the effect obtained with ADVA Flow 410 is governed by the quantity of product used, water-cementitious ratio, and the specific nature of the concrete and its constituent materials.
It is necessary, therefore, to assess performance under site conditions using site materials to determine optimum dosage and effect on both plastic and hardened concrete properties, such as cohesiveness, workability retention, set characteristics, early rate of strength gain, ultimate compressive strength and shrinkage when these are of consequence. As a guide to these trials, an addition level of 0.8% ADVA Flow 410 volume/ weight of cement is recommended. For advice and assistance with your trials we would recommend that you consult Grace.

Effects of Over-Dosing

The effects of over-dosing ADVA Flow 410 are a function of the degree of over-dose.
When producing high workability concrete, over-dosing will increase the level of workability and may induce the onset of segregation.

Depending on the extent of the over-dose, an increase in the setting time may also occur, especially in low temperatures and/or when employing sulphate resisting cement or cement replacement materials.

In any situation where over-dosing is suspected, a careful inspection of the concrete in its plastic state should be conducted. Particular attention should be paid to consistency and cohesiveness, prior to a decision on the suitability of the concrete for the particular application in question.

Dispensing

It is preferable that liquid admixtures for concrete should be introduced into the mixer by means of automatic dispensing equipment. Such equipment is available from Grace and details will be supplied on request.

Health And Safety

ADVA Flow 410 is formulated from chemicals which present no fire or health hazards. If, however, it is split the floor will b made slippery and should be washed down immediately with cold water.
For further information see ADV Flow 410 Material Safety Data Sheet, or consult Grace Construction Products.

Packaging

ADVA Flow 410 is supplied in 205 litre non-returnable containers and in 1,000 litre transi-tanks.
Alternatively, bulk deliveries can be arranged.

Storage

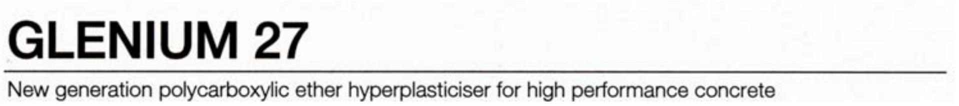
ADVA Flow 410 should preferably be stored protected from frost. If the product does become frozen, it should be carefully mixed after thawing ou to restore it to its normal state.
Storage Life:
In Manufacturers Drums:
12 months from date of manufacture.
Storage life bulk:
12 months from date of delivery.

Technical Service

The Grace Technical Service Department is available to assist you in the correct use of our products and its resources are at your disposal entirely without obligation.

Contact:
Grace Construction Products
852, Birchwood Boulevard
Birchwood
Warrington WA3 7QZ
Cheshire, England

Glenium 27, Glenium c315, Glenium sky 544 and Glenium sky 545 are produced by BASF, which is the world's leading chemical company, from oil and gas to chemicals, plastics, performance products, agricultural products and fine chemicals.



GLENIUM 27

New generation polycarboxylic ether hyperplasticiser for high performance concrete

DESCRIPTION

Glenium 27 has been primarily developed for applications in the premixed and precast concrete industries where the highest durability and performance is required, along with extended slump retention.

Glenium 27 is free from chlorides and complies with AS1478.1 – 2000 Type HWR and ASTM C494 Types A and F.

Conventional superplasticisers, such as those based on sulphonated melamine and naphthalene formaldehyde condensates, at the time of mixing, become absorbed onto the surface of the cement particles. This absorption takes place at a very early stage in the hydration process. The sulphonic groups of the polymer chains increase the negative charge on the surface of the cement particle and dispersion of the cement occurs by electrostatic repulsion.

Glenium 27 is differentiated from conventional superplasticisers in that it is based on a unique carboxylic ether polymer with long lateral chains. This greatly improves cement dispersion. At the start of the mixing process the same electrostatic dispersion occurs as described previously but the presence of the lateral chains, linked to the polymer backbone, generate a steric hindrance which stabilises the cement particles capacity to separate and disperse. This mechanism provides flowable concrete with greatly reduced water demand.

In addition, the alkalinity created by the cement paste allows the formulation of **Glenium 27** to "open up and progressively release" additional polymer chains that prevent the early stiffening of the concrete mix. This mechanism allows considerably longer workability (slump retention) to be obtained without the retardation experienced with conventional melamine or napthalene superplasticisers.

FEATURES AND BENEFITS

- ***Flowable concrete with the lowest water/cement ratio without segregation or bleeding***
- ***Excellent slump retention without retardation***
- ***Allows reduction of curing cycles – i.e. time or temperature***
- ***Possibility of elimination of steam curing***
- ***Less vibration required even in case of congested steel reinforcement***
- ***Less labour required***
- ***Improves concrete surface finish and texture***
- ***Compared to traditional superplasticisers, the addition of Glenium 27 will improve the physical properties and thus the durability of concrete***

Glenium 27 increases:

- ***Early and ultimate compressive strength***
- ***Early and ultimate flexural and tensile strength***
- ***E-modulus***
- ***Adhesion to reinforcement and prestressed steel***
- ***Resistance to carbonation and chloride ion attack of concrete***
- ***Resistance to aggressive atmospheric conditions***
- ***Slump retention***

Glenium 27 decreases:

- ***Risk of shrinkage***
- ***Creep***

APPLICATION

The excellent dispersion properties of **Glenium 27** make it the ideal admixture for precast and premixed concrete where low water cement ratios are required. This property allows the production of very high early and high ultimate strength concrete with minimal voids and therefore optimum density.

The extended slump life of **Glenium 27** concrete is ideally suited to premix concrete. It allows plant dosing to occur with little or no slump loss between dosing and placement (travel time). As no extended retardation accompanies this extended work life, normal finishing times are experienced on site.

Glenium 27 is a ready-to-use admixture to be added to the concrete mix as a separate component.

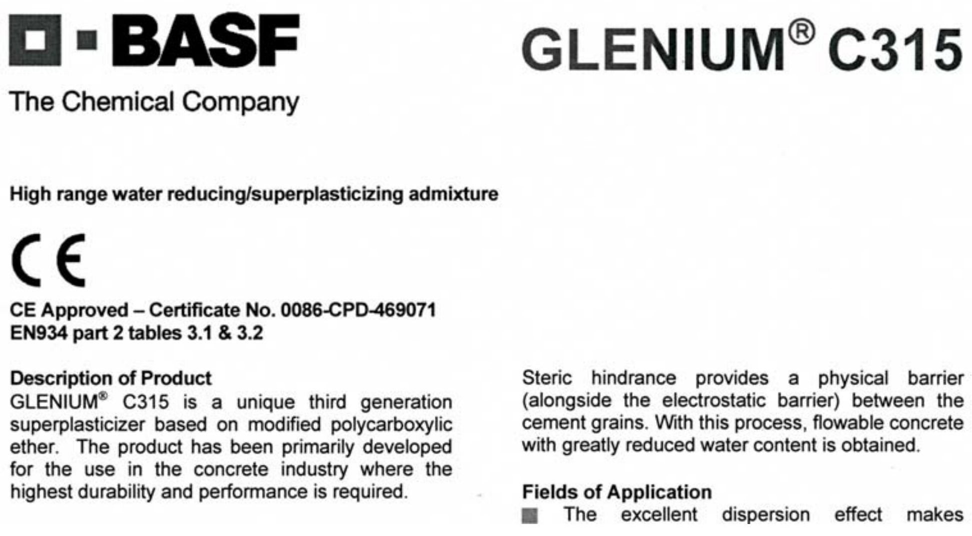
Optimal concrete plasticising effect (and thus maximum water reduction) and slump retention is obtained if **Glenium 27** is poured into the concrete mix right after the addition of the first 50-70% of the mixing water. Thorough mixing is required for complete dispersion throughout the mix.

Avoid adding the admixture to the dry aggregate or sand.

Glenium 27 is not compatible with admixtures containing melamine or napthalene sulphonates. Contact your local BASF Construction Chemicals Technical Representative to obtain the recommended compatible admixtures.

DOSAGE

The normally recommended dosage rate is between 0.4-1.6 litres per 100kg of cement (binder) depending on specific mix design and requirements. Other dosages may be recommended in special cases according to specific job conditions (consult your local BASF Construction Chemicals technical representative for advice).



BASF

The Chemical Company

GLENIUM® C315

High range water reducing/superplasticizing admixture

CE

CE Approved – Certificate No. 0086-CPD-469071
EN934 part 2 tables 3.1 & 3.2

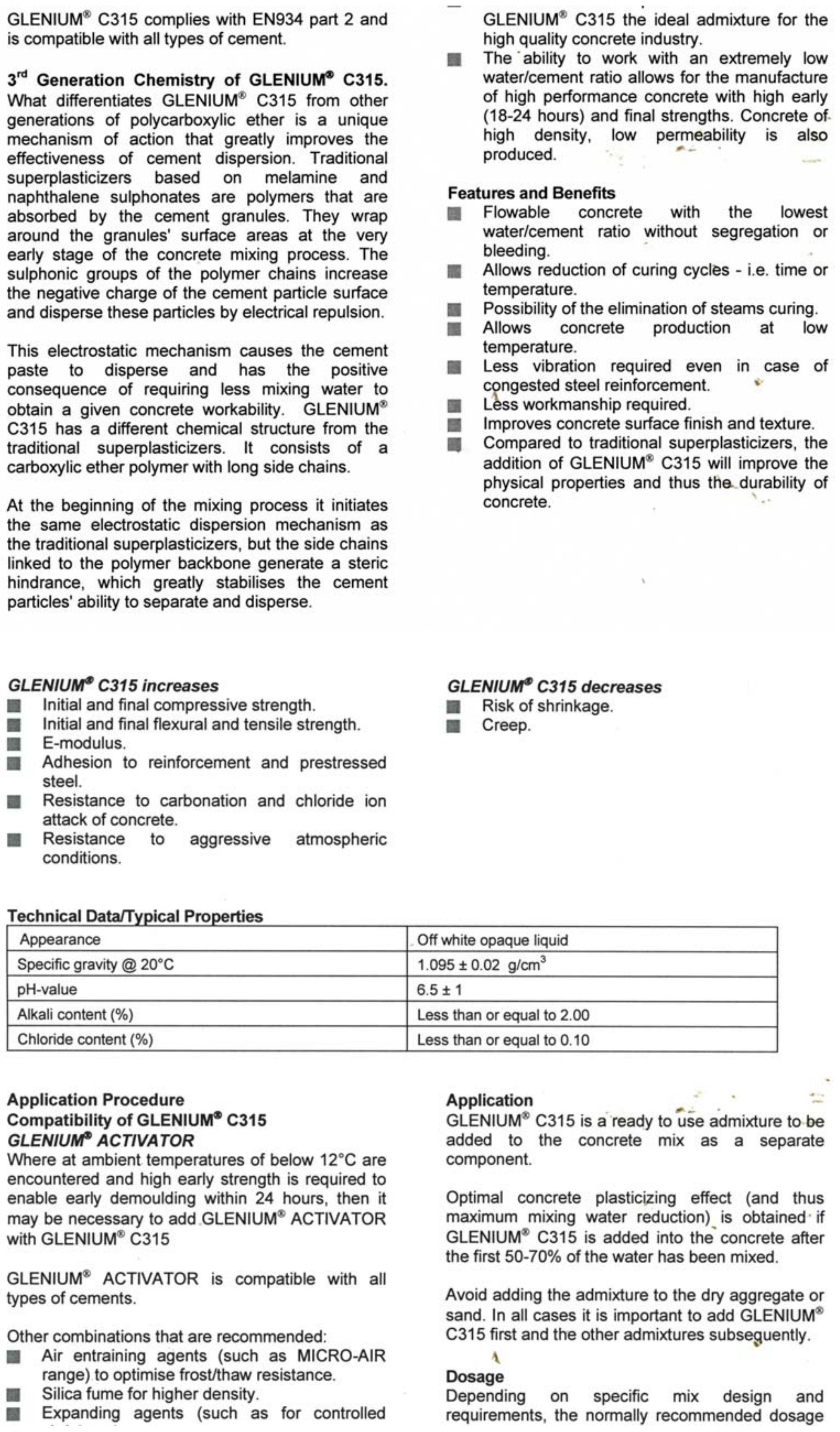
Description of Product

GLENIUM® C315 is a unique third generation superplasticizer based on modified polycarboxylic ether. The product has been primarily developed for the use in the concrete industry where the highest durability and performance is required.

Steric hindrance provides a physical barrier (alongside the electrostatic barrier) between the cement grains. With this process, flowable concrete with greatly reduced water content is obtained.

Fields of Application

■ The excellent dispersion effect makes



GLENIUM® C315 complies with EN934 part 2 and is compatible with all types of cement.

3rd Generation Chemistry of GLENIUM® C315. What differentiates GLENIUM® C315 from other generations of polycarboxylic ether is a unique mechanism of action that greatly improves the effectiveness of cement dispersion. Traditional superplasticizers based on melamine and naphthalene sulphonates are polymers that are absorbed by the cement granules. They wrap around the granules' surface areas at the very early stage of the concrete mixing process. The sulphonic groups of the polymer chains increase the negative charge of the cement particle surface and disperse these particles by electrical repulsion.

This electrostatic mechanism causes the cement paste to disperse and has the positive consequence of requiring less mixing water to obtain a given concrete workability. GLENIUM® C315 has a different chemical structure from the traditional superplasticizers. It consists of a carboxylic ether polymer with long side chains.

At the beginning of the mixing process it initiates the same electrostatic dispersion mechanism as the traditional superplasticizers, but the side chains linked to the polymer backbone generate a steric hindrance, which greatly stabilises the cement particles' ability to separate and disperse.

— GLENIUM® C315 the ideal admixture for the high quality concrete industry.

- The ability to work with an extremely low water/cement ratio allows for the manufacture of high performance concrete with high early (18-24 hours) and final strengths. Concrete of high density, low permeability is also produced.

Features and Benefits

- Flowable concrete with the lowest water/cement ratio without segregation or bleeding.
- Allows reduction of curing cycles - i.e. time or temperature.
- Possibility of the elimination of steams curing.
- Allows concrete production at low temperature.
- Less vibration required even in case of congested steel reinforcement.
- Less workmanship required.
- Improves concrete surface finish and texture.
- Compared to traditional superplasticizers, the addition of GLENIUM® C315 will improve the physical properties and thus the durability of concrete.

GLENIUM® C315 increases

- Initial and final compressive strength.
- Initial and final flexural and tensile strength.
- E-modulus.
- Adhesion to reinforcement and prestressed steel.
- Resistance to carbonation and chloride ion attack of concrete.
- Resistance to aggressive atmospheric conditions.

GLENIUM® C315 decreases

- Risk of shrinkage.
- Creep.

Technical Data/Typical Properties

Appearance	Off white opaque liquid
Specific gravity @ 20°C	1.095 ± 0.02 g/cm^3
pH-value	6.5 ± 1
Alkali content (%)	Less than or equal to 2.00
Chloride content (%)	Less than or equal to 0.10

Application Procedure

Compatibility of GLENIUM® C315

GLENIUM® ACTIVATOR

Where at ambient temperatures of below 12°C are encountered and high early strength is required to enable early demoulding within 24 hours, then it may be necessary to add GLENIUM® ACTIVATOR with GLENIUM® C315

GLENIUM® ACTIVATOR is compatible with all types of cements.

Other combinations that are recommended:

- Air entraining agents (such as MICRO-AIR range) to optimise frost/thaw resistance.
- Silica fume for higher density.
- Expanding agents (such as for controlled

Application

GLENIUM® C315 is a ready to use admixture to be added to the concrete mix as a separate component.

Optimal concrete plasticizing effect (and thus maximum mixing water reduction) is obtained if GLENIUM® C315 is added into the concrete after the first 50-70% of the water has been mixed.

Avoid adding the admixture to the dry aggregate or sand. In all cases it is important to add GLENIUM® C315 first and the other admixtures subsequently.

Dosage

Depending on specific mix design and requirements, the normally recommended dosage

shrinkage).
- Synthetic and steel fibres.
- Curing agents against evaporation of mixing water.

The recommended dosage of GLENIUM® ACTIVATOR is 1 litre per 100 kg of cement (binder). This combination guarantees a uniform and fast development of initial and final strength. At temperatures above I2°C the addition of GLENIUM ACTIVATOR is not required.

rate is between:

By Volume - 0.183 to 0.917 litres per 100 Kg of cement (binder)

By Mass - 0.20 to 1.00 kg per 100 Kg of cement (binder)

BASF

The Chemical Company

GLENIUM® SKY 544

High range water reducing/superplasticizing admixture

CE

CE Approved – Certificate No. 0086-CPD-469071
EN934 part 2 tables 3.1 & 3.2

Description of Product

GLENIUM® SKY 544 is an innovative second-generation superplasticizer based on polycarboxylic ether (PCE) polymers. It is derived directly from the Total Performance Control™ concept. GLENIUM® SKY 544 is specially engineered for ready-mix concrete. Its particular configuration allows its delayed adsorption onto the cement particles and disperses them efficiently. As compared with other PCE superplasticizers, it is possible to obtain a high quality concrete mix with accelerated strength development and extended workability without delayed setting characteristics.

The Total Performance Control™ concept ensures that ready-mix producers, contractors and engineers get a concrete that is of the same high quality as originally specified; starting from production at the batching plant, to the delivery and application into place, and followed by its hardening process. Utilizing Rheodynamic™ concrete technology it provides a concrete mix with exceptional placing characteristics and accelerated cement hydration for early strength development and high-quality concrete.

Fields of Application

GLENIUM® SKY 544 is used for the production of high quality ready-mix concrete.

GLENIUM® SKY 544 may be used in combination with GLENIUM® STREAM admixtures for producing Rheodynamic™ concrete, capable of self-compaction, even in the presence of dense reinforcement.

Features and Benefits

GLENIUM® SKY 544 offers the following benefits for:

The ready-mix producer:
- Capability of delivering high quality concrete at any time to the job site in place
- Production of a concrete with low water cement ratio that meets EN 206-1 without loss of workability
- Single product for many application needs

The contractor / applicator:
- Easier placing and faster strength development
- Improved concrete surfaces
- Guarantee to place the same concrete as specified and ordered from ready-mix plant
- More versatile and forgiving concrete mix

The engineer:
- Insurance that concrete meets original specification
- High quality concrete with better durability.

Technical Data/Typical Properties

Appearance	Brown liquid
Specific gravity @ 20°C	1.08 ± 0.02 g/cm^3
pH-value	6.0 ± 1
Alkali content (%)	Less than or equal to 2.00
Chloride content (%)	Less than or equal to 0.10

BASF

The Chemical Company

GLENIUM® SKY 545

High range water reducing/superplasticizing admixture

CE

CE Approved – Certificate No. 0086-CPD-469071
EN934 part 2 tables 3.1 & 3.2

Description of Product

GLENIUM® SKY 545 is an innovative second-generation superplasticizer based on polycarboxylic ether (PCE) polymers. It is derived directly from the Total Performance Control™ concept. GLENIUM® SKY 545 is specially engineered for ready-mix concrete. Its particular configuration allows its delayed adsorption onto the cement particles and disperses them efficiently. As compared with other PCE superplasticizers, it is possible to obtain a high quality concrete mix with accelerated strength development and extended workability without delayed setting characteristics.

The Total Performance Control™ concept ensures that ready-mix producers, contractors and engineers get a concrete that is of the same high quality as originally specified; starting from production at the batching plant, to the delivery and application into place, and followed by its hardening process. Utilizing Rheodynamic™ concrete technology it provides a concrete mix with exceptional placing characteristics and accelerated cement hydration for early strength development and high-quality concrete.

Fields of Application

GLENIUM® SKY 545 is used for the production of high quality ready-mix concrete.

GLENIUM® SKY 545 may be used in combination with GLENIUM® STREAM admixtures for producing Rheodynamic™ concrete, capable of self-compaction, even in the presence of dense reinforcement.

Features and Benefits

GLENIUM® SKY 545 offers the following benefits for:

The ready-mix producer:

- Capability of delivering high quality concrete at any time to the job site in place
- Production of a concrete with low water cement ratio that meets EN 206-1 without loss of workability
- Single product for many application needs

The contractor / applicator:

- Easier placing and faster strength development
- Improved concrete surfaces
- Guarantee to place the same concrete as specified and ordered from ready-mix plant
- More versatile and forgiving concrete mix

The engineer:

- Insurance that concrete meets original specification
- High quality concrete with better durability.

Technical Data/Typical Properties

Appearance	Brown liquid
Specific gravity @ 20°C	1.13 ± 0.03 g/cm^3
pH-value	6.0 ± 1
Alkali content (%)	Less than or equal to 2.00
Chloride content (%)	Less than or equal to 0.10

Application Procedure

Dosage

The normally recommended dosage rate of GLENIUM® SKY 545 is approximately:

By Volume - 0.177 to 1.327 litres per 100 kg of cement (binder) content.

By Weight - 0.20 to 1.50 kg per 100 kg of cement (binder) content.

Other dosages may be recommended in special cases according to the specific site conditions. In this case please consult our Technical Services Department for advice.

Mixing

GLENIUM® SKY 545 is a ready-to-use admixture to be added to the concrete as a separate component. Optimal result is obtained if GLENIUM® SKY 545 is poured into the concrete mix right after the addition of the first 80% of the mixing water, i.e. when all solids are wetted. Avoid adding the admixture to the dry aggregates.

Packaging

GLENIUM® SKY 545 is supplied in 208 liter drums, 1'000 liter containers or in bulk.

Storage

GLENIUM® SKY 545 must be stored in original sealed containers and at temperatures between 5°C and 30°C. Store under cover, out of direct sunlight and protect from extremes of temperature. Failure to comply with the recommended storage conditions may result in premature deterioration of the product or packaging. For specific storage advice consult our Technical Services Department.

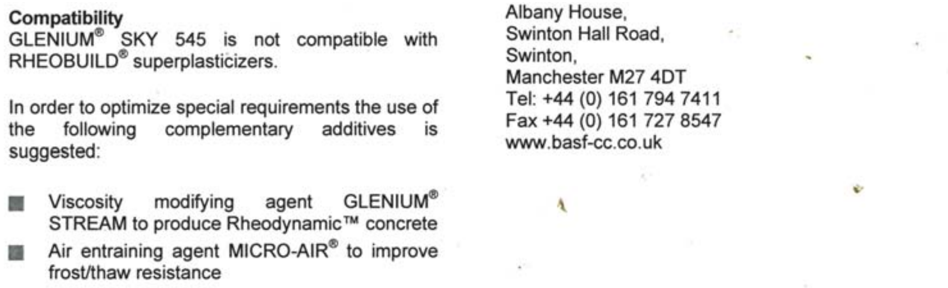
Shelf Life

12 months if stored according to manufacturer's instructions in unopened containers.

Handling and Transport

No special requirements must be observed during use. Protection gloves and glasses are however recommended. GLENIUM® SKY 545 is non-flammable, non-toxic or irritant and is not subject to special transport requirements.

BASF Construction Chemicals (UK) Ltd,



Compatibility

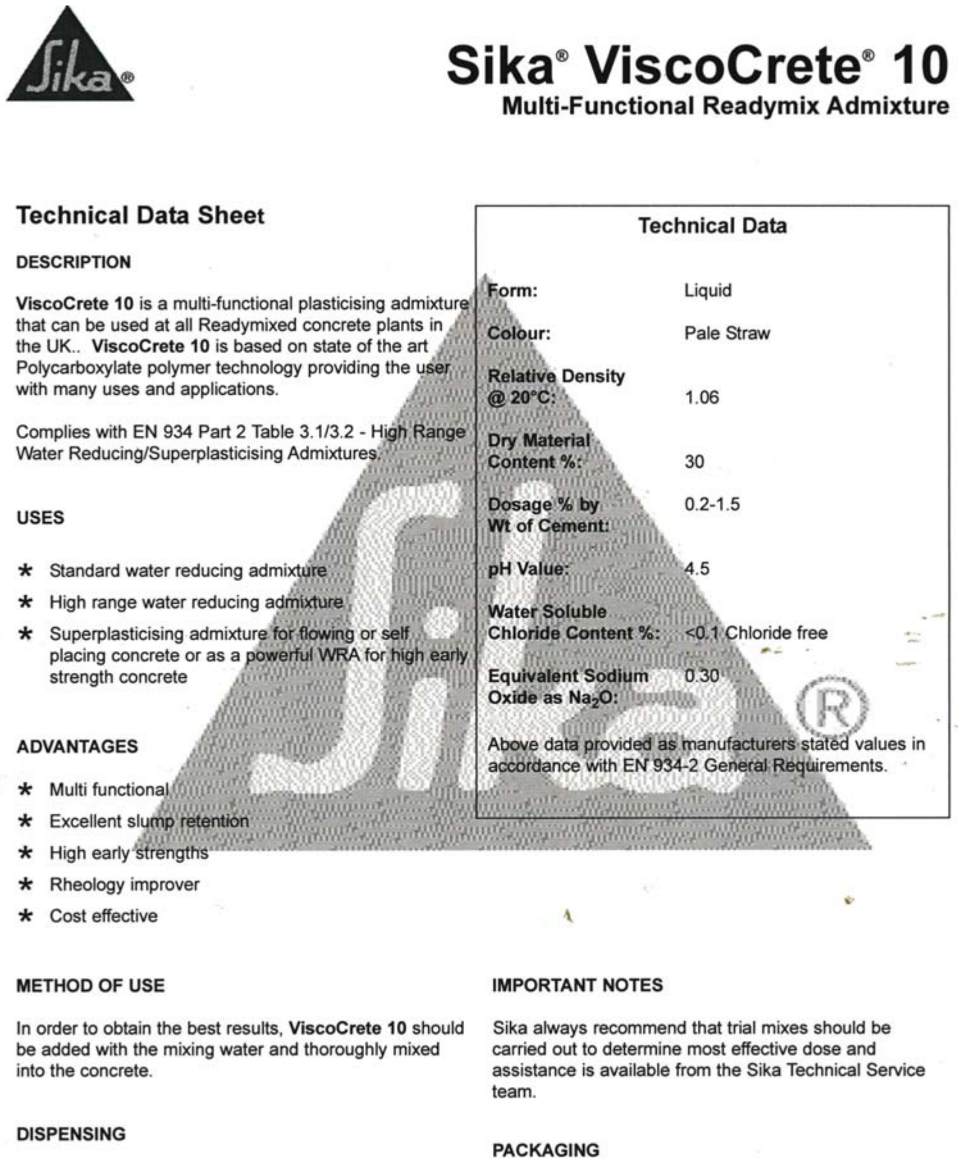
GLENIUM® SKY 545 is not compatible with RHEOBUILD® superplasticizers.

In order to optimize special requirements the use of the following complementary additives is suggested:

- Viscosity modifying agent GLENIUM® STREAM to produce Rheodynamic™ concrete
- Air entraining agent MICRO-AIR® to improve frost/thaw resistance

Albany House,
Swinton Hall Road,
Swinton,
Manchester M27 4DT
Tel: +44 (0) 161 794 7411
Fax +44 (0) 161 727 8547
www.basf-cc.co.uk

Sika ViscoCrete 10 and Premier are produced by Sika, which was founded in Switzerland in 1910. Sika operates as a global company and is active in the field of special chemicals.



Sika® ViscoCrete® 10

Multi-Functional Readymix Admixture

Technical Data Sheet

DESCRIPTION

ViscoCrete 10 is a multi-functional plasticising admixture that can be used at all Readymixed concrete plants in the UK.. **ViscoCrete 10** is based on state of the art Polycarboxylate polymer technology providing the user with many uses and applications.

Complies with EN 934 Part 2 Table 3.1/3.2 - High Range Water Reducing/Superplasticising Admixtures.

USES

- * Standard water reducing admixture
- * High range water reducing admixture
- * Superplasticising admixture for flowing or self placing concrete or as a powerful WRA for high early strength concrete

ADVANTAGES

- * Multi functional
- * Excellent slump retention
- * High early strengths
- * Rheology improver
- * Cost effective

Technical Data

Form:	Liquid
Colour:	Pale Straw
Relative Density @ 20°C:	1.06
Dry Material Content %:	30
Dosage % by Wt of Cement:	0.2-1.5
pH Value:	4.5
Water Soluble Chloride Content %:	<0.1 Chloride free
Equivalent Sodium Oxide as Na_2O:	0.30

Above data provided as manufacturers stated values in accordance with EN 934-2 General Requirements.

METHOD OF USE

In order to obtain the best results, **ViscoCrete 10** should be added with the mixing water and thoroughly mixed into the concrete.

DISPENSING

IMPORTANT NOTES

Sika always recommend that trial mixes should be carried out to determine most effective dose and assistance is available from the Sika Technical Service team.

PACKAGING

Calibrated equipment should always be used.

EFFECTS OF OVERDOSING

Substantial overdosing may cause retardation.

COMPATIBILITY

Cements: All

Sika ViscoCrete 10 is supplied in 25 litre drums and 200 litre drums. Bulk deliveries can be arranged.

STORAGE AND SHELF LIFE

Minimum 1 year in sealed containers stored in dry warehouse condition (+5°C – +25°C). Protect from frost.

Sika® ViscoCrete® Premier

Super Plasticiser/Accelerator

Technical Data Sheet

DESCRIPTION

Sika ViscoCrete Premier is a super plasticising and accelerating concrete admixture based on Polycarboxylate polymers.

Sika ViscoCrete Premier can be used to either produce 'flowing concrete' or enable large water reductions to be made for the same workability. **Sika ViscoCrete Premier** however, has the advantage of producing very high early strengths and thus makes the material suitable for use in pre-cast concrete applications and in areas where higher workability concrete and fast shutter stripping is required. It can also be used to produce Self-Placing concrete when used with **Sika ViscoCrete Stabiliser**.

Complies with EN 934 Part 2 Table 3.1/3.2 - High Range Water Reducing/Superplasticising Admixtures.

ADVANTAGES

Sika ViscoCrete Premier provides the following benefits:-

As a superplasticiser:

- Substantial improvements in workability without increased water or the risk of segregation.
- Reversion from high workability within 1-2 hours
- Improved concrete density and surface finish.

As a water reducer:

- Up to 40% water reducing. 40% increase in 28 day strengths are possible.
- High strength between 6 hours and 18 hours can be obtained for faster turnaround of moulds.
- Increases frost and water resistant properties of the concrete because of reduced water contents and low permeability.
- Little vibration required
- Can replace steam curing
- Faster mould turn round
- Higher strength at all ages
- High durability concrete
- Ultra-high strength concrete
- Ideal for power finished floors

Technical Data

Form:	Liquid
Colour:	Yellow
Relative Density @ 20°C:	1.080
Dry Material Content %:	40.0
pH Value:	4.3
Water Soluble Chloride Content %:	<0.1 Chloride free
Alkali Content %: (as Na_2O equivalent)	0.60

Above data provided as manufacturers stated values in accordance with EN 934-2 General Requirements.

METHOD OF USE

In order to obtain the best results, **Sika ViscoCrete Premier** must be used with specially designed mixes designed for the particular requirements of strength, cost saving or flowing concrete. For maximum dispersion **Sika ViscoCrete Premier** should be added with the mixing water. On no account should it be added to the dry cement. **Sika ViscoCrete Premier** can be added at the plant or on site, when added at site the mixer trucks should rotate their drums at maximum revolutions until a uniform mix is achieved.

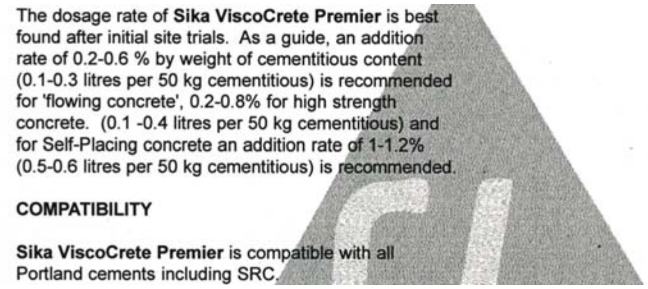
DOSAGE

PACKAGING

Sika ViscoCrete Premier is supplied in 25 litre and 200 litre containers. Bulk deliveries can be arranged.

STORAGE AND SHELF LIFE

Sika ViscoCrete Premier should be stored in sealed containers between 5°C and 30°C and protected from frost. Under these conditions the shelf life is 1 year minimum.

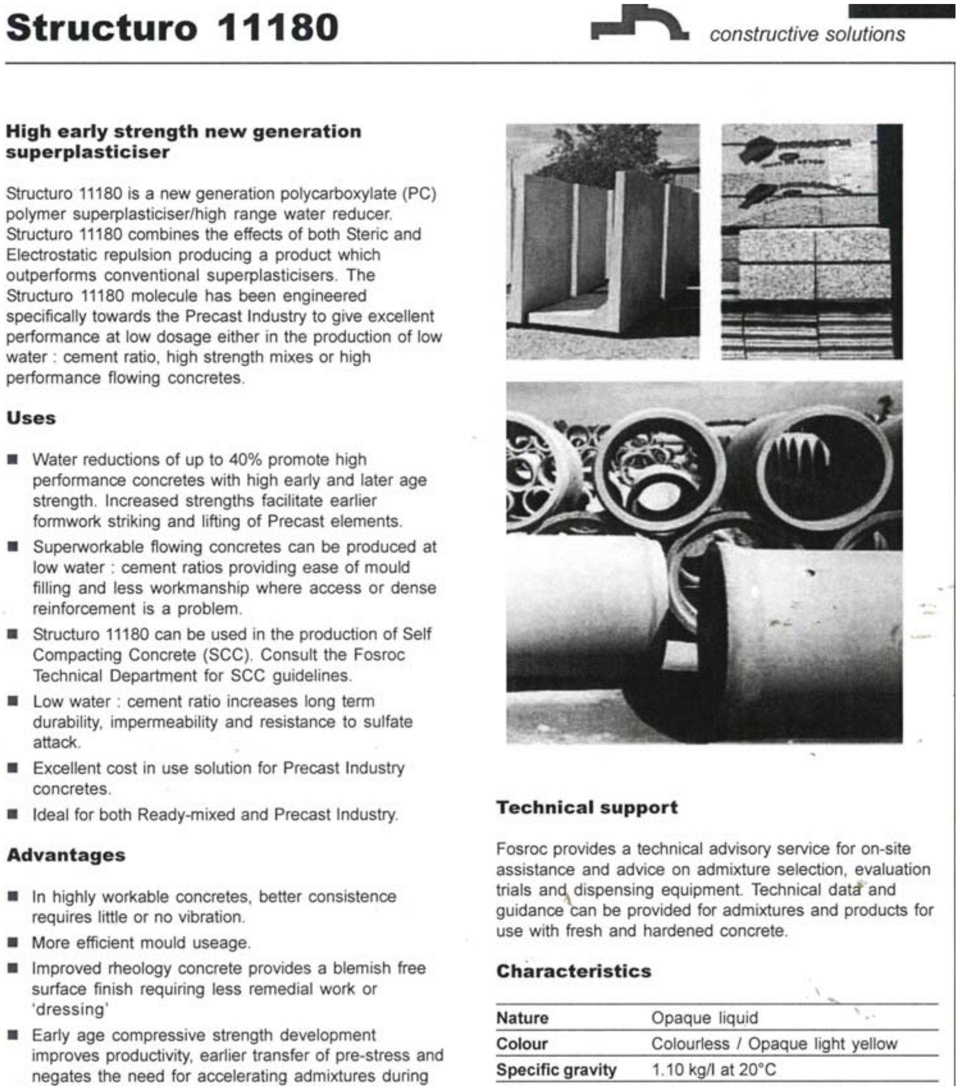


The dosage rate of **Sika ViscoCrete Premier** is best found after initial site trials. As a guide, an addition rate of 0.2-0.6 % by weight of cementitious content (0.1-0.3 litres per 50 kg cementitious) is recommended for 'flowing concrete', 0.2-0.8% for high strength concrete. (0.1 -0.4 litres per 50 kg cementitious) and for Self-Placing concrete an addition rate of 1-1.2% (0.5-0.6 litres per 50 kg cementitious) is recommended.

COMPATIBILITY

Sika ViscoCrete Premier is compatible with all Portland cements including SRC.

Structure 11180 is produced by Fosroc, which was founded in UK. Fosroc has become an international leader in providing constructive Solutions for a variety of projects across a broad range of sectors including commercial, industrial, residential, and marine and infrastructure.



Structuro 11180

constructive solutions

High early strength new generation superplasticiser

Structuro 11180 is a new generation polycarboxylate (PC) polymer superplasticiser/high range water reducer. Structuro 11180 combines the effects of both Steric and Electrostatic repulsion producing a product which outperforms conventional superplasticisers. The Structuro 11180 molecule has been engineered specifically towards the Precast Industry to give excellent performance at low dosage either in the production of low water : cement ratio, high strength mixes or high performance flowing concretes.

Uses

- Water reductions of up to 40% promote high performance concretes with high early and later age strength. Increased strengths facilitate earlier formwork striking and lifting of Precast elements.
- Superworkable flowing concretes can be produced at low water : cement ratios providing ease of mould filling and less workmanship where access or dense reinforcement is a problem.
- Structuro 11180 can be used in the production of Self Compacting Concrete (SCC). Consult the Fosroc Technical Department for SCC guidelines.
- Low water : cement ratio increases long term durability, impermeability and resistance to sulfate attack.
- Excellent cost in use solution for Precast Industry concretes.
- Ideal for both Ready-mixed and Precast Industry.

Advantages

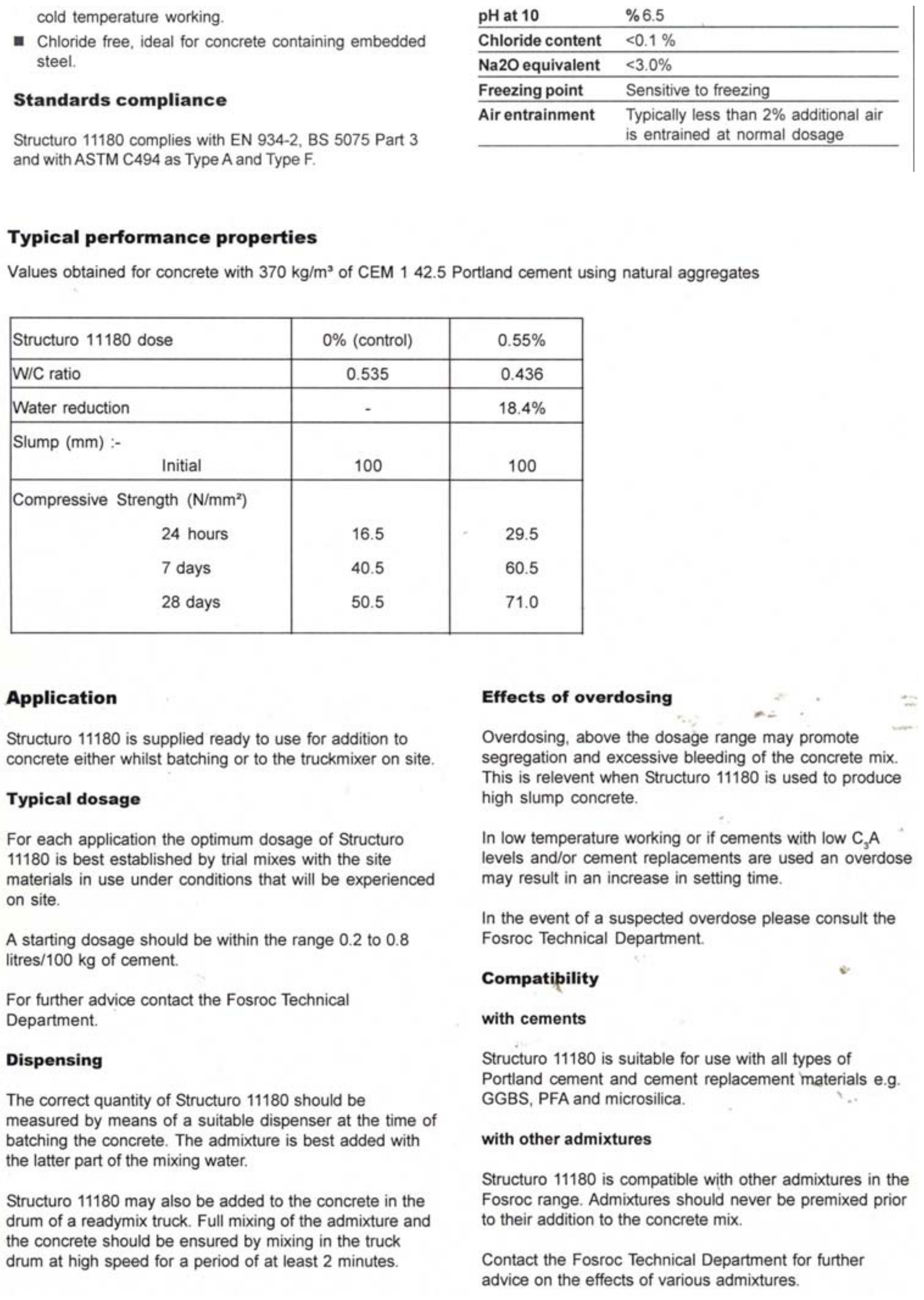
- In highly workable concretes, better consistence requires little or no vibration.
- More efficient mould useage.
- Improved rheology concrete provides a blemish free surface finish requiring less remedial work or 'dressing'
- Early age compressive strength development improves productivity, earlier transfer of pre-stress and negates the need for accelerating admixtures during

Technical support

Fosroc provides a technical advisory service for on-site assistance and advice on admixture selection, evaluation trials and dispensing equipment. Technical data and guidance can be provided for admixtures and products for use with fresh and hardened concrete.

Characteristics

Nature	Opaque liquid
Colour	Colourless / Opaque light yellow
Specific gravity	1.10 kg/l at 20°C



cold temperature working.

- Chloride free, ideal for concrete containing embedded steel.

Standards compliance

Structuro 11180 complies with EN 934-2, BS 5075 Part 3 and with ASTM C494 as Type A and Type F.

pH at 10	% 6.5
Chloride content	<0.1 %
Na2O equivalent	<3.0%
Freezing point	Sensitive to freezing
Air entrainment	Typically less than 2% additional air is entrained at normal dosage

Typical performance properties

Values obtained for concrete with 370 kg/m³ of CEM 1 42.5 Portland cement using natural aggregates

Structuro 11180 dose	0% (control)	0.55%
W/C ratio	0.535	0.436
Water reduction	-	18.4%
Slump (mm) :-		
Initial	100	100
Compressive Strength (N/mm²)		
24 hours	16.5	29.5
7 days	40.5	60.5
28 days	50.5	71.0

Application

Structuro 11180 is supplied ready to use for addition to concrete either whilst batching or to the truckmixer on site.

Typical dosage

For each application the optimum dosage of Structuro 11180 is best established by trial mixes with the site materials in use under conditions that will be experienced on site.

A starting dosage should be within the range 0.2 to 0.8 litres/100 kg of cement.

For further advice contact the Fosroc Technical Department.

Dispensing

The correct quantity of Structuro 11180 should be measured by means of a suitable dispenser at the time of batching the concrete. The admixture is best added with the latter part of the mixing water.

Structuro 11180 may also be added to the concrete in the drum of a readymix truck. Full mixing of the admixture and the concrete should be ensured by mixing in the truck drum at high speed for a period of at least 2 minutes.

Effects of overdosing

Overdosing, above the dosage range may promote segregation and excessive bleeding of the concrete mix. This is relevent when Structuro 11180 is used to produce high slump concrete.

In low temperature working or if cements with low C_3A levels and/or cement replacements are used an overdose may result in an increase in setting time.

In the event of a suspected overdose please consult the Fosroc Technical Department.

Compatibility

with cements

Structuro 11180 is suitable for use with all types of Portland cement and cement replacement materials e.g. GGBS, PFA and microsilica.

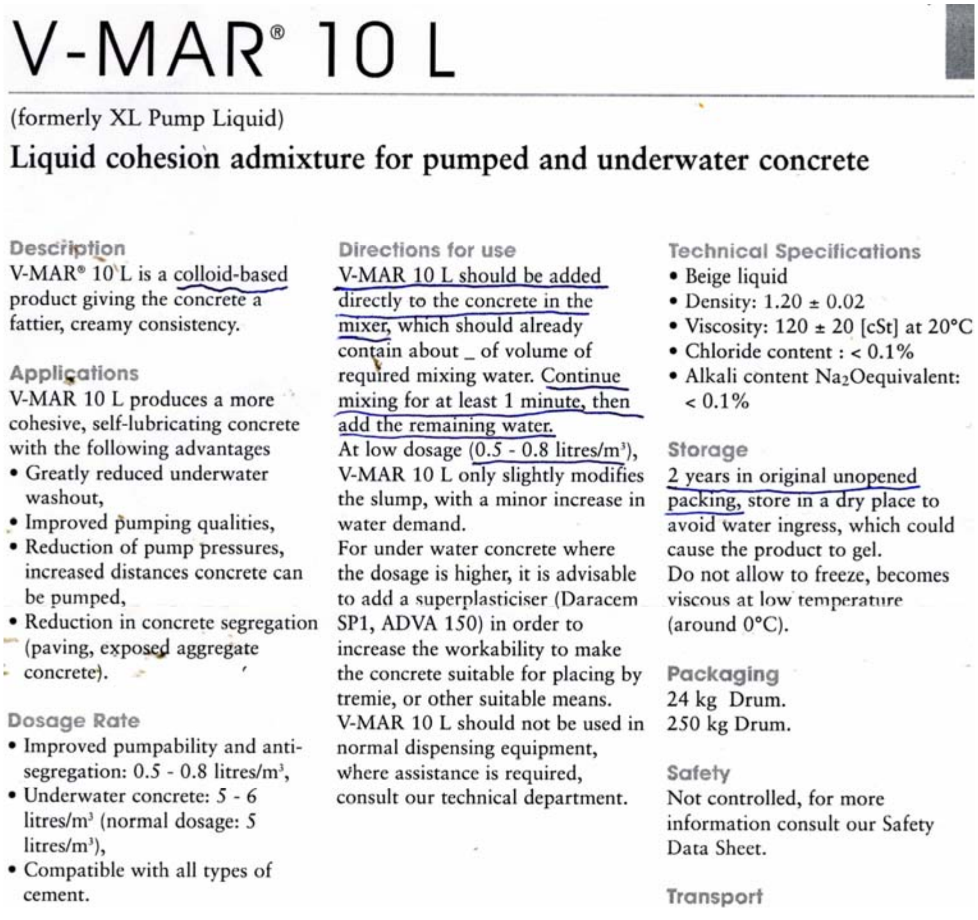
with other admixtures

Structuro 11180 is compatible with other admixtures in the Fosroc range. Admixtures should never be premixed prior to their addition to the concrete mix.

Contact the Fosroc Technical Department for further advice on the effects of various admixtures.

Appendix 5 Viscosity Modifying Agents' data sheets

Four VMAs' data sheets are demonstrated as follows.



V-MAR® 10 L

(formerly XL Pump Liquid)

Liquid cohesion admixture for pumped and underwater concrete

Description

V-MAR® 10 L is a colloid-based product giving the concrete a fattier, creamy consistency.

Applications

V-MAR 10 L produces a more cohesive, self-lubricating concrete with the following advantages

- Greatly reduced underwater washout,
- Improved pumping qualities,
- Reduction of pump pressures, increased distances concrete can be pumped,
- Reduction in concrete segregation (paving, exposed aggregate concrete).

Dosage Rate

- Improved pumpability and anti-segregation: 0.5 - 0.8 litres/m^3,
- Underwater concrete: 5 - 6 litres/m^3 (normal dosage: 5 litres/m^3),
- Compatible with all types of cement.

Directions for use

V-MAR 10 L should be added directly to the concrete in the mixer, which should already contain about _ of volume of required mixing water. Continue mixing for at least 1 minute, then add the remaining water.

At low dosage (0.5 - 0.8 litres/m^3), V-MAR 10 L only slightly modifies the slump, with a minor increase in water demand.

For under water concrete where the dosage is higher, it is advisable to add a superplasticiser (Daracem SP1, ADVA 150) in order to increase the workability to make the concrete suitable for placing by tremie, or other suitable means.

V-MAR 10 L should not be used in normal dispensing equipment, where assistance is required, consult our technical department.

Technical Specifications

- Beige liquid
- Density: 1.20 ± 0.02
- Viscosity: 120 ± 20 [cSt] at 20°C
- Chloride content : < 0.1%
- Alkali content Na_2Oequivalent: < 0.1%

Storage

2 years in original unopened packing, store in a dry place to avoid water ingress, which could cause the product to gel.

Do not allow to freeze, becomes viscous at low temperature (around 0°C).

Packaging

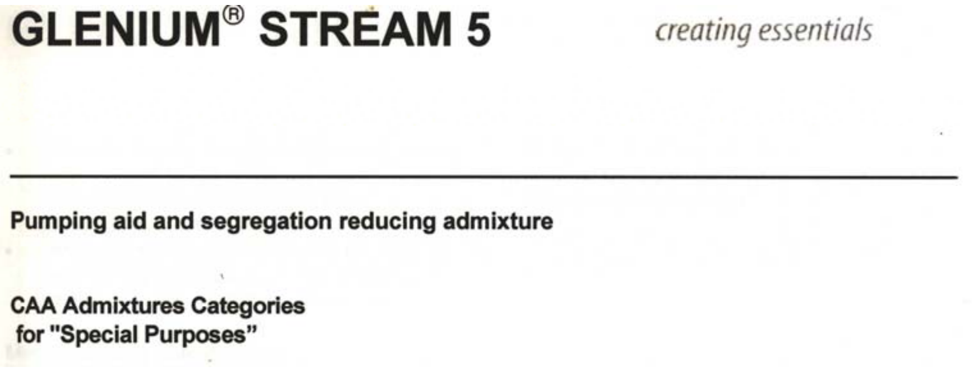
24 kg Drum.

250 kg Drum.

Safety

Not controlled, for more information consult our Safety Data Sheet.

Transport

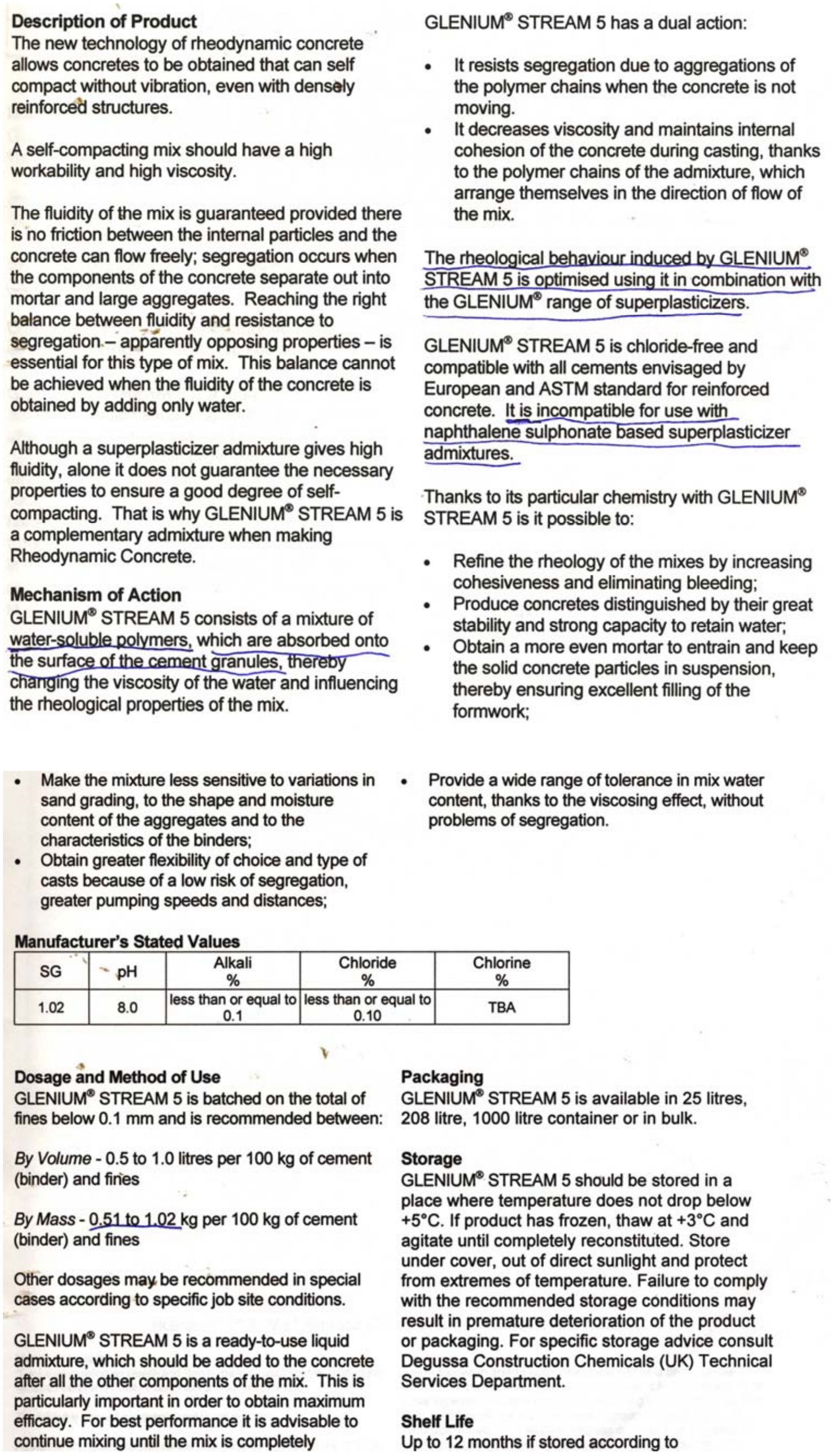


GLENIUM® STREAM 5

creating essentials

Pumping aid and segregation reducing admixture

CAA Admixtures Categories for "Special Purposes"



Description of Product

The new technology of rheodynamic concrete allows concretes to be obtained that can self compact without vibration, even with densely reinforced structures.

A self-compacting mix should have a high workability and high viscosity.

The fluidity of the mix is guaranteed provided there is no friction between the internal particles and the concrete can flow freely; segregation occurs when the components of the concrete separate out into mortar and large aggregates. Reaching the right balance between fluidity and resistance to segregation – apparently opposing properties – is essential for this type of mix. This balance cannot be achieved when the fluidity of the concrete is obtained by adding only water.

Although a superplasticizer admixture gives high fluidity, alone it does not guarantee the necessary properties to ensure a good degree of self-compacting. That is why GLENIUM® STREAM 5 is a complementary admixture when making Rheodynamic Concrete.

Mechanism of Action

GLENIUM® STREAM 5 consists of a mixture of water-soluble polymers, which are absorbed onto the surface of the cement granules, thereby changing the viscosity of the water and influencing the rheological properties of the mix.

GLENIUM® STREAM 5 has a dual action:

- It resists segregation due to aggregations of the polymer chains when the concrete is not moving.
- It decreases viscosity and maintains internal cohesion of the concrete during casting, thanks to the polymer chains of the admixture, which arrange themselves in the direction of flow of the mix.

The rheological behaviour induced by GLENIUM® STREAM 5 is optimised using it in combination with the GLENIUM® range of superplasticizers.

GLENIUM® STREAM 5 is chloride-free and compatible with all cements envisaged by European and ASTM standard for reinforced concrete. It is incompatible for use with naphthalene sulphonate based superplasticizer admixtures.

Thanks to its particular chemistry with GLENIUM® STREAM 5 is it possible to:

- Refine the rheology of the mixes by increasing cohesiveness and eliminating bleeding;
- Produce concretes distinguished by their great stability and strong capacity to retain water;
- Obtain a more even mortar to entrain and keep the solid concrete particles in suspension, thereby ensuring excellent filling of the formwork;
- Make the mixture less sensitive to variations in sand grading, to the shape and moisture content of the aggregates and to the characteristics of the binders;
- Obtain greater flexibility of choice and type of casts because of a low risk of segregation, greater pumping speeds and distances;
- Provide a wide range of tolerance in mix water content, thanks to the viscosing effect, without problems of segregation.

Manufacturer's Stated Values

SG	pH	Alkali %	Chloride %	Chlorine %
1.02	8.0	less than or equal to 0.1	less than or equal to 0.10	TBA

Dosage and Method of Use

GLENIUM® STREAM 5 is batched on the total of fines below 0.1 mm and is recommended between:

By Volume - 0.5 to 1.0 litres per 100 kg of cement (binder) and fines

By Mass - 0.51 to 1.02 kg per 100 kg of cement (binder) and fines

Other dosages may be recommended in special cases according to specific job site conditions.

GLENIUM® STREAM 5 is a ready-to-use liquid admixture, which should be added to the concrete after all the other components of the mix. This is particularly important in order to obtain maximum efficacy. For best performance it is advisable to continue mixing until the mix is completely

Packaging

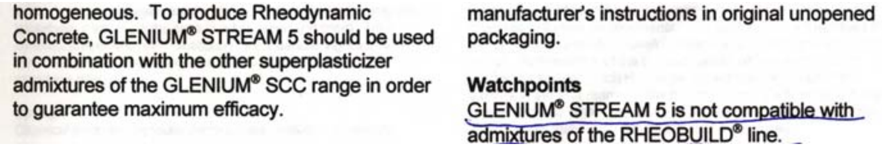
GLENIUM® STREAM 5 is available in 25 litres, 208 litre, 1000 litre container or in bulk.

Storage

GLENIUM® STREAM 5 should be stored in a place where temperature does not drop below +5°C. If product has frozen, thaw at +3°C and agitate until completely reconstituted. Store under cover, out of direct sunlight and protect from extremes of temperature. Failure to comply with the recommended storage conditions may result in premature deterioration of the product or packaging. For specific storage advice consult Degussa Construction Chemicals (UK) Technical Services Department.

Shelf Life

Up to 12 months if stored according to

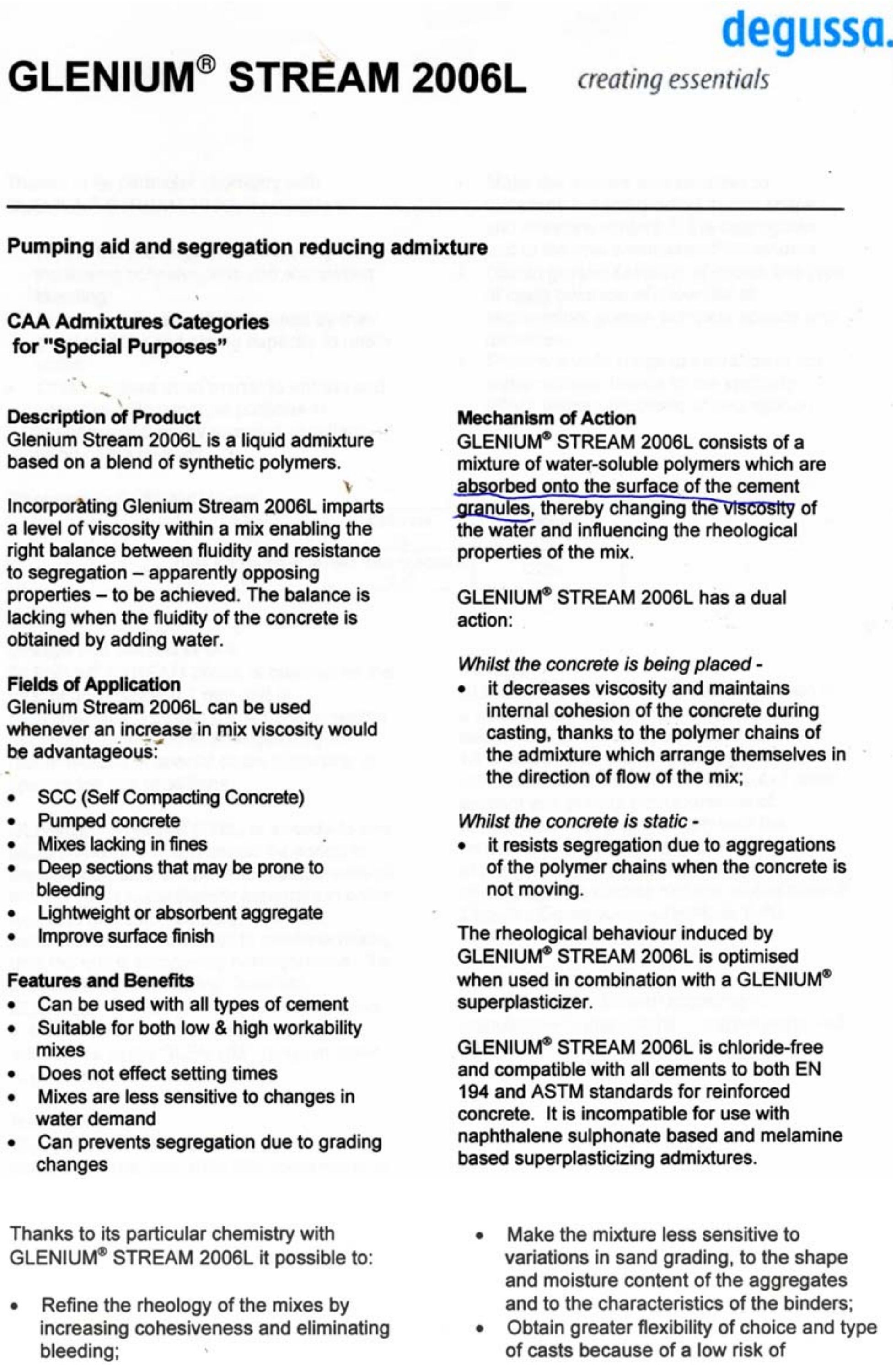


homogeneous. To produce Rheodynamic Concrete, GLENIUM® STREAM 5 should be used in combination with the other superplasticizer admixtures of the GLENIUM® SCC range in order to guarantee maximum efficacy.

manufacturer's instructions in original unopened packaging.

Watchpoints

GLENIUM® STREAM 5 is not compatible with admixtures of the RHEOBUILD® line.



degussa.

GLENIUM® STREAM 2006L

creating essentials

Pumping aid and segregation reducing admixture

CAA Admixtures Categories for "Special Purposes"

Description of Product

Glenium Stream 2006L is a liquid admixture based on a blend of synthetic polymers.

Incorporating Glenium Stream 2006L imparts a level of viscosity within a mix enabling the right balance between fluidity and resistance to segregation – apparently opposing properties – to be achieved. The balance is lacking when the fluidity of the concrete is obtained by adding water.

Fields of Application

Glenium Stream 2006L can be used whenever an increase in mix viscosity would be advantageous:

- SCC (Self Compacting Concrete)
- Pumped concrete
- Mixes lacking in fines
- Deep sections that may be prone to bleeding
- Lightweight or absorbent aggregate
- Improve surface finish

Features and Benefits

- Can be used with all types of cement
- Suitable for both low & high workability mixes
- Does not effect setting times
- Mixes are less sensitive to changes in water demand
- Can prevents segregation due to grading changes

Mechanism of Action

GLENIUM® STREAM 2006L consists of a mixture of water-soluble polymers which are absorbed onto the surface of the cement granules, thereby changing the viscosity of the water and influencing the rheological properties of the mix.

GLENIUM® STREAM 2006L has a dual action:

Whilst the concrete is being placed -

- it decreases viscosity and maintains internal cohesion of the concrete during casting, thanks to the polymer chains of the admixture which arrange themselves in the direction of flow of the mix;

Whilst the concrete is static -

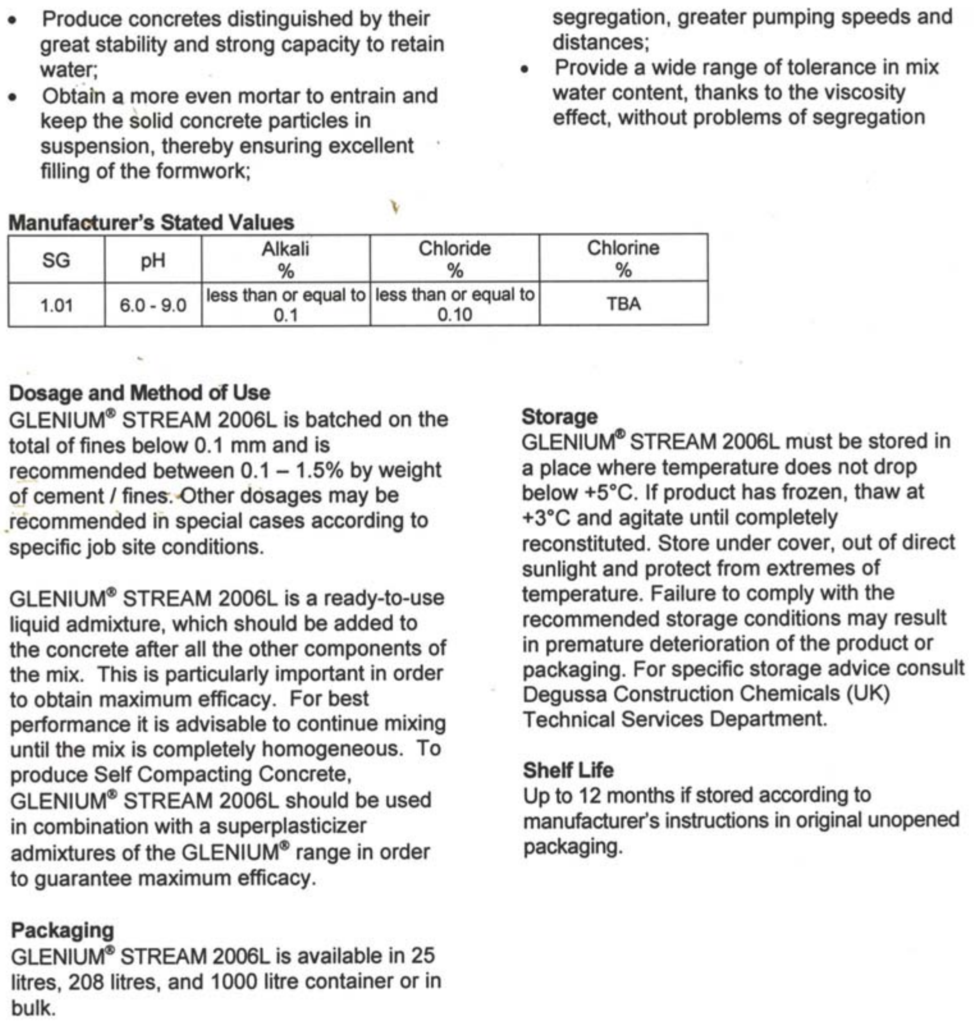
- it resists segregation due to aggregations of the polymer chains when the concrete is not moving.

The rheological behaviour induced by GLENIUM® STREAM 2006L is optimised when used in combination with a GLENIUM® superplasticizer.

GLENIUM® STREAM 2006L is chloride-free and compatible with all cements to both EN 194 and ASTM standards for reinforced concrete. It is incompatible for use with naphthalene sulphonate based and melamine based superplasticizing admixtures.

Thanks to its particular chemistry with GLENIUM® STREAM 2006L it possible to:

- Refine the rheology of the mixes by increasing cohesiveness and eliminating bleeding;
- Make the mixture less sensitive to variations in sand grading, to the shape and moisture content of the aggregates and to the characteristics of the binders;
- Obtain greater flexibility of choice and type of casts because of a low risk of



- Produce concretes distinguished by their great stability and strong capacity to retain water;
- Obtain a more even mortar to entrain and keep the solid concrete particles in suspension, thereby ensuring excellent filling of the formwork;

segregation, greater pumping speeds and distances;

- Provide a wide range of tolerance in mix water content, thanks to the viscosity effect, without problems of segregation

Manufacturer's Stated Values

SG	pH	Alkali %	Chloride %	Chlorine %
1.01	6.0 - 9.0	less than or equal to 0.1	less than or equal to 0.10	TBA

Dosage and Method of Use

GLENIUM® STREAM 2006L is batched on the total of fines below 0.1 mm and is recommended between 0.1 – 1.5% by weight of cement / fines. Other dosages may be recommended in special cases according to specific job site conditions.

GLENIUM® STREAM 2006L is a ready-to-use liquid admixture, which should be added to the concrete after all the other components of the mix. This is particularly important in order to obtain maximum efficacy. For best performance it is advisable to continue mixing until the mix is completely homogeneous. To produce Self Compacting Concrete, GLENIUM® STREAM 2006L should be used in combination with a superplasticizer admixtures of the GLENIUM® range in order to guarantee maximum efficacy.

Packaging

GLENIUM® STREAM 2006L is available in 25 litres, 208 litres, and 1000 litre container or in bulk.

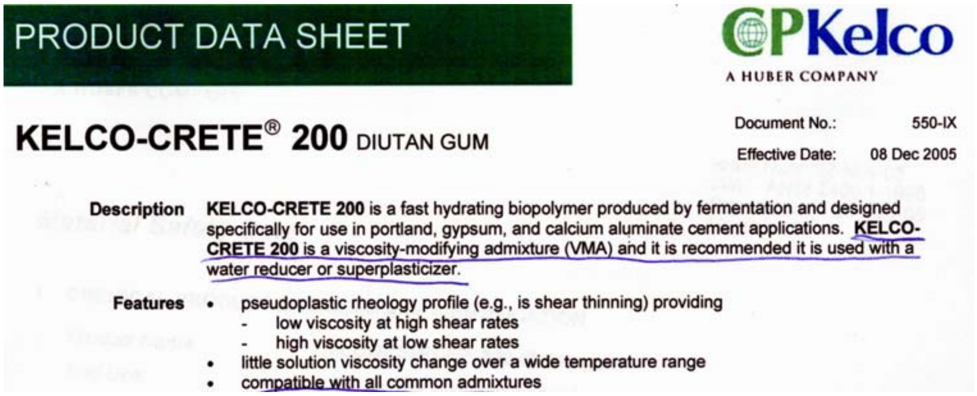
Storage

GLENIUM® STREAM 2006L must be stored in a place where temperature does not drop below +5°C. If product has frozen, thaw at +3°C and agitate until completely reconstituted. Store under cover, out of direct sunlight and protect from extremes of temperature. Failure to comply with the recommended storage conditions may result in premature deterioration of the product or packaging. For specific storage advice consult Degussa Construction Chemicals (UK) Technical Services Department.

Shelf Life

Up to 12 months if stored according to manufacturer's instructions in original unopened packaging.

KELCO-CRETE 200 diutan gum is produced by CP Kelco, which is a leading global producer of specialty hydrocolloids with more than 2,000 customers in over 100 countries, and facilities in North America, Europe, Asia and Latin America.



PRODUCT DATA SHEET

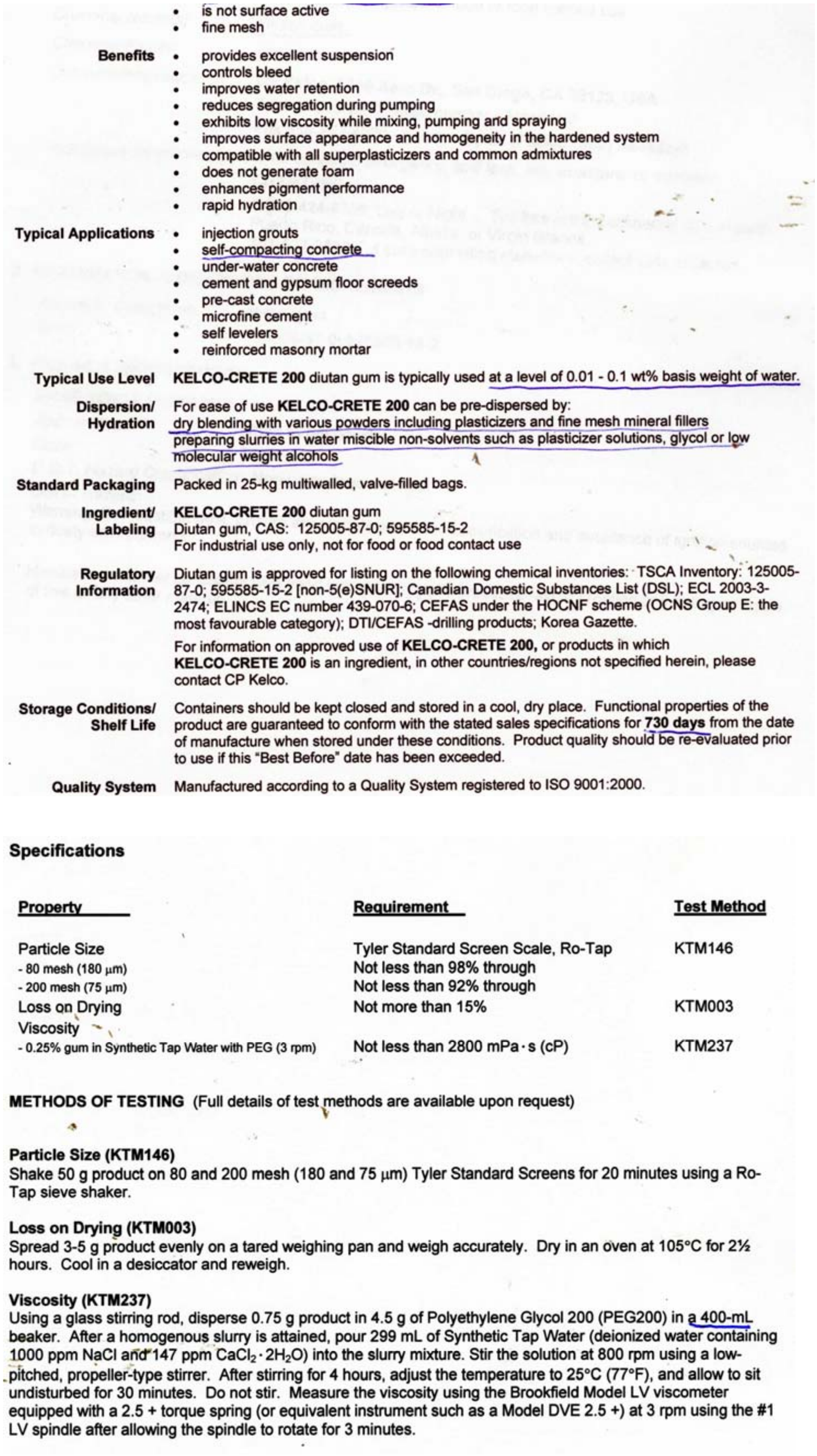
CPKelco
A HUBER COMPANY

KELCO-CRETE® 200 DIUTAN GUM

Document No.: 550-IX
Effective Date: 08 Dec 2005

Description **KELCO-CRETE 200** is a fast hydrating biopolymer produced by fermentation and designed specifically for use in portland, gypsum, and calcium aluminate cement applications. **KELCO-CRETE 200** is a viscosity-modifying admixture (VMA) and it is recommended it is used with a water reducer or superplasticizer.

Features
- pseudoplastic rheology profile (e.g., is shear thinning) providing
  - low viscosity at high shear rates
  - high viscosity at low shear rates
- little solution viscosity change over a wide temperature range
- compatible with all common admixtures



- is not surface active
- fine mesh

Benefits

- provides excellent suspension
- controls bleed
- improves water retention
- reduces segregation during pumping
- exhibits low viscosity while mixing, pumping and spraying
- improves surface appearance and homogeneity in the hardened system
- compatible with all superplasticizers and common admixtures
- does not generate foam
- enhances pigment performance
- rapid hydration

Typical Applications

- injection grouts
- self-compacting concrete
- under-water concrete
- cement and gypsum floor screeds
- pre-cast concrete
- microfine cement
- self levelers
- reinforced masonry mortar

Typical Use Level **KELCO-CRETE 200** diutan gum is typically used at a level of 0.01 - 0.1 wt% basis weight of water.

Dispersion/ Hydration For ease of use **KELCO-CRETE 200** can be pre-dispersed by:
dry blending with various powders including plasticizers and fine mesh mineral fillers
preparing slurries in water miscible non-solvents such as plasticizer solutions, glycol or low molecular weight alcohols

Standard Packaging Packed in 25-kg multiwalled, valve-filled bags.

Ingredient/ Labeling **KELCO-CRETE 200** diutan gum
Diutan gum, CAS: 125005-87-0; 595585-15-2
For industrial use only, not for food or food contact use

Regulatory Information Diutan gum is approved for listing on the following chemical inventories: TSCA Inventory: 125005-87-0; 595585-15-2 [non-5(e)SNUR]; Canadian Domestic Substances List (DSL); ECL 2003-3-2474; ELINCS EC number 439-070-6; CEFAS under the HOCNF scheme (OCNS Group E: the most favourable category); DTI/CEFAS -drilling products; Korea Gazette.

For information on approved use of **KELCO-CRETE 200,** or products in which **KELCO-CRETE 200** is an ingredient, in other countries/regions not specified herein, please contact CP Kelco.

Storage Conditions/ Shelf Life Containers should be kept closed and stored in a cool, dry place. Functional properties of the product are guaranteed to conform with the stated sales specifications for **730 days** from the date of manufacture when stored under these conditions. Product quality should be re-evaluated prior to use if this "Best Before" date has been exceeded.

Quality System Manufactured according to a Quality System registered to ISO 9001:2000.

Specifications

Property	**Requirement**	**Test Method**
Particle Size	Tyler Standard Screen Scale, Ro-Tap	KTM146
- 80 mesh (180 μm)	Not less than 98% through	
- 200 mesh (75 μm)	Not less than 92% through	
Loss on Drying	Not more than 15%	KTM003
Viscosity		
- 0.25% gum in Synthetic Tap Water with PEG (3 rpm)	Not less than 2800 mPa·s (cP)	KTM237

METHODS OF TESTING (Full details of test methods are available upon request)

Particle Size (KTM146)
Shake 50 g product on 80 and 200 mesh (180 and 75 μm) Tyler Standard Screens for 20 minutes using a Ro-Tap sieve shaker.

Loss on Drying (KTM003)
Spread 3-5 g product evenly on a tared weighing pan and weigh accurately. Dry in an oven at 105°C for 2½ hours. Cool in a desiccator and reweigh.

Viscosity (KTM237)
Using a glass stirring rod, disperse 0.75 g product in 4.5 g of Polyethylene Glycol 200 (PEG200) in a 400-mL beaker. After a homogenous slurry is attained, pour 299 mL of Synthetic Tap Water (deionized water containing 1000 ppm NaCl and 147 ppm $CaCl_2 \cdot 2H_2O$) into the slurry mixture. Stir the solution at 800 rpm using a low-pitched, propeller-type stirrer. After stirring for 4 hours, adjust the temperature to 25°C (77°F), and allow to sit undisturbed for 30 minutes. Do not stir. Measure the viscosity using the Brookfield Model LV viscometer equipped with a 2.5 + torque spring (or equivalent instrument such as a Model DVE 2.5 +) at 3 rpm using the #1 LV spindle after allowing the spindle to rotate for 3 minutes.

Appendix 6 The Influence of Viscosity Modifying Agents on Segregated Mortar Mixes

The complete results of the effect of VMAs on segregated mortar mixes as shown in Figure 5-20 Effects of four Sp-VMA combinations on (a) spread (b) V-funnel flow time (c) yield stress (d) plastic viscosity of mortar are demonstrated in the following table.

SP&VMA	W/C BY WT.	SP (% CEMENT MASS)	VMA'S DRY CONTENT[1] (% CEMENT WT.)	SPREAD (MM)	V-FUNNEL TIME (SECS)	PLASTIC VISCOSITY (PA.S)	YIELD STRESS (PA)
ADVA Flow 410 & V-Mar 10L	0.40	1.6%	0%	380	1.7	3.9	-4
	0.40	1.6%	0.01%	337	1.7	3.4	1
	0.40	1.6%	0.01%	308	2.1	3.9	7
	0.40	1.6%	0.02%	292	2.2	4.5	16
	0.40	1.6%	0.01%	320	1.9	3.4	4
	0.40	1.6%	0.01%	297	2.1	4.1	13
	0.40	1.6%	0.02%	274	2.7	5.1	26
Glenium Sky 544 & Glenium Stream 5	0.45	2.2%	0%	390	1.2	1.2	-2
	0.45	2.2%	0.01%	383	1.3	1.5	-2
	0.45	2.2%	0.02%	390	1.2	1.6	-2
	0.45	2.2%	0.03%	390	1.3	1.4	-2
	0.45	2.2%	0.04%	375	1.3	1.5	-2
	0.45	2.2%	0.05%	390	1.3	1.5	-2
	0.45	2.2%	0.06%	380	1.3	1.6	-1
	0.45	2.2%	0.13%	375	1.4	1.7	-1
	0.45	2.2%	0.32%	361	1.5	2.0	-1
Glenium Sky 544 & Glenium Stream 2006L	0.45	2.2%	0%	400	1.2	3.0	-7
	0.45	2.2%	0.01%	303	1.3	2.1	9
	0.45	2.2%	0.02%	262	1.4	2.5	31
	0.45	2.2%	0.03%	230	1.8	3.1	81
	0.45	2.2%	0.04%	211	2.0	2.4	82
Sika ViscoCrete 10 & KELCO-CRETE 200 diutan gum	0.40	1.2%	0%	370	1.5		
	0.40	1.2%	0%	358	1.3	3.0	-8
	0.40	1.2%	0.05%	231	4.3	7.1	76
	0.40	1.2%	0.1%	197	8.1	8.7	124
	0.40	1.2%	0.2%	155	27.1		

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[1] To compare the effects, VMA contents were expressed as the ratio between dry content to cement wt.

	0.40	1.2%	0.4%	100	-		

Appendix 7 Minimum Paste Volume Calculation

The calculations for the minimum paste volume using CBI method's parameters and the sizes of aggregate in the project (results shown in Figure 6-4 Relationship between coarse aggregate ratio, void content and minimum paste volume).

STEP	DESCRIPTION		OUTPUT										
1	Agg. size (M_i)		0/4 mm				4/10 mm				10/20 mm		
2	Agg. particle size[1]		3.0 mm				8.5 mm				17.5 mm		
3	D_{ca}=C/D_{af}		11.3				4.0				1.9		
4a	Blocking ratio (n_{abi})[2]		0.76				0.59				0.34		
4b	Agg. i to total agg. vol. ratio (V_{ai}) %	0/4 mm	100	90	80	70	60	50	40	30	20	10	0
		4/10 mm	0	3	7	10	13	17	20	23	26	30	33
		10/20 mm	0	7	13	20	27	33	40	47	54	60	67
	Max. total agg. vol.[3]		0.76	0.69	0.64	0.59	0.55	0.52	0.48	0.46	0.43	0.41	0.39
5	Min. paste vol.[4]		0.24	0.31	0.36	0.41	0.45	0.48	0.52	0.54	0.57	0.59	0.61

The calculations for the minimum paste volume using CBI method's parameters and the sizes of aggregate are shown in the following table.

STEP	DESCRIPTION		OUTPUT										
1	Agg. size (M_i)		0/8 mm					8/16 mm					
2	Agg. particle size		6 mm					14 mm					
3	D_{ca}=C/D_{af}		5.7					2.4					
4a	Blocking ratio (n_{abi})[5]		0.65					0.51					
4b	Agg. i to total agg. vol. ratio (V_{ai}) %	0/8 mm	100	90	80	70	60	50	40	30	20	10	0
		8/16 mm	0	10	20	30	40	50	60	70	80	90	100
	Max. total agg. volume		0.65	0.63	0.62	0.60	0.59	0.57	0.56	0.55	0.54	0.52	0.51
5	Min. paste vol.[6]		0.35	0.37	0.38	0.40	0.41	0.43	0.44	0.45	0.46	0.48	0.49

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[1] $D_{af}=M_{i-1}+(M_i-M_{i-1})*3/4$

[2] n_{abi} is determined by the model in Figure 6-5. Blocking volume ratio. $v_{abi} = n_{abi}$ when concrete volume V_t, was considered to be 1.

[3] $V_{tmax}=1/(\Sigma V_{ai}/n_{abi})$ (V_{tmax} is the volume at which the risk of block equals to 1. $\sum (n_{ai}/n_{abi}) = \sum (v_{ai}v_{tmax}/v_{abi}) = 1$)

[4] $V_{pmin}=1-V_{tmax}$

[5] n_{abi} is determined by the relationship of K=1.05 in Figure 6-5.

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[6] Plotted in Figure 6-4.

Appendix 8 UCL Mix Design Method

The complete results shown in Figure 6-7 The relationships between (a) yield stress and spread and (b) between plastic viscosity and V-funnel time in mortar tests are demonstrated in the following table.

MORTAR MIXES	CEM. REPLACE. (VOL.)	W/P BY WT	SP (POWDER WT./WT.)	VMA (CEM. WT.)	SPREAD (MM)	V-FUNNEL TIME (SECS)	PLASTIC VISCOSITY (PA.S)	YIELD STRESS (PA)
with fly ash	0%	0.300	1.3%		300	4.2	8.4	5
	20%	0.317	1.3%		335	4.2	7.2	-3
	40%	0.336	1.3%		343	4.1	8.1	-19
	60%	0.358	1.3%		335	4.3	6.2	-20
	80%	0.383	1.3%		324	5.4	8.4	-15
	100%	0.411	1.3%		317	9.6	15.2	0
	0%	0.30	1.3%		327	3.9	6.9	-6
	20%	0.30	1.3%		333	5.8	10.6	-14
	40%	0.30	1.3%		331	6.9	12.1	-24
	60%	0.30	1.3%		325	10.6	25.3	-25
	80%	0.30	1.3%		319	19.2	39.2	-19
	20%	0.34	1.6%		340	3.0	5.6	-16
	0%	0.36	1.6%		355	1.6	2.8	-11
	20%	0.36	1.6%		345	2.1	4.2	-15
	20%	0.37	1.5%		344	1.9	3.0	-9
	0%	0.34	1.3		343	2.5	4.4	-4
	20%	0.34	1.3%		352	2.9	5.4	-13
	40%	0.34	1.3%		352	3.5	4.3	-8
	60%	0.34	1.3%		343	4.7	7.2	-12
	80%	0.34	1.3%		336	7.2	10.2	-15
	100%	0.34	1.3%		340	21.1	30.4	-92
	0%	0.34	1.3%		333	2.6	4.0	-9
	0%	0.34	1.3%		330	2.6	4.3	-9
	20%	0.34	1.3%		336	3.1	4.6	-13
	40%	0.34	1.3%		335	3.4	5.5	-14
	60%	0.34	1.3%		340	3.9	6.5	-17
	80%	0.34	1.3%		340	4.8	6.5	-19
	100%	0.34	1.3%		337	6.0	8.7	-27
	25%	0.34	0.7%		278	3.8	7.9	32
	50%	0.34	0.9%		324	4.1	7.4	-5
	50%	0.34	0.9%		342	3.5	6.3	-6
	50%	0.34	0.9%		329	3.5	6.5	-5
	50%	0.34	0.9%		332	3.4	6.7	-4
	50%	0.34	0.9%		332	3.5	6.4	-6
	75%	0.34	1.1%		342	4.7	8.0	-19
	100%	0.34	1.3%		346	5.9	8.5	-27
	50%	0.37	0.7%		309	2.8	5.3	8
	50%	0.37	0.7%		306	2.6	5.0	13
	50%	0.37	0.7%		312	2.5	4.3	12

	50%	0.37	0.7%		313	2.6	5.0	9
	50%	0.37	0.7%		312	2.5	4.8	11
	25%	0.37	0.9%		337	1.9	3.4	-6
	100%	0.37	1.1%		342	4.1	5.9	-18
	75%	0.37	1.3%		348	2.7	4.0	-14
	75%	0.40	0.7%		319	2.3	3.9	5
	100%	0.40	0.9%		348	2.9	5.1	-10
	25%	0.40	1.1%		317	5.1	12.3	-11
	50%	0.40	1.3%		354	1.7	2.3	-6
	100%	0.43	0.7%		329	2.1	3.3	6
	75%	0.43	0.9%		350	1.6	3.1	-8
	50%	0.43	1.1%		356	1.3	1.6	-1
	25%	0.43	1.3%		353	1.3	1.9	0
With ADVA Flow 410 & V-Mar 10		0.4	1.6%	0.00%	380	1.7	3.9	0
		0.4	1.6%	0.05%	337	1.7	3.4	1
		0.4	1.6%	0.09%	308	2.1	3.9	7
		0.4	1.6%	0.14%	292	2.2	4.5	16
		0.4	1.6%	0.05%	320	1.9	3.4	4
		0.4	1.6%	0.09%	297	2.1	4.1	13
		0.4	1.6%	0.14%	274	2.7	5.1	26
		0.4	1.6%	0.09%	296	2.3	4.3	15
		0.4	1.6%	0.09%	300	2.1	3.9	14
With Glenium 544 & Stream 5		0.31	2.2%	0.0%	275	6.8	14.1	52
		0.40	2.2%	0.0%	365	1.7	2.5	0
		0.45	2.2%	0.0%	390	1.2	1.2	-2
		0.45	2.2%	0.3%	383	1.3	1.5	-2
		0.45	2.2%	0.6%	390	1.2	1.6	-2
		0.45	2.2%	0.9%	390	1.3	1.4	-2
		0.45	2.2%	1.2%	375	1.3	1.5	-2
		0.45	2.2%	1.5%	390	1.3	1.5	-2
		0.45	2.2%	2.0%	380	1.3	1.6	-1
		0.45	2.2%	4.0%	375	1.4	1.7	-1
		0.45	2.2%	10.0%	361	1.5	2.0	-1
With Glenium 544 & Stream 2006L		0.31	2.2	0.0%	327	4.9	12.8	-7
		0.45	2.2	0.0%	400	1.2	3.0	-7
		0.45	2.2	0.3%	303	1.3	2.1	9
		0.45	2.2	0.6%	262	1.4	2.5	31
		0.45	2.2	0.9%	230	2.3	3.1	81
		0.45	2.2	1.2%	211	2.0	2.4	82
Sika Viscocrete 10 & KELCO-CRETE 200 diutan gum		0.4	1.2%	0.00%	358	1.3	3.0	-8
		0.4	1.2%	0.05%	231	4.3	7.1	76
		0.4	1.2%	0.10%	197	8.1	8.7	124

The complete results shown in Figure 6-8 Relationships between (a) spread of mortar and slump flow of concrete and (b) V-funnel times of mortar and concrete, Figure 9-1 Spread of mortar vs. slump flow of SCC and Figure 9-2 V-funnel time of mortar vs. V-funnel time of SCC are demonstrated in the following table.

CONCRETE MIXES											MORTAR MIXES	
Coarse aggregate content dry-rodded bulk density (volume ratio)	Ref.	Slump flow (mm)	SF at 65min (mm)	T500 (secs)	T500 at 65 min (secs)	V-funnel time (secs)	t_v at 65 min. (secs)	J-ring (mm)		SI (%)	Spread (mm)	V-funnel time (secs)
								Step	Spread			
	6.2	555				15.4					250	5.2
		790				6.5					315	4.7
		760				7.2					315	4.7
50% (32.3%)	**6.1**	790				3.8						
		510				8.0						
		830				10.0						
		760				4.9		10				
		730				5.3		15				
	6.3	795				5.0					343	2.5
		740				7.9					334	4.0
		735				9.0					328	4.0
55% (35.5%)		662				14.2					328	4.0
		658				4.6					326	1.6
		663				8.3					333	3.3
		683				7.7					327	2.6
60% (38.8)		805				4.9					365	1.2
		602				10.7					337	2.0
		765				5.6					359	1.4
		712				7.4						
65% (42.0%)		716									360	
		666				13.0					353	1.4
		721									363	

50% (32.3%)	**Chapter 7**, **Chapter 8** (cement only)	805	635	1.0	1.9	5.0	6.5	6	735	16%	343	2.5
55% (35.5%)		662	443	2.5		14.2	34.7	31		5%	328	4.0
		690				8.9					332	3.0
		779		1.3		5.6		18	653	11%	340	2.8
		658	454	1.3	3.1	4.6	5.9	26	500	6%	326	1.6
60% (38.8%)		463	366	8.7		35.0	block	35	343	1%	317	3.3
		602	517	2.8	3.8	10.7	16.1	24	530	6%	333	2.0
		760	754	1.7	1.9	5.6	7.7	14	721	16%	359	1.4
		805	770		1.3	4.0	10.8	7	750	30%	365	1.2
65% (42.0%)		646	658	2.9	3.2	17.0	block	34	608	4%	353	1.6
		721	709	3.0	4.3	13.0	27.4	26	662	10%	360	1.3
		716	655	2.5	3.1	14.0	28.2	31	634	9%	360	1.3
55% (35.5%)	**Chapter 7** (20% fly ash)	665	552	3.5	4.5	11.4	15.1	17	634	6%	332	3.7
		627	426	3.2		13.3	27.0	24	489	4%	329	4.4
		634	497	3.0	10.5	10.8	16.2	23	548	5%	334	3.7
		795	683	2.2	3.4	7.0	11.4	12	705	17%	348	2.2
		703	565	3.6	7.6	12.3	20.2	17	604	8%	334	4.1
		615	458	2.0		6.0	10.1	25	514	5%	329	2.5
60% (38.8%)		670	502	3.6	6.4	15.9	48.4	27	560	6%	338	2.9
		803	743	3.5	3.5	10.0	21.2	19	704	15%	360	2.2
		735	643	5.0	7.1	22.3	40.6	26	624	4%	348	3.0
55% (35.5%)	**Chapter 7** (40% fly ash)	555	345			10.0	29.2	21	390	3%	300	3.4
		591	384	2.0		7.3	15.6	25	410	4%	310	2.9
		636	420			5.8	10.1	17	499	7%	327	2.7
		529	350	3.4		15.0	21.8	38	387	2%	310	4.0
	Chapter 7 (60% fly ash)	580	335	2.6		8.9	36.6	35	365	2%	313	3.3
		725	385	1.9		6.6	13.1	20	560	13%	343	2.8
		622	356	2.2		7.0	25.5	21	421	3%	320	2.3
		528	295	2.9		8.7	block	25	358	3%	305	2.6
		715	433			6.3	9.8	20	548	13%	333	3.1
	Chapter 7	705	415	2.0		9.4	18.9	22	553	5%	346	2.8

	(80% fly ash)	510	305	2.5		8.4	30.9	44	363	2%	300	2.8
		803	455			6.3	10.3	10	646	18%	355	2.5
		529	345			9.0	11.9	21	369	3%	305	2.7
		648	368			5.8	9.8	30	407	5%	334	3.0
	Chapter 7 (fly ash only)	610	320	2.1		10.0	block	31	392	3%		
		521	409			5.3	7.8	24	410	3%		
		825				6.9					355	2.0
		773				6.7					352	2.0
		754				7.8					346	2.8
		577		6.0		25.0					310	6.6
		658				10.7					326	4.0
		769				6.3					352	2.5
		815		1.8		5.5		6	790	26%	352	2.1
		582	396			10.7	7.3	30	443	6%	315	3.3
		521	409			6.3	7.8	24	410	3%	303	2.6
	Chapter 8	757	645			8.2	9.6	14	694	9%	334	3.0
		790								25%	342	3.3
		775	413			7.9	16.7	24	609	10%	346	3.2
		710	338			9.5	block	29	463	3%	333	3.5
		720	488			13.9	13.8	24	638	5%	333	3.4

Appendix 9 Hardened Self-compacting Concrete with Fly Ash

The complete results shown in Table 7-7 Hardened properties of target SCC are demonstrated as follows.

MIX NO.	AGE	TESTS ON CUBES					TESTS ON CYLINDERS			TESTS ON PRISMS		
		density (kg/m^3)	UPV (km/s)	Average (km/s)	compressive strength (MPa)	Average (MPa)	density (kg/m^3)	splitting strength (MPa)	Average (MPa)	density (kg/m^3)	Ed (GPa)	Average (GPa)
F0 -1	7d	2382	4.73	4.71	65.0	63.4				2385	47	47
F0 -2		2381	4.69		62.3					2382	47	
F0 -3		2380	4.72		63.0					2380	47	
F0 -1	28d	2385	4.88	4.91	62.7	73.3	2384	5.5	5.5	2386	48	48
F0 -2		2392	4.88		76.7		2380	5.0		2384	49	
F0 -3		2388	4.98		69.8		2385	5.9		2382	48	
F0 -1	60d									2387	49	49
F0 -2										2385	49	
F0 -3										2384	49	
F0 -1	90d	2378	4.82	4.93	78.8	79.0	2383	6.5	5.9	2389	50	49
F0 -2		2388	4.88		79.3		2374	6.0		2387	50	
F0 -3		2381	4.98		78.9		2377	5.3		2384	49	
F0 -1	120d									2395	50	50
F0 -2										2388	50	
F0 -3										2385	49	
F0 -1	150d									2375	49	50
F0 -2										2388	50	
F0 -3										2401	50	
F0 -1	180d	2385	5.00	4.97	91.2	84.1				2389	50	50
F0 -2		2388	5.01		84.1					2386	50	

F0 -3		2381	4.89		77.1					2385	50	
F20 -1	7d	2365	4.64	4.63	55.7	53.1				2378	46	45
F20 -2		2367	4.61		49.9					2371	45	
F20 -3		2360	4.65		53.7					2371	45	
F20 -1	28d	2385	4.82	4.89	62.7	69.7	2371	5.6	5.5	2380	48	47
F20 -2		2392	4.88		76.7		2371	5.5		2373	47	
F20 -3		2388	4.98		69.8		2371	5.5		2373	47	
F20 -1	60d									2385	49	49
F20 -2										2376	49	
F20 -3										2376	48	
F20 -1	90d	2364	4.88	4.93	77.0	78.0	2370	5.8	6.0	2384	50	49
F20 -2		2375	4.98		79.0		2380	6.1		2378	49	
F20 -3		2382	4.93		78.1		2370	6.2		2378	49	
F20 -1	120d									2392	50	50
F20 -2										2379	50	
F20 -3										2379	49	
F20 -1	150d									2385	50	50
F20 -2										2378	50	
F20 -3										2378	49	
F20 -1	180d	2370	4.94	4.94	89.4	83.2				2385	51	50
F20 -2		2384	4.91		78.6					2379	50	
F20 -3		2379	4.98		81.5					2379	50	
F40 - 1	7d	2289	4.52	4.53	43.4	43.3				2305	41	41
F40 - 2		2293	4.51		42.8					2307	42	
F40 - 3		2301	4.55		43.8					2303	41	
F40 - 1	28d	2307	4.72	4.71	58.5	58.5	2305	4.2	4.2	2309	44	44
F40 - 2		2298	4.69		57.1		2304	3.8		2309	45	
F40 - 3		2298	4.72		60.0		2304	4.7		2306	44	
F40 - 1	60d									2310	45	46

F40 - 2										2312	46	
F40 - 3										2309	46	
F40 - 1	90d	2288	4.76	4.75	61.6	63.0	2306	5.9	5.6	2311	46	46
F40 - 2		2303	4.73		62.4		2306	5.0		2313	47	
F40 - 3		2310	4.77		65.0		2309	5.9		2309	46	
F40 - 1	120d									2310	46	47
F40 - 2										2311	47	
F40 - 3										2309	46	
F40 - 1	150d									2318	47	47
F40 - 2										2314	47	
F40 - 3										2312	47	
F40 - 1	180d	2310	4.87	4.86	66.3	68.0				2313	47	47
F40 - 2		2303	4.82		69.6					2314	47	
F40 - 3		2311	4.89		68.1					2309	47	
F60 - 1	7d	2235	4.40	4.37	25.0	24.5				2269	36	36
F60 - 2		2231	4.34		24.9					2271	37	
F60 - 3		2248	4.39		23.6					2267	36	
F60 - 1	28d	2258	4.55	4.56	32.6	37.2	2261	3.5	3.3	2270	39	39
F60 - 2		2242	4.57		38.0		2268	3.2		2273	40	
F60 - 3		2258	4.66		41.2		2263	2.4		2269	39	
F60 - 1	60d									2278	41	41
F60 - 2										2276	41	
F60 - 3										2272	41	
F60 - 1	90d	2246	4.66	4.65	46.6	49.3	2268	4.1	4.2	2274	42	42
F60 - 2		2251	4.63		50.7		2257	4.2		2277	42	
F60 - 3		2270	4.67		50.8		2260	4.1		2272	42	
F60 - 1	120d									2274	42	43
F60 - 2										2277	43	
F60 - 3										2273	43	

F60 - 1	150d									2283	43	43
F60 - 2										2277	44	
F60 - 3										2273	43	
F60 - 1	180d	2234	4.72	4.72	61.6	56.4				2274	43	43
F60 - 2		2252	4.72		54.4					2277	44	
F60 - 3		2246	4.74		53.4					2273	43	
F80(2) - 1	7d	2266	4.20	4.20	8.5	8.4				2223	27	26
F80(2) - 2		2254	4.25		8.7					2100	25	
F80(2) - 3		2234	4.15		8.1					2215	27	
F80(2) - 1	28d	2226	4.39	4.35	15.8	16.0	2214	1.6	1.8	2221	31	31
F80(2) - 2		2234	4.33		15.5		2207	1.8		2217	31	
F80(2) - 3		2251	4.35		16.7		2217	2.0		2214	31	
F80(2) - 1	60d									2224	33	33
F80(2) - 2										2219	33	
F80(2) - 3										2217	33	
F80(2) - 1	90d	2243	4.37	4.43	26.1	26.1	2218	2.2	2.3	2226	34	34
F80(2) - 2		2233	4.55		25.5		2217	2.6		2220	34	
F80(2) - 3		2225	4.39		26.6		2213	2.2		2218	34	
F80(2) - 1	120d									2228	35	35
F80(2) - 2										2223	35	
F80(2) - 3										2219	34	
F80(2) - 1	150d									2226	35	35
F80(2) - 2										2222	35	
F80(2) - 3										2224	35	
F80(2) - 1	180d	2278	4.51	4.55	36.9	37.2				2227	37	37
F80(2) - 2		2236	4.51		38.0					2227	37	
F80(2) - 3		2230	4.63		36.8					2219	38	

Appendix 10 Water Absorption of Self-compacting Concrete with Fly Ash

The water absorption results as shown in Figure 7-15 Short-term water intake of target mixes, Figure 7-18 Water intake with time after 7 days curing in water and Figure 7-19 Water intake over time after 90 days curing in water are demonstrated as follows.

F0-7D		F0-90D		F20-7D		F20-90D		F40-7D	
Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)
0.2	0.07	0.2	0.18	0.2	0.15	0.2	0.28	0.2	0.23
0.3	0.16	0.3	0.25	0.3	0.22	0.3	0.32	0.3	0.30
0.5	0.33	0.5	0.30	0.5	0.33	0.5	0.40	0.5	0.39
0.7	0.40	0.7	0.38	0.7	0.41	0.7	0.44	0.7	0.47
0.8	0.47	0.8	0.40	0.8	0.41	0.8	0.49	0.8	0.46
1.0	0.52	1.0	0.42	1.0	0.48	1.0	0.51	1.0	0.53
1.5	0.69	1.2	0.45	1.5	0.57	1.2	0.55	1.5	0.54
2.1	0.70	1.3	0.43	2.0	0.65	1.3	0.54	2.0	0.62
2.5	0.73	1.7	0.46	3.0	0.71	1.5	0.51	3.0	0.76
3.0	0.72	2.0	0.49	7.0	0.79	1.7	0.57	4.0	0.79
4.0	0.79	2.3	0.53	11.0	0.90	1.8	0.58	10.5	0.89
6.0	0.82	2.7	0.57	28.0	1.11	2.2	0.57	21.1	1.06
8.0	0.84	2.9	0.55	34.6	1.15	2.3	0.59	31.5	1.14
11.0	0.83	3.5	0.60	51.7	1.23	2.5	0.64	45.6	1.23
24.0	0.90	3.8	0.59	62.0	1.27	2.7	0.65	56.5	1.30
29.0	0.95	4.0	0.57	76.2	1.29	2.9	0.63	72.3	1.34
31.0	0.95	5.3	0.62	87.1	1.37	3.2	0.69	95.1	1.47
46.0	1.04	6.5	0.63	102.8	1.38	3.3	0.71	97.0	1.49
57.0	0.91	21.0	0.69	125.6	1.56	3.5	0.73	114.5	1.54
74.0	1.03	29.8	0.76	127.6	1.56	3.8	0.71	141.4	1.60
97.7	1.04	46.0	0.78	145.1	1.56	4.0	0.72	164.7	1.67
108.0	1.06	50.0	0.79	172.0	1.65	4.7	0.78	189.4	1.70
122.1	1.10	55.3	0.84	195.2	1.69	6.8	0.76	216.8	1.72
133.0	1.15	71.5	0.84	220.0	1.74	9.3	0.89	237.3	1.71
148.8	1.12	95.3	0.88	247.3	1.73	25.5	1.00	263.6	1.78
171.6	1.24	119.4	0.91	267.8	1.71	30.4	1.05	288.5	1.87
173.6	1.30	168.0	0.95	293.1	1.80	49.3	1.15	312.2	1.88
191.1	1.32	194.1	0.98	319.1	1.86	97.4	1.21	384.2	1.96
218.0	1.35	216.1	1.08	342.7	1.86	122.0	1.24	408.4	1.97
241.3	1.40	239.8	1.02	414.7	1.96	148.1	1.26	456.6	1.96
266.0	1.45	263.5	1.07	439.0	1.95	170.1	1.34	479.8	2.00
293.3	1.45	311.8	1.09	487.2	1.98	193.8	1.29		
313.8	1.47	337.7	1.08			217.5	1.39		
340.1	1.51	360.0	1.11			265.8	1.37		

365.0	1.57	390.3	1.13			291.7	1.38		
388.7	1.56	411.9	1.18			314.0	1.38		
460.7	1.63	430.0	1.20			344.3	1.42		
485.0	1.64	460.0	1.23			365.9	1.49		
		490.0	1.25			400.0	1.50		
		500.0	1.26			420.0	1.52		
						440.0	1.54		
						460.0	1.56		
						480.0	1.58		
						500.0	1.60		

F40-90D		F60-7D		F60-90D		F80(2)-7D		F80(2)-90D	
Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)
0.2	0.23	0.2	0.25	0.2	0.22	0.2	0.77	0.2	0.14
0.3	0.26	0.3	0.41	0.4	0.29	0.3	0.98	0.3	0.28
0.5	0.33	0.5	0.53	0.5	0.44	0.5	1.19	0.5	0.32
0.7	0.33	0.7	0.64	0.7	0.49	0.7	1.32	0.7	0.41
0.8	0.36	1.0	0.88	0.8	0.47	0.8	1.41	0.8	0.42
1.0	0.37	1.5	1.05	1.2	0.57	1.1	1.60	1.0	0.48
1.2	0.42	2.1	1.23	1.3	0.62	1.5	1.83	1.2	0.54
1.3	0.42	3.5	1.40	1.5	0.61	2.0	2.04	1.3	0.64
1.5	0.43	4.5	1.39	1.7	0.64	3.1	2.38	1.5	0.64
1.7	0.50	7.3	1.79	1.8	0.68	4.1	2.69	1.7	0.69
1.8	0.48	18.5	2.32	2.0	0.69	5.6	3.00	1.8	0.73
2.0	0.45	26.7	2.51	2.2	0.72	7.6	3.33	2.0	0.75
2.2	0.49	45.4	2.84	2.3	0.72	23.1	4.77	2.2	0.82
2.3	0.48	53.1	2.92	2.5	0.75	32.0	5.23	2.3	0.88
2.5	0.50	68.7	3.03	2.7	0.75	47.8	5.83	2.5	0.89
2.7	0.51	77.6	3.04	2.8	0.77	75.3	6.48	2.7	0.95
2.8	0.49	93.4	3.14	3.0	0.77	95.8	6.81	2.8	0.95
3.0	0.48	120.8	3.20	3.2	0.74	122.1	7.23	3.0	0.97
3.2	0.49	141.3	3.23	3.3	0.82	147.1	7.47	3.2	1.04
3.3	0.51	167.6	3.34	3.5	0.82	170.7	7.66	3.3	1.04
3.5	0.52	192.6	3.40	3.7	0.83	242.8	8.08	3.5	1.06
3.7	0.52	216.2	3.44	3.8	0.82	267.0	8.17	3.7	1.06
3.8	0.56	288.2	3.57	4.0	0.86	315.2	8.40	3.8	1.10
4.0	0.55	312.5	3.58	22.1	1.31	338.3	8.43	4.0	1.09
18.8	0.70	360.7	3.67	44.1	1.52	365.7	8.45	23.8	2.44
66.9	0.83	383.8	3.68	67.8	1.53	412.8	8.55	47.5	3.16
91.5	0.84	411.2	3.67	91.5	1.63	434.8	8.63	95.8	3.92
117.6	0.90	458.3	3.70	139.8	1.70	461.4	8.65	121.7	4.25
139.6	0.97	480.3	3.75	165.7	1.72	480.3	8.68	144.0	4.52
163.3	0.93			188.0	1.75			174.3	4.77
187.0	1.00			218.3	1.80			195.9	4.95
235.3	1.02			239.9	1.83			220.0	5.20
261.2	1.01			280.0	1.85			250.0	5.40
283.5	1.02			310.0	1.87			280.0	5.60
313.8	1.07			340.0	1.89			300.0	5.80
335.4	1.09			360.0	1.90			320.0	5.90

350.0	1.10			380.0	1.93			340.0	6.00
370.0	1.12			400.0	1.95			360.0	6.20
390.0	1.14			420.0	1.96			380.0	6.30
410.0	1.16			440.0	1.97			400.0	6.40
430.0	1.18			460.0	1.98			430.0	6.50
450.0	1.19			480.0	2.05			462.9	6.60
500.0	1.20			506.9	2.08			490.0	6.70
								504.9	6.76

Appendix 11 Hardened Self-compacting Concrete with Ground Glass

The complete results shown in Table 8-5 Hardened properties of target SCCs are demonstrated as follows.

MIX NO.	AGE	TESTS ON CUBES					TESTS ON CYLINDERS			TESTS ON PRISMS		
		density (kg/m^3)	UPV (km/s)	Average (km/s)	compressive strength (MPa)	Average (MPa)	density (kg/m^3)	splitting strength (MPa)	Average (MPa)	density (kg/m^3)	Ed (GPa)	Average (GPa)
W0 -1	7d	2418	4.80	4.82	58.2	63.0				2387	47	47
W0 -2		2388	4.83		68.3					2387	47	
W0 -3		2394	4.82		62.4					2384	47	
W0 -1	28d	2390	4.85	4.90	71.7	70.5	2385	5.4	4.2	2385	48	49
W0 -2		2393	4.93		68.8		2384	3.8		2389	49	
W0 -3		2392	4.93		70.9		2387	3.4		2388	49	
W0 -1	60d									2394	49	49
W0 -2										2389	49	
W0 -3										2389	50	
W0 -1	90d	2399	4.98	4.96	76.0	75.0	2387	4.9	5.4	2395	49	50
W0 -2		2390	4.95		73.5		2387	5.6		2390	50	
W0 -3		2385	4.95		75.5		2387	5.6		2389	50	
W0 -1	120d									2388	49	50
W0 -2										2391	50	
W0 -3										2390	50	
W0 -1	150d									2388	49	50
W0 -2										2391	50	
W0 -3										2388	50	
W0 -1	180d	2396	5.00	5.00	82.1	79.3				2389	50	50
W0 -2		2391	5.03		77.7					2392	50	

W0 -3		2400	4.98		78.0					2391	50	
W2.2 -1	7d	2378	4.83	4.82	59.4	62.0				2362	45	45
W2.2 -2		2373	4.85		62.5					2362	45	
W2.2 -3		2364	4.77		64.2					2359	45	
W2.2 -1	28d	2380	4.90	4.89	71.4	68.2	2368	3.9	4.1	2366	46	46
W2.2 -2		2362	4.89		71.8		2368	4.1		2368	46	
W2.2 -3		2385	4.88		61.6		2369	4.4		2365	47	
W2.2 -1	60d									2376	47	47
W2.2 -2										2369	47	
W2.2 -3										2364	47	
W2.2 -1	90d	2372	4.99	4.97	70.5	69.3	2368	4.4	4.9	2369	47	48
W2.2 -2		2385	4.94		64.3		2371	5.2		2368	48	
W2.2 -3		2383	4.98		73.2		2372	5.0		2364	47	
W2.2 -1	120d									2370	48	48
W2.2 -2										2369	48	
W2.2 -3										2366	48	
W2.2 -1	150d									2374	48	48
W2.2 -2										2369	48	
W2.2 -3										2366	48	
W2.2 -1	180d	2390	5.03	4.99	77.8	76.5				2371	48	48
W2.2 -2		2388	4.98		75.3					2370	48	
W2.2 -3		2384	4.98		76.5					2367	48	
W4.3 - 1	7d	2358	4.81	4.80	56.5	59.5				2339	43	43
W4.3 - 2		2355	4.81		59.5					2336	44	
W4.3 - 3		2345	4.77		62.5					2337	43	
W4.3 - 1	28d	2400	4.88	4.88	63.9	65.2	2345	3.4	3.8	2343	45	45
W4.3 - 2		2355	4.85		59.5		2342	3.6		2339	45	
W4.3 - 3		2352	4.90		72.2		2346	4.4		2340	45	
W4.3 - 1	60d									2342	46	46

W4.3 - 2										2339	46	
W4.3 - 3										2340	46	
W4.3 - 1	90d	2358	4.89	4.91	63.3	66.5	2345	4.8	4.7	2344	46	46
W4.3 - 2		2359	4.96		69.3		2346	4.7		2340	47	
W4.3 - 3		2355	4.88		66.8		2349	4.6		2342	46	
W4.3 - 1	120d									2345	46	46
W4.3 - 2										2341	47	
W4.3 - 3										2343	46	
W4.3 - 1	150d									2345	46	47
W4.3 - 2										2342	47	
W4.3 - 3										2344	46	
W4.3 - 1	180d	2361	4.98	4.96	70.8	71.7				2346	47	47
W4.3 - 2		2360	4.91		73.0					2343	47	
W4.3 - 3		2351	5.00		71.2					2344	47	
W6.4 - 1	7d	2354	4.76	4.78	60.3	57.6				2331	43	43
W6.4 - 2		2343	4.78		54.7					2331	43	
W6.4 - 3		2347	4.78		57.8					2329	43	
W6.4 - 1	28d	2347	4.89	4.87	68.4	62.1	2347	3.3	3.6	2337	45	45
W6.4 - 2		2369	4.85		58.8		2345	3.9		2334	45	
W6.4 - 3		2345	4.85		59.3		2343	3.7		2333	45	
W6.4 - 1	60d									2344	46	46
W6.4 - 2										2340	46	
W6.4 - 3										2343	46	
W6.4 - 1	90d	2353	4.90	4.90	68.4	64.4	2353	4.5	4.5	2337	46	46
W6.4 - 2		2352	4.93		61.7		2351	5.0		2336	46	
W6.4 - 3		2341	4.88		63.1		2351	4.2		2334	46	
W6.4 - 1	120d									2337	46	46
W6.4 - 2										2337	46	
W6.4 - 3										2337	46	

W6.4 - 1	150d									2338	46	46
W6.4 - 2										2336	46	
W6.4 - 3										2335	46	
W6.4 - 1	180d	2345	4.93	4.93	67.5	71.1				2338	46	46
W6.4 - 2		2351	4.95		73.9					2336	46	
W6.4 - 3		2334	4.93		72.0					2336	46	
G0 - 1	7d	2398	4.93	4.88	57.9	62.6				2382	47	47
G0 - 2		2400	4.87		64.7					2383	47	
G0 - 3		2383	4.84		65.3					2383	47	
G0 - 1	28d	2414	4.91	4.89	79.2	74.9	2382	5.2	4.7	2385	48	48
G0 - 2		2397	4.88		71.0		2388	4.2		2386	48	
G0 - 3		2394	4.88		74.5		2387	4.7		2386	48	
G0 - 1	60d									2386	49	49
G0 - 2										2387	49	
G0 - 3										2387	49	
G0 - 1	90d	2414	4.98	4.98	71.9	79.1	2390	5.9	5.9	2392	49	49
G0 - 2		2406	4.99		85.3		2391	5.5		2388	49	
G0 - 3		2390	4.99		80.1		2396	6.2		2387	49	
G0 - 1	120d									2388	49	49
G0 - 2										2344	49	
G0 - 3										2388	49	
G0 - 1	150d									2394	50	50
G0 - 2										2391	50	
G0 - 3										2390	49	
G0 - 1	180d	2415	5.00	4.99	85.1	85.1				2391	50	50
G0 - 2		2403	5.00		87.3					2392	50	
G0 - 3		2404	4.98		83.0					2391	49	
G2.2 - 1	7d	2388	4.82	4.85	54.7	56.0				2388	46	46
G2.2 - 2		2383	4.90		55.3					2388	47	

G2.2 - 3		2392	4.84		58.0					2388	46	
G2.2 - 1	28d	2387	4.93	4.93	65.9	68.3	2392	4.1	4.6	2398	48	48
G2.2 - 2		2390	4.93		62.9		2385	4.9		2392	48	
G2.2 - 3		2396	4.95		76.0		2387	4.9		2392	48	
G2.2 - 1	60d									2391	49	49
G2.2 - 2										2393	49	
G2.2 - 3										2395	48	
G2.2 - 1	90d	2392	4.94	4.95	73.2	77.7	2389	4.8	5.2	2393	49	49
G2.2 - 2		2398	4.95		80.5		2393	5.4		2394	49	
G2.2 - 3		2390	4.98		79.5		2390	5.5		2394	48	
G2.2 - 1	120d									2394	49	49
G2.2 - 2										2395	49	
G2.2 - 3										2396	49	
G2.2 - 1	150d									2395	49	49
G2.2 - 2										2396	50	
G2.2 - 3										2397	49	
G2.2 - 1	180d	2407	5.03	4.99	82.9	81.3				2394	50	50
G2.2 - 2		2392	4.99		77.1					2396	50	
G2.2 - 3		2392	4.95		83.9					2397	50	
G4.2 - 1	7d	2394	4.85	4.84	51.2	51.2				2381	45	45
G4.2 - 2		2392	4.80		53.6					2379	45	
G4.2 - 3		2392	4.88		48.8					2384	46	
G4.2 - 1	28d	2394	4.89	4.92	57.9	58.5	2381	4.7	4.2	2388	47	47
G4.2 - 2		2394	4.91		57.7		2390	3.0		2384	47	
G4.2 - 3		2395	4.96		60.0		2381	4.9		2387	48	
G4.2 - 1	60d									2387	48	48
G4.2 - 2										2385	48	
G4.2 - 3										2390	48	
G4.2 - 1	90d	2393	4.94	4.93	62.7	60.9	2385	5.0	5.1	2387	48	48

G4.2 - 2		2395	4.94		60.4		2388	5.3		2385	48	
G4.2 - 3		2389	4.93		59.7		2383	4.8		2390	49	
G4.2 - 1	120d									2389	48	48
G4.2 - 2										2387	48	
G4.2 - 3										2392	49	
G4.2 - 1	150									2390	48	49
G4.2 - 2										2387	49	
G4.2 - 3										2393	49	
G4.2 - 1	180d	2399	4.95	4.97	76.6	69.7				2390	49	49
G4.2 - 2		2402	4.98		60.6					2387	49	
G4.2 - 3		2397	4.98		72.0					2392	49	

Appendix 12 Water Absorption of Self-compacting Concrete with Ground Glass

The water absorption results as shown in Table 8-5 Hardened properties of target SCCs with ground glass are demonstrated as follows.

W0-7D		W0-90D		W2.2-7D		W2.2-90D		W4.3-7D	
Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)
0.1	0.25	0.2	0.16	0.2	0.30	0.2	0.20	0.2	0.31
0.3	0.36	0.3	0.20	0.3	0.37	0.3	0.26	0.3	0.39
0.5	0.36	0.5	0.23	0.5	0.44	0.5	0.27	0.5	0.44
0.7	0.45	0.7	0.27	0.7	0.46	0.7	0.30	0.7	0.47
0.8	0.51	0.8	0.30	0.8	0.49	0.8	0.26	0.8	0.50
1.0	0.51	1.0	0.30	1.0	0.56	1.0	0.33	1.0	0.53
1.2	0.47	1.2	0.33	1.2	0.59	1.2	0.33	1.2	0.55
1.3	0.56	1.3	0.34	1.3	0.60	1.3	0.33	1.3	0.57
1.5	0.59	1.5	0.34	1.5	0.61	1.5	0.37	1.5	0.59
1.7	0.56	1.7	0.32	1.7	0.61	1.7	0.39	1.7	0.60
1.8	0.57	1.8	0.36	1.8	0.58	1.8	0.42	1.8	0.61
2.0	0.58	2.0	0.37	2.0	0.64	2.0	0.37	2.0	0.64
2.2	0.59	2.2	0.36	2.2	0.65	2.2	0.42	2.2	0.65
2.3	0.58	2.3	0.34	2.3	0.69	2.3	0.39	2.3	0.67
2.5	0.61	2.5	0.34	2.5	0.67	2.5	0.39	2.5	0.67
2.7	0.59	2.7	0.36	2.7	0.66	2.7	0.43	2.7	0.68
2.9	0.63	2.8	0.38	2.8	0.71	2.8	0.46	2.8	0.69
3.0	0.59	3.0	0.38	3.0	0.71	3.0	0.41	3.0	0.70
3.2	0.62	3.2	0.34	3.2	0.74	3.2	0.44	3.2	0.71
3.3	0.63	3.3	0.35	3.3	0.68	3.3	0.43	3.3	0.71
3.5	0.68	3.5	0.37	3.5	0.66	3.5	0.39	3.5	0.71
3.7	0.65	3.7	0.36	3.7	0.72	3.7	0.43	3.7	0.72
3.8	0.62	3.8	0.39	3.8	0.68	3.8	0.45	3.8	0.74
4.0	0.63	4.0	0.36	4.0	0.73	4.0	0.42	4.0	0.76
44.3	0.84	24.2	0.54	23.8	0.90	22.8	0.54	28.6	0.97
78.1	0.94	48.0	0.60	72.1	1.14	49.2	0.64	73.4	1.10
122.0	1.00	72.0	0.68	95.0	1.17	69.7	0.66	123.0	1.21
165.3	1.10	96.0	0.70	119.5	1.27	99.0	0.72	195.6	1.35
243.2	1.15	120.0	0.75	143.1	1.26	123.1	0.81	245.9	1.41
315.9	1.23	148.0	0.83	167.8	1.37	146.6	0.81	317.5	1.47
386.8	1.34	172.0	0.85	216.3	1.37	168.6	0.82	440.0	1.56
499.0	1.37	191.2	0.86	262.1	1.41	193.2	0.84	386.1	1.52
502.8	1.38	214.5	0.91	336.9	1.56	217.0	0.86	482.2	1.61
		238.7	0.90	381.4	1.58	241.0	0.90	495.0	1.63

		263.5	0.98	429.8	1.64	265.0	0.91		
		287.0	1.00	480.0	1.61	289.0	0.95		
		311.0	0.99			313.0	0.93		
		335.0	1.05			337.0	0.95		
		361.8	1.07			360.2	0.97		
		385.3	1.11			383.5	1.01		
		412.6	1.14			407.7	0.99		
		429.7	1.17			432.5	1.07		
		454.8	1.17			456.0	1.05		
		496.0	1.18			480.0	1.10		
						500.0	1.10		

W4.3-90D		W6.4-7D		W6.4-90D		G0-7D		G0-90D	
Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)
0.2	0.30	0.2	0.19	0.2	0.19	0.2	0.23	0.2	0.22
0.3	0.35	0.3	0.30	0.3	0.31	0.3	0.28	0.3	0.29
0.5	0.36	0.5	0.26	0.5	0.26	0.5	0.31	0.9	0.31
0.7	0.40	0.7	0.37	0.7	0.33	0.7	0.43	1.0	0.39
0.8	0.39	0.8	0.39	0.9	0.31	0.8	0.41	1.1	0.33
1.0	0.43	1.0	0.48	1.0	0.38	1.0	0.45	1.3	0.36
1.2	0.47	1.2	0.43	1.3	0.40	1.2	0.41	1.4	0.38
1.3	0.46	1.3	0.45	1.4	0.42	1.3	0.49	1.6	0.39
1.5	0.46	1.5	0.54	1.6	0.43	1.5	0.47	1.7	0.37
1.7	0.48	1.7	0.52	1.8	0.40	1.7	0.51	1.8	0.34
1.8	0.53	1.8	0.52	2.0	0.43	1.8	0.53	1.9	0.37
2.0	0.52	2.0	0.54	2.2	0.44	2.0	0.53	2.0	0.38
2.2	0.50	2.2	0.55	2.3	0.49	2.2	0.47	2.2	0.40
2.3	0.51	2.3	0.53	2.5	0.44	2.3	0.52	2.3	0.41
2.5	0.51	2.5	0.57	2.7	0.47	2.5	0.51	2.5	0.41
2.7	0.56	2.7	0.63	2.8	0.49	2.7	0.57	2.7	0.38
2.8	0.56	2.8	0.55	3.0	0.51	2.8	0.53	2.8	0.40
3.0	0.55	3.0	0.58	3.2	0.47	3.0	0.56	3.0	0.35
3.2	0.54	3.2	0.61	3.3	0.52	3.2	0.54	3.2	0.41
3.3	0.54	3.3	0.66	3.5	0.51	3.3	0.60	3.3	0.41
3.5	0.54	3.5	0.59	3.7	0.46	3.5	0.53	3.5	0.44
3.7	0.57	3.7	0.66	3.8	0.50	3.7	0.56	3.7	0.44
3.8	0.62	3.8	0.64	4.0	0.51	3.8	0.57	3.8	0.45
4.0	0.59	4.0	0.67	30.2	0.67	4.0	0.57	4.0	0.45
23.0	0.74	23.1	0.87	78.1	0.83	24.0	0.76	24.1	0.59
66.3	0.91	47.8	1.05	150.7	0.94	46.0	0.79	47.6	0.63
144.2	1.03	96.3	1.19	221.7	1.06	68.8	0.80	69.6	0.70
216.9	1.10	142.1	1.29	337.6	1.17	95.2	0.89	94.2	0.72
287.8	1.24	216.9	1.44	387.0	1.16	115.7	0.91	118.0	0.75
403.8	1.30	261.4	1.45	479.4	1.32	145.0	0.96	142.0	0.80
453.1	1.29	309.8	1.56			169.1	1.01	166.0	0.85
499.0	1.30	360.0	1.55			192.6	0.99	190.0	0.86
		409.3	1.58			214.6	1.02	214.0	0.88
		453.4	1.61			239.2	1.03	238.0	0.90
		487.1	1.65			264.0	1.05	261.2	0.93
						288.0	1.10	284.5	0.98
						312.0	1.12	308.7	0.96

						336.0	1.09	333.5	1.06
						360.0	1.12	357.0	1.04
						384.0	1.12	381.0	1.06
						406.2	1.13	405.0	1.10
						429.5	1.17	431.8	1.12
						453.7	1.12	455.3	1.15
						478.5	1.22	482.6	1.19
						499.0	1.23	499.7	1.16

G2.2-7D		G2.2-90D		G4.2-7D		G4.2-90D	
Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)	Time (h)	water intake (kg/m^2)
0.2	0.23	0.2	0.25	0.2	0.26	0.2	0.27
0.3	0.31	0.3	0.32	0.3	0.40	0.3	0.34
0.5	0.36	0.5	0.34	0.5	0.47	0.5	0.39
0.7	0.40	0.7	0.40	0.7	0.52	0.7	0.42
0.8	0.43	1.0	0.40	0.8	0.54	0.8	0.45
1.0	0.46	1.2	0.44	1.0	0.52	1.0	0.48
1.2	0.48	1.4	0.44	1.2	0.54	1.2	0.50
1.3	0.49	1.6	0.46	1.3	0.62	1.3	0.52
1.5	0.51	1.8	0.50	1.5	0.64	1.5	0.53
1.7	0.52	2.0	0.51	1.7	0.65	1.7	0.55
1.8	0.54	2.2	0.43	1.8	0.68	1.8	0.55
2.0	0.54	2.3	0.53	2.0	0.70	2.0	0.57
2.2	0.55	2.5	0.50	2.2	0.70	2.2	0.57
2.3	0.57	2.7	0.49	2.3	0.71	2.3	0.58
2.5	0.57	2.8	0.50	2.5	0.69	2.5	0.59
2.7	0.58	3.0	0.46	2.7	0.70	2.7	0.60
2.9	0.62	3.2	0.55	2.8	0.71	2.8	0.61
3.0	0.62	3.3	0.52	3.0	0.70	3.0	0.61
3.2	0.62	3.5	0.54	3.2	0.70	3.2	0.62
3.3	0.63	3.7	0.49	3.3	0.75	3.3	0.62
3.5	0.64	3.8	0.56	3.5	0.76	3.5	0.63
3.7	0.64	4.0	0.53	3.7	0.73	3.7	0.63
3.8	0.64	24.7	0.63	3.8	0.76	3.8	0.64
4.0	0.65	49.3	0.71	4.0	0.74	4.0	0.64
27.5	0.81	93.3	0.79	23.5	0.88	21.4	0.78
74.5	0.97	127.1	0.86	47.2	1.06	75.4	0.97
124.9	1.03	171.0	0.91	72.7	1.04	121.8	1.06
196.5	1.13	214.3	0.98	122.4	1.20	166.7	1.13
265.2	1.20	292.2	1.05	143.9	1.22	211.4	1.16
310.0	1.26	364.9	1.08	167.8	1.21	262.8	1.27
361.2	1.32	435.8	1.16	216.1	1.29	333.7	1.35
417.0	1.37	499.0	1.18	239.0	1.30	383.9	1.41
488.7	1.41			263.5	1.36	455.5	1.43
498.0	1.42			287.1	1.35	495.0	1.46
				311.8	1.40		
				336.3	1.40		
				406.1	1.44		
				480.9	1.52		

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