To the One Who loved me, died for me and has been raised.

(Bible 2 Corinthians 5:14-15)

Acknowledgements

In this age, with the next millennium fast approaching, no one can carry out research work alone. Therefore, the author would like to show his appreciation to the many people who assisted with this study.

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I especially want to give thanks to my family - my mother, my wife Priscilla and May and Boaz for their support. I owe them very much. I also appreciated the care from the saints in the church - it is impossible to list all of them. Through their prayer and the bountiful supply of the Spirit of Jesus Christ, I finished this study and had a memorable time in the UK. Glory to God.

DESIGN AND TESTING OF SELF-COMPACTING CONCRETE

A thesis submitted to the University of London
for the degree of Doctor of Philosophy

by

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Abstract

Self-compacting concrete (SCC) can flow into place and compact under its own weight into a uniform void free mass even in areas of congested reinforcement. The research reported in this thesis examined the production of SCC with readily available UK materials, with the overall aims of evaluating test methods and establishing a suitable mix design procedure.

There have been significant recent developments and applications of SCC in several countries, notably Japan. A literature survey gave an understanding of the advantages and properties of SCC, test methods and the range of constituent materials and their relative proportions for its successful production. A range of SCC mixes can be produced with the common features of a lower aggregate content than conventional concrete and the use of superplasticizers. Most mixes also contained one or more of pulverized fuel ash, ground granulated blast furnace slag and an inert powder filler.

A four stage experimental programme was carried out:

- tests on pastes to assess the effect of the types and proportions of the powders and superplasticizers on the rheology.
- tests on mortars to determine suitable dosage of superplasticizers for high fluidity, low segregation and low loss of workability with time after mixing. Flow spread and funnel tests were used.
- tests on fresh concrete to enable suitable types and quantities of coarse aggregate to be combined with these mortars to produce SCC. Fluidity and viscosity were measured using slump flow and V-funnel tests, and passing ability using L- and U-type tests. Two-point workability tests were also carried out, and a novel way of assessing segregation resistance was developed.
- tests on hardened concrete to determine compressive strength, bond to reinforcement and drying shrinkage.

A mix design procedure, based on a method suggested by Japanese workers, has been developed. This includes optimisation of the mix with a linear optimisation tool from a commercial spreadsheet package.

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Chapter 5 Rheology of cementitious paste

Chapter 6 Properties and composition of mortar for SCC

Chapter 7 Fresh Properties of SCC

Chapter 9 Mix design of SCC

Chapter 10 Conclusions and recommendations for future work

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Notation

A	air content
A/C	aggregate/cement ratio
AE	air entraining agent
C	cement content
CA	coarse aggregate (or **G**)
CRMs	cement replacement materials
CSF	condensed silica fume
C50	characteristic strength 50 MPa
D_{max}	maximum aggregate size
E_p	deformation coefficient
FA	fine aggregate (or **S**)
FC	flowing concrete
f_c	compressive strength
GGBS	ground granulated blastfurnace slag
G/G_{lim}	$V_g/(\gamma_g/SG)$
g	rheological constant related to τ_0
h	rheological constant related to μ
K_g	aggregate coefficient
LSP	limestone powder or (**SD**)
NC	normal concrete
PC	Portland cement
R_c	cement strength measured on mortar
RH	relative humidity
s/a	$W_s/(W_s+W_g)$
SCC	self-compacting concrete
SF	slump flow
SG	specific gravity
SP	superplasticizer or (**HRWR**)
TF	total fine (powder + sand)
VA	viscosity agent
V_a	volume of air
V_g	volume of coarse aggregate
V_m	volume of mortar
V_p	volume of powder
V_s	volume of sand
V_w	volume of water
W, W_w	water content
W_g	weight of coarse aggregate
W_p	weight of powder
W_s	weight of sand
W/B_{ef}	effective water/binder ratio
W/C	water/cement ratio
W/P	water/powder ratio
W/TF	water/total fine ratio
β_p	water retained ratio
γ_g	rodded bulk density of C.A
$\dot{\gamma}$	shear strain
τ_0	yield stress
μ	plastic viscosity
μ_p*	calculated viscosity of paste
ε	strain
ρ_w	water density

Chapter 1

Introduction

1. 1 Definition and requirements of self-compacting concrete

Self-compacting concrete (SCC), also known as super workable concrete or self-compactable concrete, is a new kind of high performance concrete. It can be placed without vibration equally well in lightly or heavily reinforced sections. It has excellent deformability and segregation resistance, which result in the quality of the hardened concrete being independent of the workmanship during placing.

The full original name of SCC was *Self-compacting high performance concrete*. This was included in **Okamura**'s definition (1992), which is shown in **Fig. 1-1**.

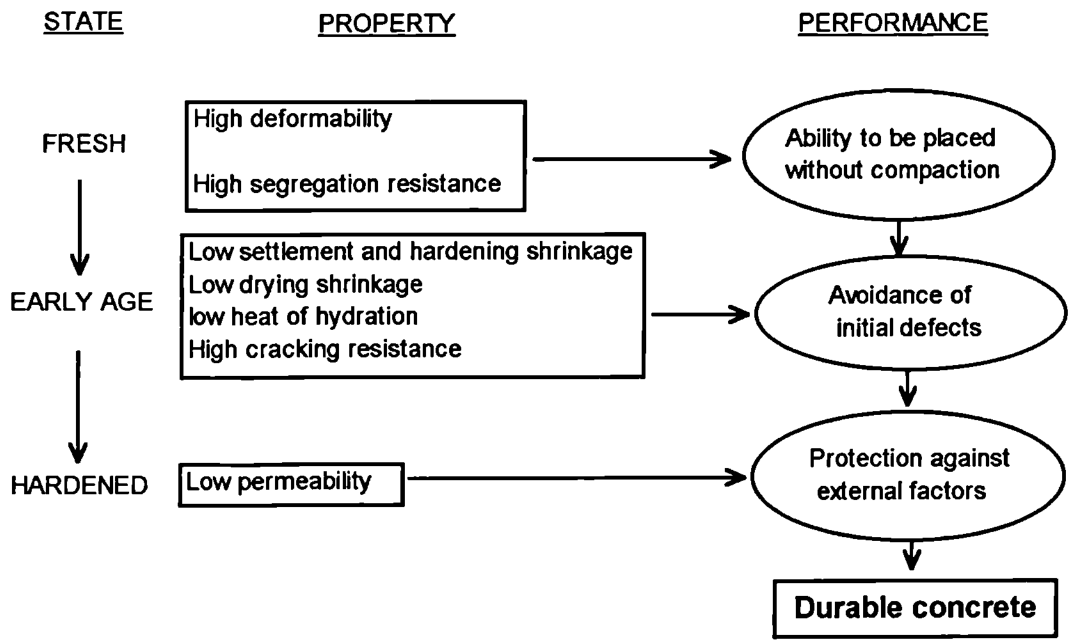


Fig. 1-1 *Definition of Self-compacting high performance concrete [Adapted from Okamura et al (1992)].*

This focuses not only on self-compacting properties during construction, but also on the resistance to defects at early ages, such as thermal and shrinkage cracking, and long term durability in service.

According to **Welton** (1987), vibration of fresh concrete has five objectives:

1) Elimination of mechanical voids in the mass.
2) Elimination of un-intentional air voids.
3) Removal of unnecessary water.
4) Shaking the particles in the mix into their closest nesting, providing uniform dispersal and distribution of the large particles, but still retaining the coating of all particle surfaces with cement mortar.
5) Attacking the micro-pores and micro-capillaries.

Superplasticized flowing concrete, with slumps in excess of 190 mm, which has been increasingly used for twenty years or more, can reduce or eliminate the need for vibration to achieve at least some of these objectives. In particular, objectives (1), (2) (3) and (5) may be possible, but (4) requires at least some vibration.

According to **Forssblad** (1987), unvibrated superplasticized flowing concrete has the following shortcomings:

- It contains a number of small and medium size air bubbles.
- There is reduced bond strength to reinforcement.
- There are often settlement cracks around the rebars.

Furthermore, according to **Tattersall** and **Banfill** (1983), some vibration is needed to compact flowing concrete into the corners of moulds and around congested reinforcement. In other words, unvibrated flowing concrete has insufficient filling ability at the corners of moulds and inadequate passing ability through gaps in congested areas.

Self-compacting concrete reduces or eliminates these shortcomings, and also ensures that objective (4) can be achieved without vibration. Objective (4) requires a high segregation resistance, and this, together with the filling and passing ability mentioned above, is the dominant consideration in producing successful SCC.

Table 1-1 shows the comparisons between the fresh properties of normal concrete (NC), flowing concrete (FC) and self-compacting concrete (SCC).

Table 1-1 Comparisons between the fresh properties of NC, FC and SCC

	Flowability	Segregation resistance	Filling ability	Passing ability	Consolidation
SCC	good	good	good	good	no need
FC	good	fair	fair	poor	partly needed
NC	poor	good	poor	poor	essential

1. 2 Development of Self-compacting concrete

Most of the development of SCC up to now has been in Japan, in response to significant durability problems with conventional concrete. Defects such as honeycombing and segregation caused by poor skill in construction work, particularly insufficient or over-vibration, are major causes of this. Poor structural design detail is another cause, often resulting from imperfect communication between the designers and the construction engineers. In cases where heavy reinforcement is required and the shape of the cross section is complicated, it is difficult to place concrete without defects with the normal level of labour skill. Professor **Okamura** (1986) proposed two alternative practical solutions for these problems.

1) To establish a durability design method by comprehensive evaluation of materials design and construction methods.

2) To develop a new vibration-free concrete, with which durable and reliable structures can be easily constructed. This was the motivation for developing self-compacting concrete.

The development of self-compacting concrete over the past ten years can be summarised as follows:

Sept. 1986: initiated by **Okamura** in his paper "Waiting for Innovation in Concrete Materials" [**Okamura** (1986)]

Aug. 1988: Prototype concrete No. 1 produced by Okamura's research student **Ozawa**

July 1989: demonstration to the construction industry at the University of Tokyo

July 1989: first publication by **Ozawa, Maekawa,** and **Okamura** [**Ozawa et al** (1989]

1990 onwards: applications by construction industry (discussed in Chapter 2)

1995 onwards: spreading to the world: research studies on self-compacting concrete have been carried out in the UK, France (LCPC), Sweden (CBI), Canada, Holland (Delft Univ.), Thailand, Korea, China and Taiwan.

1.3 Research programme

At the start of the research reported in this thesis, the author was not aware of any work being carried out in the UK on self-compacting concrete. It was decided that the research should examine the production of SCC with readily available UK materials, with the overall aims of evaluating test methods and establishing a suitable mix design procedure.

An essential first stage in this was to continually examine the published literature, which was extensive and growing. In this thesis, Chapter 2 gives a concise review of structural applications, advantages and disadvantages of SCC. Chapter 3 then gives a systematic presentation of the most important and relevant information concerning the component materials, test methods, fresh and hardened properties of SCC. Mix design methods are also summarised and reviewed.

This formed the basis for the design of the experimental programme. The general aims outlined above ~~was~~ were supplemented by the following more detailed aims:

A. to clarify the factors controlling passing ability through gaps between rebars
B. to assess the segregation resistance of SCC and to verify the minimum requirements for this.
C. to consider ways of making self-compacting concrete more economical.
D. to control the early strength of self-compacting concrete.
E. to introduce self-compacting concrete to the UK and Taiwan.

The experimental methods and materials used in the research programme are reported in Chapter 4. Then, Chapters 5 and 6 describe an experimental programme on the rheology of cementitious paste and the properties of mortar respectively. Both of these provide useful information for mix design. In Chapter 7, experiments to assess the passing ability through gaps and the segregation resistance, the most important fresh properties of SCC, are described and discussed. Chapter 8 describes measurements on some hardened properties of SCC including bond strength to rebars, drying shrinkage, and ways to control early strength. Chapter 9 presents a mix design method which uses an Excel spreadsheet Solver with performance criteria of SCC to optimise the mix proportions for least cost. Finally, conclusions and recommendations for future work are presented in Chapter 10.

The results obtained from this work will, it is hoped, provide a deeper understanding of SCC and help engineers to design a proper SCC mix according to the performance requirements of a structure.

Chapter 2

Advantages, applications, and disadvantages of SCC

Any new technology must have significant advantages over existing technology for it to be applied. This chapter briefly describes the advantages of SCC, some applications and some of its disadvantages.

2. 1 Advantages of SCC

After SCC was demonstrated in July 1989 at the University of Tokyo, it soon became a focus of research and development for Japan's construction industry. Since 1990 many projects have used self-compacting concrete; its main advantages, as summarised by **Okamura et al** (1993) are shown in **Fig. 2-1.** Each of these are discussed in this section.

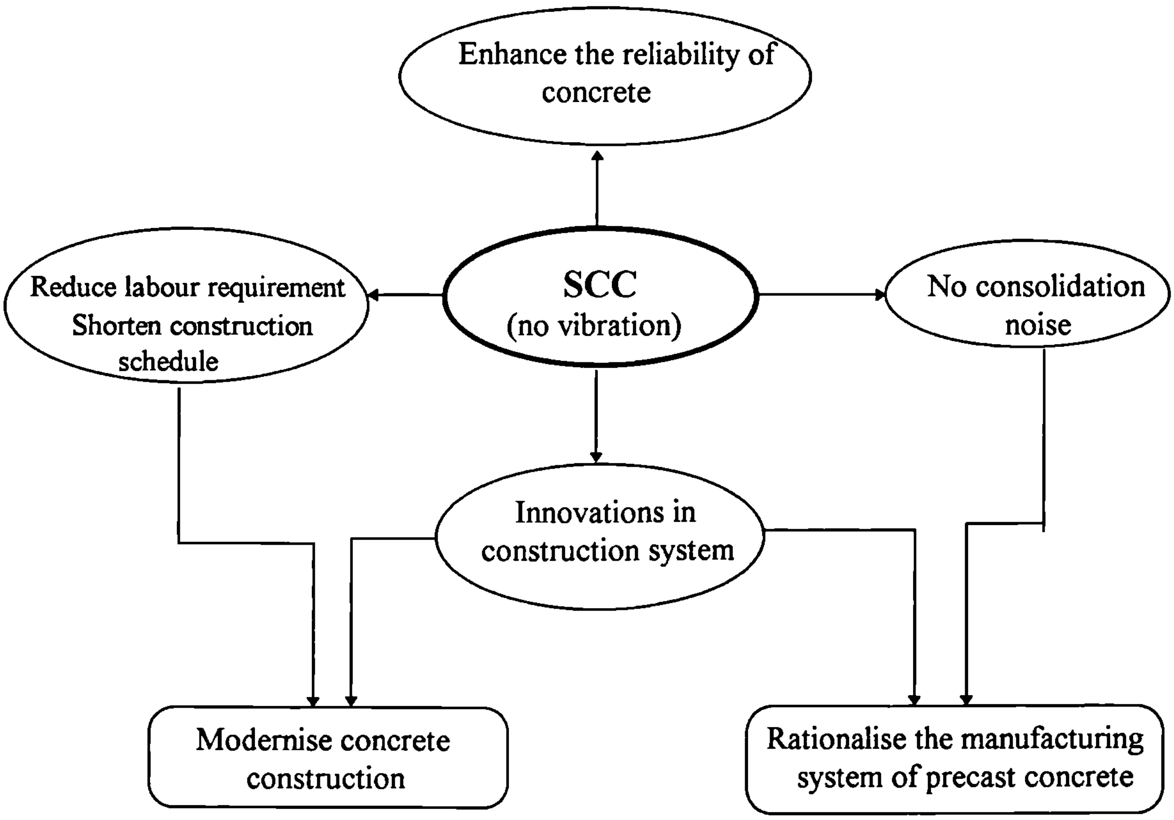


Fig. 2.1 The advantages of SCC [Translated from Okaumura et al (1993)]

2.1.1 Enhancement of the reliability of concrete

Because much attention is given to the quality control of SCC before it is placed and there is no need for vibration during placing, the quality of hardened self-compacting concrete will be enhanced. For example, two large-scale model tests for a marine structure (2.0m x 1.1m x 7.2m) with heavy reinforcement were cast, one with SCC, the other with compacted NC [**Fukute et al** (1994)]. The standard deviation of the core strength of the SCC was only 2.8 MPa. According the ACI classification (ACI 214-77), this is an "excellent" standard of quality control for the mean strength of 47.5 MPa.

The core strength of samples taken from the model also shows that the quality of SCC in the real model was higher than that of standard cured cylinders. The ratio of core strength to the strength of the standard cured cylinders was 1.0~1.3 for SCC and 0.8~1.15 for NC (**Fig. 2.2** and **Fig. 2.3**), whereas in ACI 318R-89 5.6.4.4, 0.85 of specified strength is allowed for the average strength of 3 cores. It is interesting to note that for NC, the strength ratios in the upper layer were less than those of the other layers because of undervibration due to the congested reinforcement in this layer. For SCC there is no such defect. Because the strength from the model test (47.5 MPa) was much higher than the minimum design strength 30 MPa, the W/C ratio was adjusted from 0.45 to 0.50 for the actual structure. A total of 760 m^3 SCC was cast and the standard deviation of the 28 day strength was 2.1 MPa (again "excellent"), thus confirming the high standard of control.

Table 2-1 lists the standard deviations of SCC from some construction projects in Japan. As can be seen, high quality can be secured by using SCC.

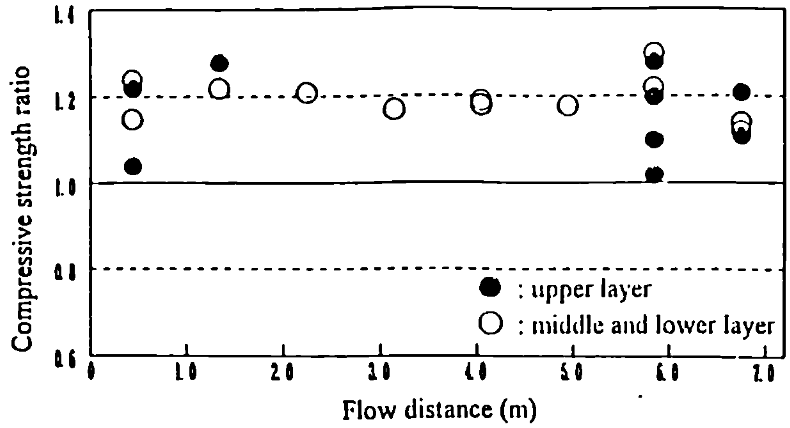


Fig. 2-2 *Ratio of core strength to standard cured cylinder strength vs. flow distance of SCC*

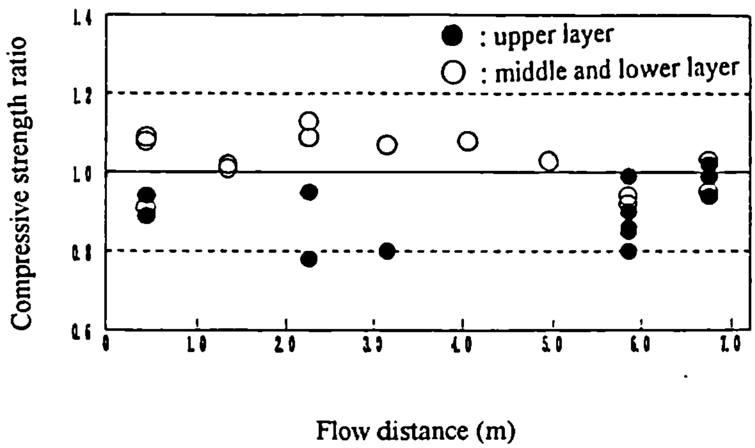


Fig. 2-3 *Ratio of core strength to standard cured cylinder strength vs. flow distance of NC [Adapted from Fukute et al (1994)]*

Table 2-1 Standard deviations of SCC from projects in Japan

Case No	Structure (see section 2.2)	Concrete volume (m^3)	Comp. strength mean (MPa)*	^S.D (MPa)
2	Blockage of pilot tunnel	3200	40	3.7
7	Top slab of box culvert	2000	48	2.3
10	Foundation of cable anchorage	90000	35	2.5
10	Body of cable anchorage	150000	33	2.2
12	Floor slab of caisson	760	38	2.1
15	Column of bridge	650	55	3.4

* cylinder strength at the age of 28 days. ^ standard deviation

2.1.2 No consolidation noise

A noisy environment is damaging to the health of human beings, especially if the noise lasts for a long time. The use of SCC not only makes concreting work less difficult but also less noisy and hence more pleasant as shown in **Photo 2-1**. Moreover, as the income per capita is increasing, the demand for higher living quality is also increasing, and in urban areas, the magnitude of noise from construction work is often limited by government. Using SCC may offer a quieter construction environment and make construction activities more acceptable to local residents. This is the main reason why Delft University (in Holland) started doing research work on SCC after the faculty of civil engineering had visited Japan [Delft (1996)].

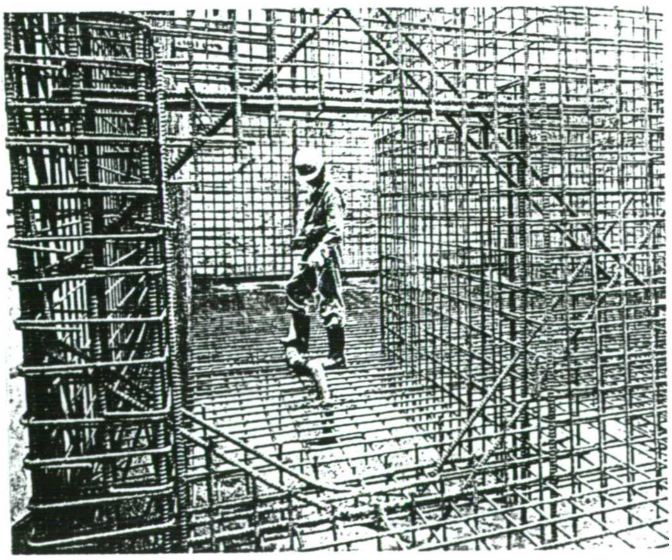


Photo 2-1 *Casting SCC*

[Adapted from Yorita (1993)]

2.1.3 Reduced labour force and shorter construction schedules

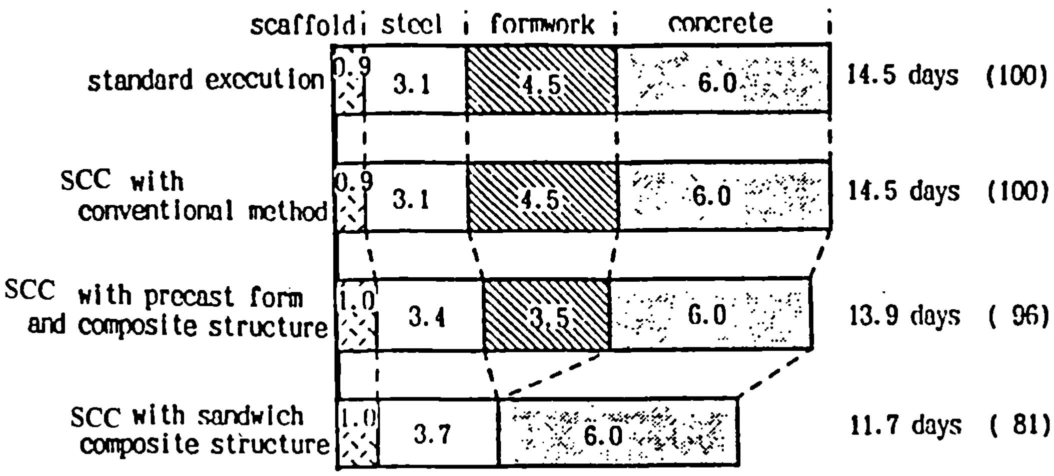
In the developed countries, labour cost is the main expenditure of concreting work, and modern construction management has the goals of reduced cost and shorter construction schedules. For most mass concrete structures, compaction is very labour intensive. Using SCC not only greatly reduces this labour requirement, but also shortens the construction period. For example, in the case of a floor slab of caisson [**Fukute et al** (1994)], 760 m^3 SCC was cast in 12 hours and only eight workers were engaged (two for operating the mobile pump, four to control the top of the flexible hose and two for operating the turn-table). Another example was the accropodes in France [**Sedran et al** (1996)], which each needed at least 15 minutes for casting with normal concrete and vibration, but only 2 minutes with SCC. Another famous example is the anchorages of Akashi Kaikyo bridge [**Okamura** (1996)], the longest suspension bridge in the world (main span 1991 m). Two anchorages (380,000 m^3 in total) were mainly placed with SCC which shortened the construction period by 20%, from 2.5 to 2 years.

SCC was also used for the wall of a large LNG tank [**Kitamura et al** (1996)], and resulted in several changes to the construction operations: (1) the number of lifts decreased from 14 to 10 whereas the height of one lift increased; (2) the number of concrete workers decreased from 150 to 50; (3) the construction period was reduced from 22 months to 18 months.

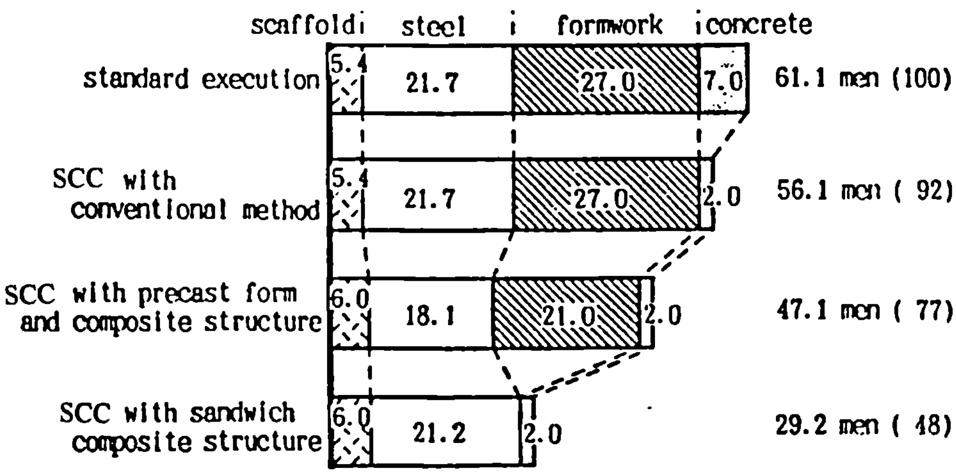
Kato et al (1993) carried out a study comparing the construction of a reinforced concrete structure using standard execution with normal concrete, and SCC with and without modification to take full advantages of its properties. The benefits shown in **Fig. 2-4** were:

1) When SCC is used with the standard execution method, the construction period is unchanged and the manpower requirement falls by about 10%.

2) When precast forms are used with a composite structure, the construction period drops by about 5% and the manpower requirement is reduced by about 20%.
3) When a steel-concrete sandwich composite structure is used with SCC, the construction period drops by about 20% and the manpower requirement is reduced by about 50%.



Comparison of the construction period



Comparison of the manpower requirement

***Fig. 2-4** Comparison of the construction period and the manpower requirement for different methods of construction [Adapted from Kato et al (1993)]*

2.1.4 Innovations in the construction system

Because of the need for compaction during placing, conventional concrete restricts construction work in many ways; such as a limitation on the height of a lift of placing, the necessity to construct the scaffolding for consolidation work, and the necessity for separate placing of the base and walls of box-section members. SCC requires no compaction, and hence, the construction system can be significantly improved and rationalised; **Okamura**'s (1996) schematic for this is shown in **Fig. 2-5**.

Two examplesof this are shown in **Fig. 2-6**, (1) a precast form used as a permanent form infilled with SCC to produce a composite structure; (2) a sandwich structure which can easily be completed by pouring SCC into a steel shell which may be assembled complete with reinforcement in a plant. Also, **Okamura** et al (1994) suggested a symmetrical branched pipe system for pumping SCC (**Fig. 2-7**) which overcame defects such as blocking and segregation in conventional methods. This new construction method is very promising.

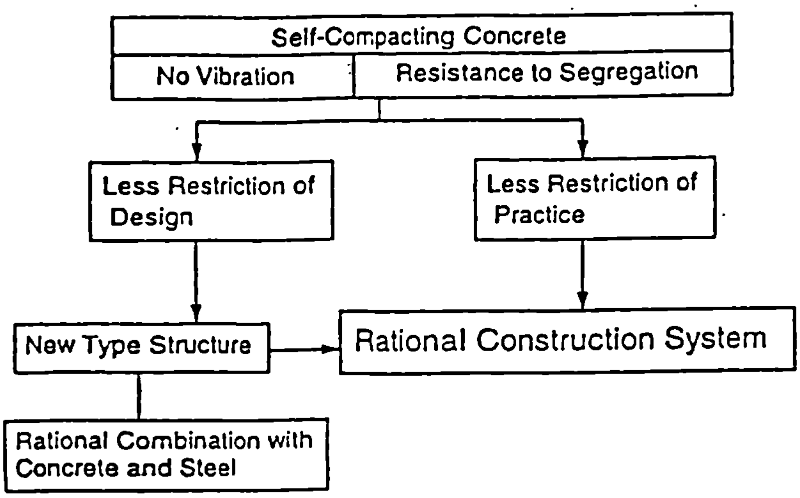
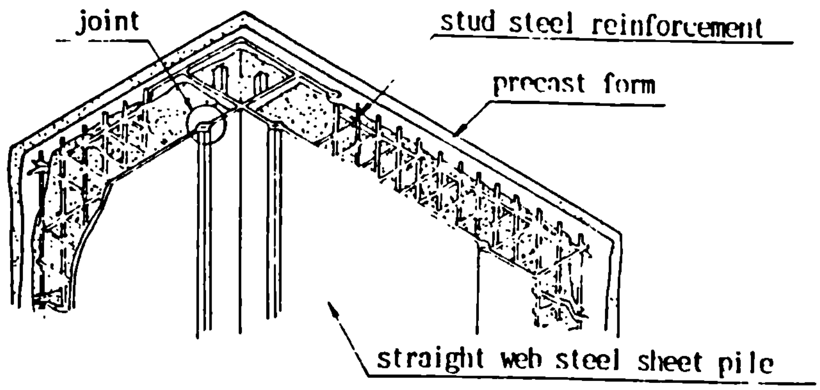
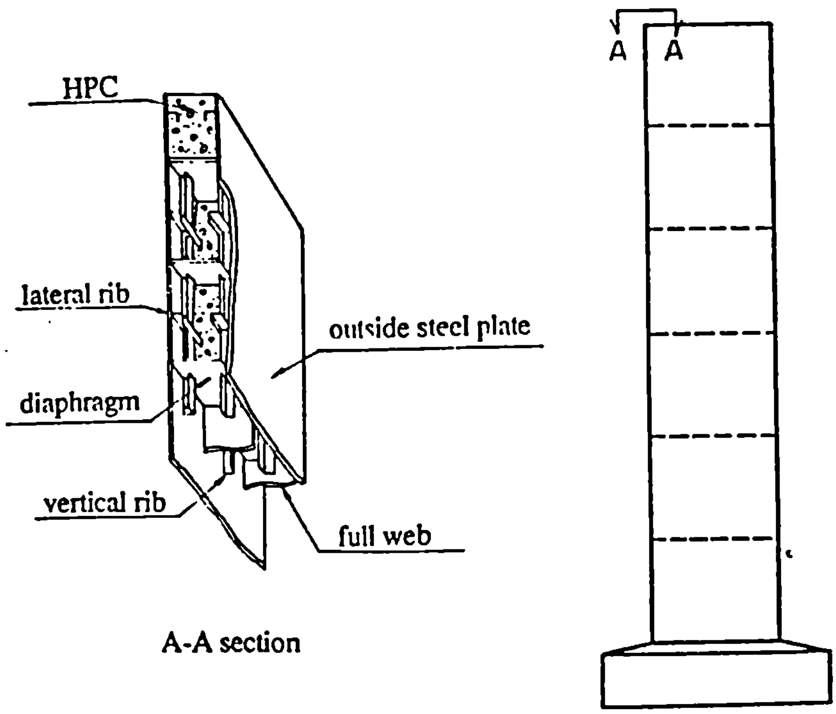


Fig. 2-5 Improvement of the construction system [Adapted from Okamura (1996)]



Outline of the structure of the precast form with the composite structure



Outline of the structure of the sandwich composite structure

***Fig. 2-6** Uses of SCC-composite structure* [*Adapted from Kato et al (1993)*]

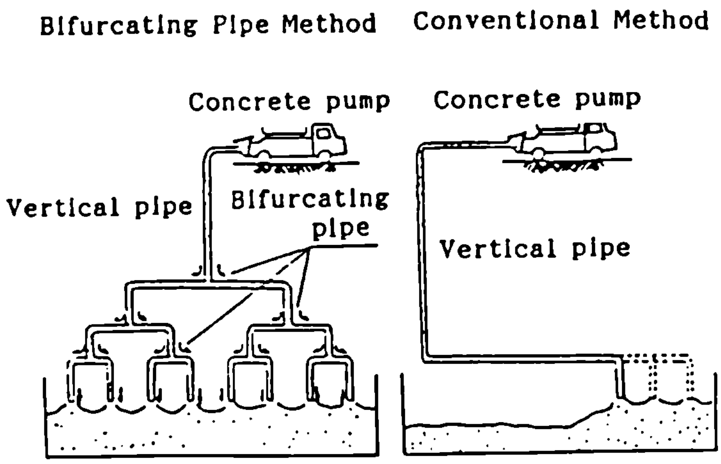


Fig. 2-7 Branched pipe method for pumping SCC [Adapted from Ozawa et al (1992)]

2. 2 Structural applications

The main structural applications that have used self-compacting concrete to advantage have been:

- heavily reinforced concrete sections
- mass concrete
- precast and sandwich composite structures
- shrinkage-compensated concrete structures

2.2.1 Examples

Table 2-2 shows nine of the reported cases of the use of SCC in heavily reinforced structural sections. In most cases, because the space of operation was limited and the reinforcement was very congested SCC was the best option for achieving the high quality of concrete required. For example, in case No. 7, a highway box culvert, which was to pass through the embankment of an existing motorway, had a high reinforcement density (130 kg/m^3) in its upper slab and the clearance between the supporting pipes and top surface of the slab was only 20 cm (**Fig. 2-8**). Full consolidation of normal concrete was probably impossible, and therefore SCC provided the optimum solution.

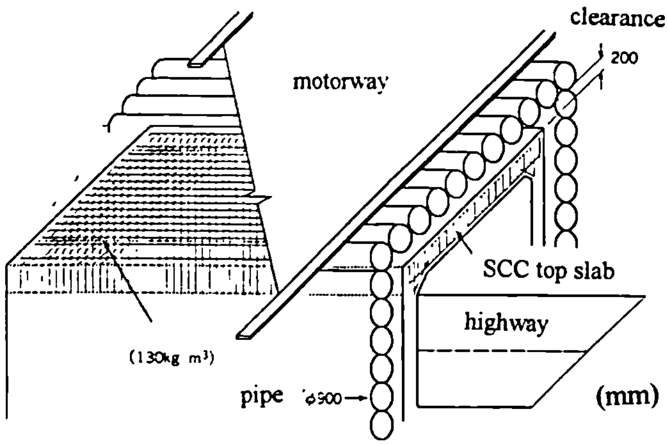


Fig. 2-8 Application of SCC to a heavily reinforced concrete section
[Adapted from Takahashi et al (1993)]

Table 2-2 Uses of SCC-heavily reinforced concrete sections

Case No.	Reference	Date	Structure	Details	Concrete vol. (m^3)
1	Hayakawa, M.	1991	building	facade	3000
2	Murao et al	1991	pilot tunnel	blockage sections	3200
3	Higuchi et al	1992	tunnel	secondary lining in a curved sewer junction	48
4	Kawai et al	1993	cable stayed bridge	lightweight concrete main span	93
5	Kuroiwa et al	1993	20 storey building	lower part of central core	1600
6	Matsuo et al	1993	stadium	guide track for retractable roof	10,000
7	Takahashi et al	1993	tunnel culvert	upper slab	2000
8	Nagayama et al	1994	arch bridge	sections	1500
9	Hon et al	1996	subway	upper slab	1500

* 1-8 in Japan. 9 in Beijing

For mass concrete, high strength is not normally needed, but low heat is essential to prevent thermal cracking. Therefore, PFA or GGBS are often used in the concrete to reduce the rate of heat output during hydration. In SCC, using a large quantity of CRMs or inert filler is one of the methods of obtaining high viscosity to prevent segregation, and thus, SCC can easily meet the low heat requirement of mass concrete and at the same time save labour cost and construction time. **Table 2-3** shows some examples of the use of SCC in mass concrete structures.

Table 2-3 Uses of SCC-mass concrete

Case No.	Reference	Date	Structure	Details	Concrete vol. (m^3)
10	Furnya et al	1992	suspension bridge	cable anchorages, (main span 1991m)	380,000
11	Miura et al	1992	LNG storage tank	heavily reinforced wall base junction	800
12	Fukute et al	1993	floor slab of caisson	heavily reinforced sections	760
13	Sedran et al	1995	accropode	plain concrete	4 each

CRMs: cement replacement materials

The use of SCC in precast concrete is very promising, because the high noise reduction is a great benefit to the workers. SCC can also be used to advantage in producing precast panels for a permanent form work. To reduce the weight and thickness of these panels, the process of compaction by the vibrator must be removed, because the vibrator often breaks off the tiles (which are stuck on the outside of the panel) and causes the leakage of paste through the tile joints. SCC has been successfully used in producing the thin precast panels shown in **Fig. 2-9** [**Umehara et al** (1994)]. Other applications include sandwich composite structures, for example, the infilling of steel tubular columns for high rise buildings [**Sakamoto et al** (1991)]. **Table 2-4** lists some applications for precast and sandwich composite structures.

Table 2-4 Uses of SCC-precast and sandwich composite structures

Case No.	Reference	Date	Structure	Details	Concrete vol. (m^3)
14	Sakamoto et al	1991	high rise building	infill of steel tubular columns- 40 m fill height	885
15	Matsuoka et al	1991	cable stayed bridge	infill of upper part of central column into permanent formwork	650
16	Imai	1992	parking lot beams	precast prestressed concrete	4 x 56
17	Umehara et al	1994	precast panels	lightweight concrete in thin section	

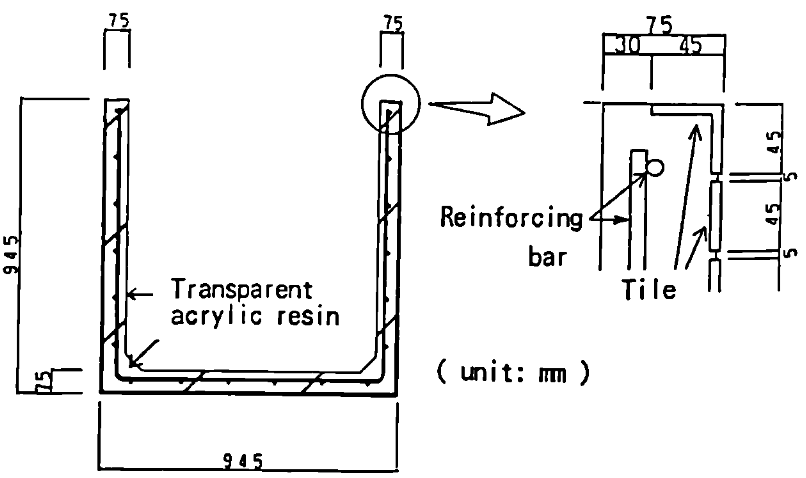


Fig. 2-9 Precast panel used as a permanent form [Apted from Umehara et al (1994)].

Certain specialised construction methods require particular properties of concrete. For example, the inverted placing method which is very popular in the Far East for high rise buildings, is in contrast with typical construction procedures (building from bottom to top, i.e. complete the substructure first and then the superstructure). The inverted placing method involves building the structure from ground level upwards and downwards simultaneously. This method significantly shortens the construction period, but requires special concrete possessing shrinkage compensating properties, in addition to having adequate self-compacting and hardened properties. This non-shrinking SCC is particularly useful for integration with previously placed upper concrete. An expansive cement or expansive admixture are needed in this case. **Table 2-5** lists two projects using non-shrinking SCC.

Table 2-5 Uses of SCC-shrinkage compensating concrete

Case No.	Reference	Date	Structure	Details	Concrete vol. (m^3)
18	Sakamoto	1992	vertical shaft	inversely casting concrete	1300
19	Chikamatsu et al	1992	closure of openings	prestressed concrete outer tank	80

2.2.2 Examples of SCC mix proportions

The mix proportions and main properties of the concrete used for the application listed in **Table 2-2** to **Table 2-5** are given in **Table 2-6**.

Table 2-6 Examples of SCC mix proportions and properties

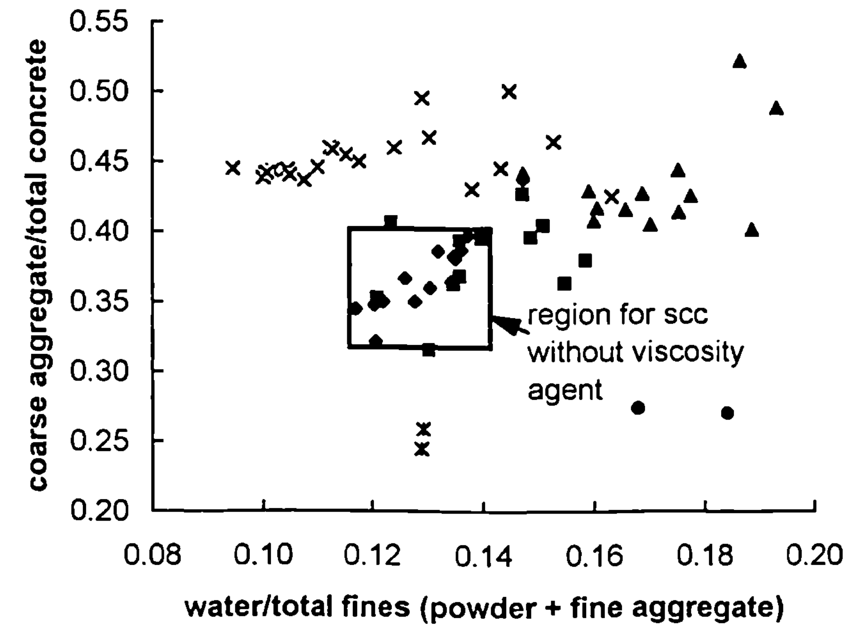
Case	Constituents (kg/m^3)							Air	Admixtures (kg/m^3)				Slump flow	Strength	Cement
No.	CA	FA	C	GGBS	PFA	LSP	W	(%)	AE	SP	AE/SP	VA	(mm)	MPa@days	type
1	920	731	193	193	96		170		1.4		9.0	1.0	600-700	50@28	PC
2	783	870	260		202		160	4.0	0.02		2.2	20g	600-700	40@28	PC
3	801	782	516				162	4.0	0.13		8.3		580-680	40@28	ternary(25/50/25)^
4	454	726	516				160	4.0	2.06		13.0	7.2	500-650	40@28	RHPC
5	910	757	500				170	3.3	0.75		8.5	1.1	600-700	48@56	PC+ternary(40/40/20)
6	880	835	425				170	4.0			4.7		500-600	30@28	BB(55/45/0)
7	815	759	285		237		167	4.0			6.3		600-700	48@28	BB
8	825	806	461				170	4.5	0.06		9.2		550-650		BB(40/60/0)
9	850	834	270		162		200			2.6			550-650	30@28	PC
10	965	769	260			150	145	4.0			6.4		500-600	24@91	ternary(25/55/20)
11	904	717	487					5.0			10.2		450-550		ternary(35/45/20)
12	811	849	380					5.0	2.3		7.6	1.0	600-700	30@28	BB
13	934	852	350			134	168			7.1			600-700	50@28	52.5N
14	926	753	180	220	100		170	2.5	0.75		7.0	1.5	600	35@28	ternary(36/44/20)
15	907	717	400		100		170	4.0	0.9		11.0	0.8	600-700	40@28	BB
16	841	762	438		100		175			10.		1.0	600-700	50@28	RHPC
17	489	632	341				160			7.5		0.07	600-700	65@28	RHPC
18	804	784	200			331	159	4.0			14.5	0.1	600-700	30@28	BB
19	776	816	370			125	165	4.5			9.0		600-700	55@28	BB

BB: Portland blast-furnace slag cement, class B ^(PC/GGBS/PFA) %

As can be seen, there is no "typical" SCC mix, but the proportions depend on the performance requirements of each project. However, SCC does possess some characteristics, e. g. a lower coarse aggregate content than conventional mixes, a high superplasticizer dose, often combined with air-entrainment which is a particular requirement of Japanese concrete (see chapter 3) and often a high proportion of CRMs. A detailed analysis of the reported mixes indicates that two important criteria are useful to distinguish SCC [**Domone** and **Chai** (1996)]:

- the ratio of water content to the total fines content, defined as the total weight of binder, inert filler and fine aggregate; and
- the coarse aggregate content, expressed as a proportion of the total concrete weight.

Fig. 2-10 shows the values of these quantities for a variety of concrete types, including SCC with and without a viscosity agent, normal structural concrete and high strength concrete. SCC mixes without a viscosity agent fall in a relative small area in the range of water/total fine ratio from 0.12 to 0.14 and coarse aggregate proportion by weight from 0.31 to 0.40.



◆ SCC	■ SCC with viscosity agent.
▲ normal concrete	× high strength concrete
✱ lwt SCC	● lwt normal concrete

Fig. 2-10 Relative mix proportions for various types of concrete [from Domone and Chai (1996)]

2. 3 Disadvantages of SCC

Everything has two sides, and advantages are often accompanied by some disadvantages. The main disadvantages of SCC are: (1) higher material cost (2) a higher standard quality control is required for its production (3) higher lateral pressure on the formwork (4) higher pumping resistance. However, such disadvantages can be reduced or eliminated through improved mix design and proper management.

2.3.1 Higher material cost

The higher material cost compared with NC mainly results from the high dosage of superplasticizer which is essential for high deformability or fluidity. The requirements for the superplasticizer properties are very demanding. It must be stable, compatible with cement, and mostly have a low workability loss with time. If early strength is required, it should have no negative influence on this. Such superplasticizers, often of the "new generation", are not cheap. Also, if a viscosity agent is used in the concrete, the cost will be even higher. Although using large quantities of CRMs, such as PFA, GGBS can reduce the cost, the same applies to NC. As a result, the material cost of SCC is inevitably higher than that of NC. However, for high compressive strength, the cost difference between SCC and NC reduces, because both need a superplasticizer. The high material cost can be offset by the reduced labour cost, which can be a significant factor in developed countries, as mentioned in section **2.1.3.**

2.3.2 Higher standard of quality control in production

According to **Kuroda** (1994), the variability of materials, particularly the sand moisture content and the overdosing of the superplasticizer, are the main problems in producing SCC. The variation of the sand moisture content has a major influence on the water content which governs the flowability of SCC. An overdose of superplasticizer often causes segregation in a concrete mix. In other words, the allowances for the variation of materials are less than in NC, and a high standard quality control needs to be enforced in a ready mix concrete plant when producing SCC. The standards for the whole production system need to be enhanced. Quality control is easier to carry out in a plant than on site, and generally, SCC makes things harder for concrete suppliers, but easier for the workers on the site.

2.3.3 Higher lateral pressure on the formwork

The high fluidity of SCC results in higher lateral formwork pressure. For safety considerations, the lateral pressure can be considered as a static pressure of "concrete liquid", i.e. the unit weight of concrete times its depth [**Okamura & Ozawa** (1994)]. The real lateral pressure depends on the pouring and hardening rates of concrete.

2.3.4 Higher pumping resistance

SCC can be pumped with conventional equipment and the possibilities of blockage in bent pipes and tapered pipes are low due to the low segregation and excellent deformability. However, the pumping resistance in straight pipes is higher than that of conventional concrete, as shown in **Fig. 2-9**. Since the frictional resistance increases as the normal pressure on the concrete increases, pumping vertically upward and increasing the pumping rate lead to a greater increase in pumping resistance compared with conventional concrete. Hence, it is generally recommended that SCC be placed slowly and continuously [**Okamura & Ozawa** (1994)], and pipes of 125 mm in diameter are recommended instead of pipes of 100 mm for pumping NC.

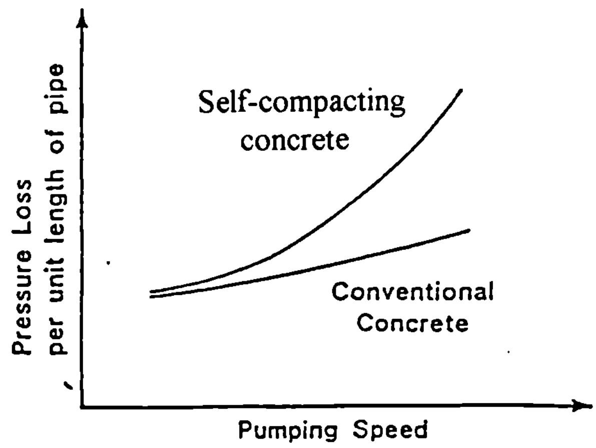


Fig. 2-11 Comparison of pumping resistance of SCC with conventional concrete
[Adapted from Okamura & Ozawa (1994)]

2. 4 Conclusions

SCC has been successfully used in many areas such as buildings, bridges, marine structures, tunnels, precast concrete, prestressed beams even with lightweight concrete. It can reduce the need for skilled labour during construction and shorten concrete placing times. It improves compaction in areas of high reinforcement density with difficult access for vibrators. Moreover, it provides a calm construction environment. Finally, SCC can promote innovations in the construction system.

The higher material cost of SCC can be offset by reduced labour cost. However, a high standard quality control is needed for its production. Formwork for SCC may also need to be strengthened.

Chapter 3

Literature review

Published literature on self-compacting concrete first appeared in 1989, and has been increasing significantly since that time, reflecting the amount of research and practical applications taking place. This chapter summarises the most important published information of direct relevance to the experimental work reported in this thesis. A significant amount of this is published in Japanese, and was translated by the author. Much was published during the course of the research, and in some cases, influenced the subsequent experimental work. To avoid unnecessary duplication, detailed information from some references is presented and discussed in later chapters together with results from the current programme.

3. 1 Background of Japan's concrete industry

Because SCC was invented in Japan and has been used in their construction industry since 1990, it is understandable that most published papers are from Japan. In reading these, it is very important to take into account of the characteristics, requirements and materials used in Japanese concrete. For example, **JIS A 5308** specifies that ordinary concrete must use a chemical admixture to produce an air content of 4.5±1.5% with maximum aggregate size of 20 mm or above and according to **JASS 5** (1986), the water content in a concrete mix cannot exceed **185 kg/m³**. Also, Japanese practice uses cylinders for strength measurement. **Table 3-1** shows a comparison of characteristic strength values for cylinders and cubes. Some results cannot be universally applied, because of the different properties of nominally similar materials.

Table 3-1 Characteristic strength values (MPa)

Concrete grade	C12	C20	C30	C40	C50	C60	C70	C80
f_{ck}-cylinder	12	20	30	40	50	60	70	80
f_{ck}-cube	15	25	37	50	60	70	80	90

Adapted from CEB-FIP 1990 Table 2.1.1.

Japan's construction industry has been very active in the research and development of SCC, for example in carrying out large scale structures tests to prove its feasibility, after initial laboratory work by university research groups. **Fig. 3-1** shows that the number of presentations by companies on SCC at the JCI annual conferences are much higher than that by the universities.

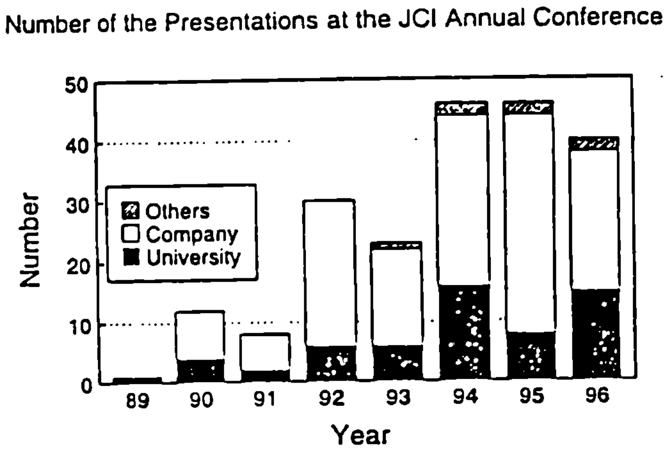


Fig. 3-1 Presentations on self-compacting concrete at the JCI annual conferences
[Adapted from Okamura (1996)]

3. 2 Materials used in SCC

3.2.1 Cement

Table 3-2 shows the different types of cement in use in Japan and their production in 1994. Portland blast-furnace slag cement, particularly class B, is often used in SCC (**Table 3-3**). Modified cement (equivalent to ASTM type II), which has no BS equivalent, is also popular in SCC mixes. There are also some special cements in use for SCC such as high belite cement and ternary blended cement. High belite cement, whose compound composition is similar to low heat cement (ASTM type IV), has the merit of low yield stress and viscosity compared to other cements (**Fig. 3-2**). **Table 3-4** shows the typical compound composition of the different kinds of cements. Ternary blended cement is normally composed of PC, GGBS and PFA, for example, 35%PC/45%GGBS/20%PFA was used in a base mat of a LNG underground storage tank. It is important to note that the rheological properties of concrete made with this ball-mill blended cement may be different from those whose CRMs (cement replacement materials) proportions are the same as the blended cement but are fed into the concrete mixer simultaneously with the Portland cement, since the particle size distributions of the CRMs may be altered during the ball-mill blending.

Table 3-2 Types of cement in Japan and their production in 1994.

Type of Portland cement	Product (1000 tons)	Percentage (%)
Ordinary	69,568	76.1
Rapid-hardening (incl. Extra)	3,541	3.9
Modified	186	0.2
Sulphate-resisting	25	0.0
Others	1	0.0
Sub-total	73,321	80.2
Portland blast-furnace slag	16,930	18.5
Portland pozzolan	53	0.1
Portland fly-ash	678	0.8
Others	386	0.4
Sub-total	18,047	19.8
Total	91,369	100.0

Translated from Cement & concrete No. 594, Aug. 1996

Table 3-3 Classification of Portland blast-furnace slag cement and Portland fly-ash cement

Class	Blast-furnace slag content (% by wt.)	Fly-ash content (% by wt.)
Class A	Over 5 to 30 incl.	Over 5 to 10 incl.
Class B	Over 30 to 60 incl.	Over 10 to 20 incl.
Class C	Over 60 to 70 incl.	Over 20 to 30 incl.

Adapted from JIS R 5211 and R 5213

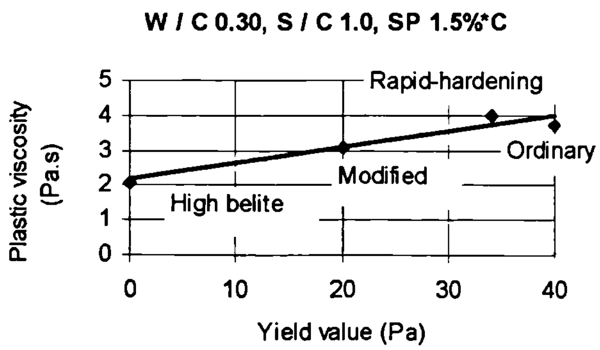


Fig. 3-2 Yield stress and plastic viscosity of paste made with different types of cement.
[Adapted from proceedings of JCI Vol. 15 No 1 [1022] by Nawa et al (1993)]

Table 3-4 Typical compound composition of cement in Japan

Type of cement	Specific gravity	Specific surface area (cm2 / g)	Compound composition			
			C_3S	C_2S	C_3A	C_4AF
Ordinary	3.16	3040	52	23	9	9
Rapid hardening	3.15	4360	65	10	8	8
Modified	3.21	3040	43	35	3	12
High belite	3.20	4080	35	46	3	9

Adapted from proceedings of JCI Vol. 15 No 1 [1022] by Nawa et al 1993

3.2.2 Cement replacement materials (CRMs)

GGBS, PFA, CSF and LSP are all used in SCC mixes. CSF is only used occasionally, mainly to produce high strength. GGBS deserves special attention, because in Japan, there are three classes according to the specific surface area, i.e., 4000, 6000 and 8000 cm^2/g. (For comparison, the specific surface area of GGBS used in this study, produced by Civil and Marine Ltd in the UK, is within the range 4000 to 4400 cm^2/g.) A high specific surface results in quicker strength development (**Fig 3-3**), and the setting, bleeding and rheological properties are also different (**Table 3-5**). In Japan, GGBS with a specific surface of 6000 cm^2/g is used for SCC. Hence, many properties of GGBS concrete are different from those in the UK. **Table 3-6** shows the merits and usage of GGBS of different fineness. It is interesting to note that only GGBS with specific surface area over 6000 cm^2/g can offer high fluidity.

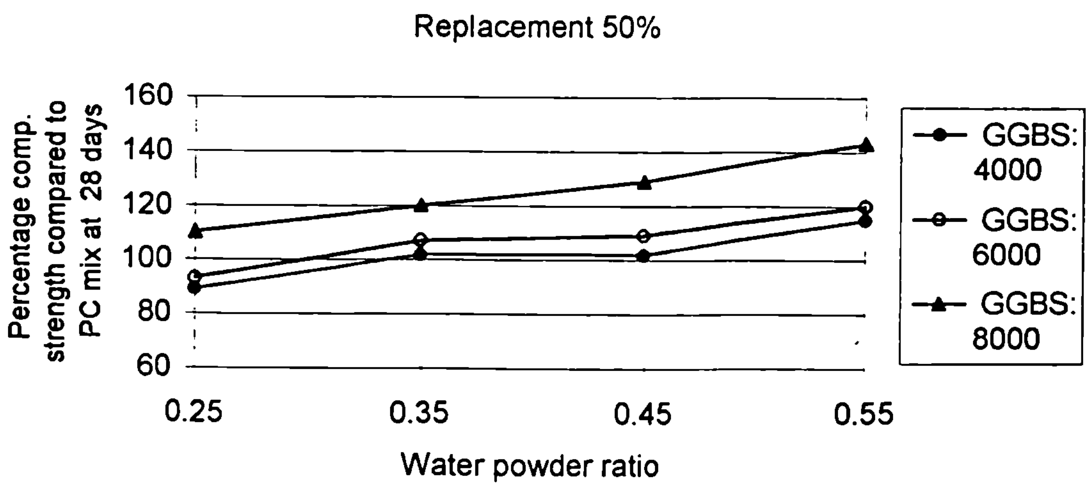


Fig. 3-3 Influence of fineness of GGBS on strength development at different W/p ratio
[Adapted from Vol. 34, No. 4,(1996) JCI Concrete Journal]

Table 3-5 Bleeding and setting of concrete with GGBS of different fineness

Specific surface area	Replacement (%)	Bleeding amount (cm^3/cm^2)			Setting time (hour-min)	
		30 min	60 min	120 min	Initial	final
4000 (cm^2/g)	30	0.12	0.28	0.37	6-50	9-00
	50	0.23	0.34	0.41	7-30	9-50
	70	0.33	0.39	0.45	8-15	11-20
6000	50	0.14	0.31	0.36	7-20	9-40
8000	50	0.13	0.25	0.28	7-00	9-25
Ref.	0	0.22	0.33	0.40	6-35	8-50

water binder ratio 0.55, slump 18 cm, Temp. 20 C, 80% R.H
Translated from Vol. 34, No. 4, 1996. 4 JCI Concrete Journal

Table 3-6 Merits and usage of GGBS as a CRM

Merits	Specific surface (cm^2/g)	Replacement (%)	Main usage
High fluidity	**6000**~8000	30~70	SCC
High retardation	4000~8000	30~70	Concrete in hot weather, large pours
Low heat evolution	4000~8000	50~70	Mass concrete
High 28 day strength	**6000**~8000	30~70	Better durability for buildings
High long term strength	4000~8000	50~70	Better durability for buildings
High strength	**6000**~8000	30~70	High rise buildings, deep underground structures
High water resistance	4000~8000	50~70	Underground or marine structures
Better resistance to salt	4000~8000	50~70	Coastal or marine structures
Better durability to sea water	4000~8000	50~70	Marine structures
Better resistance to acid, sulphate	4000~8000	50~70	Chemical engineering buildings, spring regions buildings, acid rain prevention
Better resistance to ASR	4000~8000	50~70	ASR prevention

Translated from Vol. 34, No. 4, 1996. 4 JCI Concrete Journal

Limestone powder (LSP), a chemically inert filler, is another important CRM often used in Japan. Its advantages are increased segregation resistance, reduced cost, lower heat evolution, reduced carbonation [**Tanaka et al** (1993)] and reduced shrinkage [**Ogawa et al** (1995)]. The last two merits cannot be obtained by using PFA and GGBS [**Neville** (1995)].

3.2.3 Chemical admixtures

- High range water reducing and air entraining agents

  Fig. 3-4 shows Japan's rapid increase in annual production of high range water reducing and air entraining agents. Because the rate of loss of workability and one day strength gain are mainly dependent on the superplasticizer, test results from Japan are unlikely to be reproducible in other place with different superplasticizers. The combined requirements of air-entrainment and reduced water content has resulted in a special kind of two-in-one superplasticizer (high range water reducing and air entraining agent). Products with this characteristic have predominated in SCC in Japan.

- Viscosity agents

  Viscosity agents are another important chemical admixture for the production of SCC, and, in particular, reduce the variation of SCC quality (see section **3.8**). One famous product is Welan gum [**Sakata et al** (1996)]. Unfortunately, viscosity agents are rare in the UK market, except as an anti-washout chemical admixture.

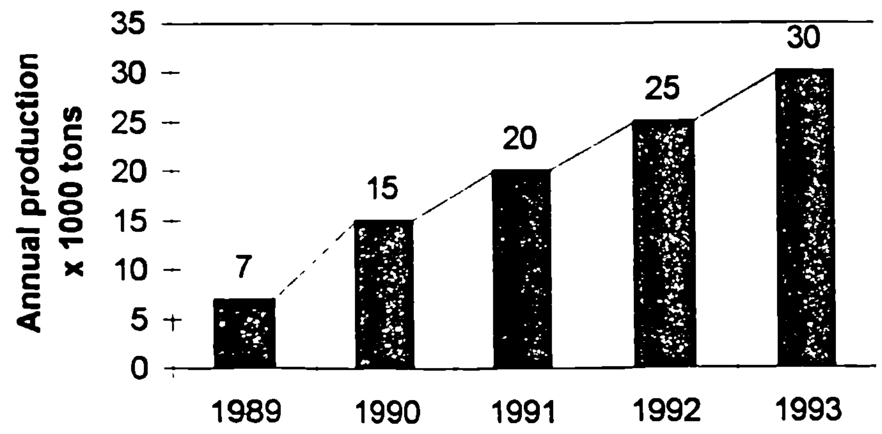


Fig. 3-4 Annual production of high range water reducing and air-entraining agents in Japan [Adapted from Moriya et al (1994)]

3.2.4 Aggregate

The fineness moduli of most sands used in Japan are in the range 2.55 to 3.10, i.e. the sand in Japan is generally coarser than Thames river sand. Some projects use a mixture of crushed and fine sand, or crushed and marine sand. Uncrushed coarse aggregate is seldom used in Japan, crushed aggregate is normally used. It is interesting to note that in Japanese publications, the sand aggregate ratio (s/a) is normally given as a percentage volume, not a percentage weight.

3. 3 Test methods for fresh properties of SCC

Tests of hardened concrete have been well documented in BS or ASTM standards, but there are no standards for the tests used to measure the fresh properties of SCC. This situation is true for nearly every new technology. **Table 3-7** shows the important fresh properties of SCC, tests currently used to assess them, and ways by which they can be improved.

3.3.1 Slump flow test

The slump flow spread, which is the diameter of the concrete after a standard slump test is the simplest and most popular test for the assessment of concrete flowability (or fluidity). For SCC, because of its good filling capacity, no tamping of the concrete is required. It is very important to know the factors influencing the slump flow spread. The superplasticizer dosage, in relation to the water/powder ratio and powder content is the dominant factor, followed by the paste volume. **Fig. 3-5** shows that at constant superplasticizer dosage the slump flow increases with reducing coarse aggregate content, and when both superplasticizer dosage and coarse aggregate content are kept constant, slump flow increases with the reducing fine aggregate content. As a result of combining these two effects, slump flow increases with the paste volume **(Fig 3-6)**. Other influencing factors include the maximum size and the shape and texture of the aggregate.

Table 3-7 Fresh properties and tests of SCC

Property	Measurement	Loading	Method of test	Way to improve the property
Rheology (Yield stress)	Ultimate deformation	Self-weight	Slump flow test L-test **Fig. 3-12(a)**	Increase superplasticizer, Control free water content
		External force	Flow table test	
	g value	External force	Two-point workability test	
Rheology (Plastic viscosity)	Speed of deformation	Self-weight	Slump flow test Funnel test **Fig. 3-7** L-test **Fig. 3-12(a)**	Use viscosity agent, or lower W / P by incorporating CRMs
	h value	External force	Two-point workability test	
Segregation resistance	mortar amount	Self-weight	Sieve test	Use viscosity agent, or lower W / P by incorporating CRMs
Passing ability through gaps	Discharge, Flowing speed	Self-weight	Box test **Fig. 3-14** L-test with rebars **Fig. 3-12(b), & 3-13** U-test **Fig.3-15& 3-16**	Increase the gap of rebars, or reduce the quantity of coarse aggregate
Filling capacity	Filling condition	Self-weight	Filling capacity test **Fig. 3-17**	Control cementitious powder content and free water content

3.3.2 Funnel tests

Two types of funnel are in use: the O-funnel and the V-funnel (**Fig. 3-7**). The latter, suggested by **Ozawa,** is based on the premise that concrete deforms two-dimensionally rather than three-dimensionally when passing through reinforcement in its usual arrangement. Different sizes of V-funnel outlet cause different results, and the most common sizes are 65 x 75 mm and 75 x 75 mm, both are used for testing concrete with a 20 mm maximum aggregate size. This test measures a viscosity property of concrete, and in addition, can also detect the arching effect of aggregate, as shown in **Fig. 3-8.** The flow time through the funnel is measured as the time to find daylight appearing when viewed

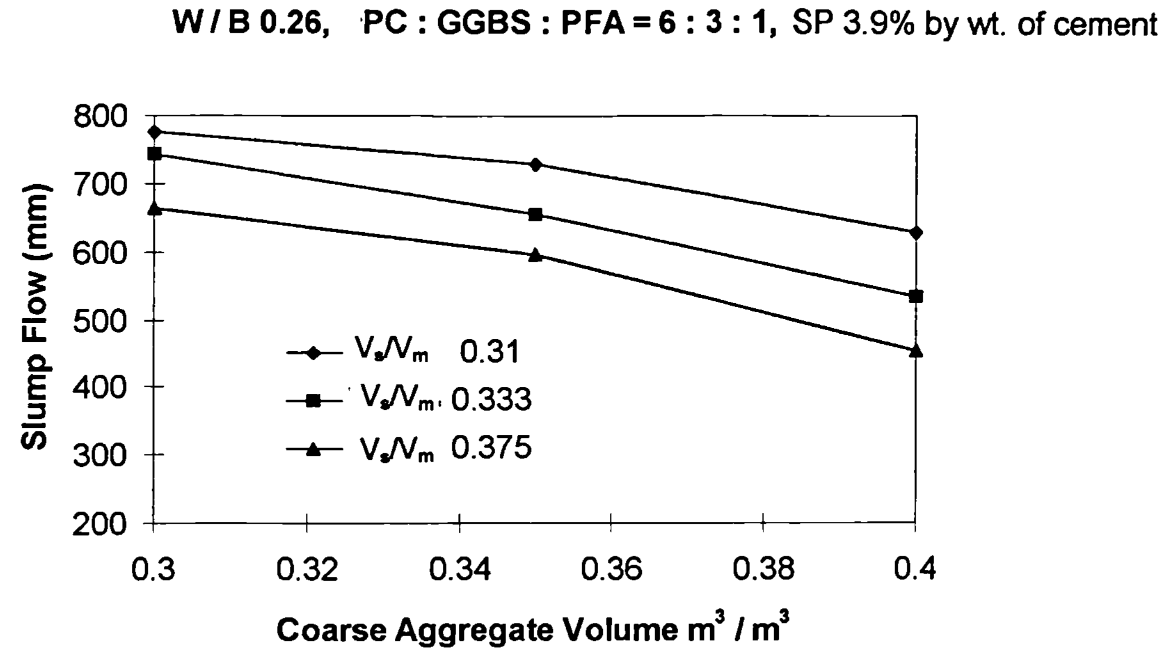


Fig. 3-5 Relationship between coarse aggregate volume and slump flow for the same superplasticizer dosage [Data adapted from Yen et al (1996)]

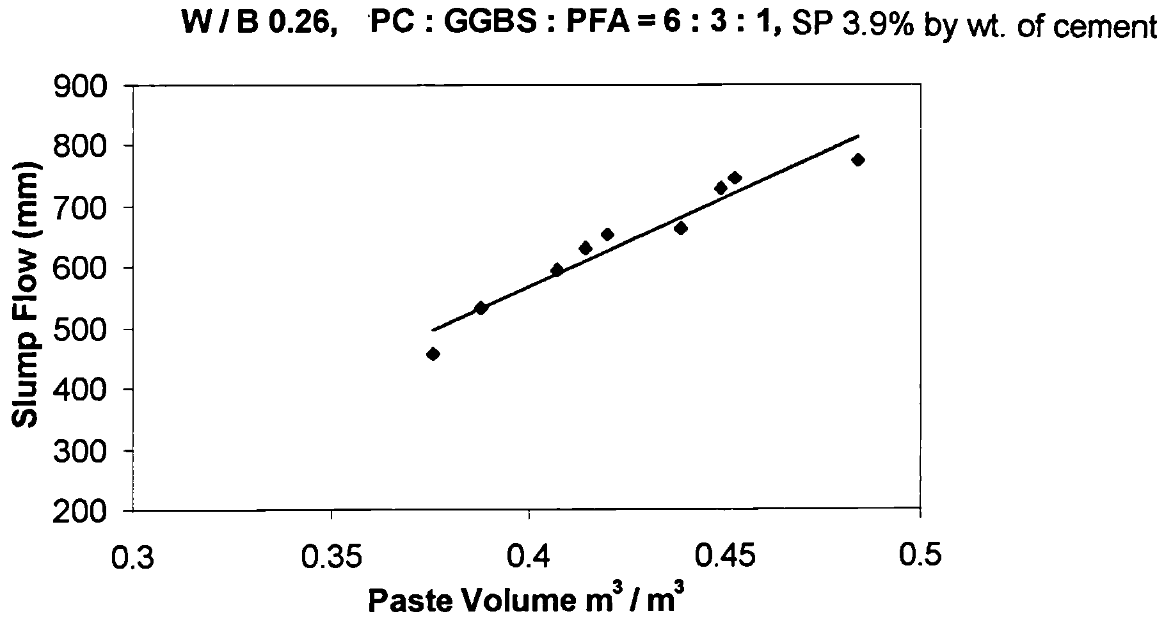


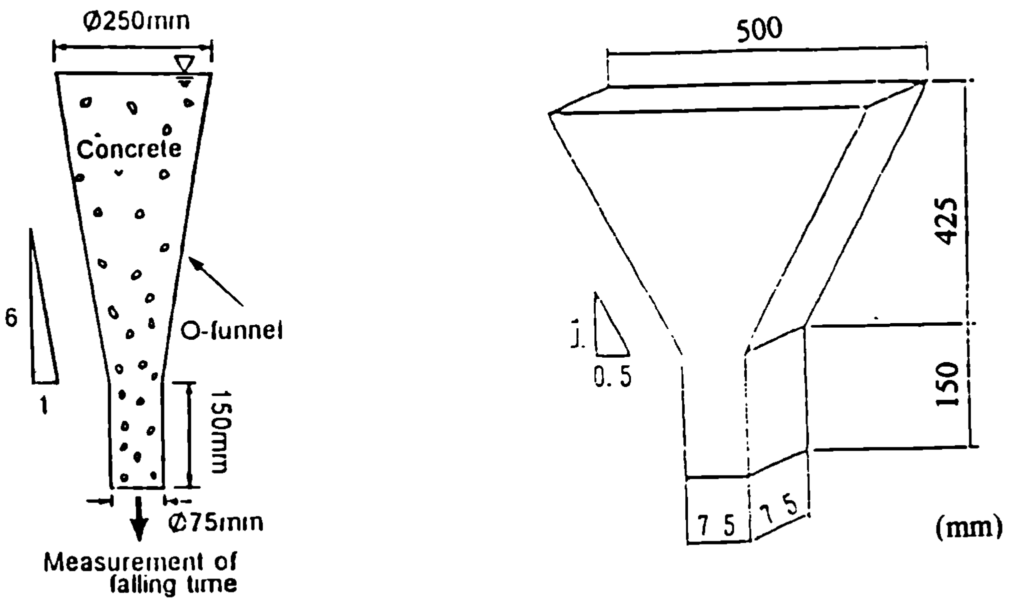
Fig. 3-6 Relationship between paste volume and slump flow for the same superplasticizer dosage.[Data adapted from Yen et al (1996)]

from above. The flow time is influenced mainly by the rheological properties of the mortar phase and the coarse aggregate content. **Fig. 3-9** shows the relationship between the coarse aggregate content and the V-funnel flow time for the same mortar properties. Large quantity of coarse aggregate increases funnel flow time significantly. **Fig. 3-10** shows that the flow speed can effectively show the effect of different water/powder ratios at the same slump flow, and is most sensitive at a coarse aggregate content of G/G_{lim} of 0.50.

Ozawa has concluded that the slump flow test (SF) together with V-funnel (75 × 75) flow time (V_t) can be used to assess the filling capacity (will be discussed in section **3.3.7**) of the concrete. The relative flow area ratio A_f and relative flow time R_f were defined as follows.

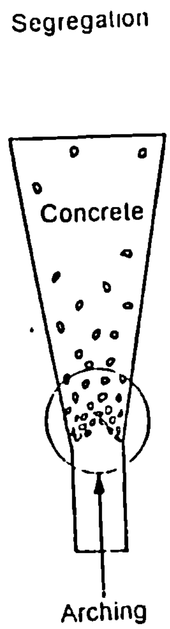
$A_f = (SF/600)^2$ $\qquad$ $R_f = 5/V_t$

An A_f vs. R_f diagram can be used to rank the concrete according to its filling capacity



[Adapted from Ushijima et al (1995)] *[Adapted from Ozawa et al (1995)]*

***Fig. 3-7** O-funnel and V-funnel tests*



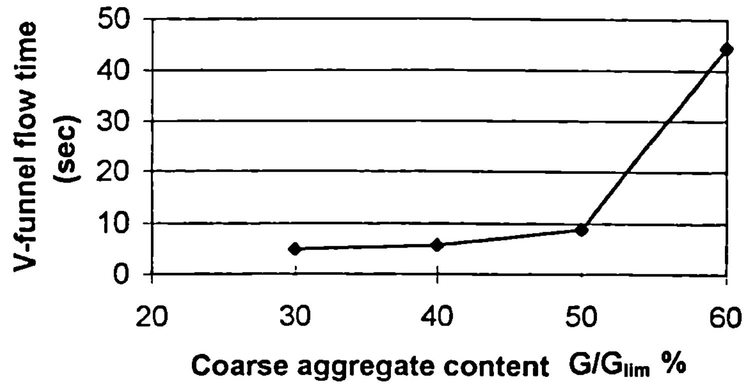


Fig. 3-9 Relationship between coarse aggregate content and V-funnel flow time for the same fresh properties of mortar
[Derived from Ozawa et al (1995)]

Fig. 3-8 Form of arching of aggregate in an O-funnel due to segregation
[Adapted from Ushijima et al (1995)]

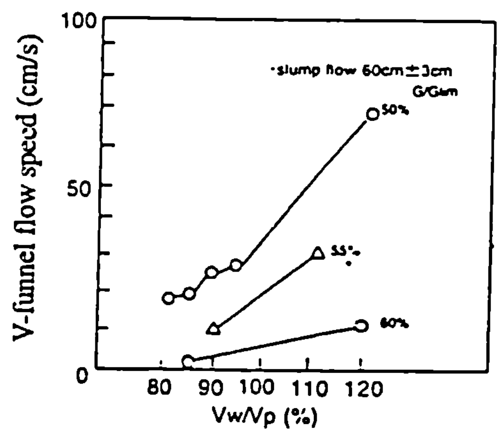


Fig. 3-10 Relationship between water/powder ratio (by vol.) and V-funnel flow speed
[Adapted from Ozawa et al (1995)]

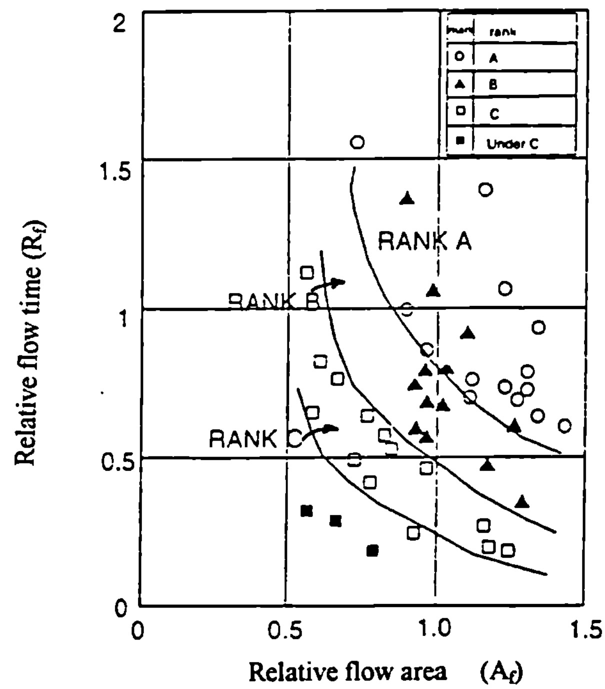


Fig. 3-11 Ranks of self-compactability
[Adapted from Ozawa et al (1995)]

3.3.3 Sieve test for segregation resistance

Segregation, easy to see and feel both in the laboratory and on the site, is difficult to measure. So far several tests have been developed for this, but **Ozawa** comments that none is fully satisfactory. A common method is to put two litres of concrete over a 5 mm sieve for five minutes, and to define a segregation index (S.I.) by the following equation.

$$\text{S.I.} = \frac{M_f}{M_c} \text{ X } 100\ (\%) \qquad \textbf{(3-1)}$$

where: M_f = weight of mortar passing through the sieve

M_c = weight of mortar contained in the two litres of concrete

There is no value generally accepted as a threshold of segregation, but according to **Nagataki** (1995), 5% is a threshold. However, according to the **JCI** Research Committee on SCC - Research report (II) (1994),. most SCC has the values of S.I. in a range from 8% to 23%.

3.3.4 L-Tests

Fig. 3-12 shows typical L-tests that have been used to assess flowability and passing ability. In **Fig. 3-12(a)** there is no reinforcement and the final flow length (L_f) is a measure of flowability. A timing device can be added to this test to measure the flow speed of concrete, which is related to the viscosity of concrete. If a reinforcement is added as in Fig. 3-12(b), then passing ability is assessed. Fig. 3-13 shows a combined funnel and L-test system, where the concrete has a free fall before passing through the reinforcement in the L-test.

3.3.5 Box test

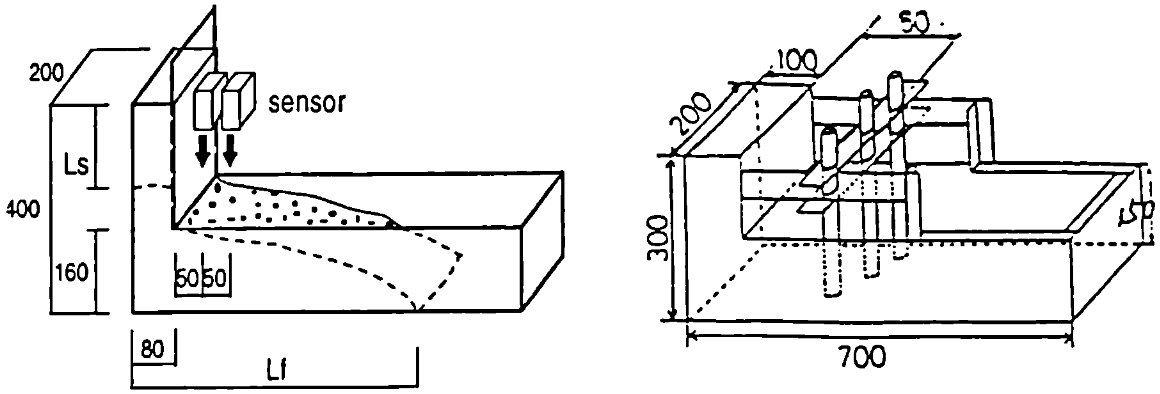
The Box test **(Fig.3-14)** is used to measure the passing ability through reinforcement with vertical concrete flow. It needs at least 30 of litres concrete. The experimental data for many published papers were obtained using this test [**Okamura et al** (1992), **Fujiwara et al** (1996)]. The passing volume of concrete through reinforcement is used as a index to assess the passing ability.

3.3.6 U-Test

The U-test, proposed by the **Taisei** group and recommended by **Okamura** (1996), is useful in evaluating the passing ability through reinforcement and hence self-compactability. The dimensions and the shape are shown in **Fig. 3-15**. The left-hand column is first filled with concrete, and after the centre gate is then opened, the concrete passes through the obstacle and rises in the right-hand column. The rise height indicates the degree of the self-compactability of the concrete. Concrete with a height of over **300 mm** has been shown to have sufficient self-compactability. **Fig 3-16** shows another similar test, in which, although the shape and measurement are different, the basic principle is the same.

3.3.7 Filling capacity test

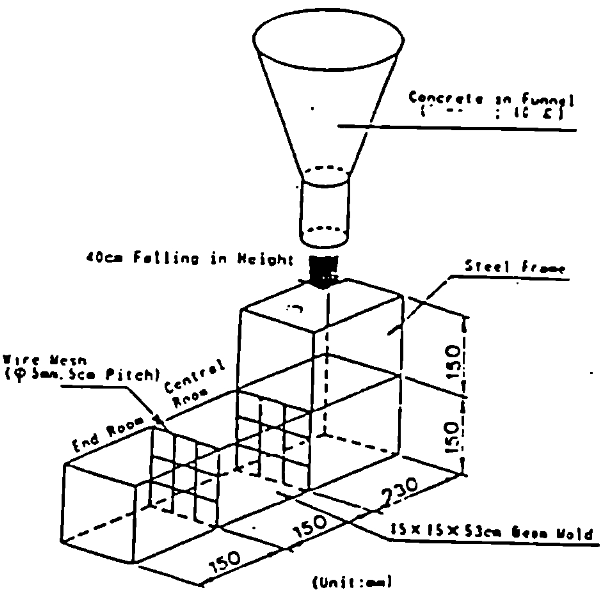
The filling capacity test **(Fig. 3-17)** was first used by **Ozawa** at Tokyo university. The ranking of self-compactability in **Fig. 3-11** were based on this test. One side of the formwork of this test was made of a transparent acrylic plate so that it is very easy to observe the flowing condition of the fresh concrete.



(a) *[Adapted from Mitsui et al (1994)]*

(b) *[Adapted from Nishibayashi et al (1994)]*

***Fig. 3-12** Typical L-test*



[Adapted from JCI Committee on SCC report (I) (1993)]

***Fig. 3-13** Typical combined funnel and L-test*

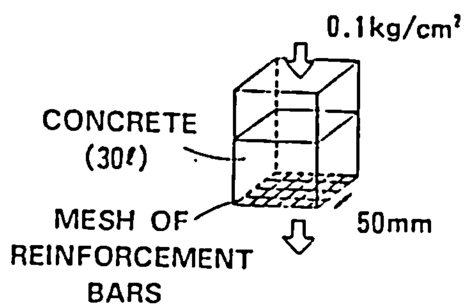


***Fig. 3-14** Box test*
[Adapted from Ozawa et al (1992)]

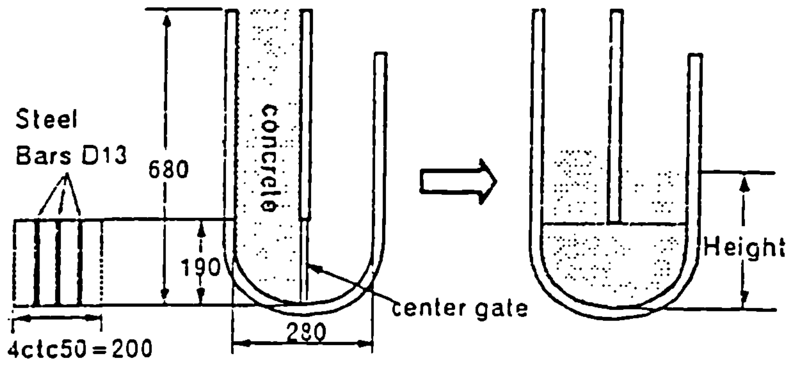


Fig. 3-15 U-test measuring filling height [Adapted from Shindoh et al (1996)]

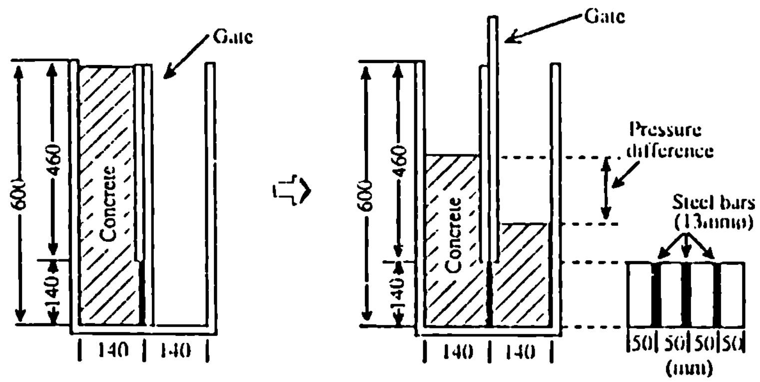


Fig. 3-16 U-test measuring pressure difference [Adapted from Nagataki et al (1995)]

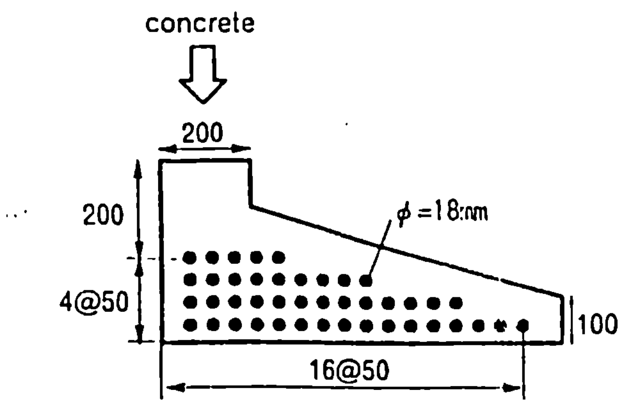


Fig. 3-17 Filling capacity test [Adapted from Okamura et al (1993)]

3.3.8 Two-point workability test

The two-point workability test, developed by **Tattersall** and his co-workers, measures the rheological properties of concrete, and is especially suitable for SCC. **Kawai et al** (1994) have used . similar apparatus to test SCC. It is well established that fresh concrete can be described by a **Bingham Model**, and the g and h values from the two-point workability test are related to the Bingham constants of yield stress and plastic viscosity respectively. It was used in the current research programme, and will be described in full in Chapter 4.

3. 4 Characteristic fresh properties

SCC is distinguished from other concrete by its characteristic fresh properties of passing ability through reinforcement under its own weight without significant segregation. This section briefly outlines the factors that have been reported as influencing these properties.

3.4.1 Passing ability through reinforcement

The main reason for the blockage of concrete when passing through reinforcement is the aggregate arching effect. **Fig. 3-18** shows the movement of aggregate approaching the gap between rebars [**Fujiwara** (1996)]. The arching action can clearly be seen in **Fig. 3-19(a),** which is in the blocking state, whereas **Fig. 3-19(b)** shows the passing state. The main factors influencing the passing ability are:

- the ratio of clear spacing between rebars to the maximum aggregate size,
- the coarse aggregate content,
- the flowability,
- segregation resistance.

3.4.1.1 Ratio of clear spacing between rebars to the maximum aggregate size

Fig. 3-20 shows the maximum gap for a stable arching in SCC suggested by **Fujiwara** (1996). For a one dimensional mesh, this gap equals $(2 + \sqrt{3})$ times the aggregate radius; whereas for a two dimensional mesh, this gap is $(2 + 2\sqrt{2})$ times the aggregate radius. With a 20 mm maximum aggregate size, these gaps are 37.3 and 48.3 mm for 1-D and 2-D mesh respectively. In other words, if the clear gaps are higher than these values, say 40 and 50 mm for 1-D and 2-D mesh respectively, then the risk of arching is greatly reduced.

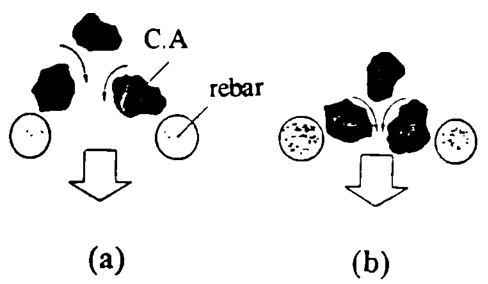


Fig. 3-18 Movement of aggregate approaching the gaps of rebars
[Adapted from Fujiwara (1996)]

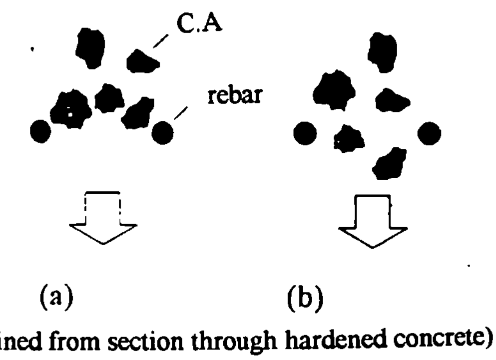


Fig. 3-19 Comparison of aggregate (a)blocking (b)passing the gaps in the rebars
[Adapted from Fujiwara (1996)]

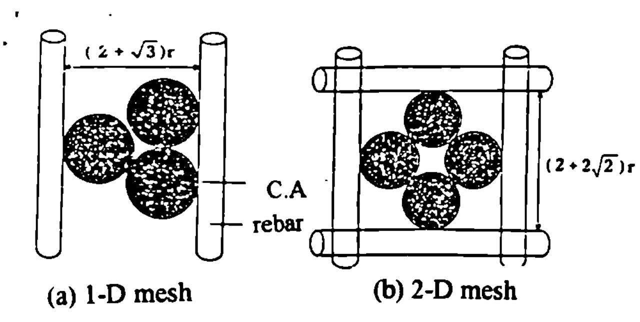


Fig. 3-20 Maximum gaps for stable arching with a 1-D and 2-D mesh
[Adapted from Fujiwara (1996)]

Table 3-8 Results of passing ability through gaps

		1-D mesh			2-D mesh				Mortar rheology		No of
Clear gap (mm)		27	37	47	27	37	47	57	τ_0 (Pa)	μ (Pa.s)	mixes
Coarse aggregate volume (%)	8.1	o	o	o	Δ	o	o	o	3.2-20.5	1.8-7.9	4
	16.1	o	o	o	×	o	o	o	5.0-30.6	3.6-8.5	8
	24.2	Δ	o	o	×	×	Δ	o	8.9-48.6	3.7-10.2	7
	28.0	×	Δ	o	×	×	×	o	3.8-50.2	2.5-11.5	6
	32.3	×	×	o	×	×	×	o	4.9-38.4	3.6-9.9	8
	36.0	×	×	o	×	×	×	o	2.8-25.9	2.1-7.2	4

o: passed, Δ: transition, ×: blocked.
mortar: w:c:f.a = 0.29:0.2:0.51 by vol.
SP/C: 2.0-3.0%, VA/C: 0-8.8 % by mass
Translated from Fujiwara et al (1996) Table 3, Proc. JSCE No 550/V-33, pp 29

The results in **Table 3-8** were obtained by using the Box test shown in **Fig. 3-14,** and are consistent with this hypothesis. The clear gaps of 37 mm and 47 mm are the critical values for the passing ability of a 1-D and 2-D mesh respectively. If the clear values are higher than these values, e.g. 47 mm and 57 mm the passing ability is markedly enhanced. Also, **Nishibayashi** by using the L-tests to investigate the effects of mix proportions and spacing of rebars on passing ability has confirmed this [**Nishibayashi et al. (1994)**]. In **Fig. 3-21,** LFs and LF were the flow values in the L-test with [**Fig. 3-12(b)**] and without **Fig. 3-12(a)** rebars respectively. When the clear spacing between rebars was 37 mm, the concrete with 20 mm maximum size aggregate could flow freely without being blocked, but, when the clear spacing between rebars was reduced to 30 mm and 27 mm, the concrete was blocked by the coarse aggregate regardless of the value of the plastic viscosity of mortar. Consequently, it is safer if the ratios of the clear spacing to maximum aggregate size are not less than **2.0** and **2.5** for 1-D mesh and 2-D mesh respectively.

3.4.1.2 Coarse aggregate content

Apart from clear gaps between rebars, **Table 3-8** also shows that coarse aggregate volume is an important factor influencing the passing ability. A lower coarse aggregate content, which increases the relative distance between aggregate particles, can effectively increase the passing ability. A high aggregate content causes a high frequency of collision and contact between aggregate particles, and as a result, the internal stress increases when concrete is deformed, particularly near obstacles. **Fig. 3-22** shows that the energy required for flow is consumed by the increased internal stress resulting from the high coarse aggregate content, which is often the cause of the blockage. **Fig. 3-23** shows that this increased internal stress dramatically prolongs the flow time through a V-funnel. **Fig. 3-22** and **3-23** both show that limiting the coarse aggregate content to about 50% of its solid volume is effective in avoiding such blockages.

3.4.1.3 Flowability

Nagataki et al (1995) carried out a series of tests on passing ability by using a U-test (**Fig. 3-16**). Normally the yield stress and viscosity of mortar are two independent parameters, but in their research, by using the addition of a viscosity agent together with a superplasticizer, they presented a relationship between these two parameters as shown in **Fig. 3-24(a)**. **Fig. 3-24(b)** shows that the yield stress is related to the flowability; the lower the yield stress of mortar, the higher the flowability of concrete. In **Fig. 3-24(d)**, when the mortar yield stress approaches zero together with a low viscosity, segregation occurred in all the mixes and caused high pressure differences (i.e. blockage) regardless of the coarse aggregate volume. It is clear that the mix with a high coarse aggregate volume (V_g = 0.345) always has a high pressure difference regardless of mortar fresh properties. On the contrary, the mix with low coarse aggregate volume (V_g = 0.245) has low pressure difference, i.e. passed. Once again, it is shown that the coarse aggregate volume is more

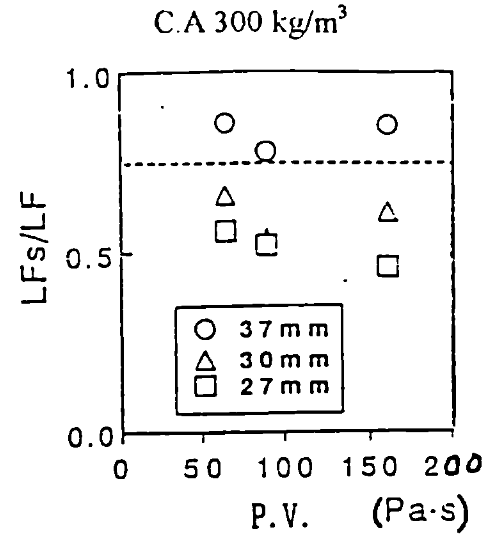


Fig. 3-21 Results of L-test for passing ability
[Adapted from Nishibayashi et al (1994)]

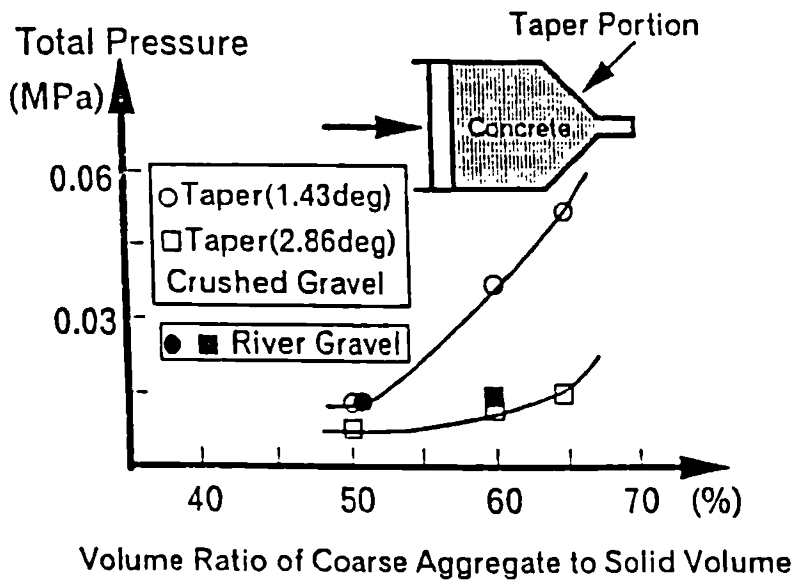


Fig. 3-22 Increasing internal stress due to increase of coarse aggregate content
[Adapted from Okamura et al (1995)]

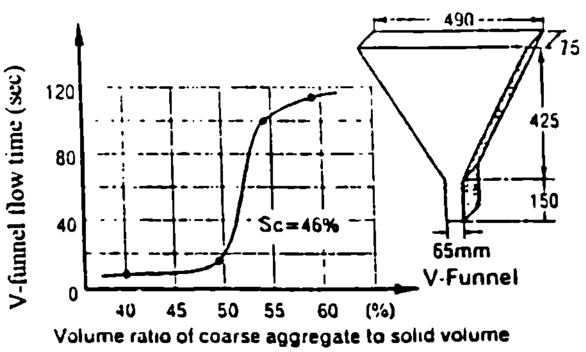
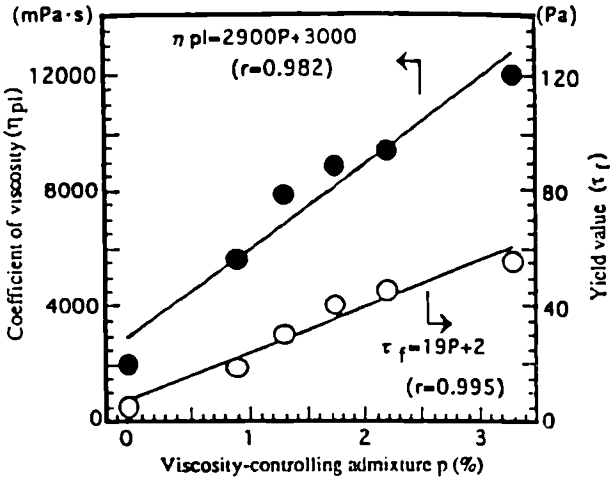
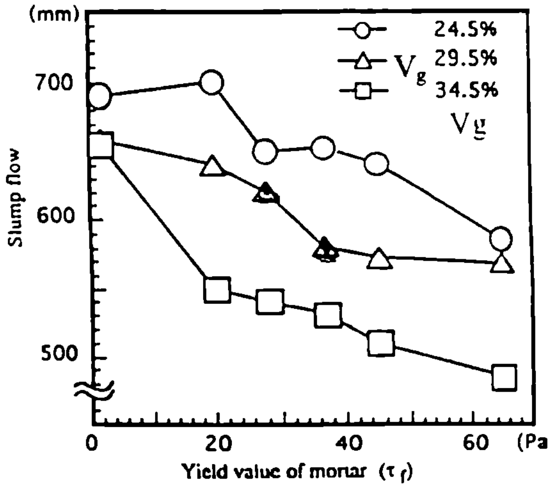


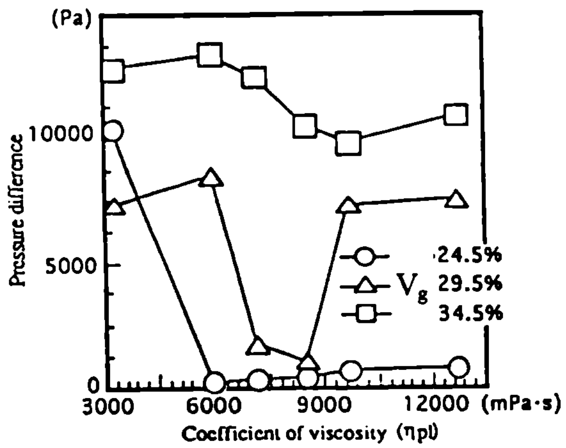
Fig. 3-23 Effect of G/G_{lim} on blockage
[Adapted from Okamura & Ozawa (1996)]



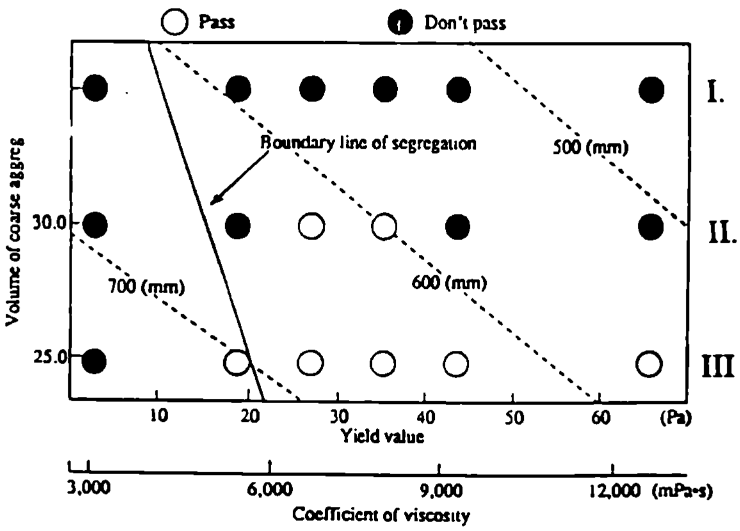
(a) —Relationship between rheological properties of mortar and addition of viscosity controlling admixture



(b) ·Relationship between yield value of mortar and slump flow of concrete



(c) -Relationship between coefficient of viscosity of mortar and pressure difference



(d) . -Results of tests of ability to pass between steel reinforcing bars

Fig. 3-24 Results of passing ability for U-tests [Adapted from Nagataki et al (1995)] influential on the passing ability than mortar yield stress. However, for the mix with a coarse aggregate volume suitable for SCC (V_g = 0.295), the yield stress and plastic viscosity become crucial factors for passing ability. **Fig 3-24(c)** and **(d)** show that for mix II the mortar yield stress and viscosity should be in the range of 30 to 40 Pa and 7 to 9 Pa.s respectively. For this mix, high yield stress impairs the passing ability, on the other hand, if both yield stress and viscosity are low, segregation often occurs and causes blockage. In other words, for SCC with a common amount of coarse aggregate (V_g approx. 0.30), passing ability can be obtained with proper rheological properties of mortar. Other research has also confirmed this phenomenon. For example, **Fig. 3-25** shows the relationship between the slump flow and the filling height of a U-test [**Kuroiwa et al (1994)**]. Obviously mixes with low slump flow have low filling height, on the other hand, mixes with high slump flow but low segregation resistance also have low filling height. **Table 3-9** lists some suitable ranges of rheological values for good passing ability. These are dependent on the gaps between rebars, coarse aggregate content, and the rheological testing apparatuses used. Therefore, it is unlikely to establish standard values for all cases. Also, because these factors are interactive, it is strongly recommended that the tests of passing ability suggested by **Hon et al** (1996) be carried out with narrowest reinforcement arrangement to be used in a structure as shown in **Fig. 3-26** (The dimensions of the test were not reported in their paper.)

Table 3-9 Suitable ranges of rheological values for good passing ability

Ref.	Yield stress Pa	Plastic viscosity Pa.s	Apparatus	CA vol.	Mesh
Kawai et al	50 Pa	30-80	Two-point test	0.327	2D 58 mm 1D 34 mm
LCPC	< 500 Pa	100- 200	BTRHEOM™		
Fujiwara et al	10-50*	3-10*	Viscometer	see **Table 3-8**	
Nagataki et al	30-40*	7-9*	Viscometer	0.295	1 D 37 mm

* Mortar

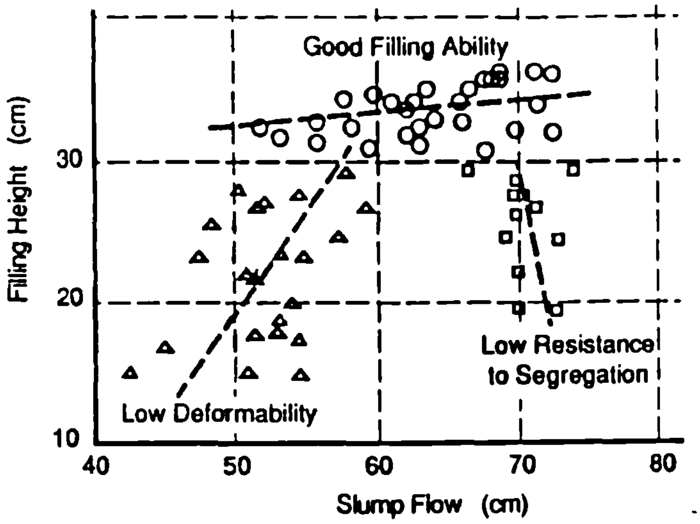


Fig. 3-25 Relationship between filling ability (U-test) and slump flow [Adapted from kuroiwa et al (1995)]

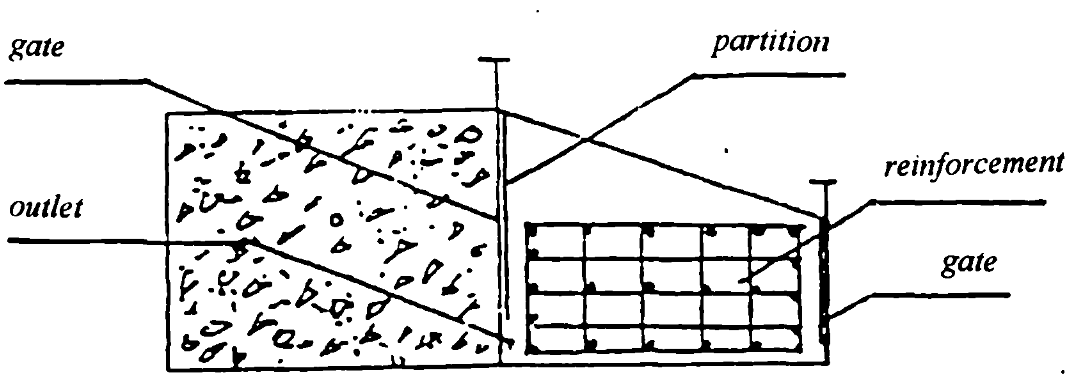


Fig. 3-26 Large scale passing ability test [Adapted from Hon et al (1996)]

3.4.1.4 Mechanism of blocking in flowing mortar

The relation between the probability of blocking and the volume fraction of sand was investigated by **Ozawa et al** (1992). In this experiment, mortar can be considered as a simulation of concrete, and sand is regarded as coarse aggregate. The testing apparatus, shown in **Fig. 3-27 (a)**, consisted of a hollow steel cylinder with an inside diameter of 10 cm, a piston with a steel shaft at the centre, a speed-controlled motor and load cell. The cylinder was filled with mortar and flow was induced through three 10 mm-diameter holes at the piston head, by lowering the piston with a force applied from the motor. The flow speed was considered proportional to the piston speed. **Fig. 3-27(b)** shows that blocking took place when the sand content approached a critical value and that blocking could be considered free from probabilistic influence i.e. blocking always takes place. **Fig. 3-27(c)** shows the relationship between the blocking volume, defined as the sand to mortar volume when blocking occurred, and the ratio of the hole diameter to sand size (D_0/D). The blocking volume increased linearly with D_0/D up to D_0/D of about 10, but then remained approximately constant at 44%. It was therefore concluded that it is very safe to use 40% (V_s/V_m) as the lower limit of sand content for mortar for Self-compacting concrete.

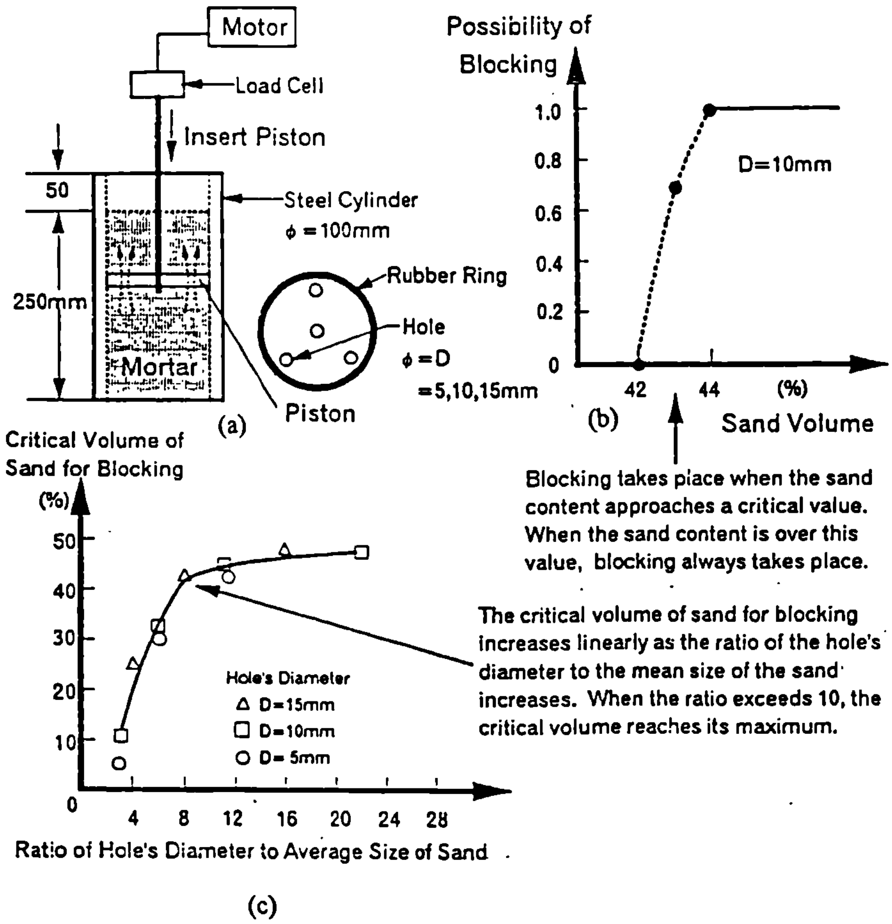


Fig. 3-27 Influence of sand on blocking of mortar [Adapted from Okamura et al (1995)]

3.4.2 Segregation resistance

3.4.2.1 Segregation of NC

Segregation can be defined as the separation of the constituents of a heterogeneous mixture so that their distribution is no longer uniform. In the case of concrete, it is the differences in the size of particles and in the specific gravity of the mix constituents that are the primary causes of segregation. There are two forms of segregation. In the first, the coarser particles tend to separate out because they tend to travel further along a slope or to settle more than finer particles. The second form of segregation, occurring particularly in wet mixes, is manifested by the separation of grout from the mix (**Neville 1995**). Obviously the segregation of SCC is of the second form.

It is important to note that the actual extent of segregation depends on the method of handling and placing of concrete. If the concrete does not have far to travel and is transferred directly from the skip or bucket to its final position in the form, the danger of segregation is small. On the other hand, dropping concrete from a considerable height, passing along a chute, particularly with changes of direction, and discharging against an obstacle all encourage segregation.

For NC, **Bartos** (1992) suggested several ways to reduce the risk of segregation by using

- continuous grading of aggregate, smaller maximum size
- air entrainment
- increased proportion of fines, including cement and cement substitutes
- optimum water/cement ratio and paste content
- admixtures causing 'thickening' of the liquid phase of the mix

3.4.2.2 Segregation resistance of SCC

Okamura attempted to clarify the mechanism of the blockage of coarse aggregate particles caused by segregation, using a technique of a visualised model concrete developed by **Hashimoto et al.**(1988). A transparent polymer material was used in place of the mortar, and the movement of the coarse aggregate could be clearly seen. The experiment indicated that blockage of the flow through a narrow cross-section occurs as a result of contact between coarse aggregate particles, and to prevent this, a moderate viscosity of mortar is necessary. **Nanayakkara** (1988) also confirmed that coarse aggregate particles interlock where the concrete flow narrows, and they form an arch, blocking the flow of concrete. This is similar to flowing through the gaps in rebars as shown in **Fig. 3-19(a).** It was also revealed that the interlocking of coarse aggregate particles was inhibited when the viscosity of mortar was increased. The same result was obtained by **Ozawa et al** (1989) where the flow was divided via a branched pipe. When the viscosity of mortar was low, the deformation of the coarse aggregate phase was not uniform and localised violent contact and collision between the particles were found. When the viscosity was high, however, the localised deformation was relaxed, and the deformation of the coarse aggregate phase occurred uniformly **(Fig. 3-27)**. Segregation during flowing is augmented not only by the difference in the specific gravity but also by the collision and contact friction between coarse aggregate particles. Increasing the viscositv of mortar or paste is therefore very effective in reducing segregation.

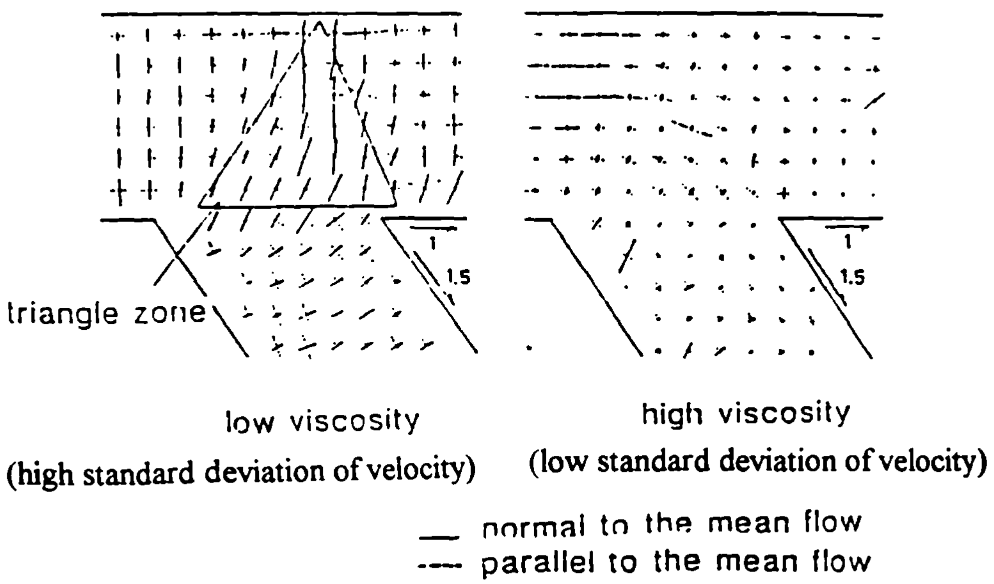


***Fig. 3-28** Standard deviation distribution for particles in a velocity field*
[Adapted from Okamura et al (1992)]

3. 5 Methods of achieving self-compactability

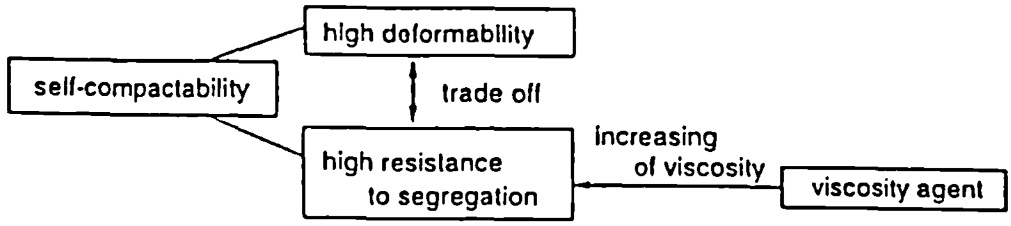
There are two methods of achieving the self-compactability of SCC [**Okamura** and **Ozawa** (1994)]. The first one is by adding a viscosity agent. The second one is by limiting the coarse aggregate volume and lowering the water/powder ratio. These can be used together but **Ozawa** (private communication) strongly recommends the second method alone.

3.5.1 Adding a viscosity agent

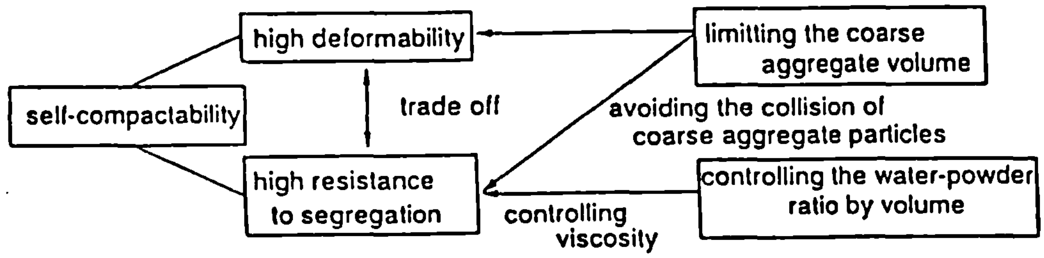
Fig. 3-29 (a) illustrates how to achieve high deformability while avoiding the risk of segregation by adding a viscosity agent. The increased viscosity of the paste is effective in inhibiting segregation. Antiwashout underwater concrete is a kind of self-compacting concrete placed under water; segregation is inhibited by the addition of a large quantity of a viscosity agent, thus preventing the cement particles from dispersing into the water. However, for SCC for non-underwater use, the viscosity needs to be adjusted, because entrapped air may not be released and the concrete may not easily pass though reinforcement if its viscosity is too high. A balance between the effect of the viscosity agent and the superplasticizer is important for achieving self-compactability.

3.5.2 Limiting the coarse aggregate volume while controlling the water/powder ratio

Fig. 3-29 (b) illustrates how to achieve self-compactability by controlling the mix proportions. The volume of coarse aggregate is limited to reduce the collision of coarse aggregate particles near obstacles, and the water/powder ratio by volume is adjusted to be approximately 1.0 to ensure an adequate paste viscosity and thus avoid segregation. The resulting powder content is inevitably higher than that of conventional concrete due to the high paste content and low water/powder ratio. As a result, CRMs are often incorporated to both reduce cost and to improve hardened properties (such as better resistance to ASR, better resistance to salt, etc.).



(a) by using a viscosity agent



(b) by controlling the mix proportions

Fig. 3-29 Realizing self-compactability
[Adapted from Okamura & Ozawa (1994)]

Table 3-10 shows the classification of SCC resulting from these two methods. It is worth noting that even with the second method when the water/powder ratio by weight is higher than 0.35 (approx. 1.0 by volume), a viscosity agent may be required to provide enough segregation resistance.

Table 3-10 Classification of SCC by its constituents

Concrete type		Viscosity agents		Powders		W / P	SP&AE agents
		Addition	Type	Content	Type		
	HSC	No	--	450-650 (kg/m^3)	PC, PC+BS, PC+SF etc.	0.20-0.35	Yes
SCC		No	--	500-700	PC+BS, PC+BS+FA, PC+LSP, M, PC+FA PC+BS+SF, BE (+BS, FA, LS, SF) etc.	0.30-0.35	Yes
SCC		Yes	Biopolymer	500-600	PC, M, PC+BS PC+FA, PC+BS+FA PC+LS, PC+BS+LS BE, BE+FA etc.	0.30-0.35	Yes
SCC		Yes	Cellulose	300-450	PC, BB, PC+BS PC+FA, PC+BS+FA PC+ BS+LS etc.	0.40-0.60	Yes
	AWC	Yes	Anti-washout admixture	320-550	PC, BB, PC+BS PC+BS+FA etc.	0.40-0.65	Yes

M: modified Portland. cement, BB: Portland blast-furnace slag Class B, FA: PFA,
BS: GGBS, LS: LSP, BE: belite cement, AWC: anti-washout underwater concrete
Translated from JCI committee on SCC Research report (II) Table 1.1-1 by JCI 1994

3.5.3 Comments

There are some limitations and confusions in **Fig. 3-29**:

- Both SCC and FC have very good deformability whereas only SCC possesses good passing ability, and therefore the term "high deformability" can apply equally to self-compacting concrete (SCC) and flowing concrete (FC); "passing ability through reinforcement" is more appropriate for SCC.
- The reason for inhibiting collisions between aggregate particles (by limiting the coarse aggregate volume) is to gain good passing ability rather than high segregation resistance. On the contrary, limiting the coarse aggregate volume will reduce the segregation resistance, as will be discussed in section **7.2.4**

- Good passing ability results from high fluidity (or high deformability) and limited aggregate content, as can be seen in section **7.1.3**

For these reasons, **Fig. 3-30** is suggested as an improvement on **Fig. 3-29**.

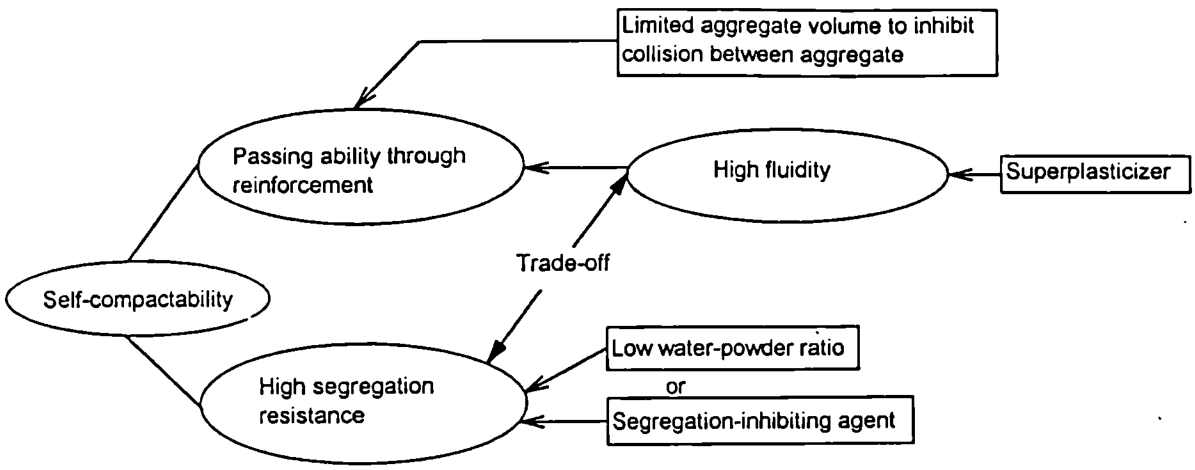


***Fig. 3-30** Methods of achieving self-compactability (modified from Fig. 3-29)*

3. 6 Mix design of SCC

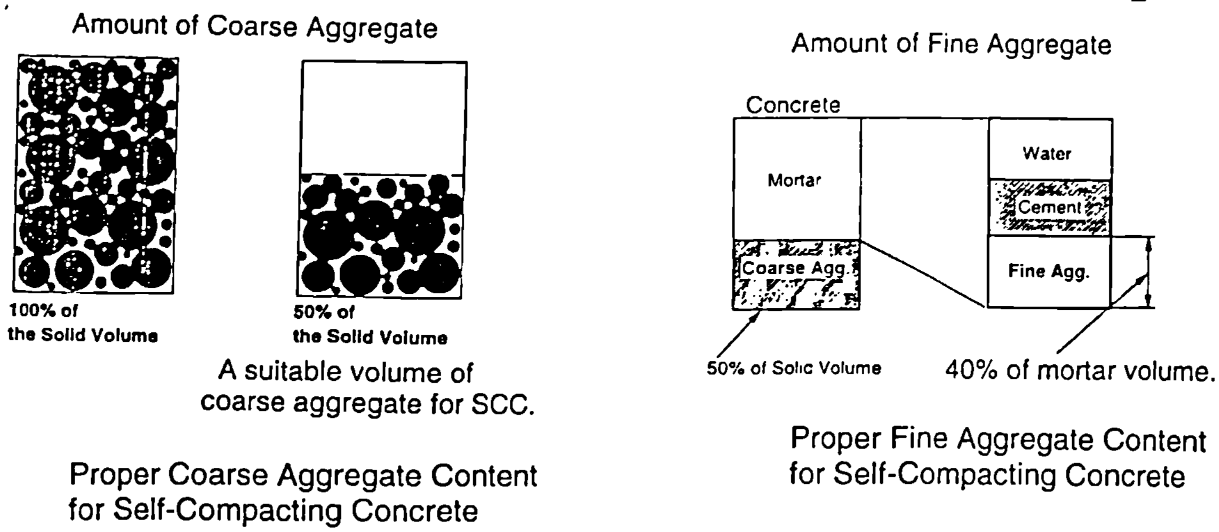
This section briefly describes the different published approaches of SCC mix design, comments comparing and contrasting these are given at the end of the section.

3.6.1 Ozawa's approach (1993)

Fig 3-31 shows the mix design procedure recommended by **Ozawa**. First, the coarse aggregate and fine aggregate volumes can be determined by using 50% of CA solid volume and 40% of mortar by volume respectively. Then the mortar flow spread test and the V-funnel test, (described in section **4.4.2)**, are used to select the water/powder ratio and the preliminary superplasticizer dosage as shown in **Fig. 3-32.** The retained water ratio β_p, a parameter of powder (see **5.4**), should be less than 0.95. Hence, the water/powder ratio by volume [(0.80-0.90)β_p] is in the range 0.76-0.86 which converted to the ratio by mass is (in most cases) less than 0.30. The required values for the flow spread test and V-funnel test are 245 mm and 9-10 seconds respectively. After the selection of water/powder ratio, concrete trial mixes are carried out, and the final dosage of superplasticizer obtained through slump flow and V-funnel tests **(Fig. 3-33)**.

3.6.2 LCPC's approach (Sedran et al 1996)

This French approach is based on research work in the Laboratoire Central des Ponts et Chaussées (LCPC). They have developed two useful tools: one is BTRHEOM™ rheometer and the other is RENE_LCPC™ software. The BTRHEOM™ is a torsional rheometer, which can give values of the yield stress τ_0 and the plastic viscosity μ_0 of concrete with and without vibration. In addition, the yield stress at rest can also be obtained. The RENE_LCPC™ software is based on the Solid Suspension Model, which can predict the packing density of all dry granular constituents. This model also provides



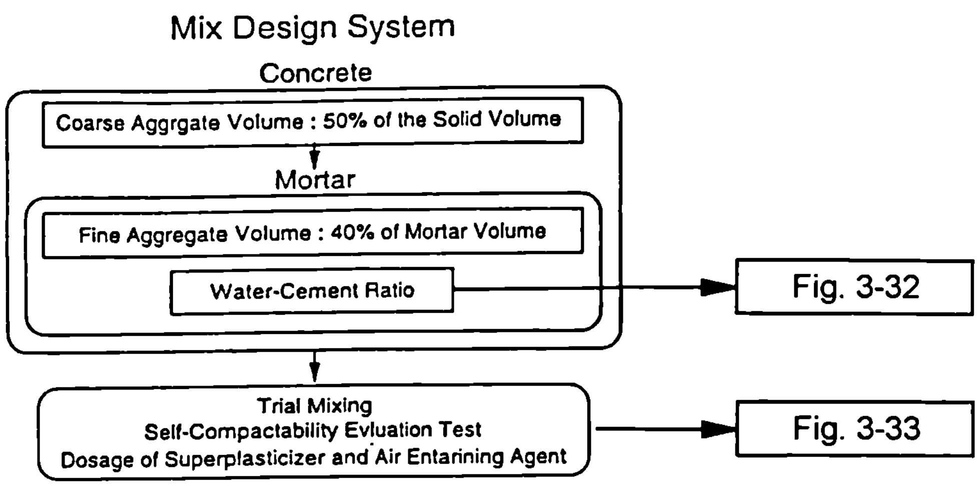
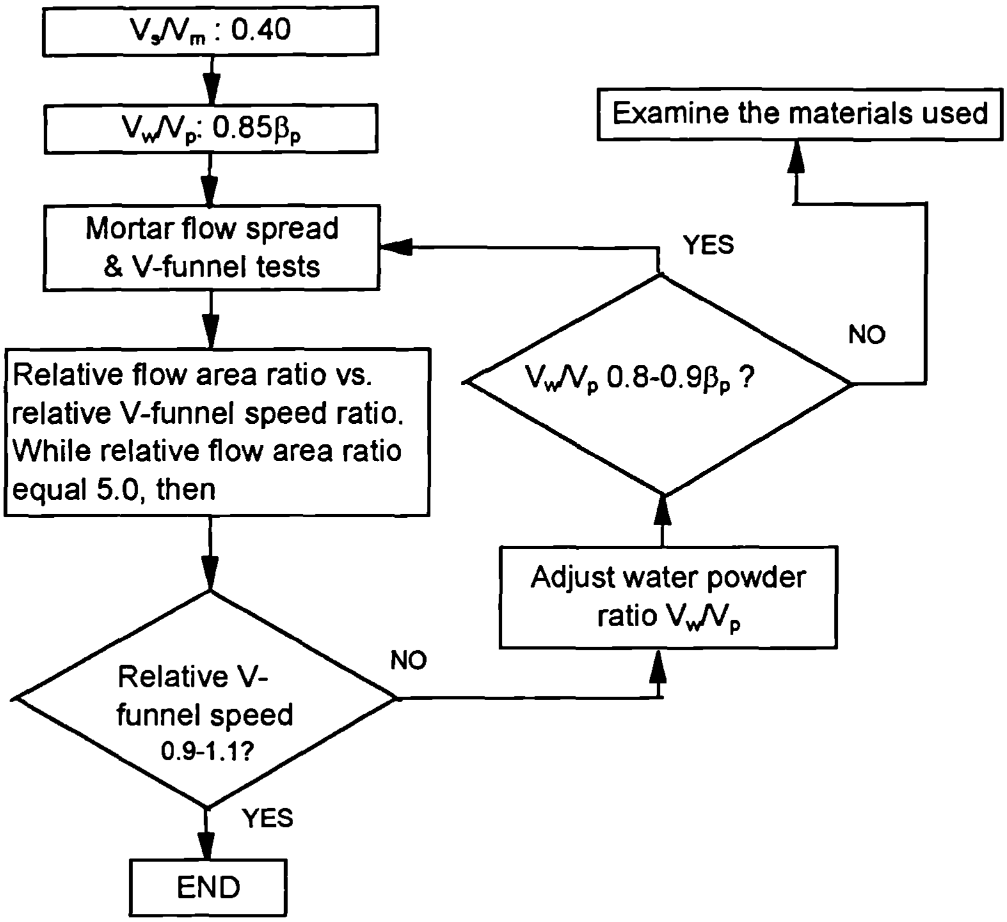


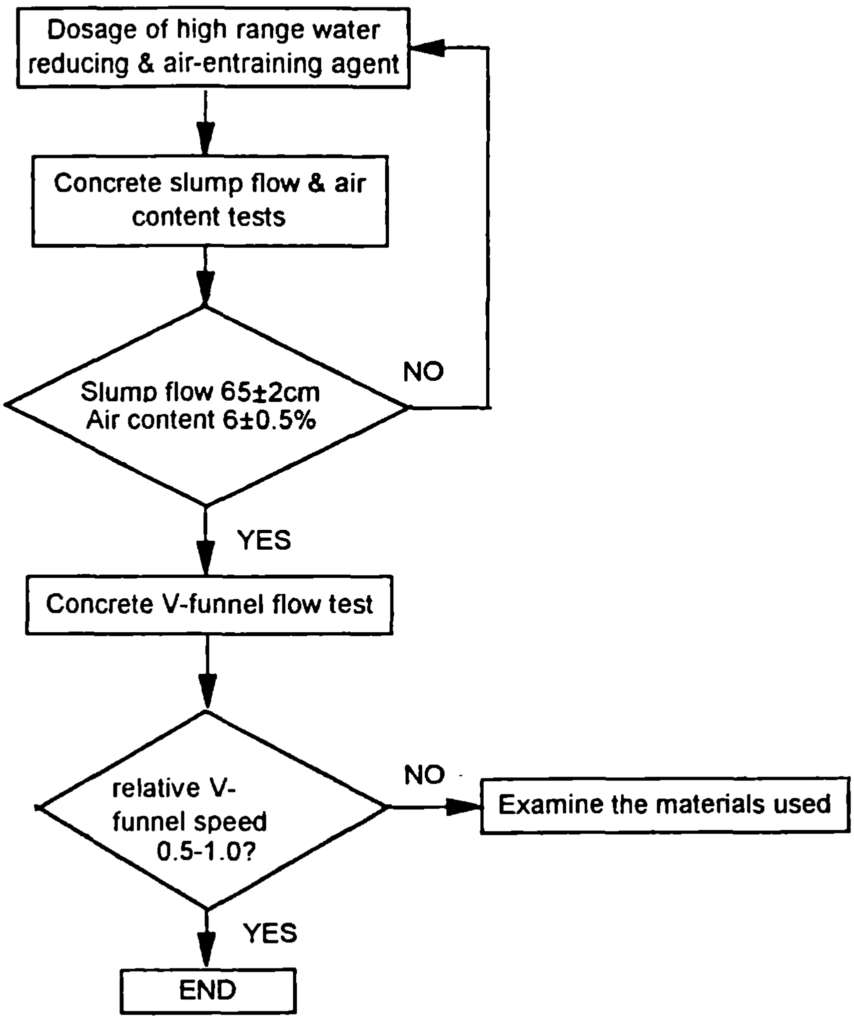
Fig. 3-31 Mix design system recommended by Ozawa

[Adapted from Okamura (1996)]



V_s: volume of sand whose particle size larger than 0.06 mm
V_p: volume of powder including fine sand whose particle size less than 0.06 mm
β_p: retained water ratio of powder (see Chapter 5)
Relative V-funnel speed ratio = 10 / V-funnel flow time

Fig. 3-32 Selection of water/powder ratio [Translated from Okamura et al (1993)]



Relative V-funnel$_{(7.5\times6.5)}$ speed ratio = 10 / V-funnel flow time

$V_s = 0.40 \times V_m = 0.40 \times (1 - V_a - V_g)$

***Fig. 3-33** Selection of dosage for high range water reducing & air entraining agent*

Translated from original Fig. 2.3t ;High performance concrete, Gihou-do 1993 by Okamura et al a value called the relative viscosity for a given concrete from the properties of its solid skeleton and its water content. The design method can be summarised as follows:

The general criteria for the mix are:

- The slump flow should be between 600 and 700 mm (or the yield stress measured with BTRHEOM™ should be less than 500 Pa);
- The plastic viscosity should be less than 200 Pa.s in order to get easy handling, easy pumping, easy finishing and acceptable appearance of hardened surface; but higher than 100 Pa.s to avoid segregation.

The specified conditions are:

- the mean compressive strength of the concrete at 28 days
- the most restricting confinement on site, e.g., pipe size or clear gap between reinforcement.

The materials requirements are: a well-graded aggregate, a compatible cement and superplasticizer, a retarder and CRMs

Fig. 3-34 shows the procedure.

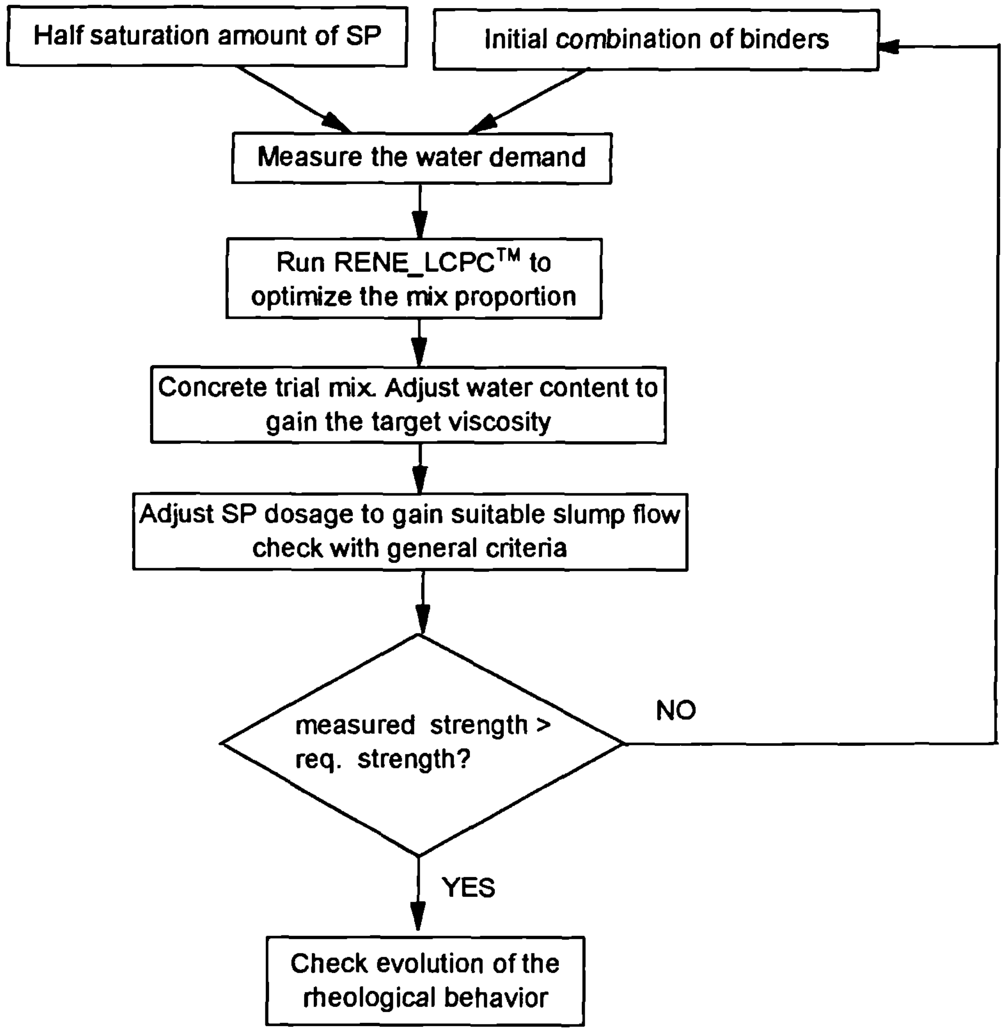


Fig. 3-34 LCPC mix design procedure for SCC[Derived from Sedran et al (1996)]

First, a combination of binders selected according to local experience or particular specification and half saturation amount of superplasticizer are used for the measuring of the water demand. Then mix proportions are optimised by running the Solid Suspension Model. Concrete trial mixes are carried out to gain the target viscosity by adjusting water content and the desirable slump flow is obtained by adjusting the dosage of superplasticizer. Finally, the evolution of its rhelogical behaviour and the compressive strength need to be checked

3.6.3 CBI's approach [Petersson et al (1996)]

The Swedish Cement and Concrete Research Institute (CBI) in conjunction with research groups in Thailand have developed the SCC design method outlined in **Fig. 3-35** .

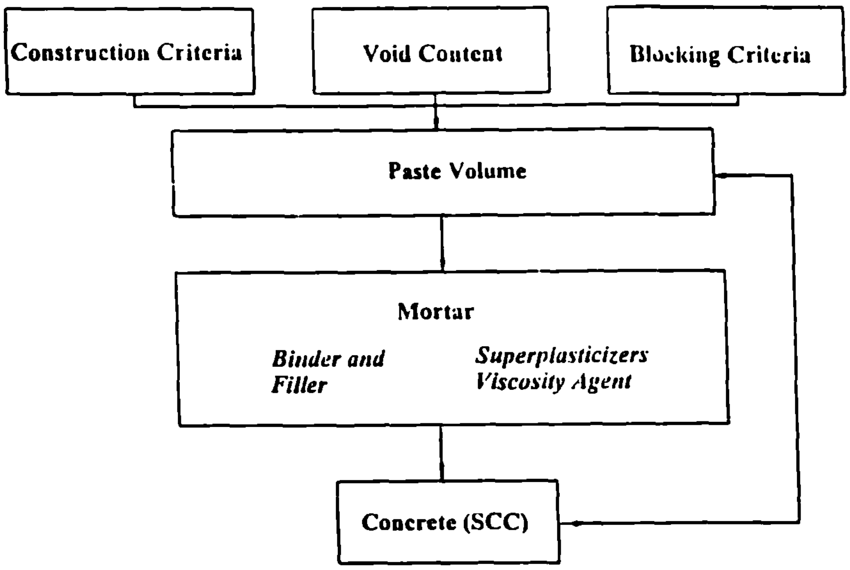


***Fig. 3-35** CBI mix design procedure for SCC[Adapted from Petersson et al (1996)]*

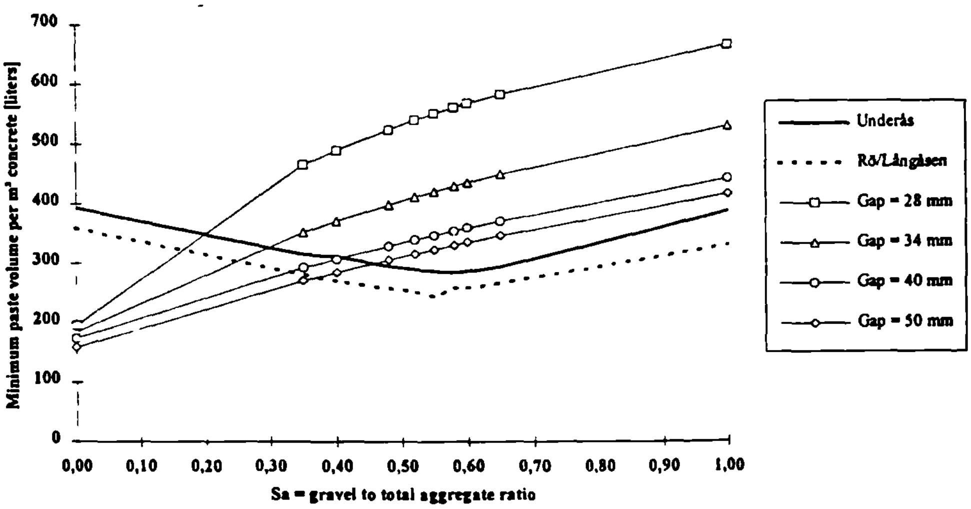


***Fig. 3-36** Relationship between paste volume and coarse aggregate proportion for different gaps through reinforcement. (Void content of aggregate also shown).*
[Adapted from Petersson et al (1996)]

In this method, the risk of blocking is calculated using the following equation.

Risk of blocking = $\Sigma(V_{ai} / V_{abi}) \leq 1$ **(3-2)**

V_{ai} = volume of aggregate group i
V_{abi} = blocking volume of aggregate group i

By using equation (3-2) together with the blocking criteria, the minimum paste volume for different gravel to total aggregate ratios can be calculated. A series of these values form a blocking boundary for a certain gap. The region above this boundary is "passing" whereas that below this boundary is "blocking". **Fig. 3-36** shows the void content of aggregate and blocking boundaries for different gaps. Moreover, the minimum paste volume can be obtained from **Fig. 3-36** according to the gap between reinforcement and the coarse aggregate proportion. Then, mortar with maximum size 0.25 mm particles are tested by Haake Rotovisco RV 20 rheometer to find the suitable binder and filler and proper dosage of superplasticizer and air-entraining agent. Finally, the concrete trial mixes are checked with the L-test. Slump flows between 670 to 720 mm are recommended.

3.6.4 Hwang's approach [Hwang et al (1996)]

Hwang's approach has been used in the concrete mix design for the columns of a 347 metre high rise building in Taiwan. His approach is based on a densified mixture design algorithm. The main outcome of his research is that on the basis of a sufficient paste volume condition, the less the cement content (or the denser the blended aggregate), the higher the concrete strength becomes. The coefficient **n** is used to control the paste volume as in the following equation:

$V_{paste} = V_v + S \times t = n\, V_v$

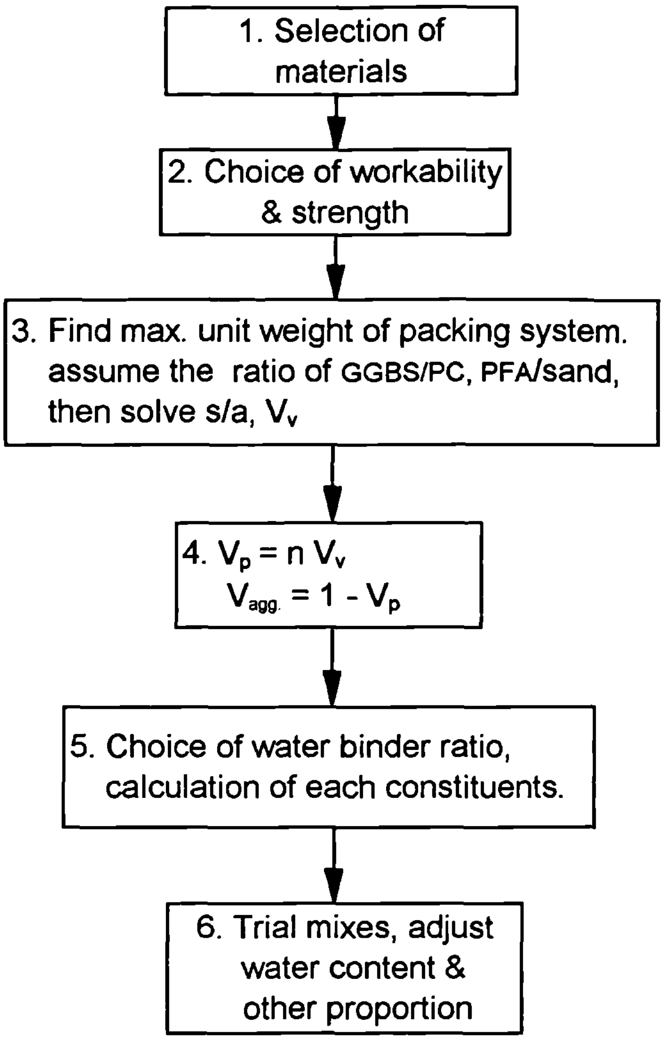
where: V_{paste}: paste volume
V_v: least void of packing system
S: surface area of the aggregate
t: thickness of the lubricant paste
n: 1.1~1.5

According to the research, n = 1.3 produces the best result in all aspects of workability, strength or cost. **Fig. 3-37** shows the design procedure. It is very important to note that the volume of PFA and GGBS is accounted as a part of aggregate volume instead of paste volume, in other words, the PFA and GGBS are regarded as fillers in the packing system. However, as far as strength is concerned, PFA and GGBS are still considered as cementitious materials.

3.6.5 Hon's approach

A series of tests on SCC has been carried out by **Hon et al** (1996) in Beijing with the following outcomes:

- Paste volume and sand/total aggregate ratio (s/a) are the critical factors influencing passing ability through reinforcement. Suitable values are 0.38 to 0.42 m^3 and 50% respectively [**Fig. 3-38 (a)**].
- PFA replacement percentage and paste volume are the main factors which control the 28 day compressive strength, whereas the sand ratio (s/a) has little influence. The suitable range of the PFA replacement is from 30% to 45%. The 28 day compressive strength decreased little when the PFA replacement percentage increased from 20% to 30% but significantly thereafter. Also, concrete mixes with a paste volume of less than 0.37 m^3 have lower compressive strength [**Fig. 3-38(b)**].
- Paste volume is the major factor influencing shrinkage.



* Maximum unit weight of packing can be gained by packing model or by experiment.

Fig. 3-37 Hwang's mix design procedure for SCC [Translated from Liu's PhD thesis(1994)]

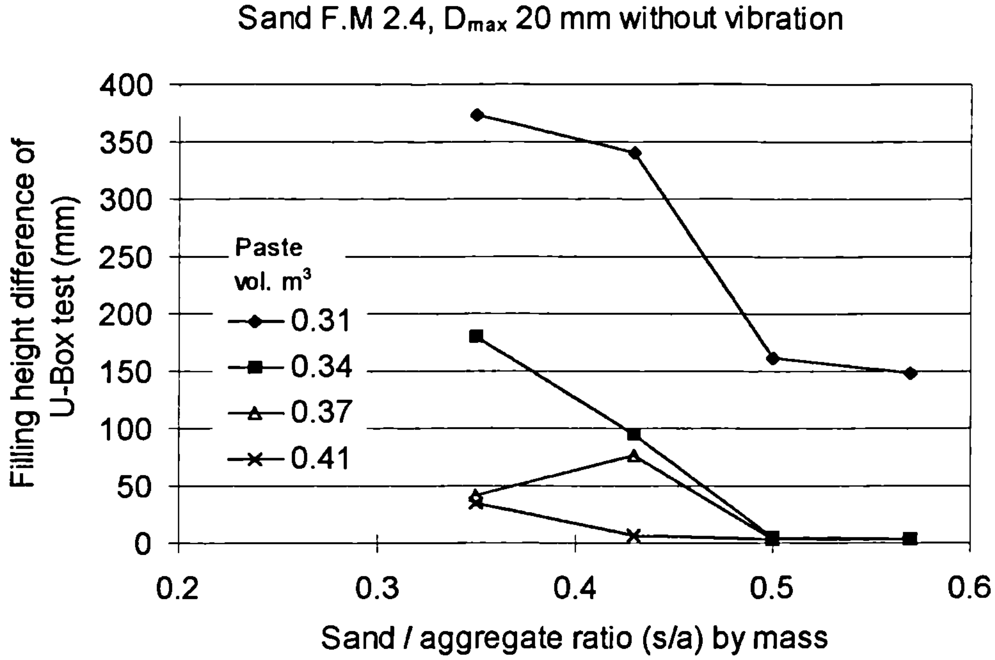


Fig. 3-38 (a) Influence of paste volume on filling height difference for various s/a
[Data adapted from Hon et al (1996)]

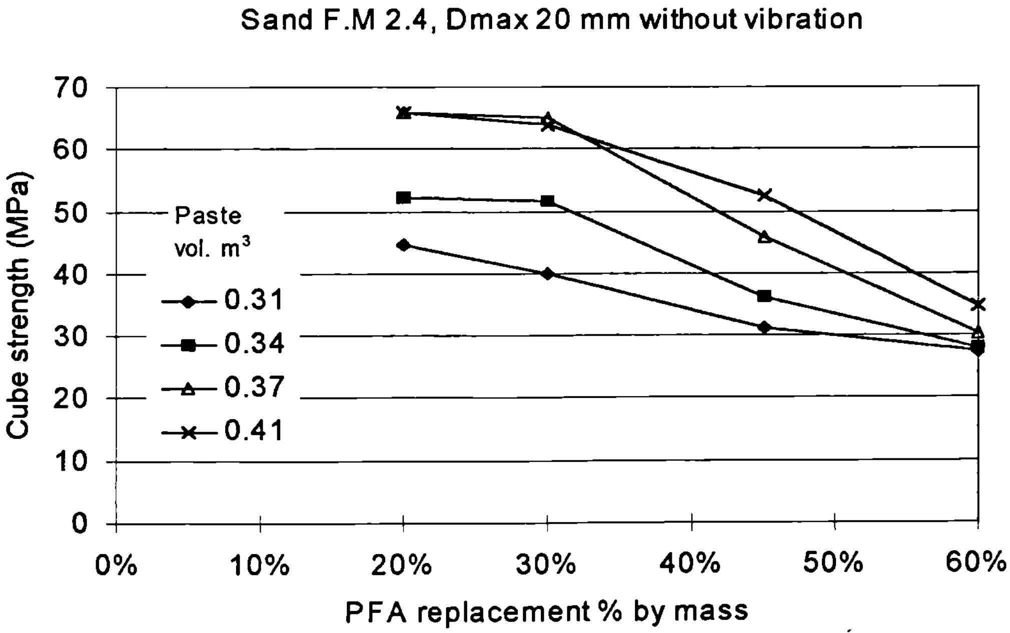


Fig. 3-38 (b) Influence of PFA replacement on cube strength for various paste volume
[Data adapted from Hon et al (1996)]

3.6.6 Comparisons and Comments

Ozawa's approach is very good, reliable and easy to follow. The shortcoming is that it results in a high paste content ($0.41m^3$), and therefore, high concrete cost. The method is only suitable for low water/powder ratios, normally less than 0.30 by mass (0.86 by volume), whereas most water/powder ratios in practice are higher than 0.30. The coarse aggregate content G/G_{lim} of 0.50 is the governing factor for passing ability. The sand content V_s/V_m of 0.40 is the lowest allowable value, and should be adjusted by water/powder ratio and mortar tests (see **Chapter 6**). It is worth noting that Okamura's paper in 1996 has amended the water/powder ratio to a range from 0.90 to 1.0 (by volume) depending on the properties of the powder.

The LCPC's approach is based on the BTRHEOM™ rheometer and RENE_LCPC™ software. This makes it impossible for others to follow this design method, if they do not buy these from LCPC. Also, the method focuses on optimising the granular skeleton of concrete from the viewpoint of packing density. Sometimes it resulted in too low a paste content, causing a rapid loss of slump flow and blockage while pumping [**Sedran et al** (1996)].

CBI's approach is based on a relationship between the blocking volume ratio and clear reinforcement spacing to fraction particle diameter ratio. According to the reference paper [**Tangtermsirikul** (1995)], this relationship resulted from a set of tests in which concrete mixes with specific size aggregate and paste (no sand) were used. It is not clear how these critical tests were carried out, because concrete mixes with coarse aggregate only and paste are susceptible to severe segregation.

Hwang's approach is based on a densified mixture design algorithm, derived from the maximum density theory and excess paste theory, [**Powers** (1968)]. There is no information presented concerning the relationship between this method with the passing ability through reinforcement and segregation resistance. Fortunately, only 10 mm maximum size aggregate was used in this design method, and there is thus little problem with these two important SCC fresh properties. However, if this method is to be extended to 20 mm (or above) maximum size of aggregate, more research is required Also, it is a little confusing that the volume of PFA and GGBS is regarded as a part of aggregate volume instead of paste volume.

Hon's approach has been successfully applied to SCC in at least six projects in Beijing, with a total concrete volume of 4000 cubic metres. They have not disclosed the mix design procedure, but just offered some useful principles. A paste volume of 0.38 m^3 as the minimum paste content is a good index for SCC mix design. It was shown that too low a paste volume not only impairs the passing ability but also reduces the compressive strength if no vibration is used. Conversely, a high paste volume causes high shrinkage.

In conclusion, different approaches to mix design have their own "know-how", and often authors are reluctant to publish full details. Moreover, concrete technology is not simply black or white, but if a concrete mix does not work, research and engineering experience are indispensable to finding a solution.

3. 7 Hardened surfaces of SCC

The content of this section is not directly related to this study but it is very important because the appearance of SCC is a very real problem in many structures. As mentioned in **Chapter 1**, one of the objectives of vibration is to eliminate unintentional air voids. For SCC without an air-entraining agent, the air content is normally less than NC at around 1.0 % to 1.5 %. However, in SCC air voids are easily formed on the hardened surface due to lack of vibration, especially when low slump flow concrete is cast into forms. **Itoh et al**

(1993) carried out a series of air voids tests on SCC. The test apparatus is shown in **Fig. 3-39**. Mix proportions and test variables are given in **Table 3-11** and **Table 3-12**.

Table 3-11 Concrete proportions for air void tests

No	D_{max} (mm)	Air (%)	W/V_p (%)	W/C (%)	s/a (%)	kg / m^3					
						W	C	S	G	Ad_1	Ad_2
1	15	4	110	34.9	51.3	202	578	755	737	6.35	3.47
2	15	4	115	36.4	51.3	206	566	755	737	6.23	3.40

Table 3-12 Test variables for air-void tests

Variable	Level
Materials used for covering form	Plywood Controlled permeability form
Angle to horizontal (°)	0, 15, 30, 45, 90
(V_w/V_p) (%)	110, 115

The paste volume of the mixes was 0.425 m^3, and the slump flow was between 600-650 mm, the size of the covering form is not clear. The results of the tests are shown in **Fig. 3-40**. It is very clear that the controlled permeability forms can eliminate at least three quarters of the air voids. In other words, permeable forms can solve the aesthetic problems of SCC caused by large air voids. For normal wooden forms, the vertical position has less air voids than any other position. Another important result from accelerated carbonation tests is that these air voids have little influence on the carbonation.

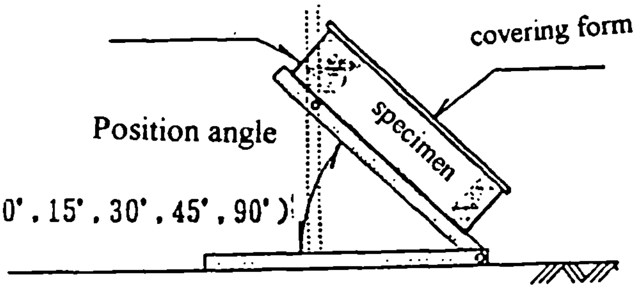


Fig. 3-39 Test apparatus for air voids on hardened SCC surface
[Adapted from Itoh et al (1993)]

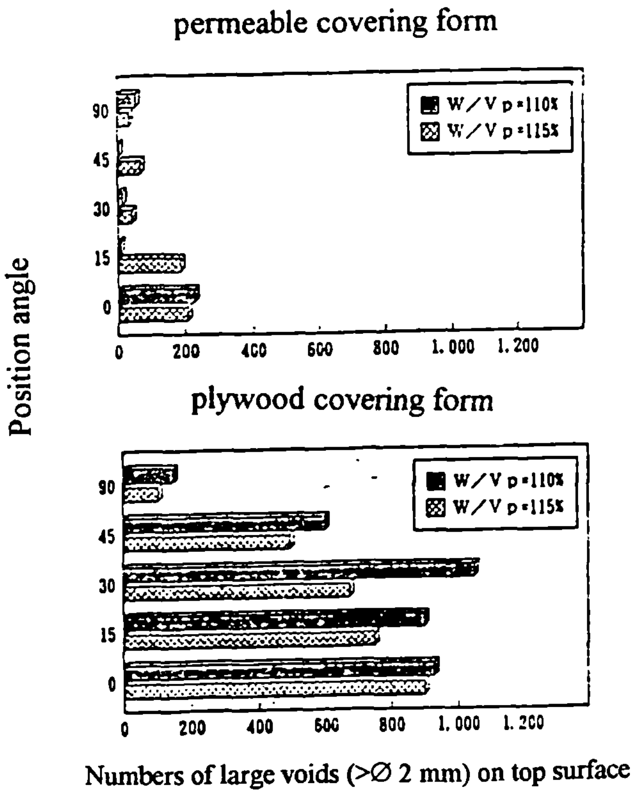


Fig. 3-40 Results of air voids test on hardened SCC surface
[Adapted from Itoh et al (1993)]

3. 8 Quality control of SCC

One purpose of using SCC is to minimise the risk of producing poor quality concrete in situ; hence, a high standard quality control is extremely important. The general quality control requirements for normal concrete are still valid for SCC, but in addition, several points need special consideration. These include variation of sand moisture content, the functions of a viscosity agent, quality control at the engineering site and the level of self-compactability. These are now briefly discussed.

3.8.1 Variation of sand moisture content

Japanese experience shows that moisture variation in fine aggregate has a major influence on the fresh properties of SCC. For most ready-mixed concrete plants, the aggregate stocks are in the open air, and after rain, the moisture contents varies with time and the location in a pile, and can be significantly different from the average. For example, for a typical sand content of 800 kg/m^3 in a concrete mix, a 1% moisture content variation will cause 8 kg/m^3 variation of water content. **Fig. 3-41** shows the relationship between the variation of unit water content and the filling height from a U-test, and from this, in the case of no segregation inhibiting agent (viscosity agent), 8 kg/m^3 variation of water content may change the SCC property from good to poor passing ability.

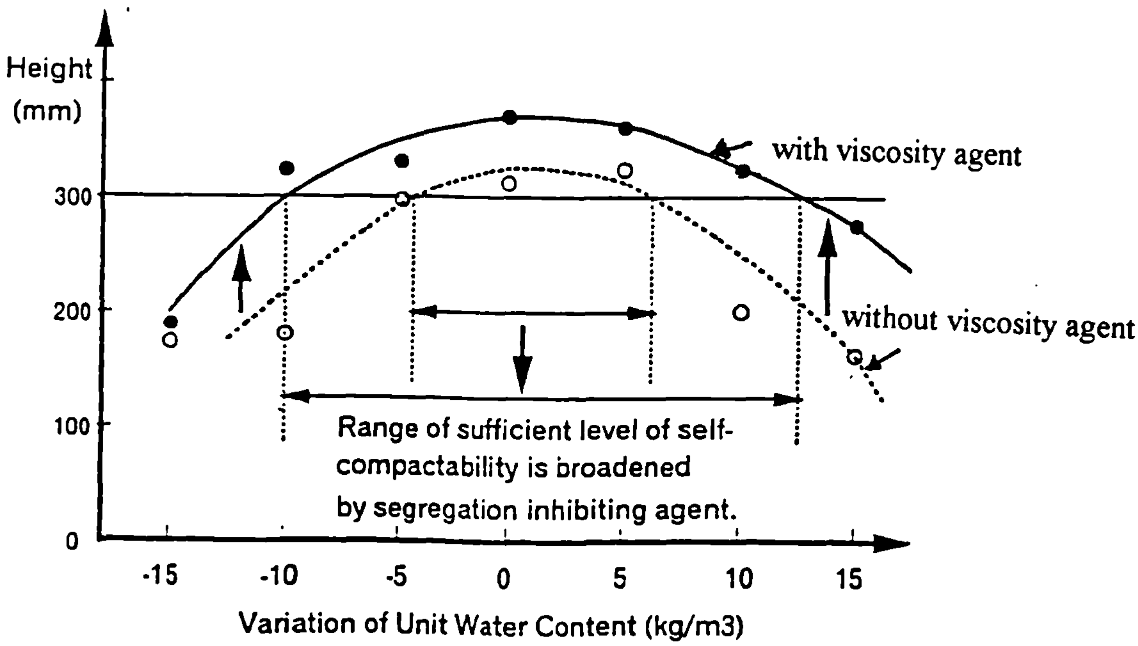


Fig. 3-41 Relationship between variation of unit water content and filling height of a U-test [Adapted from Okamura et al (1995)]

Modern techniques can help to solve the problem of the variation of sand moisture content. For example, a new moisture measuring device can be set up at the bottom of the sand outlet to the mixing pan of a ready-mixed concrete plant. For each batch of sand, moisture can be measured automatically and passed to the automatic controlling system to adjust the unit water content. Although the addition of viscosity agent can stabilise the concrete mixes, it requires a higher dosage of superplasticizer which together with the viscosity agent inevitably increase the cost of SCC.

3.8.2 Functions of viscosity agents

Viscosity agents, also known as segregation inhibiting agents or rheology-modifying admixtures (RMAs), are water-soluble polymers that increase the viscosity of the mixing water and enhance the stability of a mix. Commonly used viscosity agents in cement-based materials include polysaccharides of microbial sources, such as Welan gum; cellulose derivatives, such as methyl cellulose; acrylic-based polymers, such as partial hydrolysis products of a polyacrylamide copolymer of acrylamide; and sodium acrylate that contains acrylamide as the main component. A good viscosity agent in a mix should possess a higher deformability in a flowing state than when it is in a state of rest. This property, Sakata et al (1996) referred to pseudoplastic, is very useful in SCC.

There are two main functions of a viscosity agents in SCC:

- to provide segregation resistance;
- to reduce the variation of SCC due to the changes of temperature, sand grading, and unit water content.

The first function has been described in section 3.5, the second one will be discussed in this section.

Yurugi et al (1995) carried out three series of experiments to investigate the effect of viscosity agents. The experimental programme and mix proportions are shown in **Table 3-13.** **Fig. 3-42** shows the results of experiments in Series I where the concrete temperature was varied from 10 to 30°C. For mixes with viscosity agents, the slump flows were nearly unchanged, whereas for mixes without a viscosity agent the slump flows increased from 550 mm to 750 mm. The V-funnel flow time reduced with increasing temperature for mixes both with and without a viscosity agent.

Table 3-13 Influence of viscosity agent on slump flow of SCC with different temperature, cement and sand grading [Adapted from Yurugi et al (1995)]

(a) Experimental programme

Series	Mix	VA*	Variable	Level
I	1	Used	Concrete Temperature	10, 20, 30 ℃
	2	Not used		
II	1	Used	Cement**	A (3,300)
				B (3,250)
				C (3,420)
	2	Not used		D (3,180)
				E (3,310)
				F (3,250)
III	1	Used	Gradation of sand	FM=2.08, 2.43, 3.06
	2	Not used		

* Viscosity agent

** Obtained from 6 Companies, Blaine finess value given in ( )

(b) Mix proportions of concrete

Mix No.	W/C (%)	s/a (%)	Slump flow (cm)	Air (%)	Unit content (Kg/m³) W	C	SD	S	G	HRWR[1] (%)	V.A[2] (Kg/m³)
1	53.0	45.1	65	4	175	331	216	703	861	2.5	0.35
2	53.0	45.1	65	4	175	331	216	703	861	1.8	–

1 Calculated on the basis of (C+SD) content
β-Naphthalene sulfonate type HRWR

2 Polysaccharide-based viscosity agent

The results of experiments in Series II, using cements from six companies, are shown in **Fig. 3-43**. It can be seen that although the fineness of all cements was almost the same, there was a large variation in the slump flow of the concrete when the viscosity agent was not used. On the other hand, the addition of the viscosity agent resulted in very similar slump flows in the range of 620 to 660 mm, for all cements. Similar behaviour was observed for V-funnel flow time.

Fig 3-44 shows the results of experiments in Series III, which examined the effect of sand gradings. The coarser the sand, the higher the slump flow, but the less the V-funnel flow time. Both the variations of the slump flow and V-funnel test were much less for the mixes with viscosity agent compared to the mixes without viscosity agent.

Sakata et al (1996) carried out another series of tests to investigate the effect of viscosity agent on the variation of the fresh properties of SCC with time. The mix proportions are shown in the **Table 3-14**. The viscosity agent used is Welan gum, the same viscosity agent used by **Yurugi** in the preceding experiments. **Fig. 3-45** show the relationship between the slump flow, V-funnel (65x75) flow speed, and the filling height of a U-test with the change of unit water content. In these three figures, all the X-axes are the same: the change of unit water content from -10 kg/m^3 to +10 kg/m^3, at the times 0, 30 and 60 min. after mixing. For the concrete mixes without a viscosity agent, a variation of water content of +5 kg/m^3 and +10 kg/m^3 resulted in segregation just after mixing as shown by the low filling height in the U-tests, and the mixes with a variation of water content of -5 kg/m^3 and -10 kg/m^3 also resulted in a low filling height at 60 min. after mixing. However, in all cases, the mixes with Welan gum had a filling height at least 300 mm or above. It is clear that the addition of a suitable dosage of viscosity agent can minimise the influences caused by the variation of water content.

In conclusion, it was found that the flow properties of SCC are extremely sensitive to change in concrete temperature, cement quality, sand grading and water content. By using the suitable viscosity agent, the degree of variation could be reduced significantly, thus providing stable properties of SCC.

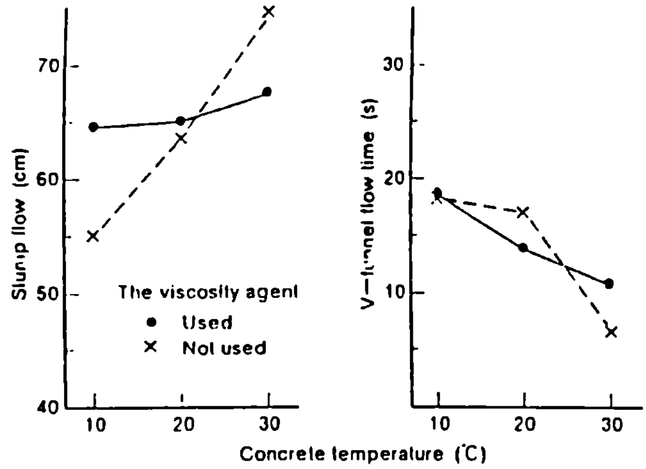


Fig. 3-42 Effect of temperature on slump flow for mixes with and without viscosity agent

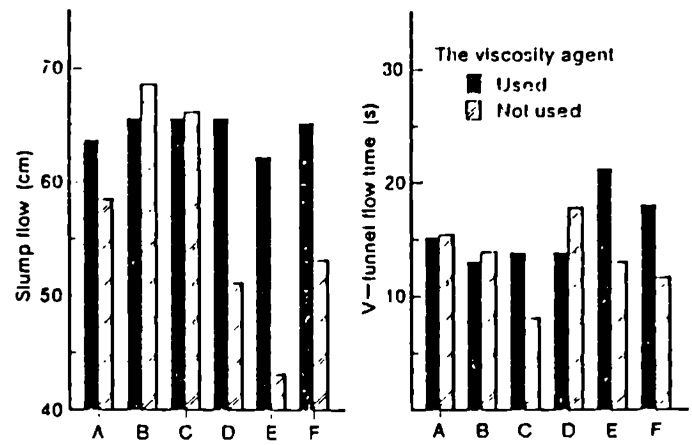


Fig. 3-43 Effect of cement quality on slump flow for mixes with and without viscosity agent

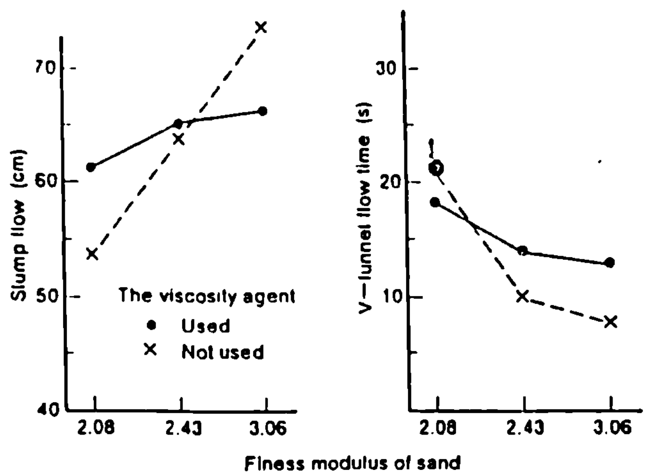


Fig. 3-44 Effect of sand grading on slump flow for mixes with and without viscosity agent [Adapted from Yurugi et al (1995)]

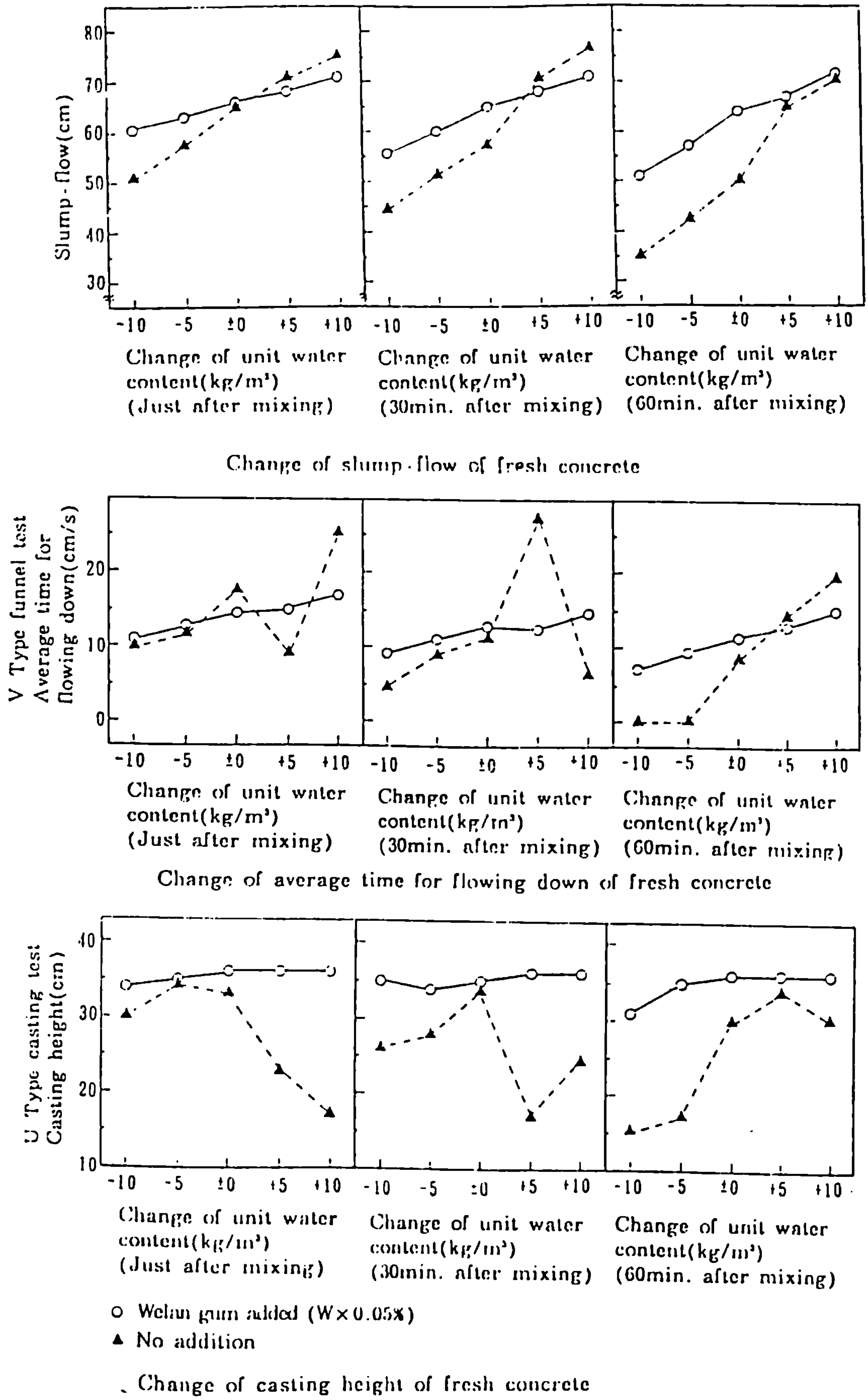


Fig. 3-45 Influence of viscosity agent on fresh properties of SCC with change of unit water content [Adapted from Sakata et al (1996)]

Table 3-14 Mix proportions of concretes in Fig. 3-45

Mix No	W/P	Slump flow	Air (%)	Unit weight (kg/m^3)					SP (%)	VA (%)	AE (%)
				W	C	SD	S	G			
1	0.30	650	4.5	165	331	216	713	888	1.7	0	0.05
2	0.30	650	4.5	165	331	216	713	888	2.5	0.05	0.02

* SP & AE calculated by weight of (C+SD), VA calculated by weight of water
* SD: limestone dust

3.8.3 Quality control on site

To promote the using of SCC, it is necessary for the self-compactability to be examined for all concrete at the job site; even a small quantity of concrete with insufficient self-compactability may result in poor compaction in the structure. The conventional methods of examining the self-compactability, such as slump flow test, V-funnel test and U-test are not suitable for testing all the concrete to be placed because they require sampling of concrete. **Ouchi et al** (1996) proposed the testing method shown in **Fig. 3-46**, which he suggests should be carried out just before casting as an acceptance test. The test apparatus (**Fig. 3-47**) is located between an agitator truck and concrete pump. If the concrete flows through the apparatus before pumping, the concrete is considered as self-compactable.

3.8.4 Level of self-compactability

Whether or not self-compactability is realised depends not only on the properties of the concrete, but also on the placing conditions, as well as the boundary conditions determined by the obstacles, e.g. the arrangement of reinforcement. It is therefore possible to select a methodology in which the degree of self-compactability of concrete is altered depending on the placing conditions and the structure being constructed, while a high level of quality control is maintained as in conventional concreting. However, according to **Okamura et al** (1994), choosing a high degree of self-compactability is normally easier than maintaining a high level of quality control. In other words, it is safer to set a high level of self-compactability even when a lower level is adequate, and then to adapt to various conditions of the structure and construction by permitting a wider variability in production, thereby widening the control limits.

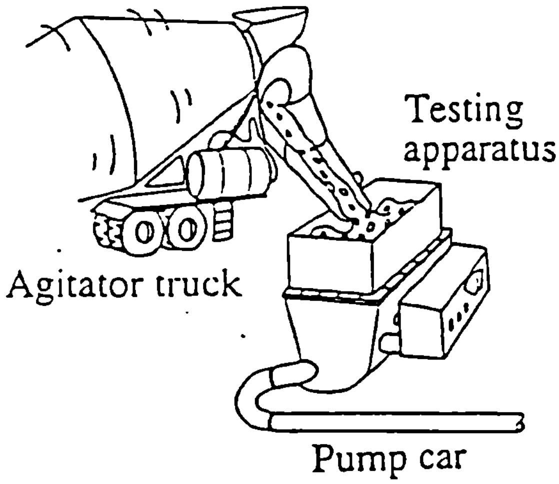
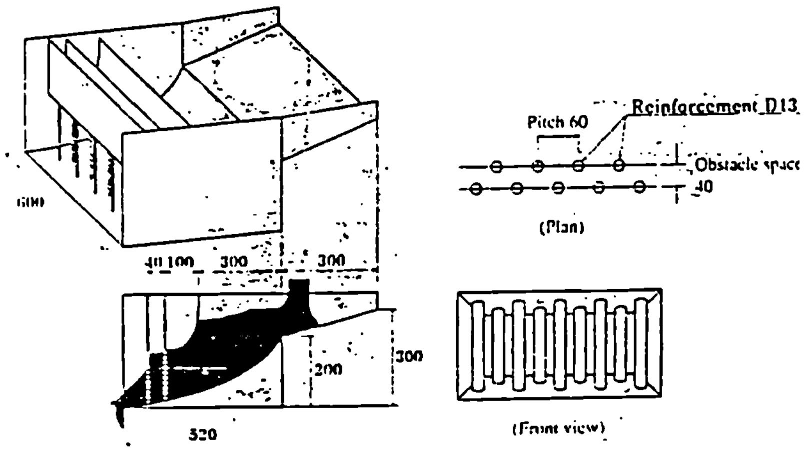


Fig. 3-46 *Proposed acceptance testing method for SCC [Adapted from Ouchi et al (1996)]*



Acceptance testing apparatus

Fig. 3-47 *Apparatus to guarantee self-compactability [Adapted from Okamura (1996)]*

3. 9 Conclusions

This chapter has reviewed the following aspects of SCC; i.e.

- test methods
- characteristic fresh properties
- methods of achieving self-compactability
- mix design
- hardened surface characteristics
- quality control

From this literature review, it is clear that SCC has two distinguishing fresh properties:

- passing ability through reinforcement;
- segregation resistance.

Poor passing ability through reinforcement usually results from:

- too small gaps in reinforcement
- too much aggregate
- poor flowability
- segregation

Hence, the methods to achieve self-compactability are:

- controlling the minimum clear spacing of reinforcement;
- limiting the coarse aggregate content;
- increasing the flowability of concrete;
- increasing the viscosity of concrete.

It is clear that much work has been carried out on SCC, and that this has distinct advantages for some forms of construction and in some construction situations. For any concrete, local materials have to be used, and therefore, if SCC is to be used in the UK, the suitability of using UK materials needs to be established. For example:

- In Japan, it has been reported that most slump flows of SCC can be maintained at least for 90 minutes, but it is not clear whether such workability can be achieved in the UK by using different types of superplasticizers.
- The Thames river sand is finer than most sand used in Japan, therefore, its influence on the mix design needs to be determined.

Moreover, several important gaps can be found in the literature. For example:

- Although Ozawa has suggested a mix design method, it is only suitable for low water/powder ratios (<0.3), and the water/powder ratios of most SCC used in Japan's construction work are higher than this. Therefore, a more suitable mix design method needs to be developed for a wider range of water/powder ratios.
- Although increasing the viscosity of SCC can reduce the risk of segregation, it is not clear whether this is the only way to control segregation resistance.
- The way of assessing segregation resistance using a sieve as reported in section 3.3.3 is a static method which cannot account for the influences resulting from the transportation, pumping, placing and handling of the concrete. Hence, a more suitable method would be useful.
- Concrete with 10 mm maximum size aggregate is not included in JIS A5308. Therefore, there is little information on SCC made with this size. The difference between this and the SCC with 20 mm maximum size of aggregate is not clear. The mix design criteria for SCC with 10 mm aggregate also need to be determined.

There is surely a gap between the knowledge obtained merely from papers and that resulting from experiences in the laboratory. The aim of this study was to eliminate this gap, and then to extend the work as described in section **4.1**.

Chapter 4

Objectives, materials and experimental methods

4. 1 Objectives

Although much work has been carried out on SCC, it was clear when reviewing the published literature that there are still many areas where further research is needed, if complete confidence in this new material is to be achieved. These include durability, temperature effects, reinforcement corrosion in SCC and hardened properties such as elasticity, shrinkage, and creep. This work could form the basis of a national or European research project, but were all considered far too extensive for this research.

Since there was no direct experience of SCC at UCL, and probably in the UK, it was decided to make use of existing facilities at UCL and carry out a programme designed to fill some of the gaps in knowledge listed at the end of the last chapter. This started with examining the properties of the cementitious paste, then moved on to look at mortar and then to fresh concrete properties. Finally, some hardened properties of the concrete were considered.

The objectives can be summarised as follows:

1) The influences of combined CRMs on the rheological properties of paste are still not clear. A model to describe these influences will be extremely useful in SCC mix design.
2) Although **Ozawa** suggested a sand content V_s/V_m of 0.40 for a mix with low W/P, it is not clear whether this is suitable for finer sand gradings. For higher water/powder ratios, e.g. 0.34 to 0.37, it is also not clear what are the optimum sand contents. Is a low mortar flow of 245 mm (relative flow area ratio 5) sufficient to obtain a concrete slump flow of 650 mm? Is there a relationship between mortar flow and concrete

slump flow? Is there any minimum requirement of mortar viscosity for SCC? What are the factors influencing the dosage of superplasticizer? All of these uncertainties need to be clarified.

3) From the literature review, the methods of achieving self-compactability are clear. However, the production of SCC with the UK materials according to Ozawa'a method needs examining, and then some modifications may be needed for higher water/powder ratios. For these SCC's, both passing ability and segregation resistance need to be checked. In doing this, the slump flow loss of SCC needs to be minimised and an effective test to assess the segregation is required. It is not clear if there are any other factors (except viscosity) influencing the segregation resistance.
4) For NC, full compaction guarantees the bond to reinforcement; for SCC the influence of lack of vibration on bond is not clear. Since the paste volume of SCC is higher than NC, drying shrinkage may be increased, and therefore needs to be checked. According to **Ozawa** (1997), a one day (cylinder) strength of 10 MPa is required for satisfactory construction. However, there are many factors influencing the early strength of concrete, and the controlling factors for SCC need to be determined. For SCC, the influence of cube size on compressive strength is not clear.
5) In the SCC mix design process, methods to control the segregation resistance and to minimise the cost need to be determined.

In the study aimed at achieving these objectives, a series of experiments on paste, mortar and concrete were carried out. The particular aims and variables of each set of experiments are reported in Chapters 5 to 8. Detailed test results for paste, mortar and concrete are included in Appendix 1, 2 and 3 respectively.

This chapter presents the details of the materials and experimental methods used in the research: the materials are reported in section **4.2**, the mixing procedures are presented in section **4.3**, and the test methods are described in section **4.4**.

4. 2 Materials

The materials used in this study are readily available in the UK market.

4.2.1 Portland cement

Portland cement (PC, class 42.5N), complying with BS 12:1989, was used. There were five batches collected at different times from Rugby Cement. **Table 4-1** shows the compositions.

Table 4-1 Composition of Portland cement

Date (mm/yy)	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	Alkalis (%) $Na_2O_{(eq)}$	SSA (m^2/kg)	*Comp. (MPa)
04/95	59	12	9.6	9.0	0.61	376	62.5
01/96	55	14	10.6	9.1	0.63	355	59.4
07/96	56	15	9.9	8.9	0.64	335	58.3
11/96	50	18	11.0	9.6	0.63	380	55.0
03/97	57	13	9.5	9.2	0.62	395	60.5

* mortar compressive strength at the age of 28 days

4.2.2 Cement replacement materials (CRMs)

In this study, several types of CRMs were used. They were:

- Pulverised fuel ash (PFA), complying with BS 3892: Part 1:1982, supplied by Ash Resources Ltd.
- Ground granulated blast furnace slag (GGBS), complying with BS 6699:1992, supplied by Civil and Marine Ltd.
- Limestone powder (LSP)-L100, supplied by Longcliffe Quarries Ltd.
- Condensed silica fume (CSF), in slurry form (50% water), supplied by Elkem Chemicals.

The compositions and physical properties of CRMs are shown in **Table 4-2**.

Table 4-2 Compositions and physical properties of CRMs

Powders	*SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	LOI	SSA (m^2/kg)	S.G
PFA	51.4	25.0	9.4	1.4	1.4	4.8	(87.5%<45μm)	2.40
GGBS	33.7	11.5	1.8	41.3	9.0		400-440	2.90
LSP	0.1	0.1	0	55.6	0.2	43.8	270-370	2.68
CSF	92	1.0	1.0	0.3	0.6		15000-20000	^2.20

*percent by weight LOI: loss on ignition
SSA: specific surface area S.G: specific gravity ^ Powder: 2.20, slurry: 1.38

The particle size distributions of powders measured by a laser diffraction instrument are shown in **Fig. 4-1.** The range of particle size distributions of CRMs (not including CSF) are similar to that of PC. The fineness is in the sequence PC<GGBS<LSP<PFA. This trend is consistent with that measured by Blaine method.

4.2.3 Admixtures

All SCC mixes tested contained a superplasticizer, some mixes also contained an air-entraining agent or a viscosity agent.

The superplasticizers used were:

1) Conplast SP435: a low alkali, sulphonated naphthalene formaldehyde
2) Conplast SP333: blended organic polymers with retarder
3) Sikament 10: a sulphonated vinylcopolymer

At the start of the work, SP435 was used, but it was found that the slump flow loss of some mixes was significant, SP 333 was then tried, and most mixes had a very low slump flow loss, but not in the winter time. Also, because there is a retarder in SP333, it affects the one day strength gain. Sikament 10, a new type of superplasticizer, was recommended by the manufacture, Sika, during the international conference in Paisley (1996). It does not affect concrete one day strength, and also provides a low loss of slump flow.

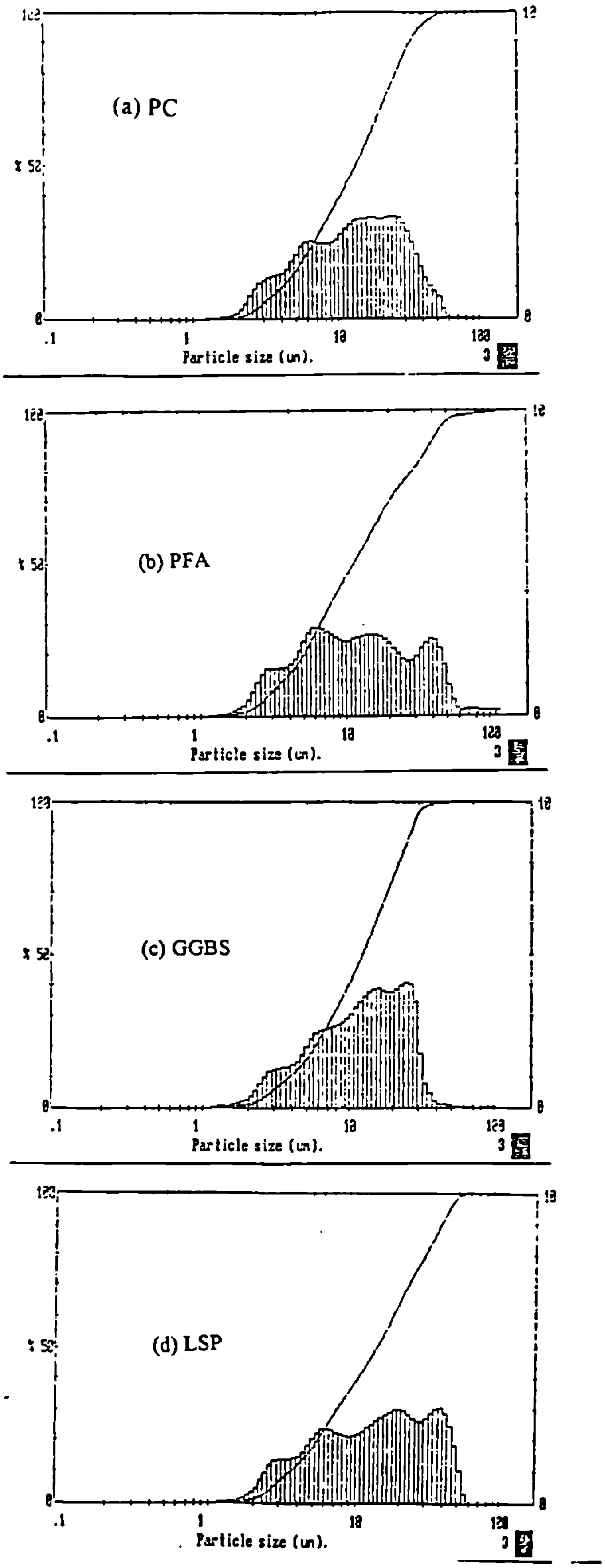


Fig. 4-1 Particle size distributions of powders

The air-entraining agent was a combined water reducing air-entraining agent, Conplast PA21, and the viscosity agent was a cellulose powder.

Conplast SP435, SP333, PA21 and the cellulose powder were supplied by Fosroc Expandite Ltd. Details of all the admixtures are given in **Table** 4.3.

Table 4-3 Details of chemical admixtures

	Solid content by weight	Specific gravity	Standards compliance BS5075	ASTM C494
Sikament 10	20%	1.11	Part 3	Type F
Conplast SP435	40%	1.19	Part 3	Type F
Conplast SP333	40%	1.19	Part 1	Type A, Type G
Conplast PA21	36%	1.18	Part 2	Type A

In this study, the superplasticizer dosage is expressed in percentage of solids by weight of binder powders.

4.2.4 Water

Tap water was used in all the mixes, and the temperature of water was normally about 19°C. Occasionally this rose to 24°C in the summer and dropped to 15°C in the winter.

4.2.5 Aggregate

Thames Valley gravel and Thames Valley sand were mainly used in the mixes. In addition, granite aggregates (5-10 mm) were also used for a few mixes.

Table 4-4 Properties of aggregates

Sieve size	$Sand_1$	$Sand_2$	Granite (5-10 mm)	Gravel (5-10 mm)	$Gravel_1$ (10-20 mm)	$Gravel_2$ (10-25 mm)
25.4 mm	^100	100	100	100	100	100
19.1 mm	100	100	100	100	94	75
10.0 mm	100	100	81	92	16	7
5.00 mm	99	98	5	16	2	0
2.36 mm	87	87	3	3	1	0
1.18 mm	77	75	0	1	0	0
600 μm	69	55	0	1	0	0
300 μm	41	19	0	1	0	0
150 μm	8	4	0	0	0	0
F.M	2.2	2.6	6.1	5.9	6.9	7.2
S.G	2.64	2.64	2.70	2.60	2.60	2.60
Absorption	1.2%	1.2%	1.1%	1.1%	1.0%	1.0%
*γ_g (kg/m^3)	-	1756	1590	1592	1566	1566

^ percentage of passing * Dry rodded bulk density

The fine grading of the sand is a characteristic of Thames Valley sand, but is worth noting that sand with a F.M of 2.2 complies with BS 882: 1992, but not ASTM C33-93.. The fineness modulus of sand varied from 2.2 to 2.6 for different batches, and there were no significant influence on the fresh properties of SCC except a slight different dosage of superplasticizer. The bulk density (dry rodded) of the combined gravel (5-20 mm) is in the range of 1620-1680 kg/m^3, depending on the aggregate gradings and the proportion of coarse aggregate fractions. The grading of coarse aggregate (10 -20 mm) has a major influence on the result of L-test. For instance, a batch of coarse aggregate ($Gravel_2$ in **Table 4-4**), F.M 7.2, 75% by weight passing a 19 mm sieve, has a maximum aggregate size of 25 mm rather than 20 mm, because according to BS 882, 85% is the minimum value for passing a 19 mm sieve.

Fig. 4-2 shows a typical combined grading curve of aggregate used in this study for SCC compared with that used for FC mixes and the Road Note No. 4 type grading curves for 19.05 mm aggregate. It is clear that the grading curves of aggregate for SCC, due to the required high proportion of sand, are even finer than curve No. 4 of Road Note No. 4. For 10 mm maximum size aggregate, the grading curve for SCC mixes was typically around curve 4 or curve 3 as shown in **Fig. 4-3**. In general, the grading of aggregate for

SCC is finer than that for FC because of the lower coarse aggregate content required.

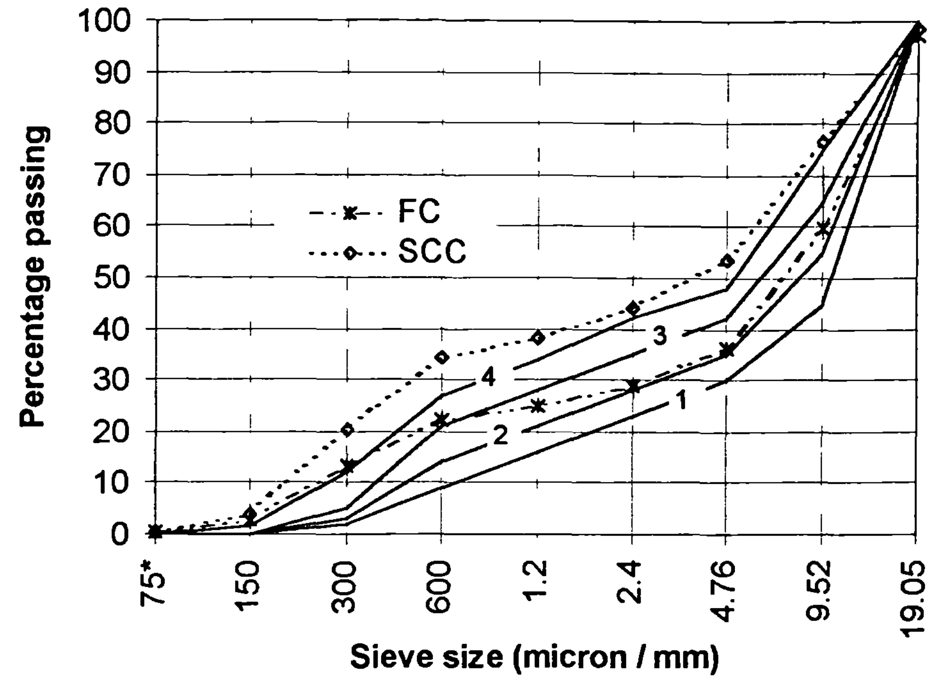


Fig. 4-2 Grading curve of aggregate for SCC compared with FC and Road Note No. 4 type grading curves for 19.05 mm aggregate. [Road Note No. 4 type grading curves adapted from Road research laboratory(1950)]

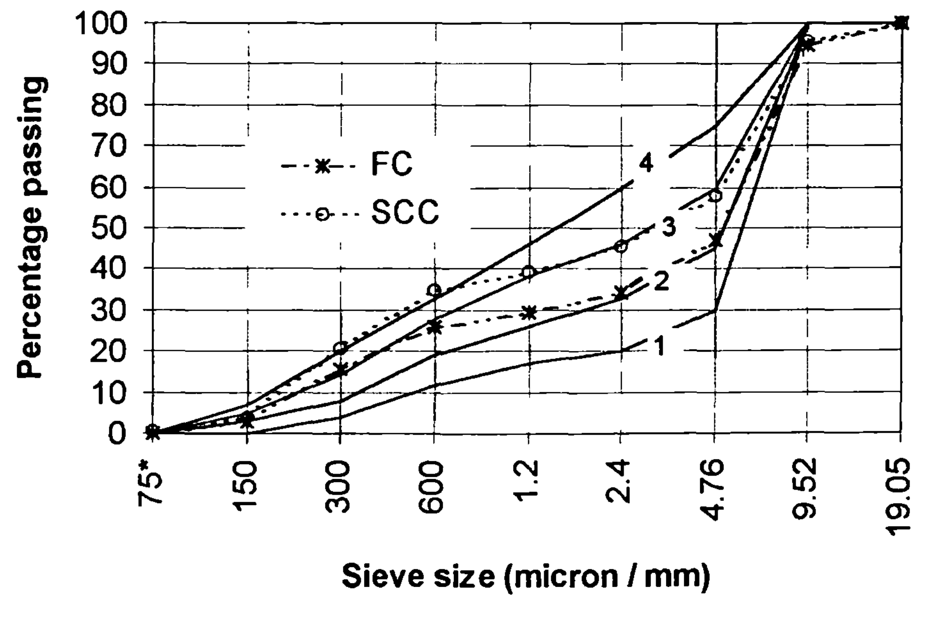


Fig. 4-3 Grading curve of aggregate for SCC compared with FC and McIntosh and Erntroy's type grading curves for 9.52 mm aggregate [McIntosh and Erntroy's type grading curves adapted from McIntosh et al (1955)]

4. 3 Mixing Procedures

Control of the mixing procedures is very important because they must provide a uniform and reproducible starting condition for the concrete.

Before June 1996, oven dry aggregates were used in the laboratory, therefore the mixing water of concrete or mortar should include the absorption water of the aggregates. After that time, wet aggregates were used, the moisture content of aggregates was measured before mixing, and appropriate reduction made to the batch weight of water.

4.3.1 Paste

First, all the mixing water together with superplasticizer was poured into a container followed by the adding of the powder. Paste was mixed using a Silverson high shear mixer at full speed for two minutes, then a palette knife was used to strip off all the agglomerated paste which had adhered to the mixer and mixing bowl, then the mixing was continued for three minutes. According to **Thurairatnam** and **Domone** (1984), five minutes' mixing time is sufficient for paste. The amount of paste was usually one litre. If superplasticizer is used, it is first mixed with mixing water, because this provides the best mixing effect and consistent results.

4.3.2 Mortar

Usually two litres of mortar were mixed using a Hobart mixer. The mixing procedure was modified from that used by **Ozawa** (1994), and is shown in the **Fig. 4-4**. First, the primary mixing water, together with superplasticizer, was poured into the mixer bowl and the mixer was started at low speed. Then the premixed powders and sand were gradually added over 60 sec. The mortar was then mixed for further two minutes, and then the remaining water added (W_2), followed by mixing for a further two minutes. The primary water content [$W_1 = (\beta_p - 3\ E_p)\ V_p$] is related to the powder parameters β_p and E_p which will be defined in **Chapter 5**.

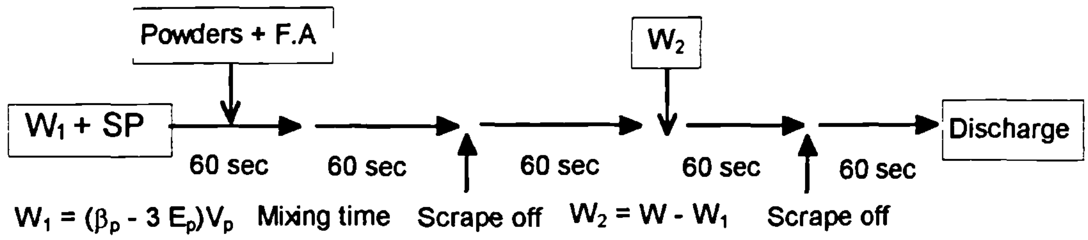


Fig. 4-4 Mixing procedure for mortar

4.3.3 Concrete

Most of the concrete was mixed using a Liner Cumflow mixer. This pan mixer is robust and reliable, and has a capacity of four feet cube (113 litres) at a speed 18 rpm. For thorough mixing, a concrete volume of between 38 and 76 litres is desirable. There were three mixing methods used in this study, all of them with a two-step mixing technique. Method 2 was used to investigate the relationship between mortar flow and concrete slump flow. Method 1 and Method 3 were modified from the reported methods in order to cope with the UK materials.

- Method 1 (M1)

  This method was suggested by **Tamimi** (1994). The concrete was produced by adding water at two separate times. In the first stage, the aggregate (coarse + fine) and a water content (W_1) of 25% of the specified weight of cement were mixed for 30 sec; the cement was then added and mixing continued for a further 60 sec. In the second stage, the remaining water (W_2) was added and mixed for 90 sec. **Tamimi** claims that higher compressive strength with a significant decrease in bleeding capacity at an early age can be achieved. However, this method is generally for NC without a superplasticizer, and hence, a way of adding this needs to be included. This is shown in **Fig. 4-5**, the superplasticizer dosage divided into two parts by proportion of W_1 and W_2

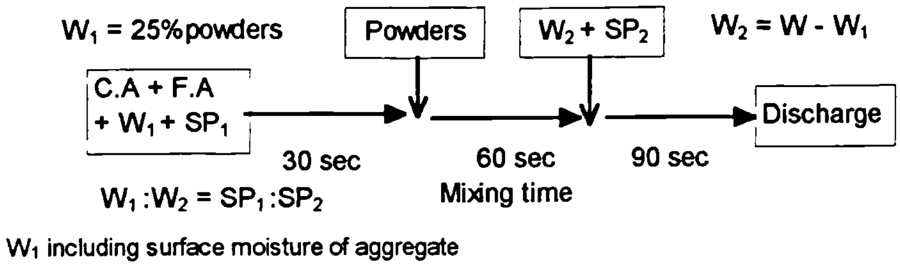


Fig. 4-5 Mixing procedure for concrete (M1)

- Method 2 (M2)

In this method mortar was first mixed with all of the water and superplasticizer for two minutes. Then the flow spread test and V-funnel test were checked, and adjustment was made if needed. Finally the coarse aggregate was added, and the mixing continued for another two minutes. The mixing procedure is shown in **Fig. 4-6**

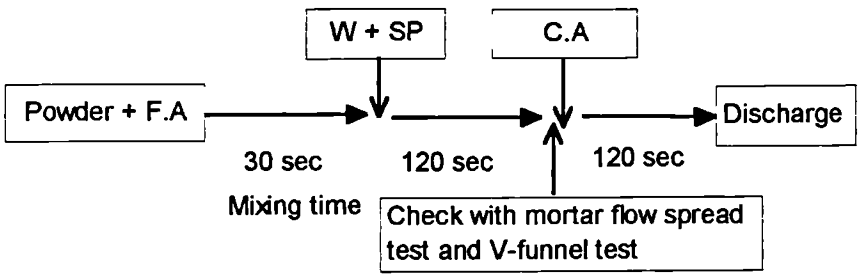


Fig. 4-6 Mixing procedure for concrete (M2)

- Method 3 (M3)

This method, modified from that used by **Okamura** and **Ozawa** (1993), is shown in **Fig. 4-7**.

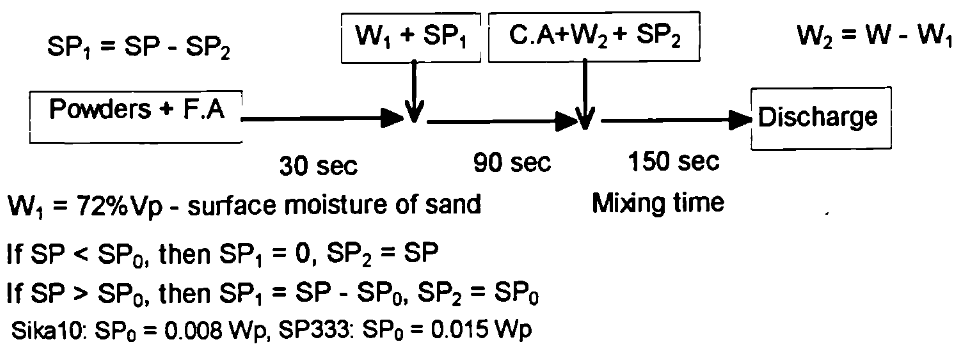


Fig. 4-7 Mixing procedure for concrete (M3)

This method was the same as **Okamura's** method, except that the superplasticizer was divided into two parts, SP_1, SP_2, whereas **Okamura** added it all with W_2. However, it was found in this research that his method was suitable only when the superplasticizer dosage was low. For mixes with low water/powder ratio and high superplasticizer dosage, his method easily causes segregation. If the superplasticizer dosage was less than a certain amount (SP_0), Okamura's method was used; if the superplasticizer dosage was higher than SP_0, then superplasticizer was added in two parts. SP_0 was found to be dependent on the type of superplasticizer, and was obtained through mixing experiences.

In this method, first all the powders and sand were dry mixed for 30 sec, then SP_1, if there is, together with W_1 were added and mixed for a further 90 sec; and then the remaining water W_2 and SP_2 and all coarse aggregate were added, followed by mixing for a further 150 sec.

After mixing, the concrete needs to be checked with the slump flow test and V-funnel test. If the slump flow was too low, adjust it with a further dose of superplasticizer, and mixed for one more minute. According to **Okamura & Ozawa** (1993), this check and adjustment are normal procedures in the production of SCC.

The method of adding the superplasticizer into the mixer was established by trial-and-error, and it was found to be different for different superplasticizers. In this study, most mixes were mixed by Method 1 and Method 2, three mixes by Method 3 as shown in Appendix 3 (**Table A.3.3**). Further discussion will be in section **6.4.5**.

4. 4 Test methods

This section describes all the test methods used in this research as listed in **Table 4-5**.

Table 4-5 List of tests for paste, mortar and concrete

	Experiments	Measured value	Property assessed
Paste	Flow spread test	Spread (mm)	β_p, E_p
	Viscometer	Flow curve	τ_0, μ
Mortar	Flow spread test	Spread (mm)	Flowability
	V-funnel test	Flow time (sec)	Viscosity
	Adhesion test	Glass balls weight	Adhesion
	Cube test	Load (KN)	Compressive strength
Concrete	Slump flow test	Spread (mm)	Flowability
	V-funnel test	Flow time (sec)	Viscosity
(Fresh	L-test	Concrete weight	Passing ability
properties)	U-test	Filling height (mm)	Passing ability
	Two-point test	Flow curve	g, h
	Segregation resistance	weight of C.A.	Segregation index
Concrete	Bond test	Load (KN)	Bond strength
(Hardened	Shrinkage test	Change of length	Shrinkage
properties)	Cube test	Load (KN)	Compressive strength

4.4.1 Tests for paste

4.4.1.1 Flow spread test

The apparatus for the flow spread test consists of a mould in the form of a frustum of a cone, 60 mm high with a diameter of 70 mm at the top and 100 mm at the base **(Fig. 4-8)**. The cone is placed at the centre of a glass plate, and is filled with the cement paste in two layers, each layer being compacted with 15 strokes of steel rod if needed. (For most paste or mortar used for SCC, due to its high flowability, no compaction was required.) Immediately after filling, the cone is then lifted and the paste spreads over the table. The average diameter (D) of the spread is measured, the relative flow area ratio (R) is then calculated using:

$$R = \frac{(D^2 - 100^2)}{100^2} = (D/100)^2 - 1 \qquad \textbf{(4-1)}$$

Values of R are typically in the range from 0.2 to 15.

The comparison between this flow spread test and the ASTM C230 flow table test is shown in **Table 4-6**. For the flow spread test, the spread is measured without the paste being subjected to any jolting, hence the flow is solely due to self-weight.

Table 4-6 Comparison between ASTM C230 and flow spread test

	ASTM C230	Flow spread test
Mould dimension	50.8 mm high	60 mm high
Flow table	dropped 25 times in 15 sec	Still
Results expressed	by the ratio of increasing diameter	by the ratio of increasing area

4.4.1.2 Viscometer test

The rheological properties of paste were measured by a concentric cylinder viscometer (Rheomat 115) with bob and cup diameters of 45 mm and 48.8 mm respectively. Before obtaining the flow curve, the paste was sheared in the viscometer at a high strain rate (704/sec) for one minute to ensure full irreversible structural break down [**Tattersall & Banfill** (1983)] thereby providing a reproducible starting condition [**Struble &. Sun** (1995)]. The viscometer test and flow spread test were completed within 10 minutes after mixing of the paste. The flow curves were drawn by Rheoscan 115, with the speed changing from 0 to 112 rpm (maximum) and back to 0 in two minutes. The value of yield stress τ_0 and plastic viscosity μ were obtained from the down curve. **Photo 4-1** shows the Rheomat 115 viscometer with the Rheoscan 115 control Unit.

4.4.2 Tests for mortar

4.4.2.1 Flow spread test

The flow spread test procedure for mortar is the same as for paste (**4.3.1.1**). As will be discussed in section **6.2.1**, a mortar flow of 310 mm is normally required for SCC. If the mortar flow was less than this, more superplasticizer was added (usually not higher than 5 grams for a mortar volume of two litres) and the test was repeated until an average diameter of at least 310 mm was obtained. Then the total superplasticizer dosage (solid content) was recorded and expressed as a percentage of cementitious materials by weight. **Photo 4-2** shows a typical mortar flow and **Photo 4-3** shows mortar with many bubbles due to an overdose of the superplasticizer.

4.4.2.2 V-funnel flow test

This test, suggested by **Okamura** and **Ozawa** (1993), was used together with the flow spread test to select a suitable water/powder ratio (see **Fig. 3-32**). The dimensions are shown in **Fig. 4-9**. The funnel is filled with 1.1 litres of mortar, and the gate is then opened and the stop-watch simultaneously started. The watch is stopped when light first appears when looking down into the funnel from above. The flow time is then read.

4.4.2.3 Adhesion test

This test is used to measure the adhesion of mortar to glass ball. The adhesion is related to the segregation resistance as discussed in Chapter 7.

The apparatus was:

1) a flow table as described in ASTM C230-90
2) 30 glass balls, having a diameter of 18.5 mm and surface area of 10.75 cm^2 each
3) a 10 mm sieve with a pan

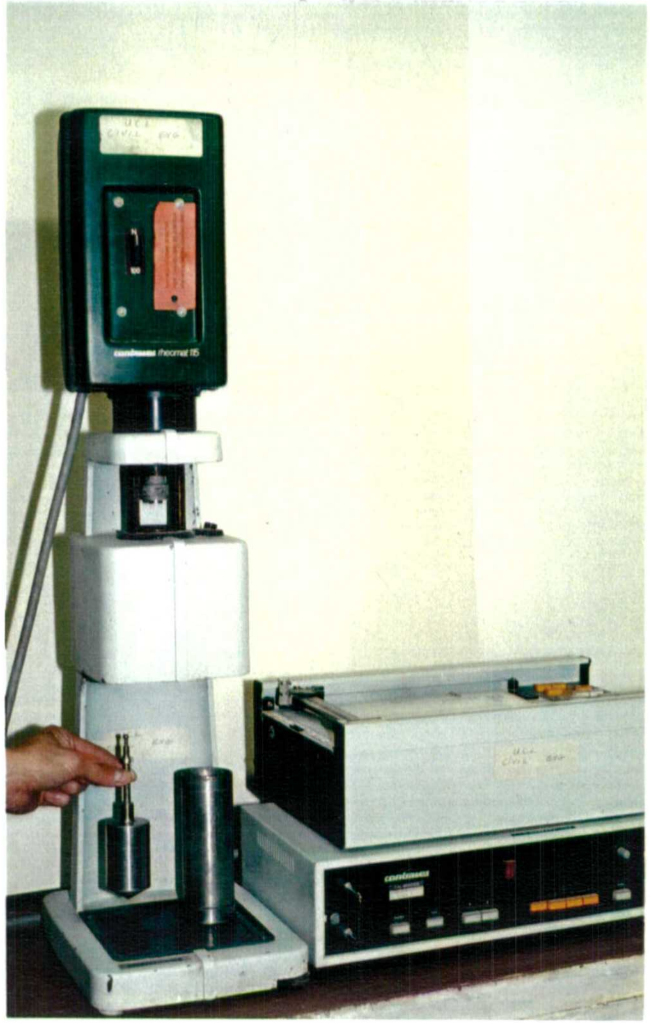


Photo 4-1 Rheomat 115 viscometer with Rheoscan 115

Photo 4-2 Mortar flow

Photo 4-3 Mortar with many bubbles due to overdose of superplasticizer

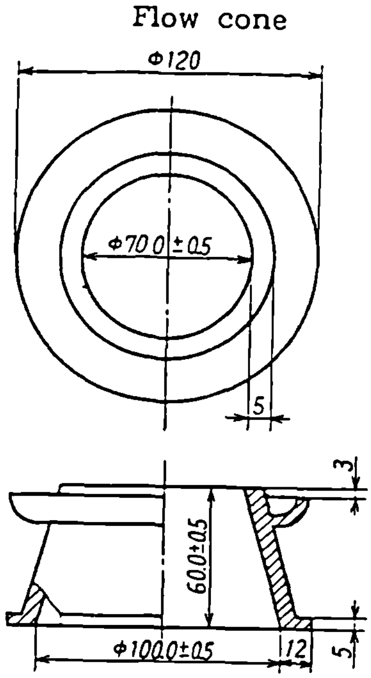


Fig. 4-8 Dimensions of flow cone for the flow spread test (Adapted from JIS R5201-1992)

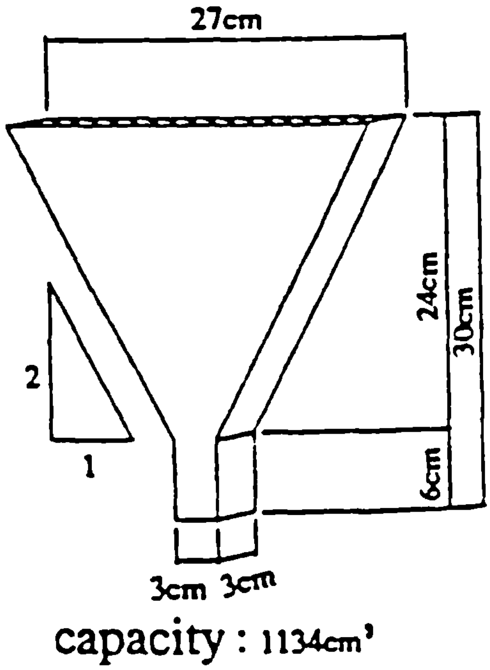


Fig. 4-9 Dimensions of V-funnel test for mortar
[Adapted from Okamura et al (1993)]

The test procedure is:

1) The weight of 30 dry clean glass balls (W_1 in grams) was measured
2) One litre of mortar was poured into a container, and was mixed thoroughly with 30 glass balls by a spatula, then allowed to stand for three minutes.
3) A 10 mm sieve with a pan underneath it and was put on the flow table, and the mortar and glass balls mixture was poured on to the sieve.
4) The flow table is jolted 15 times in 10 seconds; most of mortar passes through the sieve into the pan, except that adhering to the glass balls.
5) The weight of glass balls plus adhered mortar (W_2) is recorded, and the adhesion of mortar is defined by

$$\text{Mortar adhesion} = (W_2 - W_1) / (30 \times 10.75) \quad \textbf{(4-2)}$$

4.4.2.4 Compressive strength

The mortar cube strength at the age of one day was measured because it was found to be a good indication of concrete strength. After the flow spread test and V-funnel test were completed, the mortar was poured into the pre-oiled steel moulds, usually three 50 mm cubes and one 100 mm cube for every mix. Since the mortar was flowable and self-compacting, no vibration was required. All the moulds were covered with a polythene sheet overnight and, strength allowing, demoulded 24 hours later. Normally, the one day strength was tested on both a 100 mm cube and a 50 mm cube, and the remaining two cubes were placed in a 20°C curing tank for further testing.

4.4.3 Tests on fresh concrete

4.4.3.1 Slump flow test

The procedure of the slump flow test is similar to the slump test (BS 1881: Part 102: 1983) except that, because concrete is self-compacting, when it is put into the cone, no tamping is required. For SCC, the slump will collapse, and the value of slump flow is the average of the maximum and minimum diameter of the concrete spread. Some researchers like to record the flow time (in seconds) for the concrete spread to reach 500 mm, but this value is not easy to obtain with only one operator. The concrete spread needs to be visually checked carefully, in case there is any segregation, particularly at the edges. If the slump flow measured was lower than the desired value, more superplasticizer was added (usually not more than 50 grams for every adjustment) and the test was repeated until the required slump flow was obtained. **Photo 4-4** shows a typical concrete slump flow.

4.4.3.2 V-funnel test

The dimensions of the V-funnel used for concrete are shown in **Fig. 3-7.** It has a capacity of 10 litres, and test procedure is the same as for the V-funnel test for mortar.

4.4.3.3 L-test

The L-test used in this study is shown in **Fig. 4-10** which was modified from that shown in **Fig. 3-13.** The purpose of this test is to measure the passing ability of concrete. First, concrete was poured into the funnel and then released to fall under its own weight into the trough. Two sets of meshes, with clear gaps of 40 mm, were located in the flow path of the concrete, and divided the trough into three sections. The 40 mm gap was chosen according to **Mitsui** (1994), the gap between rebars should be at least 1.85 times of maximum aggregate size. The parallel meshes were used as an simulation of a confined zone in a reinforced concrete structure. After the concrete had been released and the flow had stopped, any noticeable blockage at either of the meshes was noted and the weight of concrete contained in each of the three sections of the trough was measured. Another test was conducted immediately following this without the meshes and the weight of concrete in each section was again measured. The passing ability is defined as follows:

Passing ability (mesh 1 %) = (weight X1 + weight Y1)/(weight X2 + weight Y2) × 100 **(4-3)**

Passing ability (mesh 2 %) = (weight X1)/(weight X2) × 100 **(4-4)**

weight X1, Y1, X2 and Y2 are shown in **Fig. 4-10**

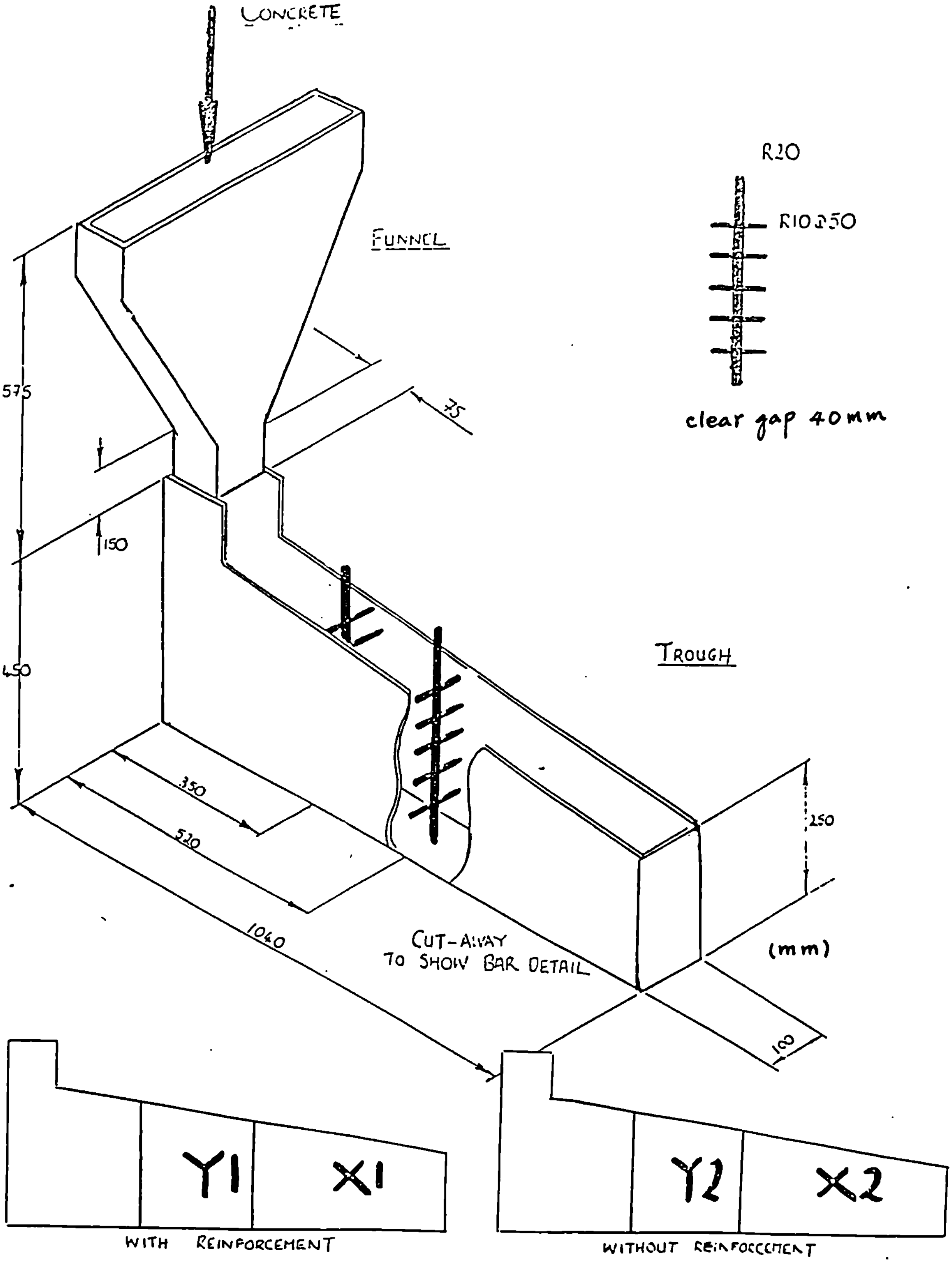


Fig. 4-10 *L-test for assessing passing ability through reinforcement*
[Adapted from Tucker & Kinloch report (1997)]

4.4.3.4 U-test

The U-test used in this study was the same as that shown in **Fig. 3-15** and described in **3.3.6.** The test procedure is very simple. 18 litres of concrete is poured into one column, and allowed to stand for one minute to check if there is any segregation. The gate is then opened, and the concrete then passes through the rebars into the other column. The filling height of concrete is then measured.

4.4.3.5 Two-point workability test

The **Tattersall** two-point workability test used in this study has been described by **Tattersall** and **Banfill** (1983). There are two impellers that can be used: (1) a helical impeller for concrete with medium and high workability (**MH** system); (2) an offset H-impeller for concrete with low and medium workability (**LM** system). In this study, only the MH system was used. Some improvements have been made at UCL to the recording system. A pressure transducer enabled the oil pressure to be recorded, and an optical interference tachometer fitted to enable the drive shaft speed to be recorded. A Windograf digital recorder was used to record the fly wheel voltage and the pressure transducer voltage. These two voltages can be printed out on a chart or recorded on a disk. The two point test apparatus (MH) and the Windograf digital recorder are shown in **Photo 4-5**.

- Test procedure

1) The apparatus is warmed up for one hour at speed setting 4;
2) the Windograf recorder is connected to the MH apparatus, Glitch mode is used to record the data, the chart recorder is zeroed and the diskettes are formatted in advance;
3) with the bowl in the raised position and the impeller rotating slowly, the concrete is loaded to about 75 mm from the top of the bowl;

Photo 4-4 Concrete slump flow (640 mm)

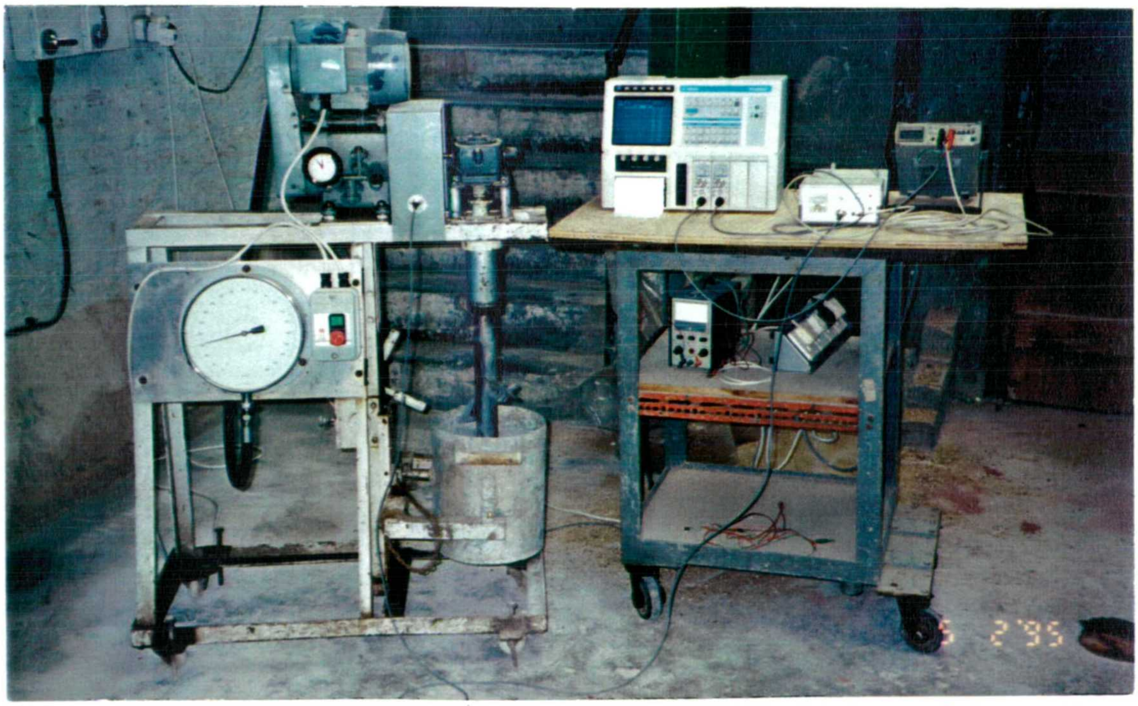


Photo 4-5 Two point test (MH) apparatus and Windograph digital recorder

4) the impeller speed is increased to speed setting 4, and the recording of the chart recorder and floppy disk are started; (2.5 mm/sec is chosen as the chart recorder speed)
5) the recording is continued with the speed reducing through the settings of $3^1/_2$, 3, $2^1/_2$, 2, $1^1/_2$, 1, and $^1/_2$, for 8 seconds at each stage and then the chart recorder and floppy disk are stopped. With FC and SCC, due to their good flowability, test can be recorded continuously from speed setting 4 to 0 in 30 seconds.
6) the bowl is emptied, the impeller speed is increased to speed setting 4, and the recording of the idling pressure is started, then the speed setting is changed uniformly and continuously to speed setting 0 in 30 seconds.

Because the idling pressure varies slightly with time, it should be measured right after or before every concrete test. Idling pressure voltage has a strong linear relationship with fly wheel voltage, hence it can be recorded continuously instead of at increment of. speed settings, and the relationship is obtained by linear regression as equation (4-5).

idling pressure voltage (volts) = fly wheel voltage (volts) × B + A (4-5)

- Data analysis

The recorded disk data is convert into ASCII code using the Dasa Utilities and View to ASCII software supplied by Windograf. These ASCII text files can be analysed by the use of a spread sheet or by a particular programme written for this purpose. The author has written three programmes in FORTRAN 77 to process the data:

1) icon.exe, processing the idling pressure
2) med.exe, processing the incremental data for NC
3) mc.exe, processing the continuous data for SCC and FC

The results of the programmes have been proved excellent when compared to those by the spread sheet. It saves plenty of time processing the data. The algorithm of data analysis by the programmes and the spread sheet is briefly described as follows.

The impeller speed (N in rps) is obtained from the flywheel voltage (V_{ss} in volts) with the relationship:

$$N = V_{ss} / 0.50 / 4.6815 \qquad \textbf{(4-6)}$$

where 4.6815 is the gear ratio

The impeller torque (T in Nm) is obtained from the net pressure (P in psi) with the relationship:

$$T = 0.0215 \times P \qquad \textbf{(4-7)}$$

P is the difference in pressure between the test run with concrete (P_c) in the bowl and the idling pressure without concrete (P_i). These are obtained from the pressure voltage for each test condition (V_{pc}, V_{pi}), using

$$P = P_c - P_i = \{(176.44\ V_{pc} - 155.5) - (176.44\ V_{pi} - 155.5)\} \qquad \textbf{(4-8)}$$

Finally, coefficient g and h of the relationship between T and N, i.e.

$$T = g + hN \qquad \textbf{(4-9)}$$

are obtained by linear regression.

The coefficients in equation (4-6) were related to the setting of the apparatus. The coefficient in equation (4-7) was obtained from a torque/pressure calibration carried out with a lever arm and a spring balance system as described by **Tattersall** and **Banfill** (1983). The coefficients in equation (4-8) were obtained by measuring the pressure with the pressure gauge and the pressure voltage. It is important to note that different two-point test apparatuses may have different coefficients.

Fig 4-11 (a) shows a typical chart output from the incremental two point test. As can be seen, the values of pressure voltage fluctuated significantly, and it is crucial to obtain the representative values at each speed increment. The average is obviously not suitable, due to the many kicks (when the impeller hits aggregate). **Wimpenny** and **Ellis** (1987) found that statistical analysis of the pressure transducer measurements after the removal of kicks showed that it was significantly skewed. Standard methods of outlier removal based on a normal frequency distribution are not strictly appropriate for treating data with a skewed base. They found that the *median* was the best because it is not so readily affected by a very large or a very small individual value. Hence, they suggested that the median be the suitable measure of location for data in each stage.

With FC and SCC, due to their good flowability, the two-point test can be recorded continuously instead of by stages. This can shorten the recording time from 60 seconds to 30 seconds, therefore increasing the reliability of the test, because the longer the testing time the higher the risk of segregation. **Fig. 4-11 (b)** and **(c)** show typical charts from the continuous two-point test with SCC and idling respectively. For data processing, the continuously recorded data were divided into several small stages. In each stage, the range of flywheel voltage was less than 0.15 volt, and the mean and median were taken as the representative values of flywheel voltage and pressure voltage respectively.

A typical output of the programme "mc.exe" is shown in **Fig. 4-12.** Typical flow curves for different kinds of concrete are shown in **Fig. 4-13** (will be discussed in **7.1.3.3**). The values of the constants g and h can be calculated from the best fit flow curve. These are proportional to the yield stress and plastic viscosity of the concrete respectively. The correlation coefficient can also be calculated to confirm the confidence of the test.

4.4.3.6 Segregation resistance test

Segregation, easily observed when it occurs, is hard to assess quantitatively. Although many testing methods have been used [JCI committee on SCC, Report I (1993)], according to Ozawa (1996), none of them is satisfactory. However, in this study from the experience in using the two-point tests, an effective way has been developed to assess the segregation resistance. Usually, at the end of two-point test, any segregation can be seen in the concrete in the bowl, caused by the stirring of the helical impeller. The difference of

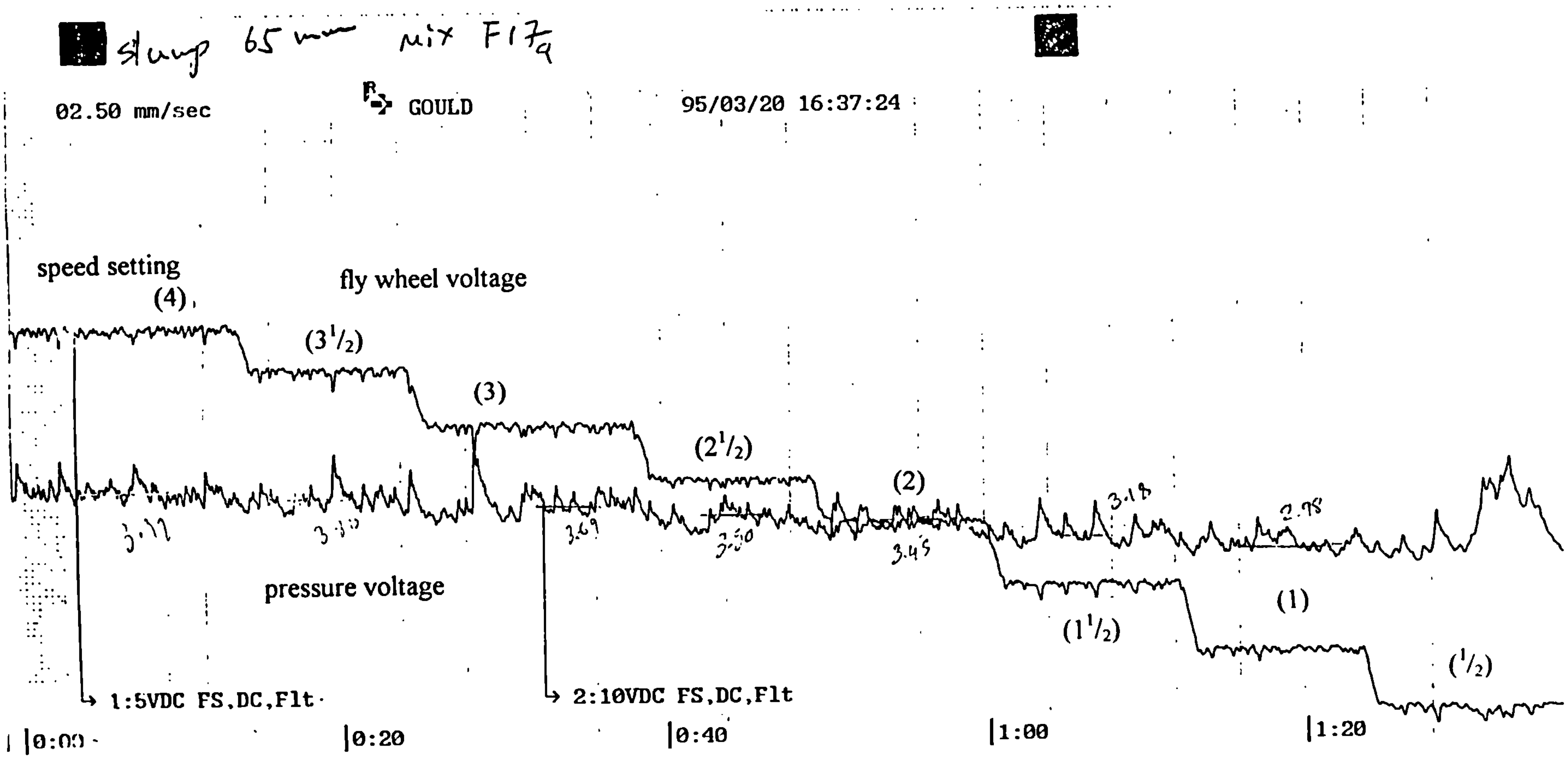


Fig. 4-11 *Chart recorder output of two-point test* (a) *with NC*

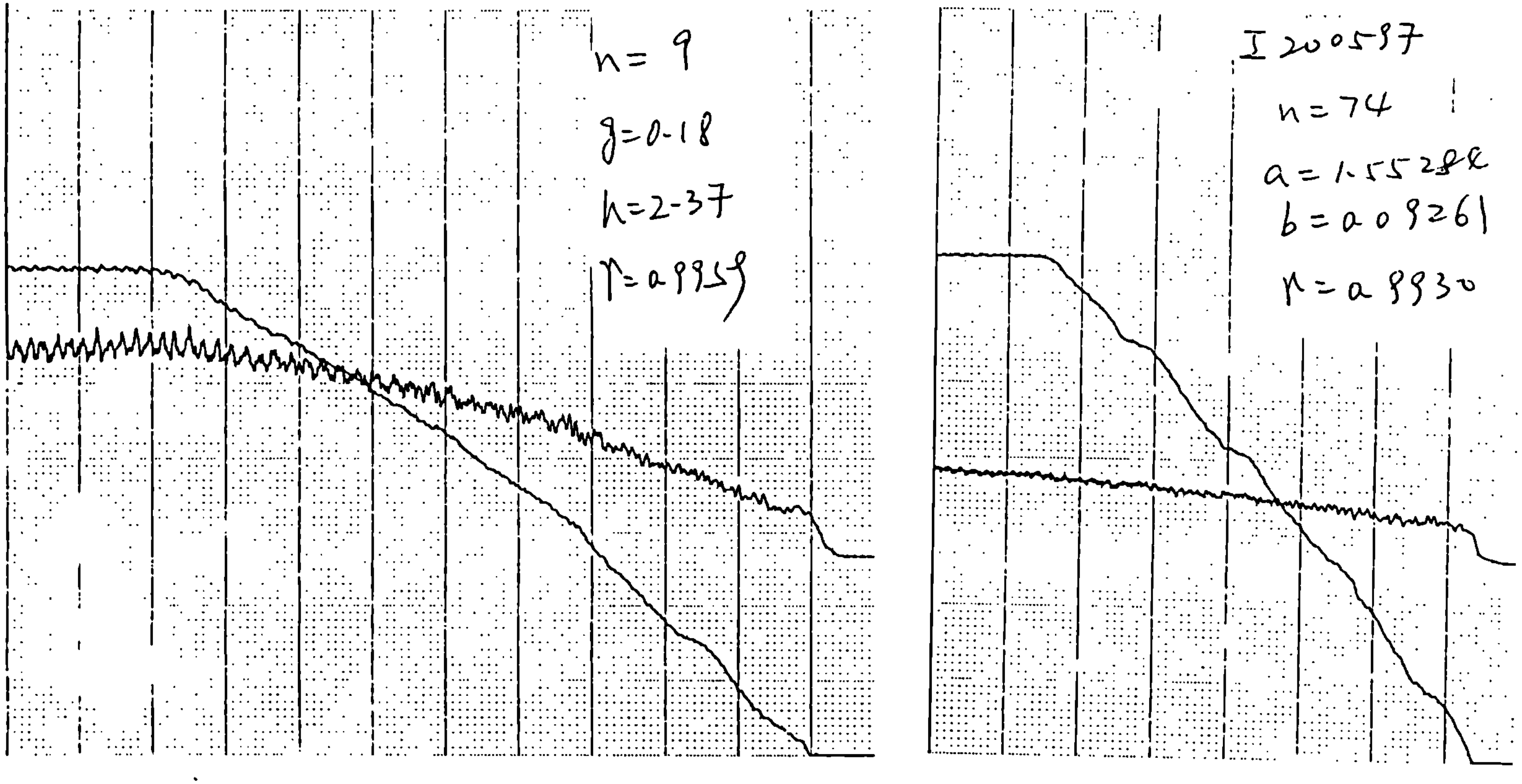


Fig. 4-11 *continued* (b) *with SCC* *(c) idling*

```
Run mc.exe under DOS system(<0.15,k1=100,<0.40 out    T=0.0215P,use median,19/
Sept/96)
Test:   C200597        C2 Trigger Date:           20/05/97
Test:   I200597        Trigger Date:              20/05/97
Idling pressure n and correlation coefficient r==>   74   0.9930
Idling pressure ai bi==>           1.55284         .09261
 n   flywheel speed voltage  pressure voltage          idling pressure voltage
1200          3.250                  2.731                      1.854
 800          2.911                  2.646                      1.822
 600          2.607                  2.548                      1.794
 700          2.299                  2.451                      1.766
 600          1.964                  2.326                      1.735
 600          1.654                  2.220                      1.706
 400          1.269                  2.055                      1.670
 600           .892                  1.918                      1.635
 300           .618                  1.794                      1.610
------------------------------------------------
             Torque(Nm)        Shaft speed(rps)
              3.329                  1.388
              3.124                  1.244
              2.860                  1.114
              2.598                   .982
              2.243                   .839
              1.949                   .707
              1.459                   .542
              1.073                   .381
               .696                   .264
-----------------------------------------------------
n= 9
Two point test constant g(Nm)=  .18
Two point test constant h(Nm s)= 2.37
Linear regression correlation coefficient r= .9959
```

Fig. 4-12 Data analysis output from two-point test

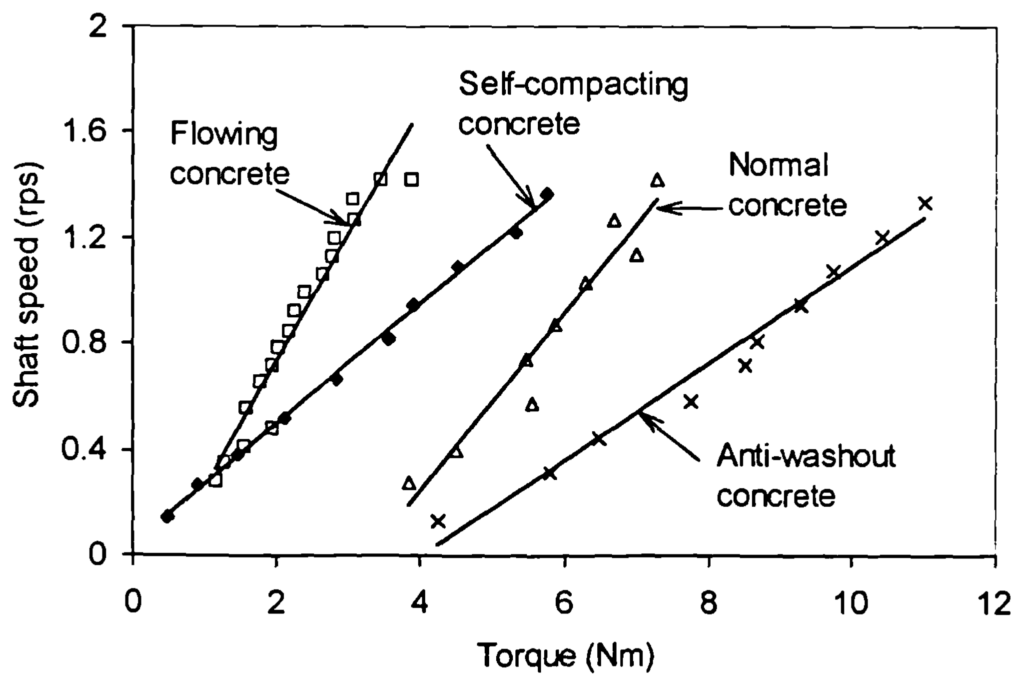


Fig. 4-13 Typical flow curves of two-point test for different types of concrete

coarse aggregate content between the top and bottom layer of the concrete can be used as a index to measure the degree of segregation resistance. The method uses a MH two-point test machine as follows:

1) Fresh concrete is mixed in the bowl with the impeller at speed setting 1 (0.31 rps) for one minute. (Speed setting 1 was chosen because it is more effective causing segregation than speed setting 4)
2) 2 kg samples are taken from the top and bottom part of the concrete in the bowl.
3) The mortar is removed from each sample by washing through a 5 mm sieve, and the coarse aggregate content obtained.

The segregation index is defined by

$$S.I\ (\%) = CA_{bottom}\ (\%) - CA_{top}\ (\%) \quad \textbf{(4-10)}$$

where CA (%) = S.S.D weight of CA / total weight of sample

(S.S.D: saturated and surface-dry)

This method effectively estimates the segregation resistance of concrete. In this study, the segregation indices in the range of 5% to 52% were obtained.

4.4.4 Tests on hardened concrete

After the tests for fresh properties were completed, the concrete was cast into moulds. For SCC, specimens were not normally vibrated unless comparison between the vibrated and non-vibrated concrete was required.

4.4.4.1 Bond between concrete and reinforcement

The pull-out test method is well documented in ASTM C234 (1986), which compares concrete on the basis of the bond developed with reinforcing steel. It is very important to note that this test method does not establish bond values for structural design purposes, and the results are only comparative, e.g. the bond to SCC compared to that to NC.

Both plain bar and deformed 16 mm diameter bars were used. The inside mould dimensions were 150×150×300 mm (L×W×H). When demoulding, extreme care was taken to prevent striking or otherwise disturbing the rebars, and it was safer to demould at least three days after casting. **Photo 4-6** shows the testing apparatus. In this study, only specimens with horizontally embedded bars (upper and lower bars) were tested.

4.4.4.2 Shrinkage

Shrinkage strain measurements were carried out according to BS 1881: part 206. Concrete prisms (102 × 102 × 507 mm) were used, and a Demec mechanical strain gauge with a gauge length of 8 inches was used to measure the shrinkage .

This instrument consists of an Invar main beam with two conical locating points, one in a fixed position at one end, and the other pivoting on a special knife edge. This pivoting movement is transmitted to a dial gauge, graduated in 0.0001 inch, and mounted on the Invar beam. Location of the gauge points is made by drilled stainless steel discs (7 mm in diameter) cemented to the prism. Each measurement was taken as the average of two readings (the second reading being taken after rotate the gauge through 180°). One division on the dial represents a strain of 0.997×10^{-5}. **Photo 4-7** shows the specimen and the strain gauge.

According to CEB-FIP (1990), for curing periods of concrete members of less than 14 days at normal ambient temperatures, the duration of moist curing does not significantly affect shrinkage. In this study, the water curing periods of the specimens were from 6 to 12 days. After curing, the specimens were quickly surface dried and then the drilled discs stuck to the prisms by epoxy resin, using a setting-out bar. When these discs ~~was~~ were firmly adhered, the initial measurement for each specimen was taken. The specimens were then placed in a chamber to minimise the variation of temperatures and humidities until the

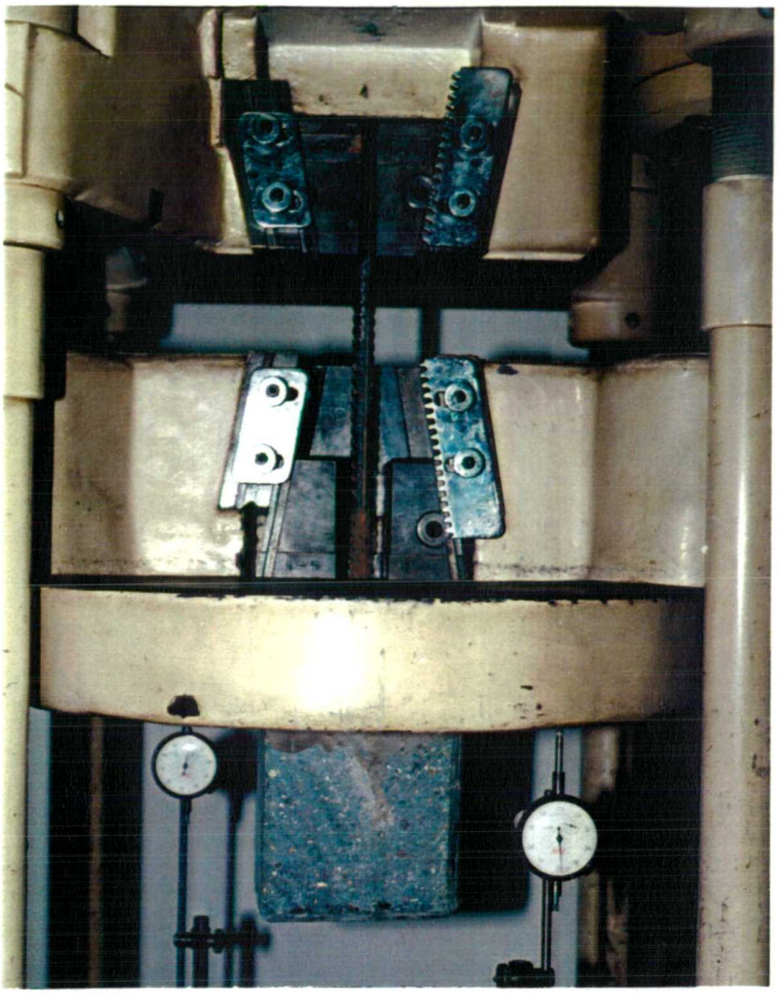


Photo 4-6 Pull-out test

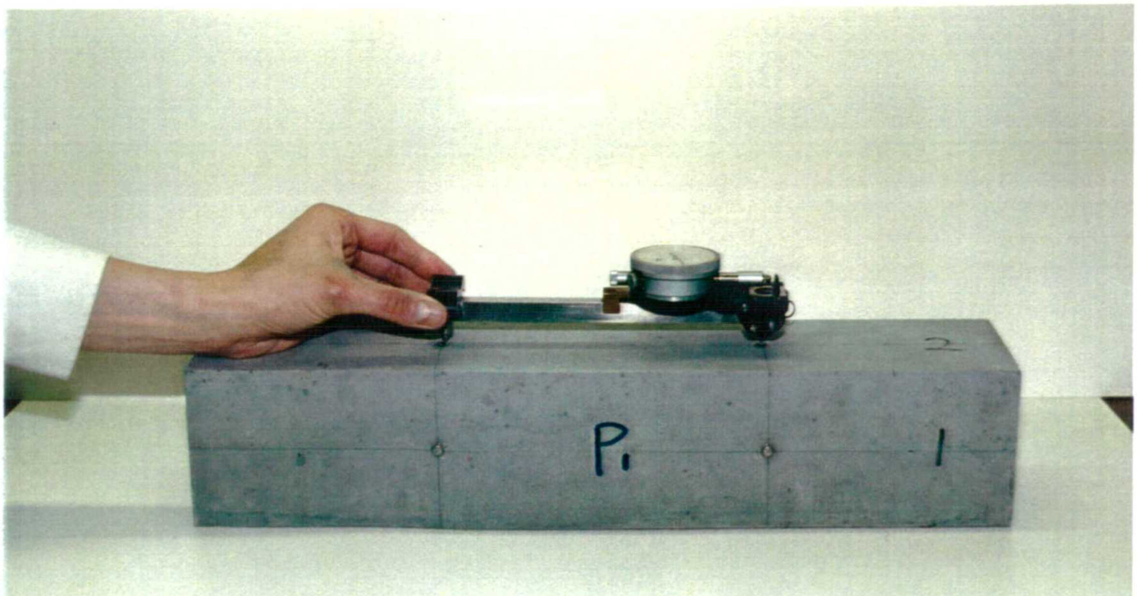


Photo 4-7 Shrinkage specimen and Demec strain gauge

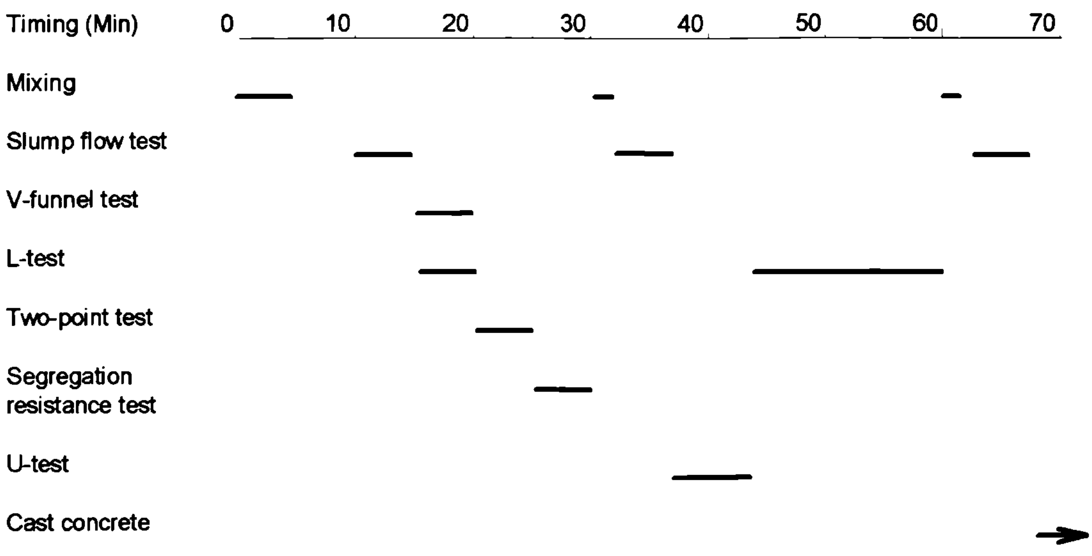
required age to measure the shrinkage. The readings were taken monthly, for at least three months. The average temperature and humidity of chamber were 20°C and 65% respectively.

4.4.4.3 Compressive strength

Compressive strength is the most common and useful property of concrete. In this study, concrete cubes were demoulded once enough strength had been gained, normally after one day, and placed in the curing tank until the age of testing. Then, the cubes were crushed according to BS1881: Part 116: 1983 using a Contest GD10A test machine with a maximum capacity of 2500 KN. Both 150 mm cubes and 100 mm cubes were tested for most mixes. The numbers of samples were dependent on the experimental objectives, e.g. for the experiment *Influence of cube size on standard deviation of compressive strength for SCC,* four 100 mm cubes and three 150 mm cubes were used.

4.4.5 Test sequence for concrete

The bar chart of test sequence is shown in the following figure. After the concrete was first mixed it was allowed to stand for about five minutes, and the slump flow was then measured. L-tests with and without rebars together with V-funnel test were then carried out, followed by the two-point and segregation resistance tests. Before the U-test was carried out, the concrete was remixed for 30 sec. and its slump flow was again measured. Then the concrete in the troughs of the L-test was weighed. This together with the concrete used in the other tests was then placed back in the mixer, and remixed for 30 sec. Then slump flow was measured again before casting specimens for hardened property testing.



Test sequence for concrete

*In mixes requiring redosing with superplasticizer, an additional one minute remixing was used.

Chapter 5

Rheology of cementitious paste

The main considerations in concrete mix design are achieving adequate workability, strength and durability. For SCC, the rheological properties are more demanding than in normal concrete, with high flowability and high viscosity being required. Both properties are highly influenced by the rheology of the cementitious paste, and therefore a proper understanding of this is essential, particularly in the selection of the powders and their proportions. In the past, much work has been reported on the rheology of cement paste, e.g. **Tattersall & Banfill** (1983), **Domone** et al. (1984), but, in a literature survey, very little was found on the effect of different combinations of CRMs such as pulverised-fuel ash (PFA), ground-granulated blast furnace slag (GGBS), and limestone powder (LSP), which are all extensively used in SCC.

5. 1 Objectives

The objectives of the research on cementitious paste were:

- to investigate the rheological properties of paste containing various combinations of CRMs
- to find a model which can describe these properties
- to provide useful information for the selection of CRMs for SCC mix design.

5. 2 Materials and test methods

The pastes were tested by a flow spread test and with a viscometer. All of the test methods, including mixing, have been described in the section **4.3.1** and **4.4.1,** and the individual materials have been described in section **4.2.** Tabulated test results are included in the Appendix 1.

The rheological properties of cementitious paste, mortar and fresh concrete can be described by the Bingham model [**Tattersall & Banfill** (1983)].

$$\tau = \tau_0 + \mu \dot{\gamma} \qquad \textbf{(5-1)}$$

where τ: shear stress, τ_0 = yield stress, μ: plastic viscosity, $\dot{\gamma}$: shear rate

The yield stress and plastic viscosity of the paste were obtained from the flow curve of torque vs. impeller speed from the viscometer test.

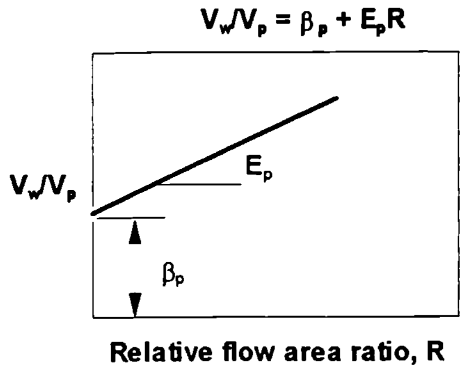
From flow spread test results, **Okamura et al** (1993) found a strong linear relationship between water/powder ratio (by volume) and relative flow area ratio R (**Fig. 5-1**). They called the intercept and the slope of the best-fit line the retained water ratio (β_p) and the deformation coefficient (E_p) of the cementitious powder (not paste) respectively. i.e.

$$V_w/V_p = \beta_p + E_p \bullet R \qquad \textbf{(5-2)}$$

$$\text{or } R = (V_w/V_p - \beta_p) / E_p \qquad \textbf{(5-3)}$$

The value of β_p shows the water retention capacity of the powder. For pastes with the same water/powder ratio, the smaller the β_p value, the more the free water content of the paste. The value of E_p indicates the sensitivity of paste viscosity to the change of water/powder ratio. As will be seen, different kinds of powders have different values of β_p

and E_p. The flow spread test is simple but provides useful information, and **Ozawa et al** (1993) suggested using this test for quality control of cement for fresh state of high performance concrete.



$R = (D/100)^2 - 1$

D: Diameter of the spread (mm)

Fig. 5-1 Definitions of retained water ratio β_p and deformation coefficient E_p

5. 3 Scope of experiments

Four single powders followed by several powder combinations were tested.

- The single powders were PC, PFA, GGBS and LSP.
- The combinations were
  PC + 1% SP435
  35%PC + 30%PFA + 35%GGBS
  70%PC + 30%PFA
  50%PFA + 50%LSP
  25%PC + 25%PFA + 50%GGBS
  35%PC + 20%PFA + 45%GGBS
  (The blended percentage is by weight)

Most combinations were chosen according to the mixes used in the construction work. The combination without PC (50%PFA + 50%LSP) was used in this study to produce a modified SCC without hydration in order to obtain longer time period for the testing of the properties of passing ability and segregation resistance.

5. 4 Results and discussion

5.4.1 Retained water ratio (β_p) and deformation coefficient (E_p)

The results of the flow spread test for the powders are shown in **Fig. 5-2.** The linear behaviour obtained by **Okamura** was confirmed. The resulting values of retained water ratio (β_p) and deformation coefficient (E_p), obtained by regression analysis, are shown. The relative performances of the powders can be related to their particle size and shape [**Midorikawa et al** (1996), **Edamatsu et al** (1996)]. For example, the PFA had the lowest values of both β_p and E_p which can be attributed to its spherical particle shape. The Portland cement and the GGBS had the highest β_p values, which is presumably due to their similar angular particle size and shape. However, the GGBS had a lower E_p value than the PC, indicating greater sensitivity of its viscosity to the changing water/powder ratio. The limestone powder had intermediate values of both β_p and E_p. The superplasticizer reduces the values of both β_p and E_p for the Portland cement.

5.4.2 Powder combinations

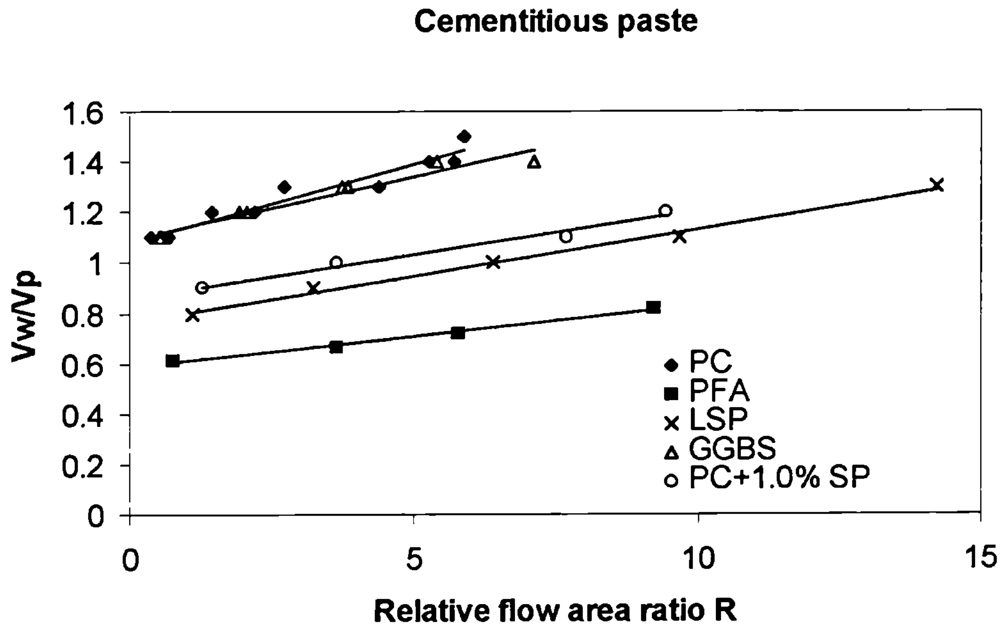
As with the single powders, all blended powders showed a linear relationship between relative flow area and water/powder ratio by volume; the resulting values of β_p and E_p are given in **Table 5-1.** It is also possible to calculate a value of β_p and E_p for the blended powders from the β_p and E_p values of its constituents and their relative proportions. i. e.

$$\beta_p = P_1 * \beta_{p1} + P_2 * \beta_{p2} + \ldots \qquad \textbf{(5-4)}$$

$$E_p = P_1 * E_{p1} + P_2 * E_{p2} + \ldots \qquad \textbf{(5-5)}$$

Where: P_1: proportion of $Powder_1$, P_2: proportion of $Powder_2$, by weight of total powder, etc.

These calculated values are also shown in **Table 5-1** and the agreement between the calculated and measured values of β_p is excellent, and that for the E_p values is good. This shows that for mix design purposes values of β_p and E_p for powder mixtures calculated from those for the individual powders may be sufficient, thus obviating the need for tests on each potential mixture.



Powder	β_p	E_p	Correlation coefficient
PC	1.08	0.061	0.96
PFA	0.59	0.024	0.99
GGBS	1.10	0.046	0.99
LSP	0.77	0.037	1.00
PC +1%SP	0.86	0.034	0.99

***Fig. 5-2** Linear relationship between relative flow area and water/powder ratio (by volume) for different cementitious powders*

Table 5-1 Flow spread results for blended powders

Powder mixture	Measured values		Values calculated from single powder values	
	β_p	E_p	β_p	E_p
35%PC+30%PFA+35%GGBS	0.95	0.056	0.94	0.045
70%PC+30%PFA	0.94	0.049	0.93	0.050
50%PFA+50%LSP	0.72	0.047	0.68	0.031
25%PC+25%PFA+50%GGBS	1.01	0.036	0.97	0.044
35%PC+20%PFA+45%GGBS	0.99	0.042	0.99	0.047

5.4.3 Yield stress

Fig. 5-3 shows that the single powder pastes of PFA, GGBS and LSP all had a linear but different relationships between yield stress (measured in the viscometer) and relative flow area ratio R. The greater the R value gained, the less the yield stress of paste found. This relationship is expected, because the yield stress is related to the fluidity of the paste which is measured by the spread. With the PC paste, the relationship was linear for R greater than 2, but when R was less than 2, (corresponding to a water/cement ratio by weight of less than 0.38) the yield stress increased drastically. The R value may therefore be considered as a direct index of yield stress. The relationships obtained by linear regression are shown in **Table 5-2**.

Table 5-2 Relation between yield stress and relative flow area ratio R

Paste	Formula	correlation coefficient
PC	τ_0=154-41.7R R≤2.0	-1.00
	τ_0=91-10.2R R>2.0	-1.00
PFA	τ_0=29-2.5R	-1.00
GGBS	τ_0=35-3.1R	-0.99
LSP	τ_0=58-3.8R	-0.97

τ_0: yield stress (Pa) R: the relative flow area ratio

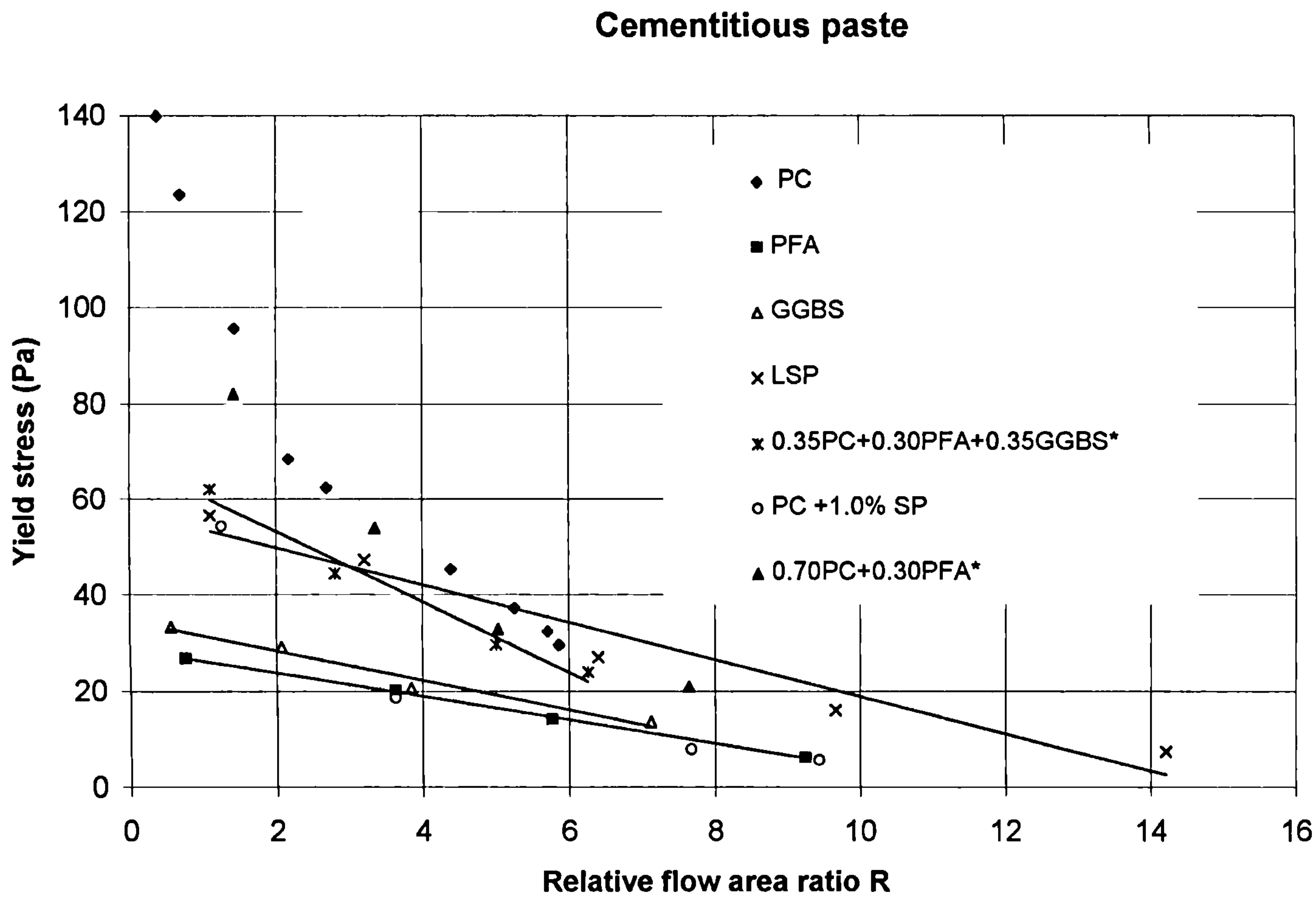


Fig. 5-3 Yield stress vs. relative flow area ratio for different powders

The equations in **Table 5-2** can be used to calculate the relationship between R and τ_0 for blended powders by a simple law of mixtures. These results are shown in **Table 5-3**.

Table 5-3 Calculated relationships between R and τ_0 for blended powders

Powder mixture	Relationship calculated from equations in **Table 5-2**
35%PC+30%PFA+35%GGBS	$\tau_0 = 52.8 - 5.41R$
70%PC+30%PFA	$\tau_0 = 72.4 - 7.89R$
50%PFA+50%LSP	$\tau_0 = 43.5 - 3.15R$
25%PC+25%PFA+50%GGBS	$\tau_0 = 47.5 - 4.73R$
35%PC+20%PFA+45%GGBS	$\tau_0 = 53.4 - 5.47R$

Based on the equations in **Table 5-3**, it is possible to predict the yield stress of blended powders.

5.4.4 Viscosity

The relationship between plastic viscosity and water powder ratio V_w/V_p (by volume) for different powders is shown in **Fig. 5-4.** The best-fit regression curve for every set of data was found to be a power law; each type of powder was found to have a unique curve. The retained water ratio β_p is the value of V_w/V_p for zero flow, and so V_w/V_p could be normalized as $V_w/V_p \times (1/\beta_p)$. **Fig. 5-5** shows the resulting curves. Furthermore, if plastic viscosity is multiplied by another parameter E_p and the product used as the ordinate, then the resulting curves for different types of powders overlap as shown in **Fig. 5-6**. Hence, if the data are plotted as values of $V_w/V_p \times (1/\beta_p)$ against $\mu \cdot E_p$ then all results fall on or very close to a single curve. The general equation describing this curve shown in **Fig. 5-7** was found to be a power law relationship of the form:

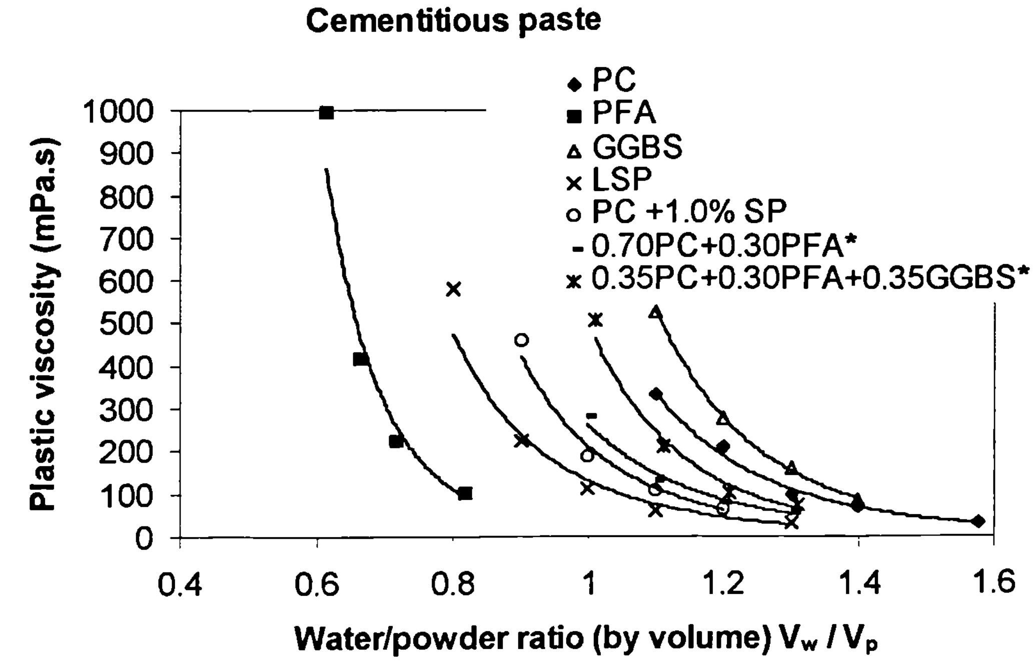


Fig. 5-4 *Relationship between plastic viscosity and water/powder ratio V_w/V_p for different cementitious paste*

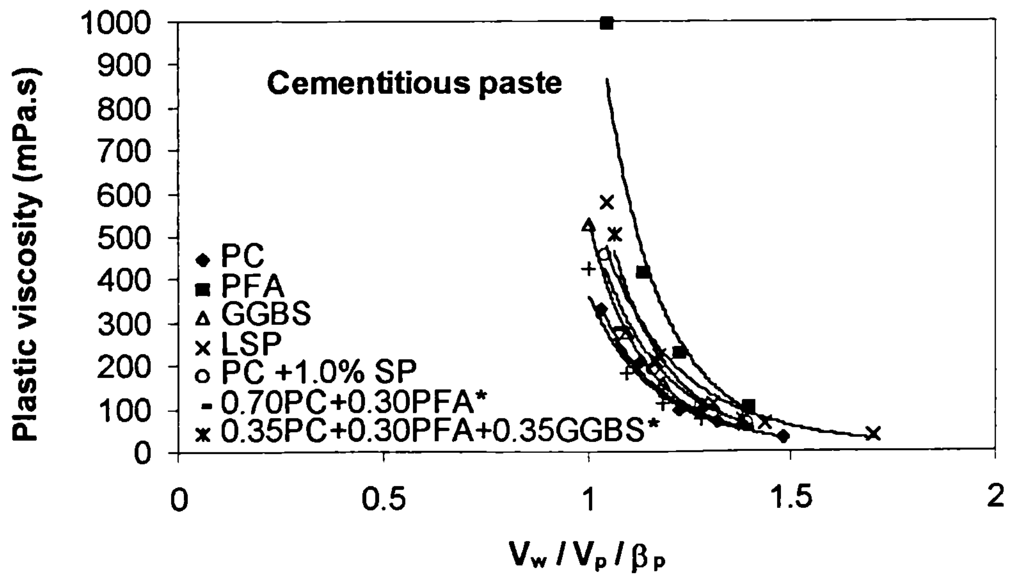


Fig. 5-5 *Relationship between plastic viscosity and $V_w/V_p/\beta_p$ for different cementitious paste*

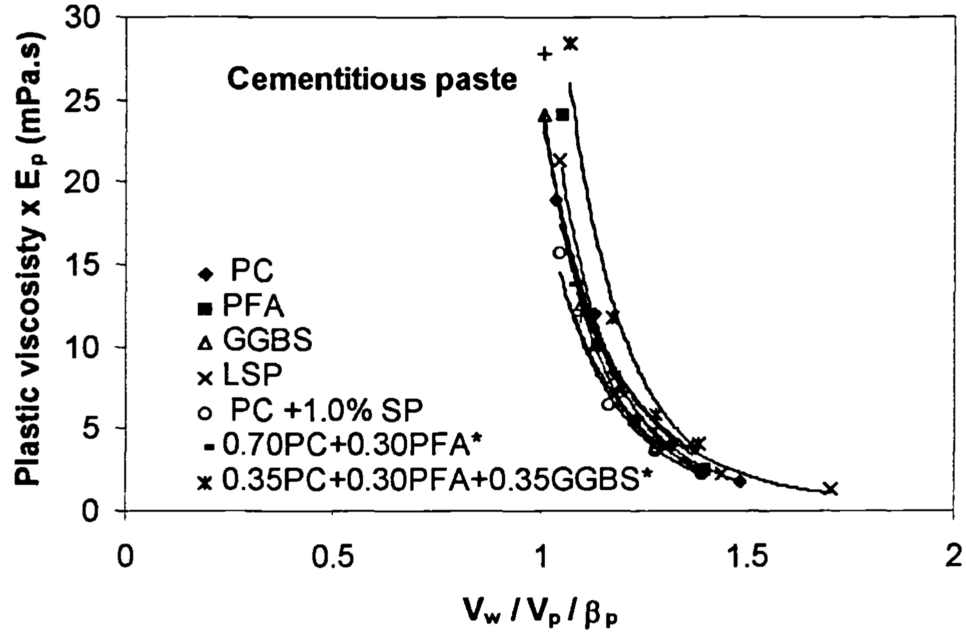


Fig. 5-6 *Relationship between (plastic viscosity× E_p) and ($V_w/V_p/\beta_p$) for different cementitious paste*

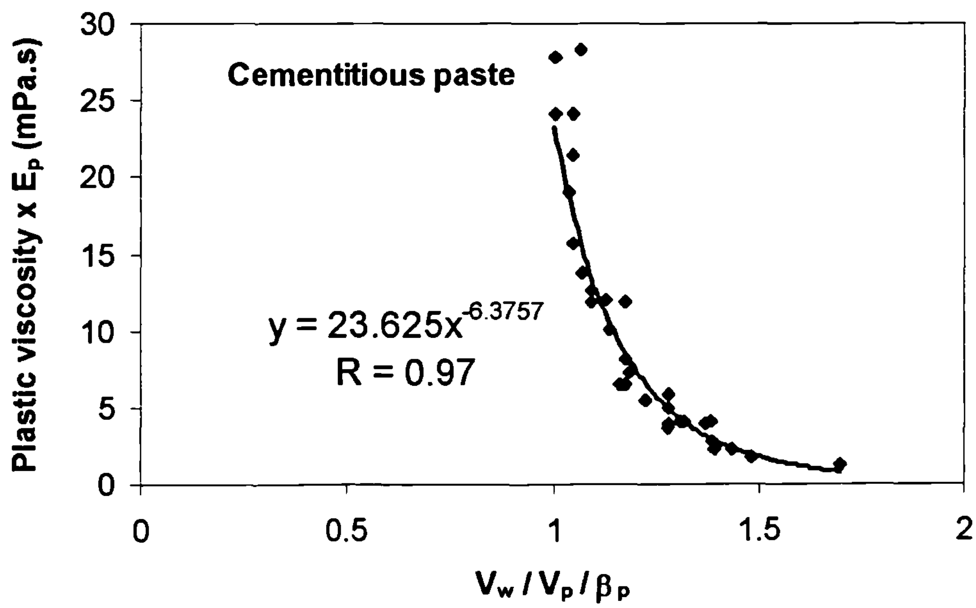


Fig. 5-7 *Graph of the novel viscosity equation for all the data*

$$\mu \times E_P = K_1 \left(\frac{V_w / V_P}{\beta_P} \right)^{-K_2} \quad \textbf{(5-6)}$$

or $$\mu \times E_P = K_1 \left(\frac{(w/p) \times S.G}{\beta_P} \right)^{-K_2} \quad \textbf{(5-7)}$$

where V_w/V_p: water powder ratio by volume,
K_1, K_2 : constants
β_p: retained water ratio of powder
E_p: deformation coefficient of powder
μ: plastic viscosity
w/p: water powder ratio by weight
S.G: specific gravity of powder

If more than two types of powder are used, the combined specific gravity should be used in the above equation. This is given by:

$$S.G = \left(\frac{1}{P_1 / S.G_1 + P_2 / S.G_2 + \ldots} \right) \quad \textbf{(5-8)}$$

Where: P_1: proportion of $Powder_1$, P_2: proportion of $Powder_2$, by weight of total powder,
$S.G_1$: specific gravity of $Powder_1$, $S.G_2$: specific gravity of $Powder_2$, etc.

This novel viscosity equation, resulted from the data analysis of the test results and the inspiration from the Krieger-Dougherty equation, is valid for pastes of PC, LSP, GGBS, PFA, even PC with superplasticizer and their combinations [**Domone** and **Chai** (1997)]. For all of the data, regression analysis gives values for k_1 and k_2 of 23.6 and 6.38 respectively, with a correlation coefficient of 0.97. **Fig. 5-7** shows a plot of equation (5-7) with these values of k_1 and k_2.

Struble and **Sun** (1995) have suggested that the Krieger-Dougherty equation is valid for a dispersed paste. A comparison between this and the novel viscosity equation is shown in **Table 5-4**.

Table 5-4 Comparison between Krieger-Dougherty equation and author's viscosity equation

	Krieger-Dougherty Equation	Author's Viscosity Equation
Formula	$\frac{\eta}{\eta_c} = (1 - \frac{\phi}{\phi_M})^{-[\eta]\phi_M}$	$\mu \times E_P = K_1(\frac{V_w / V_P}{\beta_P})^{-K_2}$
flow curve	Power-law model $\tau = a\dot{\gamma}^b$	Bingham model $\tau = \tau_0 + \mu\dot{\gamma}$
Viscosity	Apparent viscosity	Plastic viscosity
Variable	ϕ:concentration of solids by vol.	V_w/V_p: water powder ratio by vol.
Parameter	ϕ_M: maximum solids concentration by vol. [η]:intrinsic viscosity of the suspension	β_p: minimum water powder ratio by vol. E_p: deformation coefficient of the powder.
Constant	1	K_1, K_2

The conclusions from these tests can be summarised as follows:

1) The yield stress τ_0 and the plastic viscosity μ are the two rheological parameters which describe the flow behaviour of the paste. Different concentrations of the same powder have different values of τ_0 and μ; but the same concentrations of different powders also possess different values of τ_0 and μ.

2) The two parameters β_p and E_p of cementitious powders can be used to describe this difference. Values τ_0 and μ can be calculated from β_p and E_p and the water/powder ratio.

As will be discussed in **Chapter 7**, for SCC mix design, the paste viscosity is the controlling factor for segregation resistance and the novel viscosity equation is very useful in this process. However, on the other hand, the use of yield stress is less, due to the dominant effect of superplasticizer in controlling the flowability of SCC.

5. 5 Application of the rheology of the cementitious paste

There is no doubt that CRMs will be increasingly used in concrete in the future, one reason being that they are often waste materials. Their effect on rheology is an important consideration. Prediction of concrete rheology from that of the paste is extremely difficult, but it could be expected that, for example, the less the yield stress of paste, the better flowability the concrete, the higher the viscosity of paste, the better the segregation resistance of concrete. In concrete practice, the water/powder ratio (W/P) by weight is normally used, and **Fig. 5-8** and **Fig. 5-9** show the relationships obtained from the current study between the rheological constants τ_0 and μ and water/powder ratio respectively. **Fig. 5-8** shows that yield stress generally increases in the sequence PFA<LSP<GGBS<PC, whereas **Fig. 5-9** shows that plastic viscosity increases in the sequence PFA<LSP<PC<GGBS. These effects are summarized together with the effect on strength in **Table 5-5.**

Table 5-5 Strength and rheological properties of cementitious paste

	*Strength	Yield stress	plastic viscosity
PC	VH	VH	H
GGBS	H	H	VH
PFA	M	L	L
LSP	L	M	M

VH: very high, H: high, M: medium, L: low
* PC (1.0), GGBS (1.0), PFA (0.40), LSP (0.2) The values of the constants in modified Feret's compressive strength equation [see 8.3 equation (8-5)]

In SCC, a high plastic viscosity is required, and increasing the content of GGBS is therefore an option instead of adding a viscosity agent. A low yield stress is also required, and increasing the content of PFA is therefore a good alternative.

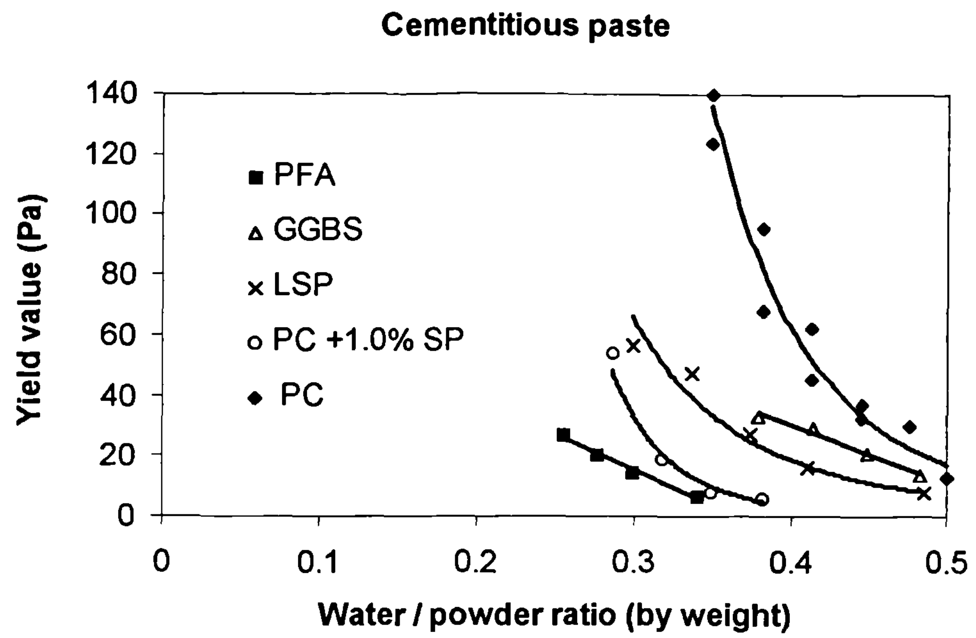


Fig. 5-8 Relationship between yield stress and water/powder ratio (by weight)

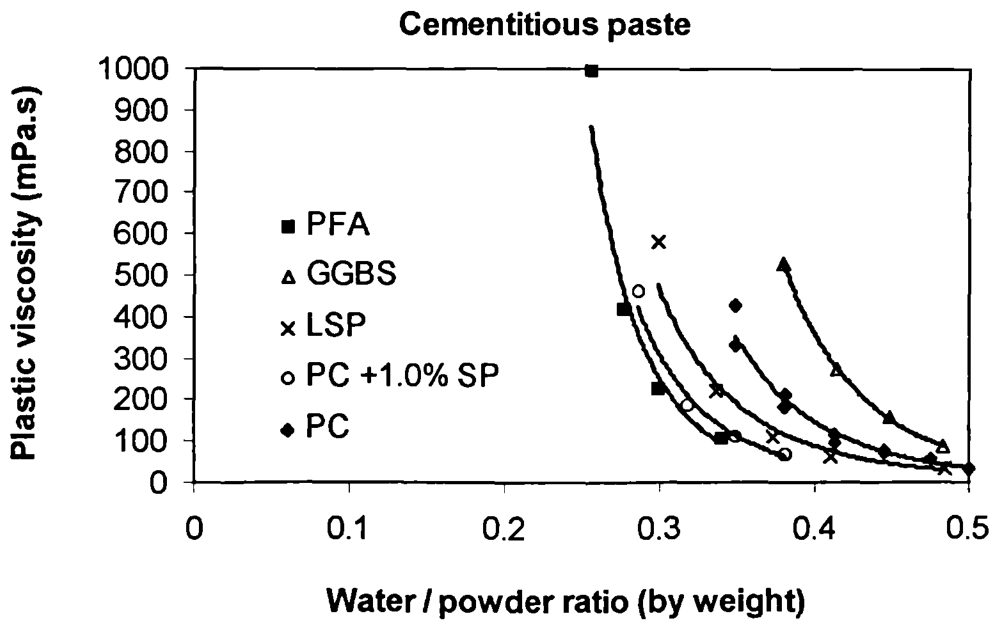


Fig. 5-9 Relationship between plastic viscosity and water/powder ratio (by weight)

5. 6 Prediction of the rheological properties of blended cementitious paste

The preliminary estimation of the rheological constants τ_0 and μ for a blended powder can be obtained according to the following steps.

1) Test each single powder to obtain β_p and E_p

2) Calculate the values β_p and E_p of the blended powder, using the equations

$$\beta_p = P_1 * \beta_{p1} + P_2 * \beta_{p2} + ... \quad (5.4)$$

$$E_p = P_1 * E_{p1} + P_2 * E_{p2} + ... \quad (5.5)$$

Where: P_1: proportion of Powder$_1$, P_2: proportion of Powder$_2$, by weight of total powder, etc.

3) Calculate the relative flow area ratio R, according to the following equation.

$$R = (V_w/V_p - \beta_p) / E_p \quad (5.3)$$

$$\text{or } R = (W/P \times S.G - \beta_p) / E_p$$

4) Calculate the function $\tau_0 = f(R)$ for blended powder by using the single functions of powders ($\tau_0 = f(R)$) and their relative proportions, as in **Table 5-3.**

5) From this function, and the viscosity equation **(5-9)**, the estimated yield stress τ_0 and plastic viscosity μ for a certain water/powder ratio can be obtained.

$$\mu(mPa \cdot s) = \frac{23.6}{E_p}\left(\frac{V_w / V_p}{\beta_p}\right)^{-6.38} \quad \text{or} \quad \mu(mPa \cdot s) = \frac{23.6}{E_p}\left(\frac{(w/p) \bullet S.G}{\beta_p}\right)^{-6.38} \quad (5\text{-}9)$$

The calculated and measured yield stress and plastic viscosity of blended cementitious powders are shown in **Fig. 5-10** and **Fig. 5-11** respectively. The agreement is good, and therefore it is concluded that the prediction method is sufficient for at least a preliminary estimation of the rheological properties of the cementitious paste.

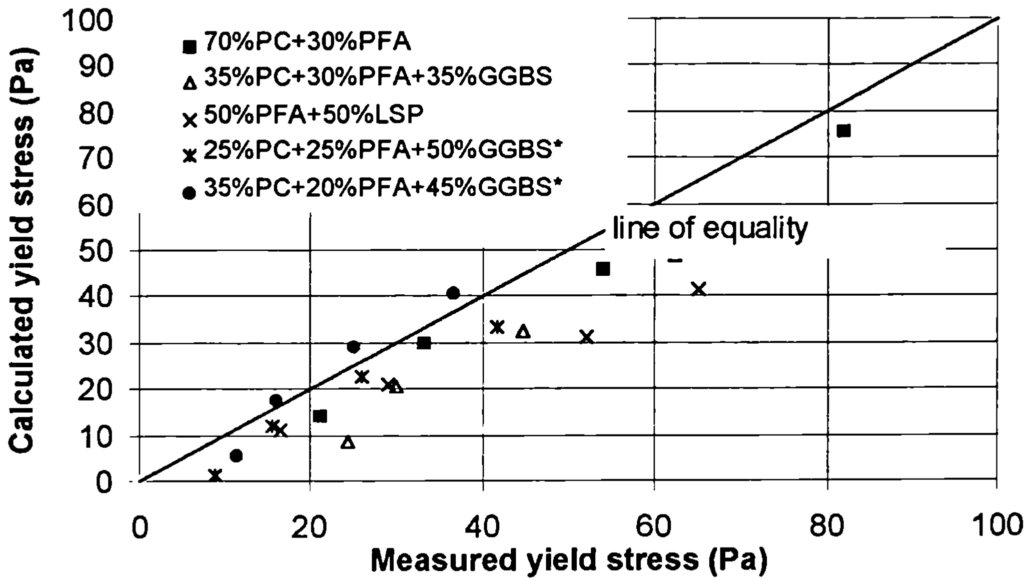


Fig. 5-10 Calculated vs. measured values of yield stress for powder mixtures

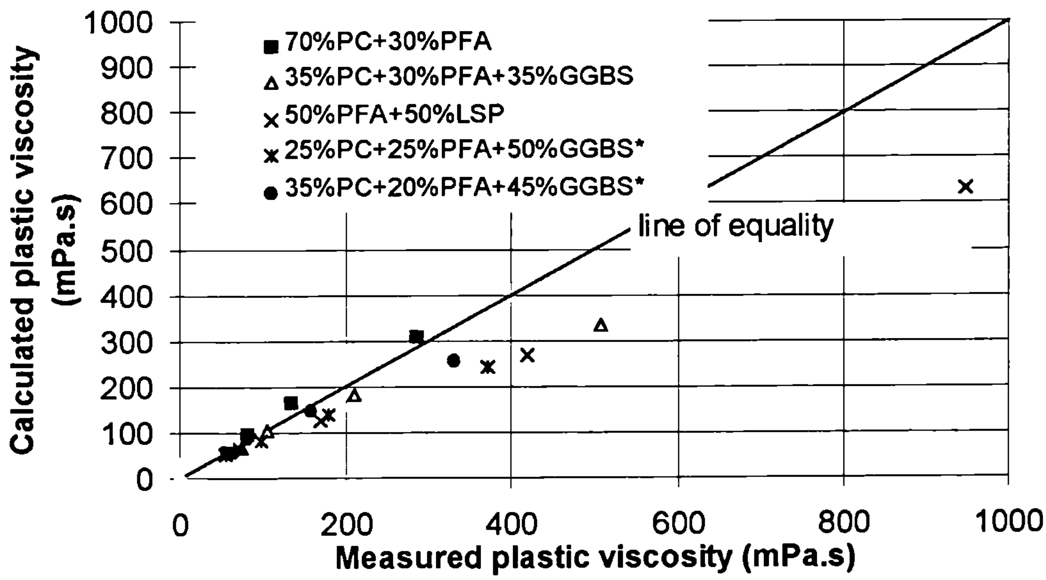


Fig. 5-11 Calculated vs. measured values of plastic viscosity for powder mixtures

5. 7 Conclusions

The simple flow spread test can be used to obtain the retained water ratio, β_p, and deformation coefficient, E_p, of powders, which are important in characterizing their performance.

Comparison of the results of the flow spread test with yield stress and plastic viscosity measured in a concentric cylinder viscometer gives confidence that this test is measuring a useful rheological characteristic. It is possible to predict with reasonable confidence the values of β_p and E_p for mixtures of powders from results of powders tested singly; this is extremely useful in the early stages of mix design of SCC, for example, to control the paste viscosity (by the novel viscosity equation) which is related to segregation resistance of fresh concrete.

Chapter 6

Properties and composition of mortar for SCC

In any concrete mix design process, trial mixes are essential because of the diversity and variety of materials used. However, by the proper use of selected mortar tests, the trial mixes required for SCC can be reduced to a minimum, thereby saving time, materials and labour.

This chapter is concerned with the role of tests on mortar and the selection of mortar composition in the development of SCC mixes. As in other parts of the study, the work carried out was aimed at examining, modifying and extending approaches suggested and developed by others. The results are therefore presented and discussed in this format.

The test methods are described in Chapter 4; fully tabulated results are included in Appendix 2 and reference to this is given where appropriate.

6.1 Objectives of mortar tests

Mortar tests are used to:

- find a suitable dosage of superplasticizer;
- estimate the loss of workability with time;
- assess bleeding and aggregate segregation resistance;
- obtain the one day strength.

6.2 Property requirements of mortar for SCC

The required properties of the mortar such as workability, loss of workability with time, stability and compressive strength all depend on the required properties of SCC.

6.2.1 Workability

As will be shown in Chapter 7, the final slump flow of SCC (just before placing the concrete) should be larger than 600 mm in order to gain good passing ability through the gaps between the rebars and a good surface finish to the hardened concrete (i.e., no large air voids). To achieve this, the initial slump flow immediately after mixing has to be somewhat higher, say 650 mm or above. Is there a corresponding value of mortar flow necessary for this? The relationship between mortar flow and concrete slump flow is not simple. **Fig. 6-1** shows that if mortar flow is kept constant (260 mm), the concrete slump flow is dependent on the coarse aggregate content and the dosage of superplasticizer, which is affected by the water/powder ratio. Moreover, the type of coarse aggregate and the maximum aggregate size are also influencing factors. Concrete trial mixes cannot therefore be entirely replaced by mortar tests. However, the range of coarse aggregate content for SCC is not wide, normally between 0.29 to 0.32 m^3, or 780 to 840 kg, per cubic metre concrete, because too much coarse aggregate will impair the passing ability. **Fig. 6-2** shows value of mortar flow and slump flow for concrete with aggregate content in this range, from which it can be seen that a mortar flow of at least 310 mm is required to obtain an initial concrete slump flow of more than 650 mm.

6.2.2 Loss of workability with time

The loss of workability is a critical factor with SCC, this reduces the filling ability and passing ability, produces large air voids on the hardened concrete surface and also reduces the compressive strength. Some information can be gained from mortar tests. As can be seen in **Fig. 6-3,** the concrete slump flow generally declines much faster than mortar flow for the same dosage of superplasticizer. Therefore, low loss of mortar flow with time cannot guarantee the low loss of slump flow of SCC. However, high loss of mortar flow with time should (as expected) result in high loss of slump flow of SCC as shown in **Fig. 6-4.** Therefore, the initial mortar flow should be larger than 310 mm and the end flow larger than 300 mm if the water powder ratio is 0.30 or above (but even with this requirement the concrete workability loss may be critical).

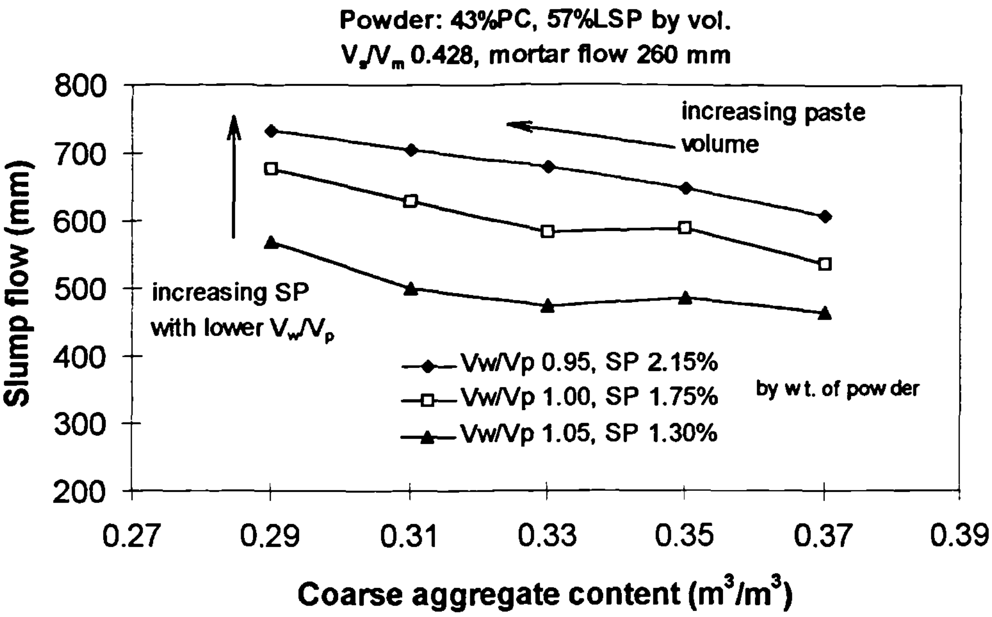


Fig 6-1 Relationship between concrete slump flow and coarse aggregate content for the same mortar flow [Data adapted from Yurugi et al (1996)]

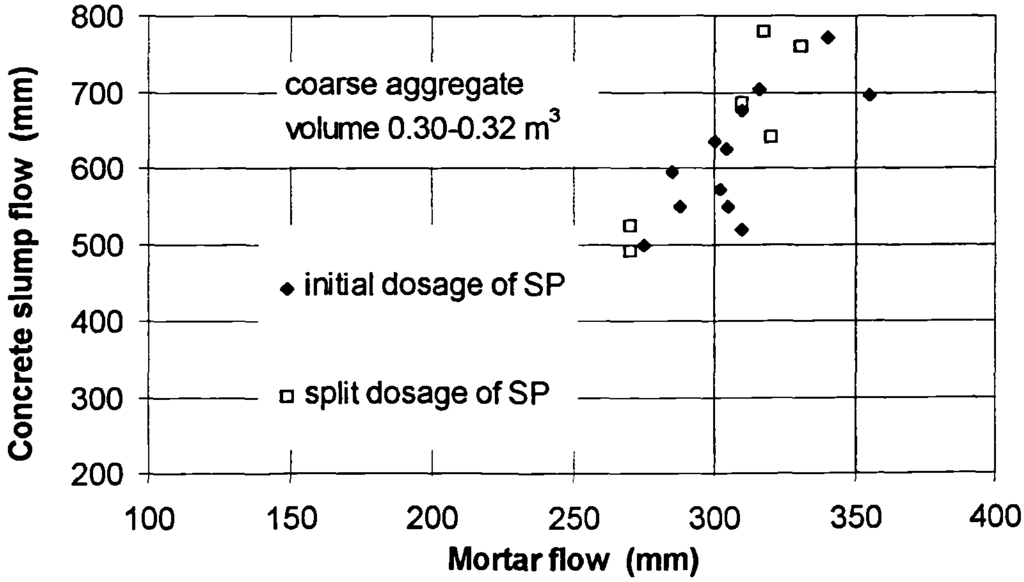


Fig. 6-2 Relationship between concrete slump flow and mortar flow.
**Initial dosage: mixing Method 2: S209, S221, S222, S226, S227, S109, S110, M103, M104, M106, M201, M202*
Split dosage mixing Method 1: S223, S103, S210
Method 3: S113, S114, S116 (see Appendix 3)

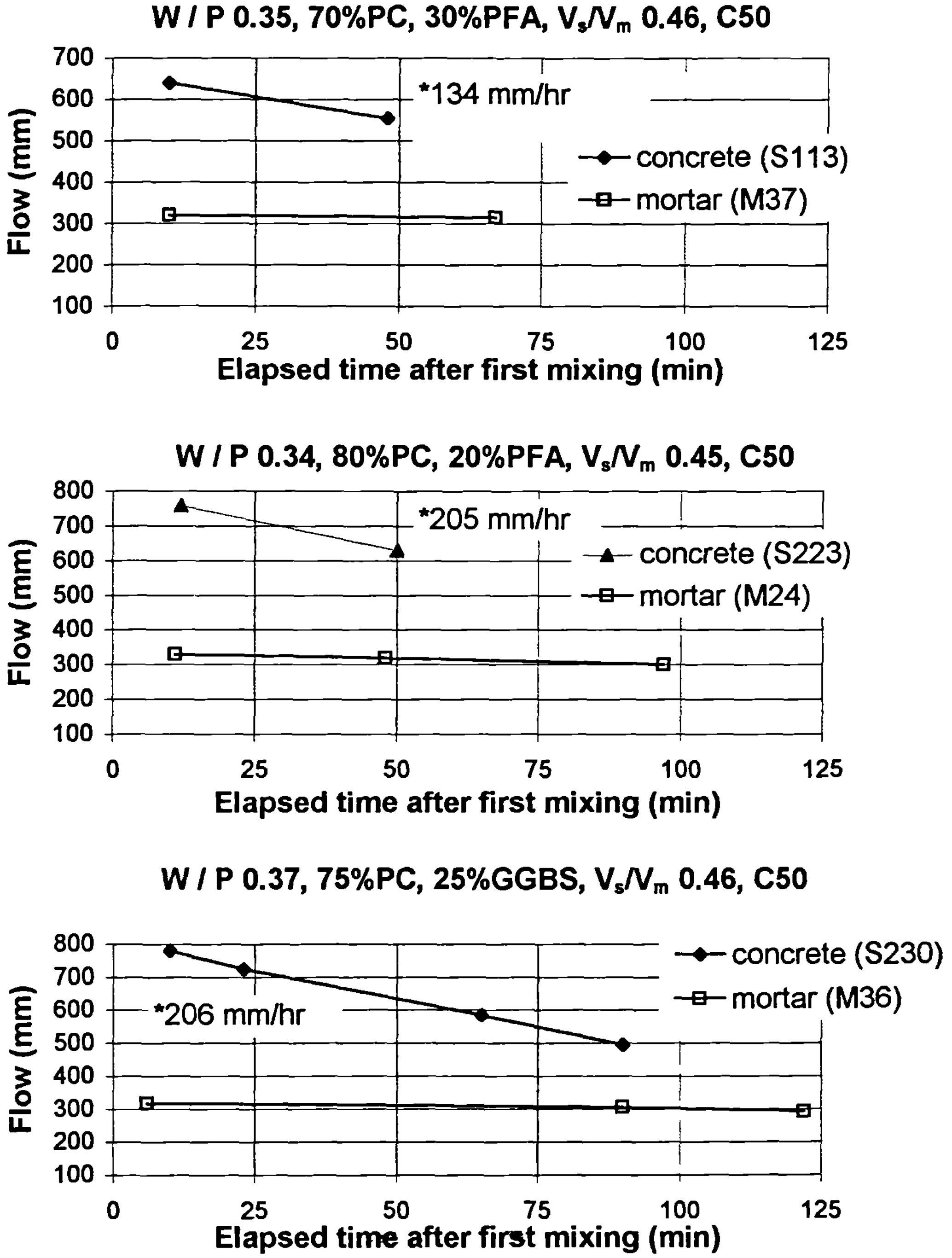


***Fig. 6-3** Relationship between concrete and mortar flow with time*

** Loss of concrete slump flow*

Mortar and concrete mix references are in Appendix 2 and Appendix 3 respectively

If the water/powder ratio is less than 0.30, these values may be less. It is worth noting that in Japan lower mortar flow values are used, from 250 mm to 280 mm. One of the reasons for this may be the type of admixture used, as mentioned in **Chapter 3**. In Japan, this is predominantly a high range water reducing and air-entraining agent, which is not available in the UK market. Another reason may be different types of sand, normally coarse sand results in higher slump flow [**Mori et al** (1996)].

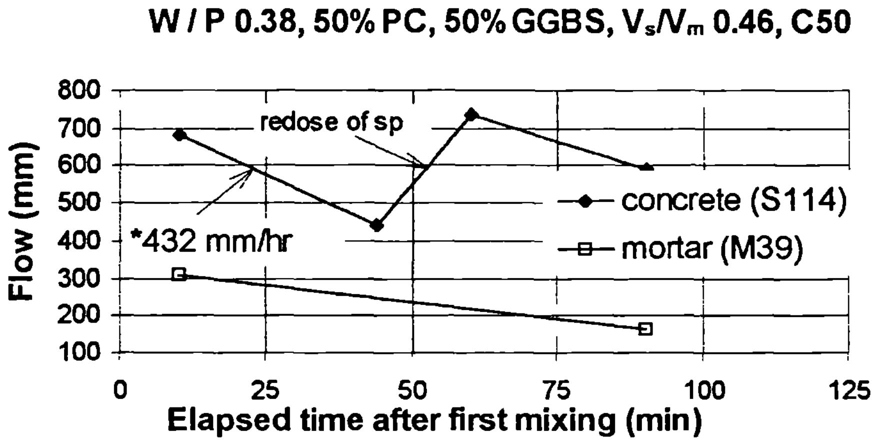


Fig. 6-4 *Relationship between concrete and mortar flow with time with unsatisfactory slump flow loss*

* *Loss of concrete slump flow*

6.2.2.1 Influence of superplasticizer

The loss of workability with time is greatly dependent on the dosage and type of superplasticizer as can be seen in **Fig. 6-5** and **Fig. 6-6**. Normally, high dosage or G-type (with retarder) superplasticizer (SP333) results in low loss of workability.

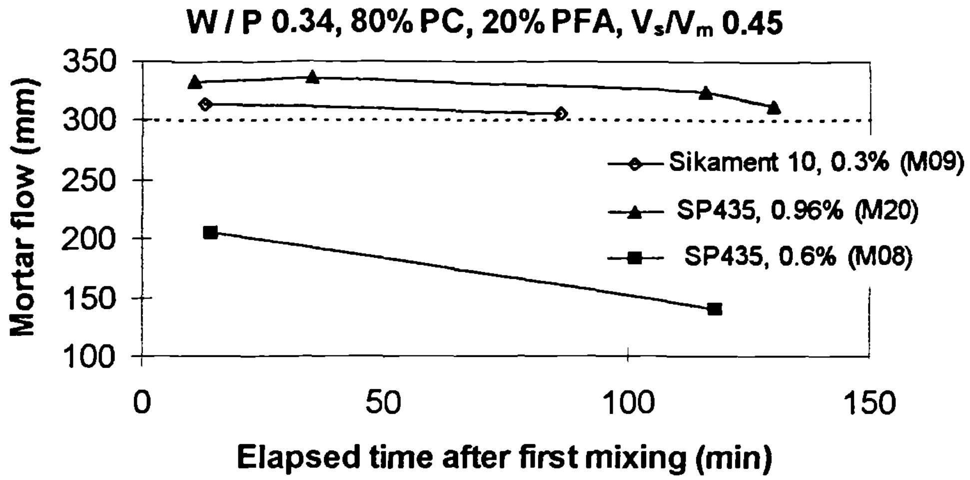


Fig. 6-5 Influence of superplasticizer on loss of mortar flow

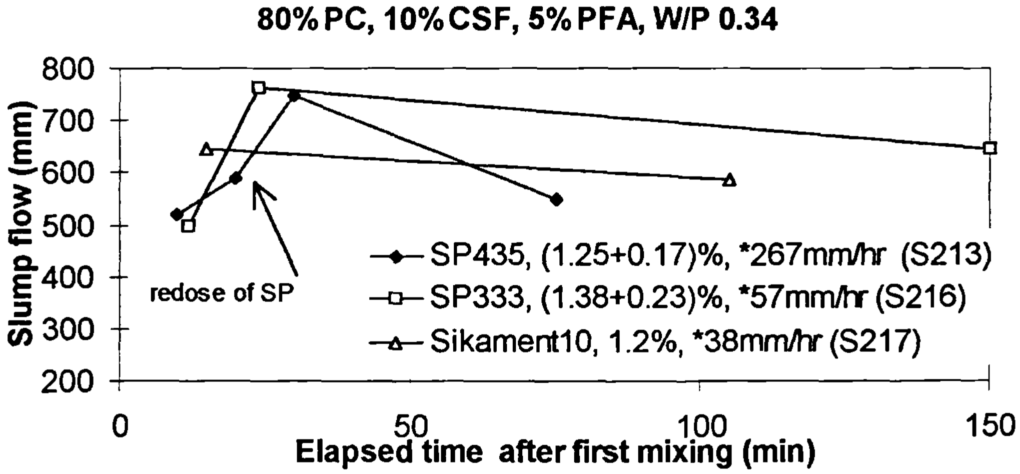


*Fig. 6-6 Influence of superplasticizer on *loss of slump flow of SCC*

It is interesting to note that for some kinds of superplasticizer the temperature of the mixing water has a significant influence on the loss of workability. **Fig. 6-7** shows the results that for SP333, which is a type G admixture with retarding effect, cool mixing water (14°C) could not maintain the flowability of mortar to the same extent as the warm mixing water (21°C). (SP333 was produced for the use in the regions of hot weather, e.g. Middle East). In contrast, this effect is not significant for copolymer superplasticizer (Sikament 10).

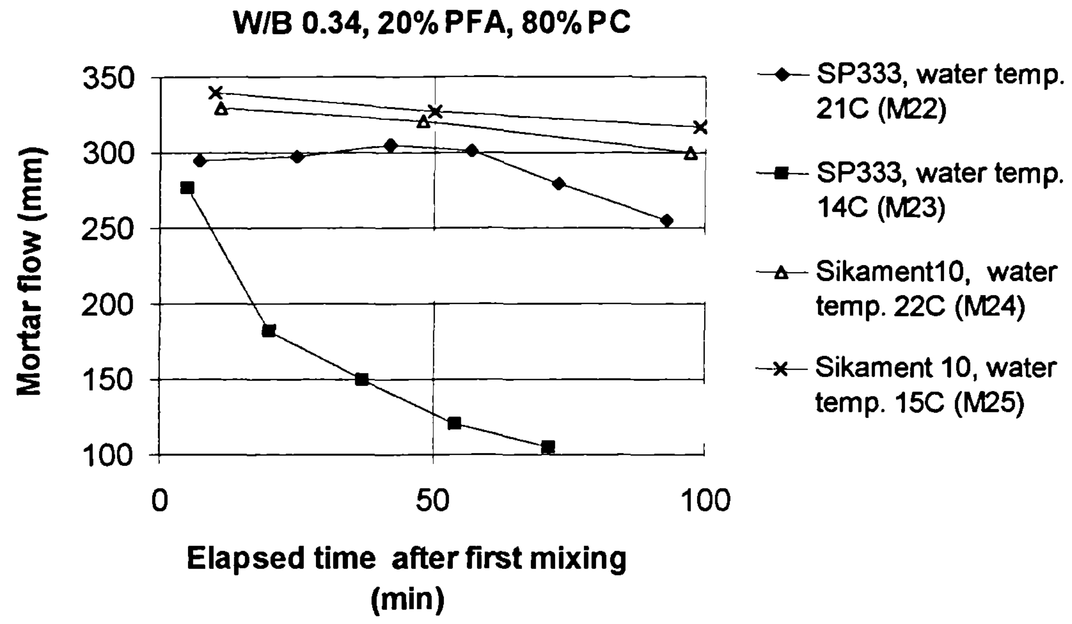


Fig. 6-7 Influence of temperature of mixing water on the mortar flow

6.2.2.2 Influence of cement replacement materials (CRMs)

It is widely accepted that fresh concrete incorporating a suitable amount of PFA increases not only the workability but also the retention of workability. **Fig 6-8** shows these effects, which are usually ascribed to the spherical shape of the PFA, creating a 'ball-bearing effect'.

In summary, many factors such as water/powder ratio, the composition of powders and chemical admixtures influence the loss of workability. Recently, many new chemical admixtures have been developed, for instance, a super-superplasticizer, which can effectively prolong the workability of fresh concrete [**Mitsui** et al (1994)]. Another way to prolong the workability is to split the superplasticizer dosage into two parts: one is added at ready mixed plant, the other is added at the job site.

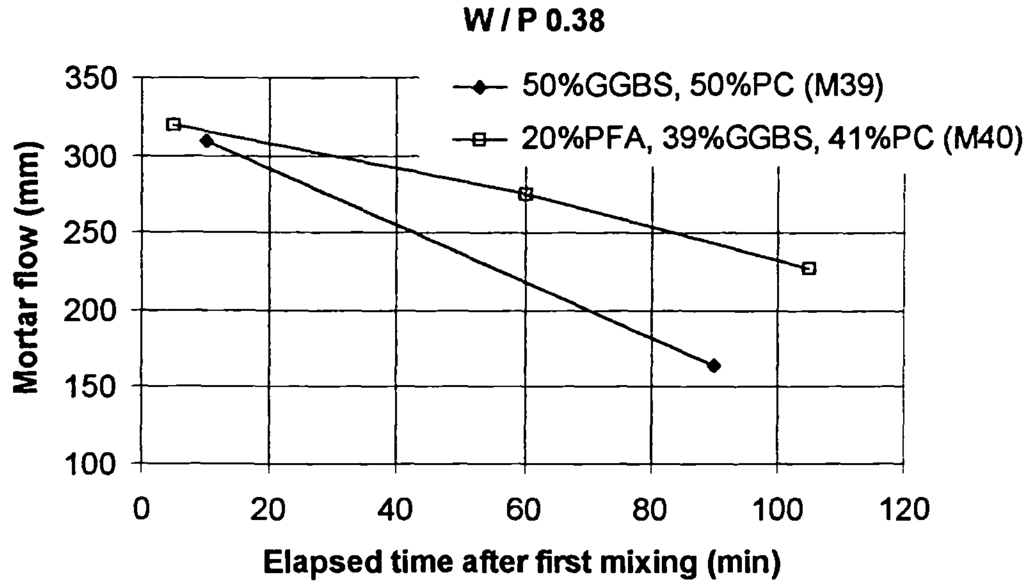


Fig. 6-8 Influence of CRMs on the mortar flow

6.2.3 Stability

6.2.3.1 Moderate viscosity

From the literature review, it is clear that moderate viscosity is required to prevent the segregation of SCC. As with concrete, a V-funnel test was used to measure the viscosity of the mortar indirectly. **Fig 6-9** shows the relationship between the V-funnel flow time of mortar and that of concrete. The longer the flow time, the higher the viscosity. The normal range of mortar flow time should be between 4 to 10 seconds when the mortar is to be used in concrete with a maximum aggregate size of 20 mm and 2 to 10 seconds when aggregate is 10 mm. This value links with the segregation resistance of concrete as described in section **7.2.5**. Furthermore, it is important to note that for SCC the viscosity should be kept as low as possible provided no segregation occurs, because excessive viscosity will impair the pumping and placing of the concrete. If the mortar is more viscous than its adhesion, this can be detected through tamping the mortar with a steel rod. If the mortar viscosity is too high, holes form and do not self-fill. Moreover, mortar does not adhere to the rod.

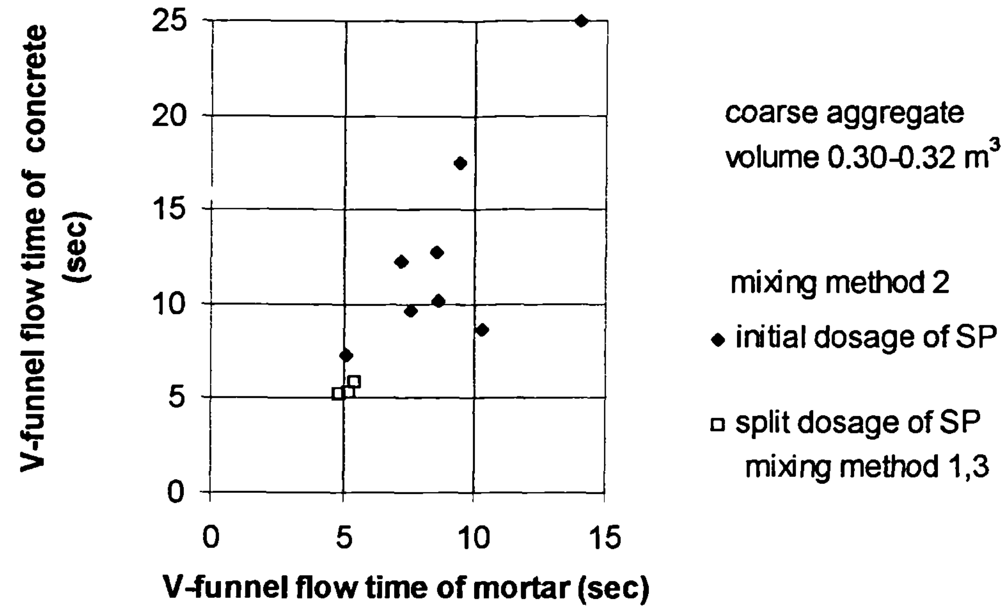


Fig. 6-9 Relationship between V-funnel time of mortar with that of concrete.

S.Nishibayashi et al suggested a method to predict the plastic viscosity of mortar. **Fig. 6-10** shows the relationship between the thickness of the excess paste around the sand particles and relative viscosity of mortar to paste. The less the thickness of excess paste, the higher the relative viscosity. As a result, increasing either the sand content or the viscosity of the paste can increase the viscosity of the mortar. More sand reduces the thickness of excess paste and results in the increase of friction and interlocking among sand particles.

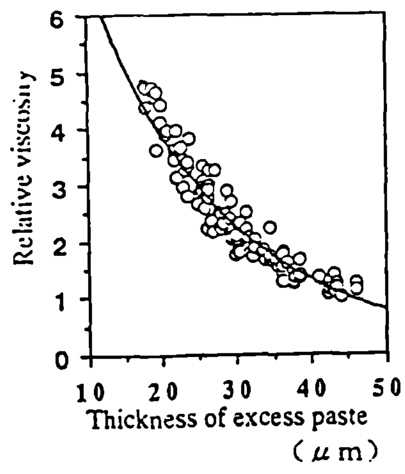


Fig. 6-10 Relationship between thickness of excess paste and relative viscosity

[Adapted from original Fig. 6 by S.Nishibayashi et al (1996)]

From the tests on paste reported in **Chapter 5**, and the literature review, the ways of adjusting the viscosity of mortar as can be summarised as in **Table 6-1**.

Table 6-1 Adjustment of mortar viscosity

Increasing viscosity	Decreasing viscosity
lower water/powder ratio	higher water/powder ratio
higher sand content	less sand content
more GGBS for the same water/powder ratio (GGBS fineness 400-440 m^2/kg)	replace GGBS with PFA or LSP
incorporating viscosity agent	no viscosity agent

6.2.3.2 Limited bleeding

As can be seen in **Fig. 6-11**, bleeding is not difficult to reduce by lowering the water/cement ratio. Cement replacement materials (CRMs) are also useful in this respect. According to **Neville** (1995), silica fume greatly reduces, or even eliminates, bleeding. PFA and GGBS (when ground to a high fineness) also can reduce bleeding. In this research, the water/powder ratio of most mixes is not higher than 0.40, and also, a large percentage (15% to 60%) of CRM was incorporated. It seems therefore that there should be no bleeding problem. However, when mortar with a water/powder ratio of 0.34 to 0.40 was placed in a container for 90 minutes after mixing, a layer of water, could be observed on the top surface. (This is different to the case of overdose of superplasticizer, which results in aggregate segregation immediately after mixing). This bleeding water was only observed in mortar, and not in concrete. However, some bleeding in concrete may be beneficial, e.g. in reducing plastic shrinkage cracking [**Yokoyama et al.** (1994)].

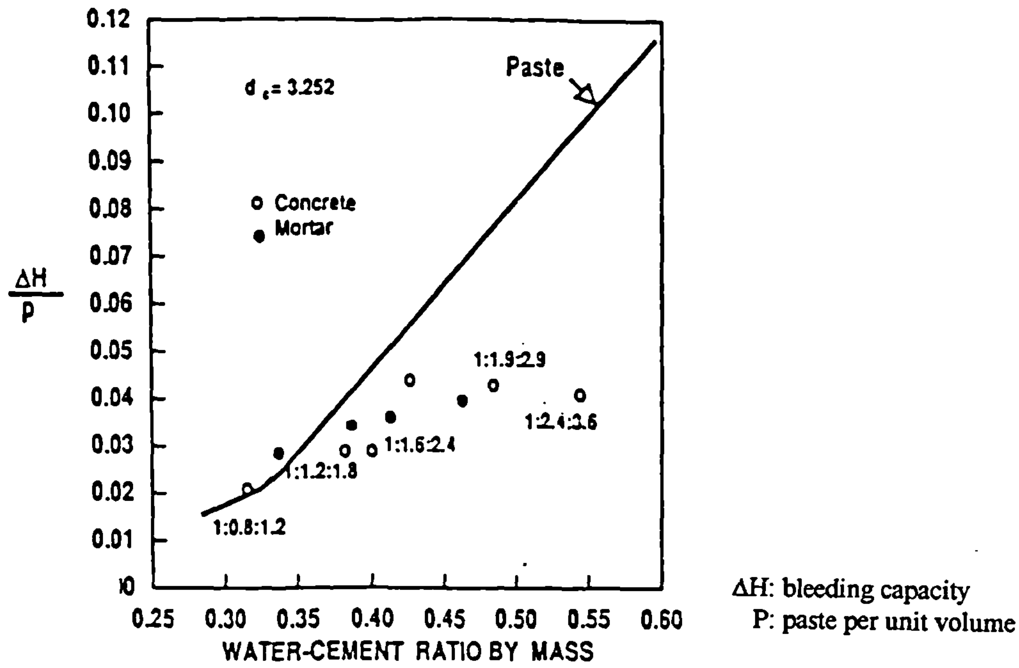


Fig. 6-11 Bleeding capacities of mortar and concrete
[Adapted from Powers (1939)]

6.2.3.3 No aggregate segregation

With an overdose of superplasticizer, aggregate segregation may occur. The sedimentation of sand can easily be observed after a spread test by disturbing the mortar with a spatula. The surface of the mortar is paste rich while the sand is at the bottom. In addition, an overdose of superplasticizer can also cause many bubbles on the top surface of the fresh mortar. The way to prevent aggregate segregation is to control the dosage of superplasticizer and mix the mortar thoroughly.

The experimental data from the current programme have suggested modifications to two of the mortar criteria defined by **Okamura et al** (1993): one is mortar flow, which is a measure of workability, the other is the V-funnel flow time, which assesses viscosity and hence stability. As can be seen in **Fig. 6-12**, the mortar of water/powder ratio 0.40 with 15%PFA was neither flowable nor viscous enough when the maximum size of aggregate was 20 mm, because these two criteria cannot be satisfied simultaneously. By lowering the water / powder ratio from 0.40 to 0.31, the other two mixes of mortar both met the requirements. Moreover, changing the sand content V_s/V_m from 0.40 to 0.45 also increased the viscosity of the mortar, as expected.

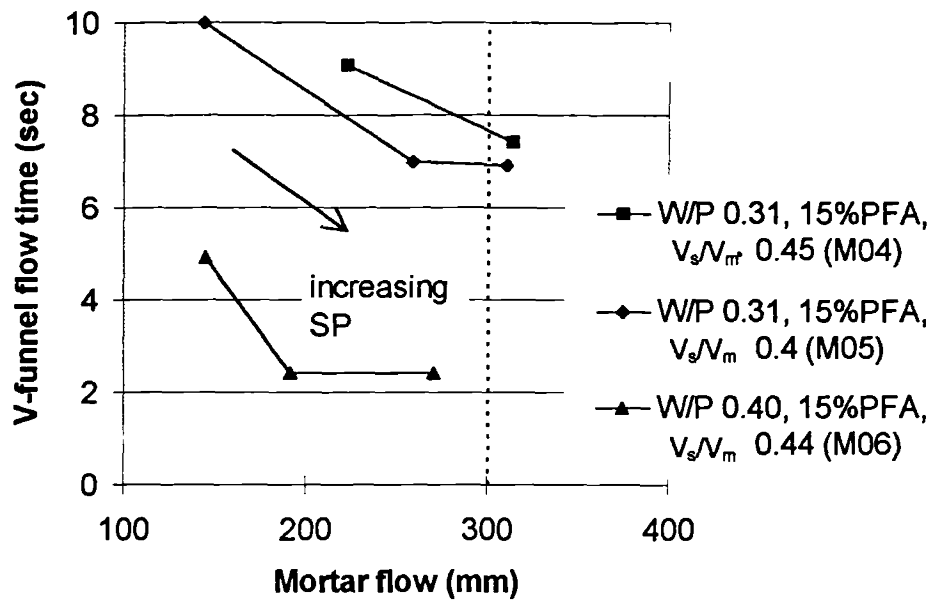


Fig. 6-12 Relationship between V-funnel flow time and mortar flow with different dosage of superplasticizer.

6.2.4 Strength requirement of mortar

According to Japanese practice, the minimum concrete strength before striking is 10.0 MPa (cylinder strength), equivalent to 12.5 MPa cube strength, which should be achieved in 24 hours. Because of the large quantities of CRM and a high dosage of superplasticizer, the early strength of SCC is not easy to predict. However, the one day strength of mortar samples can easily be measured; the strength relationship between mortar and concrete at the age of one day can be seen in **Fig. 6-13**. The concrete strength is a little higher than that of mortar at the age of one day, but at late age the concrete strength is lower than that of mortar. Typically, when the mortar achieves 10 MPa, the concrete incorporating the mortar will achieve 12.5 MPa. Since the mortar of SCC is very flowable and homogeneous, the compressive strength of mortar measured by a 50 mm cube is basically the same as that from a 100 mm cube as can be seen in **Fig. 6-14**, and so the size effect is negligible.

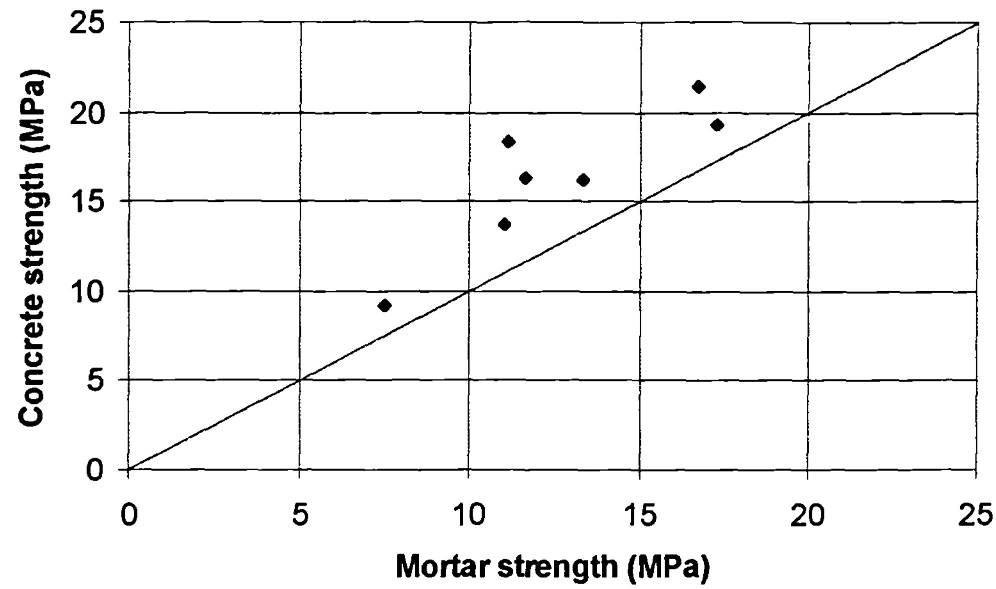


Fig. 6-13 Relationship between compressive strength of concrete and mortar at the age of one day.

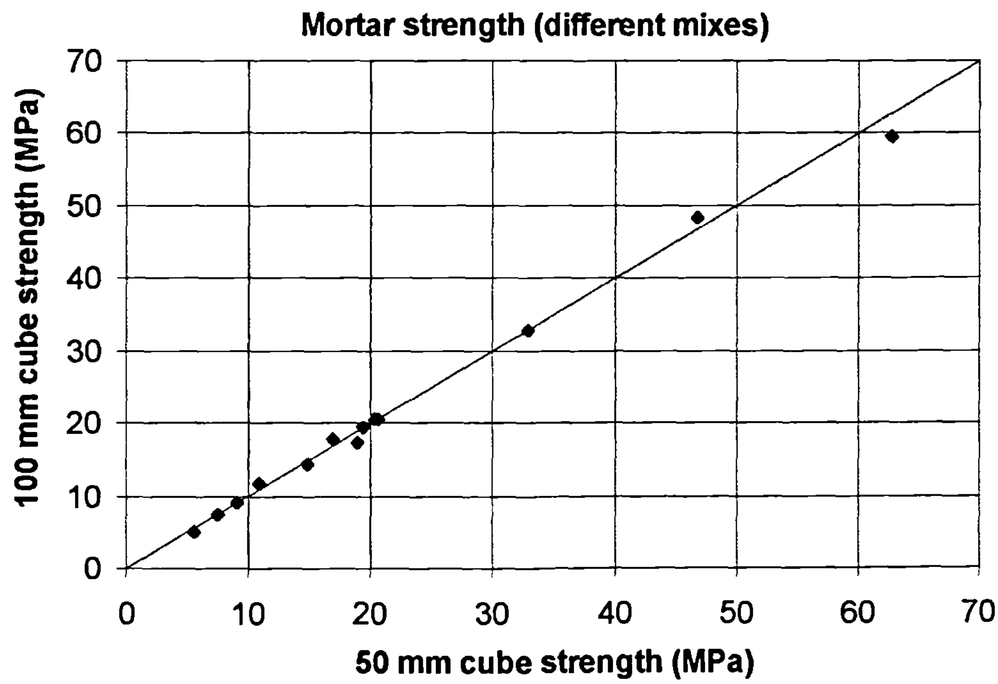


Fig. 6-14 Relationship between compressive strength of 100 mm concrete cubes and 50 mm mortar cubes.

6.2.5 Criteria for mortar tests

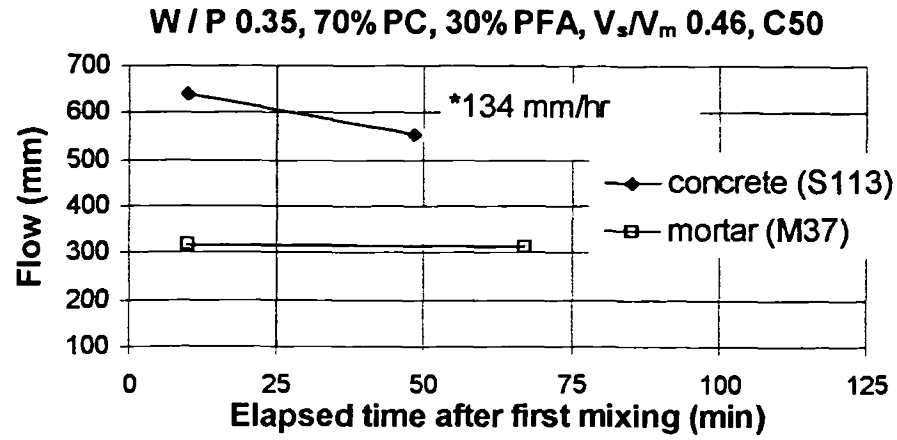
Table 6-2 gives suitable values for mortar properties. It is important to note that these values not only apply for the initial state but also for at least 90 minutes after first mixing.

Table 6-2 Required values for mortar tests

Properties	Tests	Mortar	
Workability	flow test	≥300 mm	
Stability	V-funnel test	D_{max} 20 mm	4 - 10 sec*
		D_{max} 10 mm	2 - 10 sec*
Minimum strength before striking	Cube strength at one day	≥ 10 .0 MPa	

* a value near the lower limit is preferred

Fig. 6-15 shows an example of a mix which meets the fresh property requirements of **Table 6-2**. It should be noted that the changes of fresh properties of concrete with time are often larger than that of mortar for the same dosage of superplasticizer, as previously mentioned.



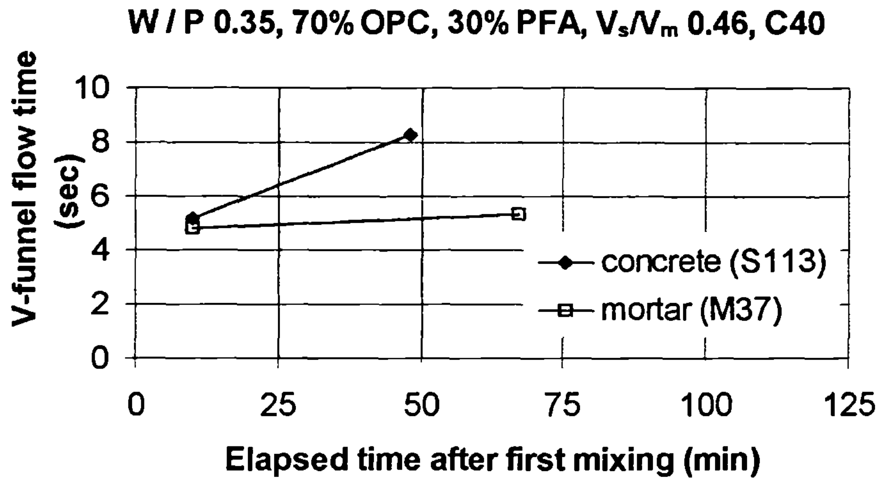
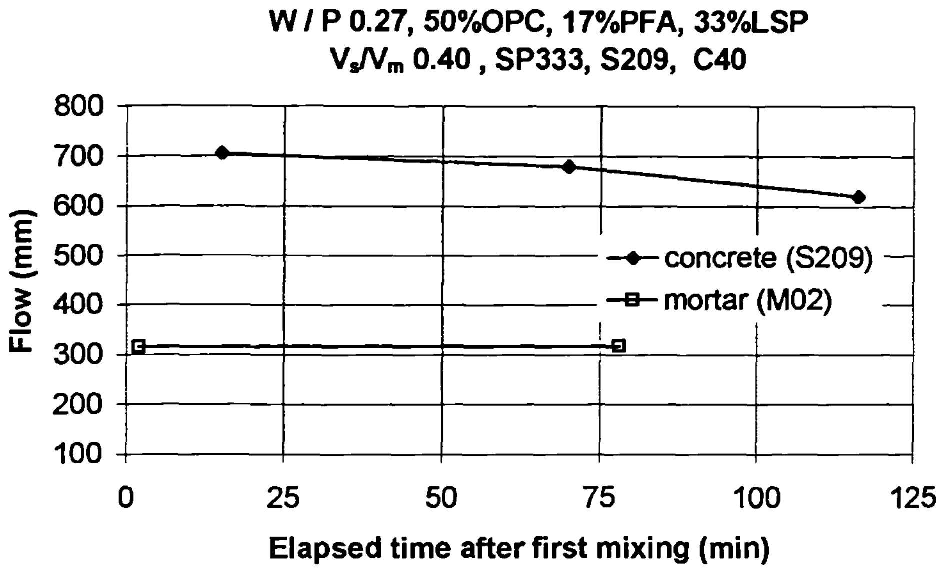


Fig. 6-15 Relationship between fresh properties of concrete and mortar with time for a typical satisfactory mix.

In another example, for the mix in **Fig. 6-16**, the flowability was adequate, but the viscosity was too high. The V-funnel flow time of concrete was over 10 seconds, though that of mortar was marginally less than 10 seconds. Hence, for V-funnel test, the values approaching the lower limit in **Table 6-2** are preferred. In contrast to **Fig. 6-15**, the changes of fresh properties of concrete and mortar in **Fig. 6-16** were very small, because the G-type superplasticizer retarded the hydration reaction of cement.



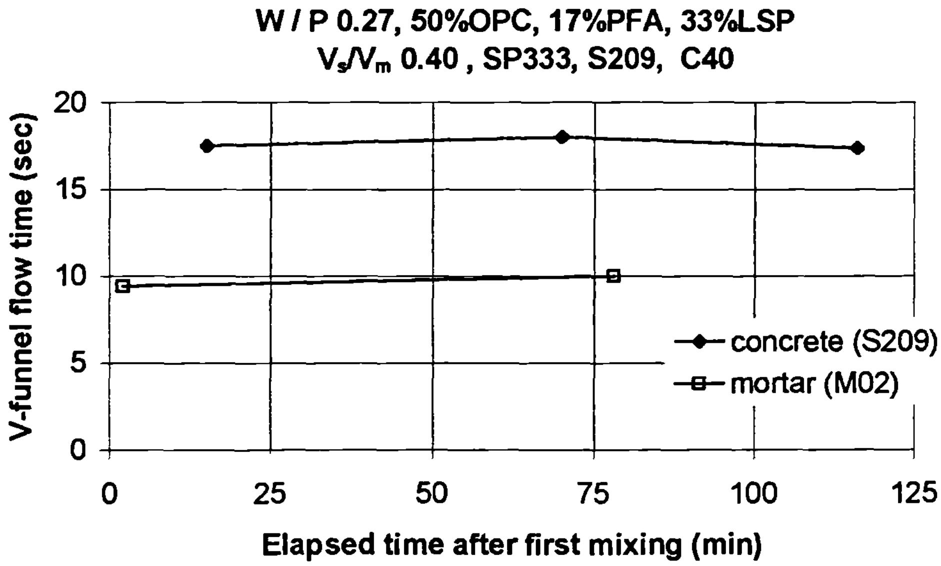


Fig. 6-16 Relationship between fresh properties of concrete and mortar with time for an unsatisfactory mix

6.3 Composition of mortar

Selection of the mortar composition will define all of the critical items of SCC except the coarse aggregate, i.e., sand content, powder composition, water/powder ratio and above all the dosage of superplasticizer.

6.3.1 Sand content

According to **Okamura** et al (1993), the fine aggregate, defined as that with a particle size larger than 0.06 mm, should have a volume (V_s/V_m) of 40% of the mortar. With this amount, no pronounced direct interlocking of the sand particles occurs. The viscosity of the mortar does not then seem to depend on the type of sand, but rather on the properties of paste. However, according to **Fig. 3-32**, this sand content is only suitable for use with a water/powder ratio of less than 0.3 (by weight). In engineering practice, not many projects need such a low value. When the water/powder ratio increases from 0.3 to 0.4, the required value of V_s/V_m will inevitably increase. Hence, the sand content (V_s/V_m 0.40) can be considered as the lower limit for SCC.

Nearly every mix design method has this general trend: the higher the water cementitious ratio, the higher the sand content. For example, **Table 6.3** and **Table 6.4** give some mix proportions based on the BRE 1988 and ACI 211.1-91 mix design methods. When W/C increases from 0.37 to 0.62, the sand content of the mortar (V_s/V_m) also increases from 0.37 to 0.50 approximately.

Table 6.3 Typical mix proportions at constant water content obtained from BRE (1988).

fcm MPa	W / C	W	PC	F.A	C.A	s/a	V_s/V_m	A/C	W/T.F
30	0.62	195	315	722	1128	0.39	0.50	5.9	0.188
40	0.52	195	375	662	1127	0.37	0.46	4.8	0.188
50	0.44	195	443	620	1102	0.36	0.42	3.9	0.183
60	0.37	195	527	557	1081	0.34	0.37	3.1	0.180

D_{max} 20 mm, slump 60-180 mm, 60% F.A passing 600 μm sieve

Table 6.4 Typical mix proportions at constant water content obtained from ACI 211.91. (1991)

f_{cm} MPa	W / C	W	PC	F.A	C.A	s/a	V_s/V_m	A/C	W/T.F
24	0.62	195	315	738	1050	0.41	0.49	5.7	0.185
32	0.52	195	375	688	1050	0.40	0.45	4.6	0.183
38	0.44	195	443	631	1050	0.38	0.41	3.8	0.181
	0.37	195	527	562	1050	0.35	0.37	3.1	0.179

Cylinder strength, D_{max} 19 mm, slump 100-150 mm, sand F.M 2.6

Table 6-5 Recommended proportions of fine aggregate for SCC from this study

Water / powder ratio	Sand volume V_s/V_m
<0.30	0.40
0.30-0.34	0.40-0.45
>0.34	≥0.45

Viscosity agent may be needed, if water/powder ratio larger than 0.37,
when maximum size of aggregate is 20 mm

A similar trend can be seen in **Table 6-5**, the sand content increases with the water/powder ratio. In addition, **Table 6-5** also shows the balance of viscosity, because both excessive and insufficient viscosity will cause problems of the handling fresh concrete. Normally, low water/powder ratio results in higher powder content, hence, less sand content is required. On the other hand, high water/powder ratio results in low powder content, hence, more sand content is required (see **7.2.4.1**).

Finally, it should be noted that the sand content has an upper limit (see **7.1.3.1**) because too much sand will impair the passing ability of SCC through reinforcement. Another limitation results from the paste volume. From the literature review, a suitable paste volume for SCC is between 0.38 to 0.42 m^3, per cubic metre concrete. **Table 6-6** lists the upper limits of sand content for different coarse aggregate sizes and types in the case of 0.38 m^3 minimum paste volume. In summary, the required sand content (V_s/V_m) of SCC is between 0.40 to 0.47, i.e., 700 to 850 kg/m^3 and generally is much higher than in normal concrete.

Table 6-6 Upper limits of sand content for 0.38 m^3 minimum paste volume

	Gravel D_{max} 20 mm	Gravel D_{max} 10 mm	Granite D_{max} 10 mm
G/G_{lim} 0.50	820 kg/m^3	800 kg/m^3	796 kg/m^3
V_s/V_m	0.453	0.460	0.470

6.3.2 Water / total fines ratio

As mentioned in section **2.2.2**, the water/total fines ratio and the coarse aggregate content are two useful parameters to distinguish SCC from other kinds of concrete. In normal concrete practice, cohesiveness is often ensured by maintaining a constant amount of total fines (cement + sand) content (**Fig. 6-17**). **Table 6-3** and **Table 6-4** also show that concretes with the same slump have nearly the same water/total fine ratio. The advantage of using water/total fines ratio is that it offers a simple way to regulate the relationship among the quantities of water, powder and sand. **Fig. 6-18** shows the calculated relationship between water/total fines ratio and water/powder ratio for different sand content. This is useful for a preliminary mix design of SCC. (From the literature review, the normal range is from 0.120 to 0.140 in case of no viscosity agent with 20 mm maximum size of aggregate.) The higher the water/total fines ratio, the less the viscosity of mortar. For instance, if a water/powder ratio of 0.34 is selected for a mix design of SCC, **Fig. 6-18** shows that V_s/V_m can be chosen as 0.45 in order to keep water/total fines ratio less than 0.14.

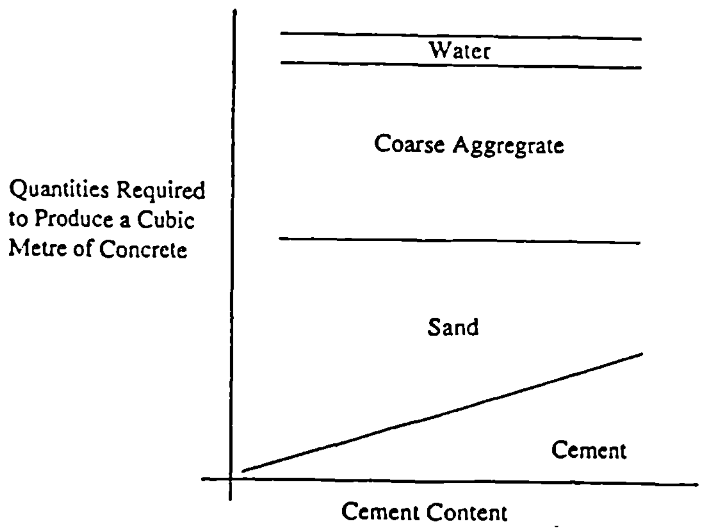


Fig. 6-17 Mix proportions for cohesiveness [Adapted from Barber, QSRMC (1996)]

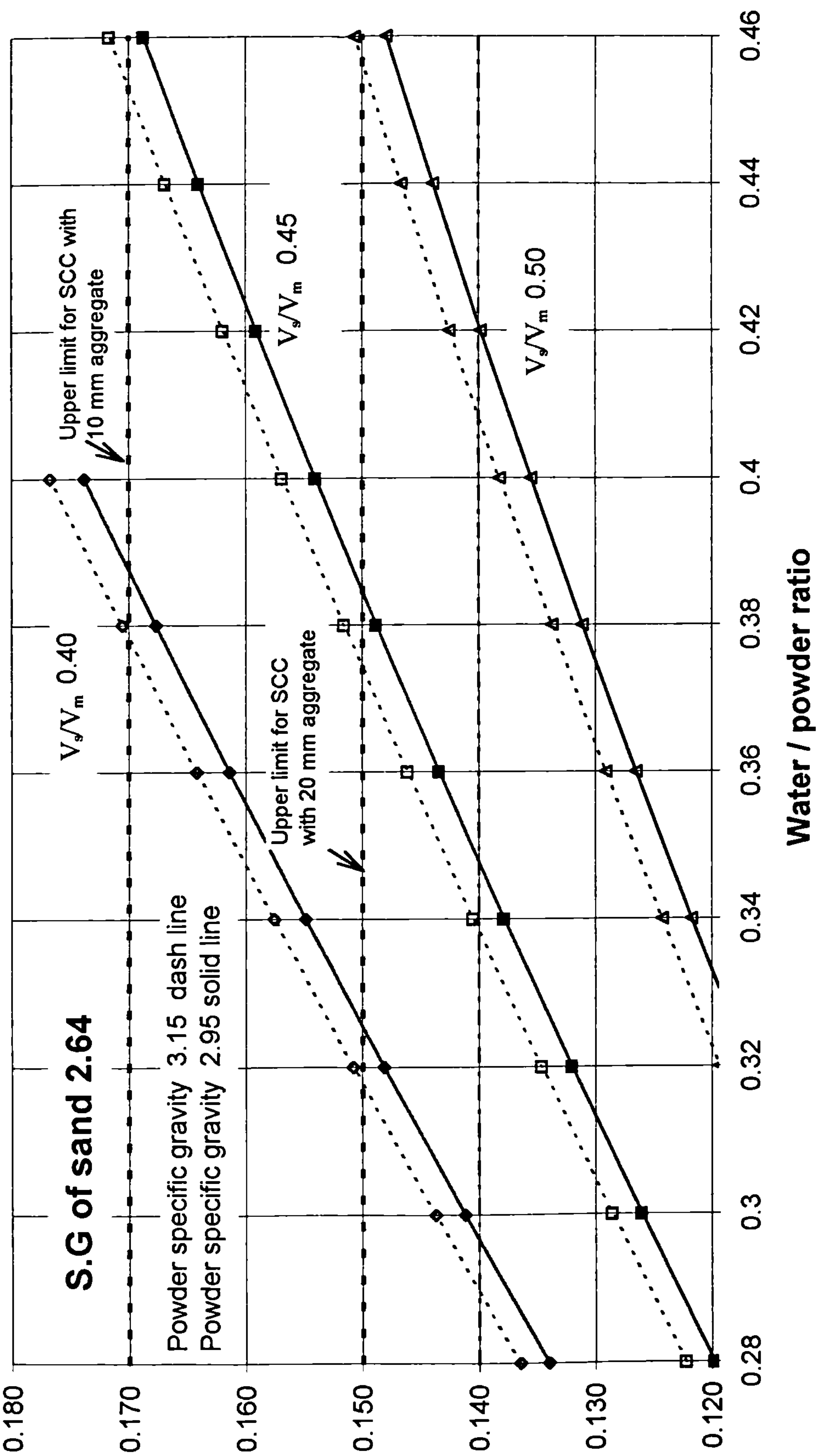


Fig. 6-18 Water/total fine ratio vs. water/powder ratio with different V_s/V_m

The limitation of using water/total fine ratio is that it does not take account of any properties of the powder or sand. For the same water/total fines ratio, a different composition of powder produces a different viscosity. For example, a powder of 20%PFA+80%PC gives lower viscosity than a powder of 20%GGBS+80%PC. Therefore the water/powder ratio needs to be adjusted according to the powder composition.

`6.3.3 Powder composition

The viscosity of paste has a significant effect on the properties of SCC. Although in practice SCC will contain a superplasticizer, and perhaps a viscosity agent, some useful information for mix design can be obtained by considering the paste viscosity with no admixture, which can be calculated using the viscosity formula given in **Chapter 5**. **Table 6-7** gives results of tests on mortars made with paste containing GGBS and PFA. All the values of V-funnel tests in **Table 6-7** were between 4 to 10 sec. In particular, the water/total fine ratios of the first three mortar mixes were higher than 0.14. Moreover, **Table 6-8** gives other results of tests on mortars of which the values of V-funnel tests were less than 4 sec, but the water/total fine ratios of the first two mortar mixes were not higher than 0.14. As a result, the criterion " 0.12 < W/ T.F < 0.14 " need to be modified. From **Table 6-7** & **Table 6-8**, the calculated viscosity of paste is a good reference for water/total fines ratio, because it includes the properties of powder. Hence, water/total fines ratio combined with calculated paste viscosity offer a good criterion for SCC mix design.

Table 6-7 Calculated viscosity of paste (1)

PC %	PFA %	GGBS %	β_p*	E_p*	W/P	μ_p* (mPas)	V_s/V_m	W/T.F	V-funnel (sec)	Flow (mm)
80	0	20	1.08	0.058	0.37	283	0.47	0.141	4.1	300
75	0	25	1.09	0.057	0.37	297	0.45	0.147	5.2	318
50	0	50	1.09	0.054	0.38	305	0.46	0.146	5.4	310
70	30	0	0.93	0.050	0.35	286	0.46	0.137	4.8	320
80	20	0	0.98	0.054	0.34	370	0.45	0.138	6.9	320
70	30	0	0.93	0.050	0.29	950	0.40	0.137	6.8	350

calculated value(see section 5.4.2), μ_p:calculated viscosity of paste

Table 6-8 Calculated viscosity of paste (2)

PC (%)	PFA (%)	LSP (%)	β_p*	E_p*	W/P	μ_p* (mPas)	V_s/V_m	W/T.F	V-funnel (sec)	Flow (mm)
80	20	0	0.98	0.054	0.37	216	0.47	0.139	3.2	—290
80	0	20	1.02	0.056	0.37	219	0.47	0.140	3.8	300
85	15		1.01	0.055	0.50	33	0.45	0.178	1.3	–

From the experimental data of this study, **Fig. 6-19** & **Fig. 6-20** show the relationship between h value and V-funnel flow time of concrete with water/total fines ratio. All the concrete mixes were divided into four groups according to the calculated paste viscosity. With 20 mm maximum size of aggregate, the suitable viscosity of SCC is in the range of h value from 2 to 5 Nms; or V-funnel flow time from 4 to 10 seconds (as will be shown in **Chapter 7, Table 7-10**). Therefore, the corresponding water/total fine ratios of most mixes were from 0.125 to 0.150. Among these, most of the paste viscosities were higher than 280 mPa.s, so this appears to be a suitable criterion. Some exceptions are those either with viscosity agent or with high sand content. (Mix ref. S109, S110, S112). Therefore, the criterion for SCC with 20 mm maximum size of aggregate "0.12 < W/ T.F < 0.14" can be modified to "0.125 < W/ T.F < 0.150 and μ_p* > 280 mPa.s"

Similarly, with 10 mm maximum size of aggregate, the suitable viscosity of SCC is in the range of h value from 1 to 5 Nms; or V-funnel flow time from 2 to 10 seconds, because the 10 mm aggregate gives better segregation resistance (see **Table 7-10**). Then, the corresponding water/total fine ratio is from 0.125 to 0.170 and the calculated viscosity of paste should higher than 70 mPas.

Table 6-9 summarises the resulting criterion

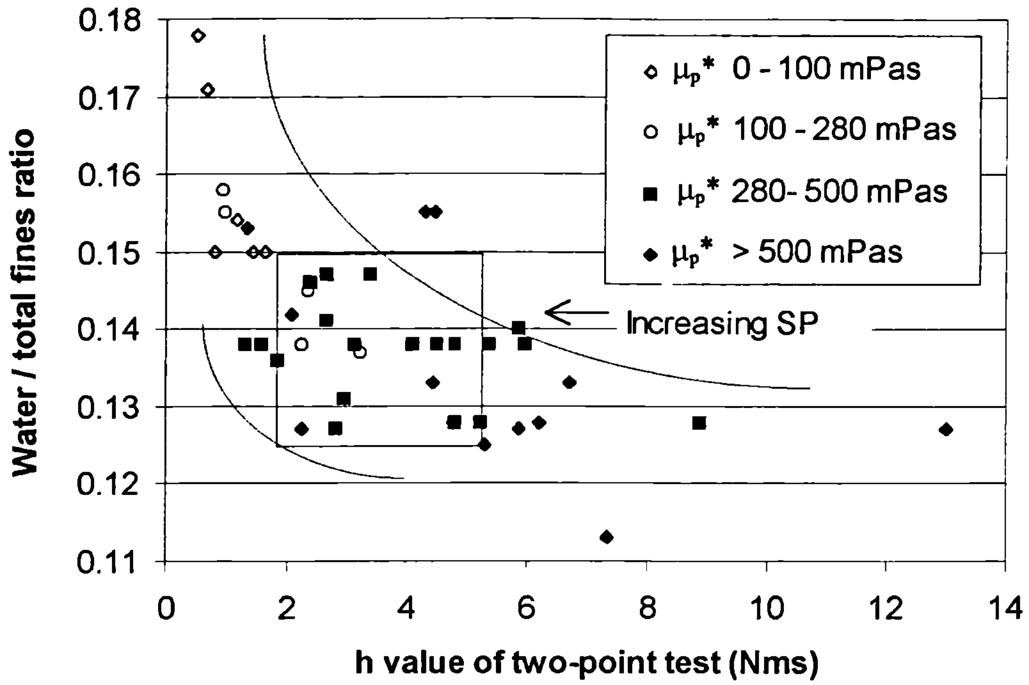


Fig. 6-19 Relationship between h value and water/total fine ratio

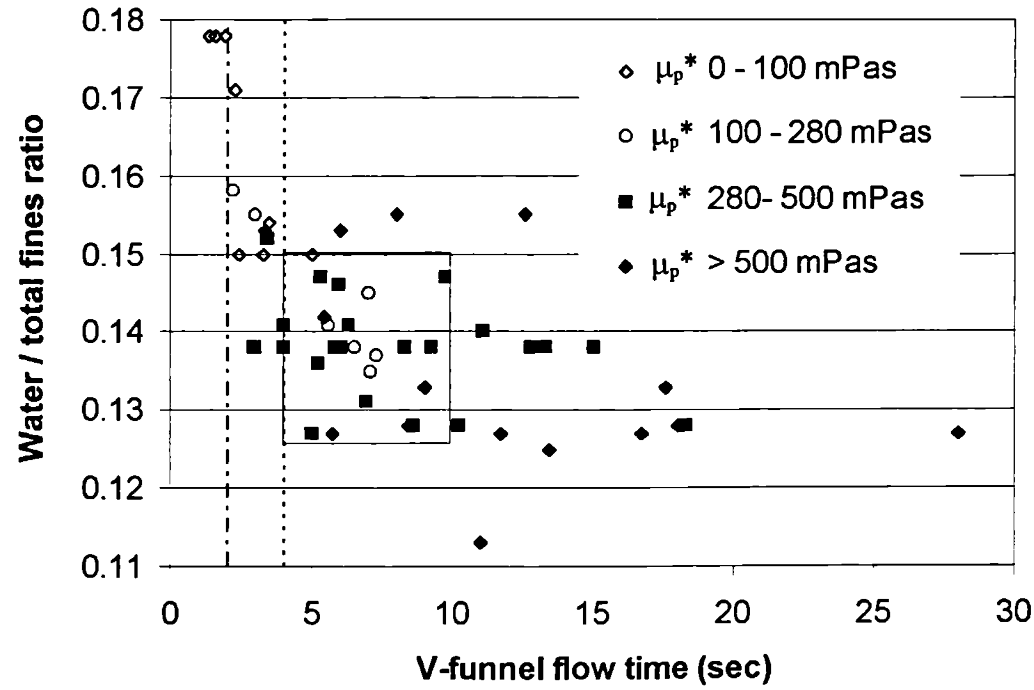


Fig. 6-20 Relationship between V-funnel flow time and water/total fine ratio

Table 6-9 Mix design criteria for viscosity requirements

Viscosity requirements for SCC			Mix design criteria	
D_{max}	V-funnel flow time	h-value	W / T.F	μp*
20 mm	4 - 10 sec	2 - 5 Nms	0.125 < W/ T.F < 0.150	≥ 280 mPa.s
10 mm	2 - 10 sec	1 - 5 Nms	0.125 < W/ T.F < 0.170	≥ 70 mPa.s

If no values of paste viscosity can be calculated, from the test results on SCC (Appendix 3) the criteria for the water/total fines ratio can be modified to:

D_{max} 20 mm

PC+GGBS W/T.F ≤ 0.147

PC+PFA W/T.F ≤ 0.137

PC+LSP W/T.F ≤ 0.137

D_{max} 10mm

W/T.F ≤ 0.170

These criteria are very helpful in the mix design of SCC. For instance, for a mix 70%PC+30%PFA, W/P 0.38, V_s/V_m 0.46, its W/T.F is 0.144, the viscosity of paste is 176 mPa.s. Obviously this mix does not have sufficient viscosity with 20 mm maximum aggregate, but it is acceptable with 10 mm maximum aggregate. In this way, the trial range and variables of mix design can be narrowed to a minimum.

So far, only calculated paste viscosity is used in this study for a SCC mix design, if the mortar viscosity can be calculated, it will be extremely useful for the controlling of segregation resistance. Though **Nishibayashi** (1996) suggested a equation to calculate mortar viscosity, the values of specific surface of fine aggregate used for the equation are not consistent with its reference paper [**Loudon** (1952)]. Hence, this equation needs to be modified.

In summary, the water/total fine ratio is a simple but useful parameter to control the viscosity of mortar. However, the composition of powders should also be taken into account. The water/total fine ratio and calculated paste viscosity can be used as mix design criteria for segregation requirements. Finally, the viscosity of the mortar needs to be proved suitable by using a V-funnel test.

6.4 Factors influencing dosage of superplasticizer

The role of superplasticizers in SCC is crucial. The type and dosage have a major influence on nearly all the fresh properties of SCC, such as workability, loss of workability with time, passing ability through reinforcement, filling ability and stability, and even the one day compressive strength and surface condition of the hardened concrete. Too much superplasticizer is not only uneconomical but also causes severe segregation, whereas insufficient will not produce self-compacting properties. For flowing concrete and high strength concrete, the dosages of superplasticizer are often determined by weight of cementitious materials. This can be used as a general guide but does not give the optimum dosage which can only be gained through trial mixes on the concrete. However, proper mortar tests enable the trial ranges to be narrowed. There are many factors which influence the required dosage of superplasticizer, such as the proportion and type of CRM, the water/powder ratio, the sand content, the amount of viscosity agent if used, and the mixing procedure

6.4.1 Proportion and type of CRM

Different CRMs have different chemical compositions and physical properties which result in different rheological properties. **Fig. 6-21** shows some results of mortar tests. It is clear that the PFA and LSP mixes have a higher flow than the GGBS mix. In other words, the dosage of superplasticizer for the combination (80%PC+20%GGBS) will be higher than for (80%PC+20%PFA) or for (80%PC+20%LSP) in order to gain the same mortar spread.

6.4.2 Water/powder ratio

For SCC without a viscosity agent, the water/powder ratios are normally in the range 0.28 - 0.38 if a 20 mm maximum aggregate is used. There is no doubt that the higher the water/powder ratio, the less the required dosage of superplasticizer for a given mortar flow as can be seen in **Fig. 6-22**. Also, for higher water/powder ratios, e.g., 0.37, the mortar is prone to segregation with increasing superplasticizer dosage.

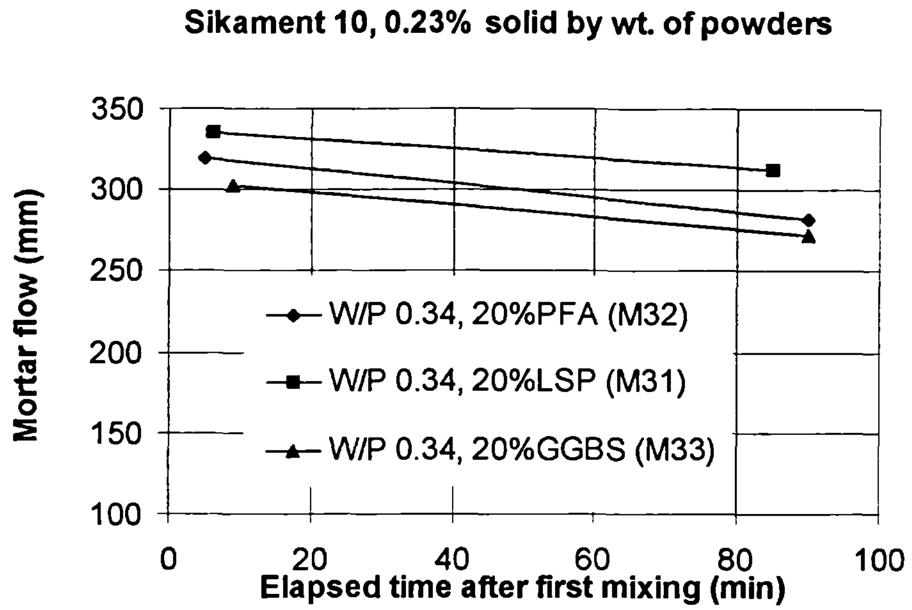


Fig. 6-21 Influence of CRMs on the mortar flow for the same dosage of superplasticizer

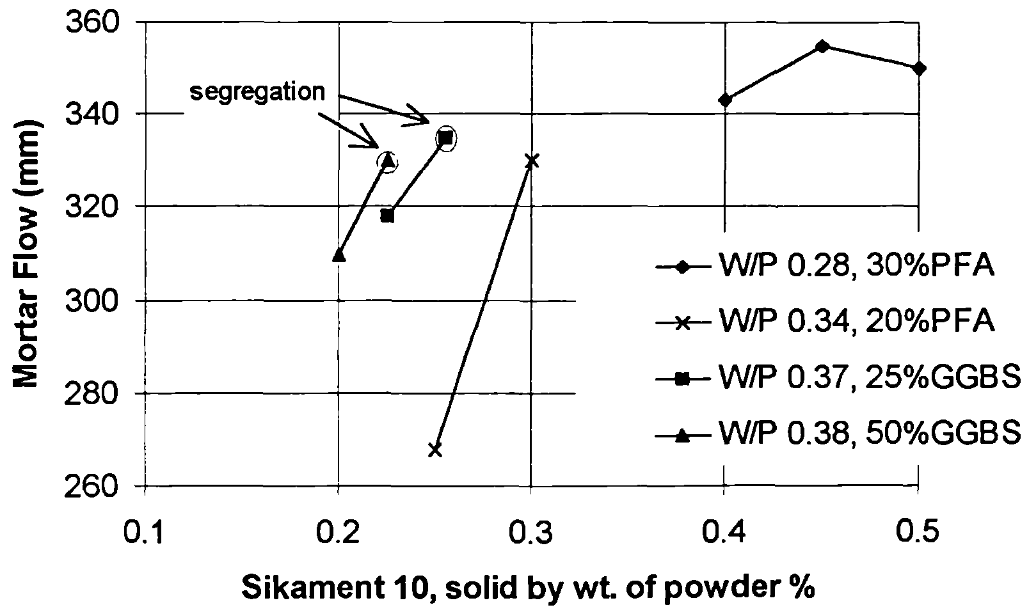


Fig. 6-22 Influence of water powder ratio on the dosage of superplasticizer

In this case, the dosage of superplasticizer which made mortar sufficiently flowable was very close to the dosage which caused segregation. In other words, the range of dosage of superplasticizer for higher water/powder ratio is comparatively narrow. Therefore, although SCC with higher water/powder ratio is cheaper, (because of less superplasticizer), its stability is inferior and it needs excellent quality control.

6.4.3 Sand content

The cementitious materials have the major influence on the dosage of superplasticizer, but the sand content can also have some influence. **Fig. 6-23** shows from data on concrete that the higher the sand content, the higher the dosage of superplasticizer required.

6.4.4 Viscosity agent

As discussed in **Chapter 3,** the function of a viscosity agent is to stabilize the SCC. **Fig. 6-24** shows that mixes with a viscosity agent require a higher dosage of superplasticizer to achieve the same flow, but have no tendency to segregate. This also results in better workability retention, as shown in. **Fig. 6- 25.**

6.4.5 Mixing procedure

Finally, it is important to note that the method of addition of the superplasticizer has a crucial effect on workability. The suitable dosage of superplasticizer defined from the mortar tests should be incorporated in the concrete trial mix by the two stage mixing procedure Method 1 or Method 3 , as mentioned in **section 4.3**. Normally, the SCC mixed according to Method 3 has a slight higher slump flow than that according to Method 1. However, experiences of concrete trial mixes for a certain type of superplasticizer are required in order to obtain the superplasticizer dosage SP_0, which is needed in Method 3. Method 1 is easy and simple, suitable for most types of superplasticizer. In general, method 2 needs a higher dosage of superplasticizer than method 1 and method 3. For method 2, if the mortar is adjusted properly according to **Table 6-2**, the unexpected slump flow of concrete will not be obtained.

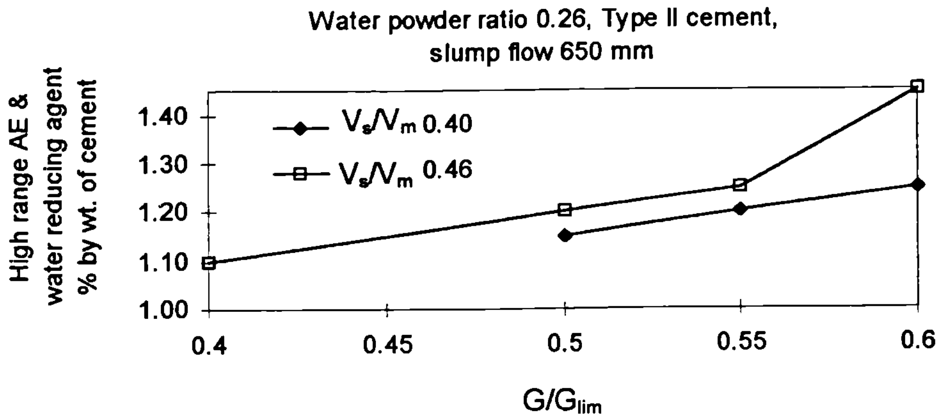


Fig. 6-23 Influence of sand content on the dosage of superplasticizer
[Data adapted from Ozawa et al (1994)]

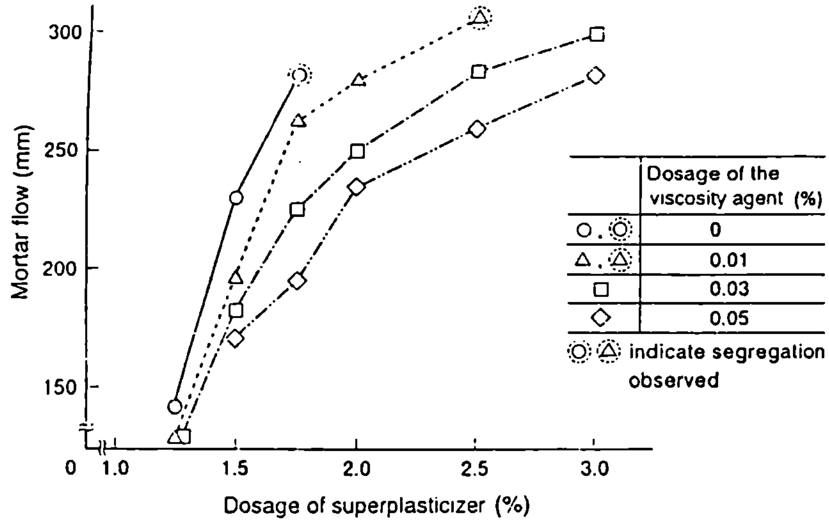


Fig. 6-24 Effect of viscosity agent on the dosage of superplasticizer
[Adapted from Yurugi et al (1995)]

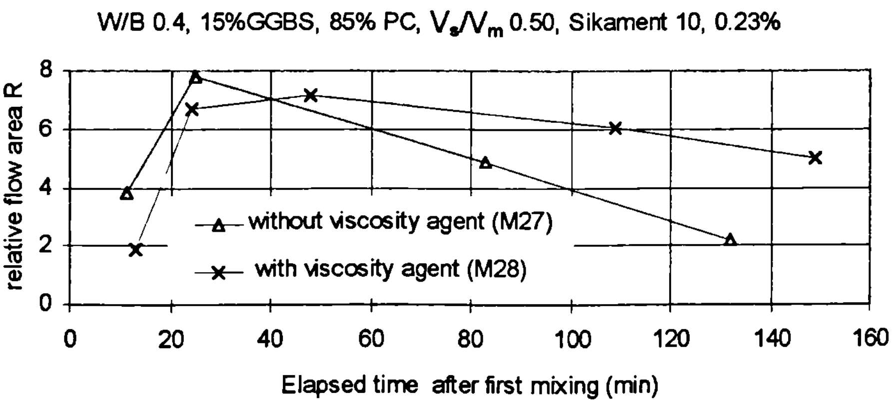


Fig. 6-25 Influence of viscosity agent on mortar flow

6.5 Conclusions

Mortar tests give much helpful information for the formulation of concrete trial mixes including the compatibility and suitable dosage of superplasticizer, the workability and stability of the mixes and early strength gain. The mortar tests are versatile, easy to carry out and should not be ignored. However, concrete tests are still necessary to ensure that the required SCC properties are achieved. **Fig. 6-26** shows the relationship between mortar test result, concrete test result and SCC properties, for concrete with a maximum aggregate size of 20 mm.

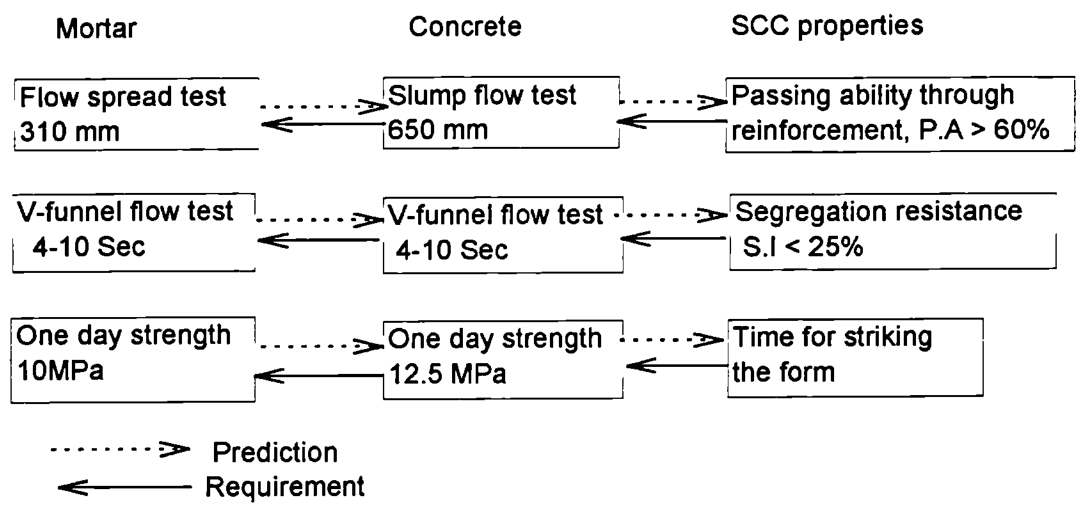


Fig 6-26 Relationship between mortar tests and concrete tests and SCC properties with 20 mm maximum aggregate size.

Chapter 7

Fresh Properties of SCC

The previous two chapters describe an experimental programme on the rheology of cementitious paste and the properties and composition of mortar which form a sound basis for SCC mix design. This chapter presents and discusses work carried out on the production of SCC with UK materials and the assessment of the two distinguishing fresh properties of this concrete, i.e. passing ability through reinforcement and the segregation resistance. Most published work has been concerned with SCC with a 20 mm maximum aggregate size; this chapter includes work with 10 mm aggregate, and also includes a novel method of increasing the segregation resistance.

The test methods have been described in Chapter 4, and full detail of mixes and tabulated test results are given in Appendix 3.

7. 1 Passing ability of SCC through reinforcement

7.1.1 Experimental objectives

Passing ability through reinforcement is the major distinction between flowing concrete and self-compacting concrete. Both are self-levelling, but in most cases, flowing concrete cannot pass through reinforcement without blockage. Thus, knowledge of the factors controlling the passing ability is essential for the understanding and development of SCC. Apart from the ratio of mesh gap to maximum size of aggregate, the other three major factors in determining the passing ability of SCC through reinforcement are the suitable aggregate content, the sufficient flowability and segregation resistance. Without the sufficient flowability, the fresh concrete will not move under its own weight, so will have no passing ability. With excessive aggregate content, the arching phenomena and interlocking among aggregate particles will occur and block the flow, no matter how fluid the concrete. Experiments and results assessing these two factors will be discussed in the following sections. Segregation resistance will be considered separately in section **7.2**. As mentioned in Chapter 4, in this project passing ability was assessed by using a U-test and an L-test. In Japan, it is generally agreed that concrete with a filling height 300 mm or more of U-test can be considered as self-compacting concrete [**Okamura** (1996)].

The objectives of the experiments reported in this section is to assess the ability of mixes produced with UK materials to achieve satisfactory passing ability, including:

- the requirements of flowability;
- the upper limit of coarse aggregate content;
- the upper limit of sand content.

7.1.2 Experimental variables

The main experimental variables were the aggregate content: G/G_{lim} and V_s/V_m for maximum aggregate sizes of 20 mm and 10 mm.

Table 7-1 Parameters for U-tests

D_{max}	G/G_{lim}	V_s/V_m	Mix ref. (Appendix 3)
Gravel 20 mm	0.5	0.40	S227, M201
		0.45	S222, S224-S226, S230
		0.47	S228, S229
		0.50	M202
Gravel 10 mm	0.515	0.40	M103
		0.45	S115
		0.48	S110
		0.50	S109, S112, M105
	0.50	0.46	S113
	0.55	0.46	S116
Granite 10 mm	0.535	0.40	M104-I
	0.60	0.40	M106-I

Table 7-2 Parameters for L-tests

D_{max}	G/G_{lim}	V_s/V_m	Mix ref.
Gravel 25 mm	0.50	0.40	S203-S206
(see **4.2.5**)		0.45	S222
Gravel 20 mm	0.50	0.40	S201, S202, S207-S209, S227
		0.43	S214
		0.44	S210, S213, S216, S217
		0.45	S211-S212, S215, S218-S225, S230
		0.47	S229
		0.50	M202
Gravel 10 mm	0.50	0.45	S103, S104, S108
		0.46	S113, S114
		0.48	S101
		0.51	S102
	0.515	0.45	S111
		0.48	S110
		0.50	S112, M105
	0.55	0.46	S116
Granite 10 mm	0.50	0.45	S105-I
		0.48	S107-I
	0.535	0.40	M104-I
	0.55	0.40	S106-I

Most water/powder ratios of the mixes in **Table 7-1** and **Table 7-2** were between 0.29 to 0.40 which were commonly used in SCC construction work. As will describe in section **9.3**, if coarse aggregate content (G/G_{lim}), fine aggregate content (V_s/V_m), powder combination, and water/powder ratio are selected first, then the water and powder contents can be calculated afterwards. Superplasticizer dosages were obtained through mortar tests.

7.1.3 Results and discussion

7.1.3.1 Aggregate content

For the 20 mm coarse aggregate, **Fig. 7-1** shows the relationship between the filling height of U-test and slump flow for various values of sand content V_s/V_m. It is clear that when the coarse aggregate content G/G_{lim} is 0.50, a suitable sand content V_s/V_m is in the range 0.40 to 0.47. This result is consistent with results from others, e.g., according to **Matsuo** and **Ozawa** (1994), the upper limit of aggregate content for 20 mm maximum size for good filling ability is:

Coarse aggregate content G/G_{lim}	Sand content V_s/V_m
0.50	0.40-0.46
0.55	0.40

Fig. 7-2 and **Fig. 7-3** show the relationship between the filling height and slump flow for concrete with 10 mm coarse aggregate. The upper limit of coarse aggregate is the same as 20 mm, that is, G/G_{lim} 0.55, but at this value, satisfactory passing ability can be achieved with V_s/V_m of 0.40 to 0.46. Over this threshold (G/G_{lim} 0.55), the interlocking among aggregate particles may impair the passing ability through reinforcement. For instance, in **Fig. 7-3**, when the G/G_{lim} was 0.60 in spite of low sand content V_s/V_m 0.40

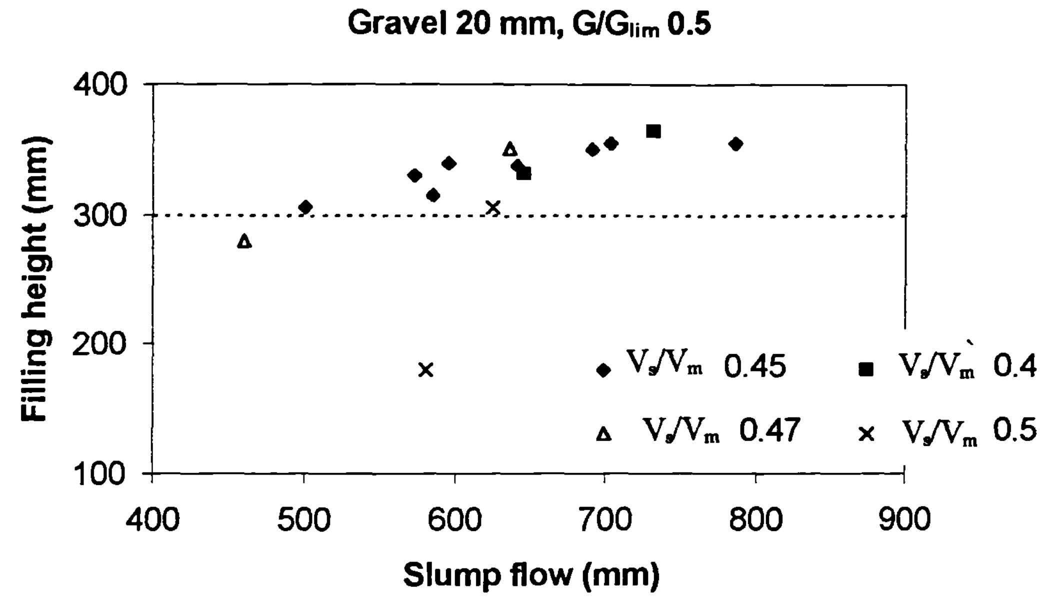


Fig 7-1 Relationship between filling height of U-test and slump flow

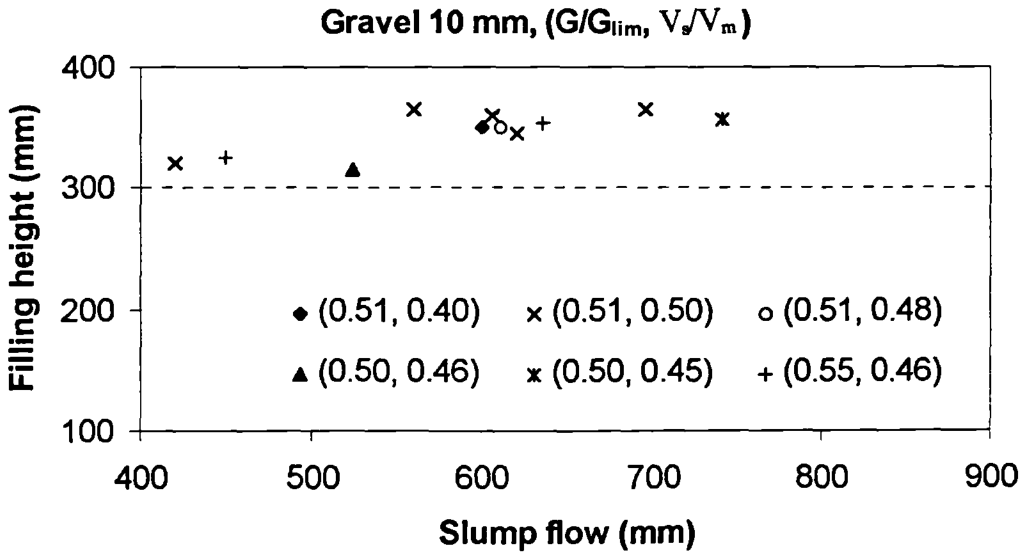


Fig 7-2 Relationship between filling height of U-test and slump flow

and high slump flow, the filling height was less than 300 mm, even with 10 mm coarse aggregate. It is clear that concrete with a coarse content (G/G_{lim}) of 0.60 or more, (for instance, flowing concrete), is not self-compacting concrete. Hence the quantity of coarse aggregate is a controlling factor for passing ability through reinforcement.

Also, within the threshold quantity of coarse aggregate, the sand content also has its limitation, as can be seen in **Fig. 7-1**. Too much sand also impaired the passing ability, and reduced the filling height, especially for 20 mm maximum size of aggregate. This result was confirmed by a complete blockage at the reinforcement with an L-test on a mix with a 20 mm coarse aggregate content (G/G_{lim}) and sand content (V_s/V_m) of 0.5 even of a slump flow of 690 mm (Mix ref.- M202).

Fig. 7-4 shows the upper limit of good passing ability from the U-test for different size of aggregate, in which the greater range for 10 mm aggregate is clear.

7.1.3.2 Flowability

With a suitable coarse aggregate content, **Fig. 7-1** and **Fig. 7-3** show that the filling height of U-test increases with slump flow. With 20 mm maximum size of aggregate **(Fig. 7-1)**, the filling height is larger than 300 mm as long as the slump flow is larger than 500 mm provided that the sand content (V_s/V_m) is in the range of 0.40 to 0.47. With 10 mm maximum size of aggregate **(Fig. 7-3)**, the slump flow should be larger than 400 mm and the sand content (V_s/V_m) should be in the range of 0.40 to 0.50 in order to get satisfactory passing ability. It is obvious that the requirements for 20 mm maximum size of aggregate are more strict than those for 10 mm.

For L-tests, the passing ability is more sensitive to the flowability of concrete, because it passes through the mesh horizontally. As can be seen in **Fig. 7-5**, the larger the slump

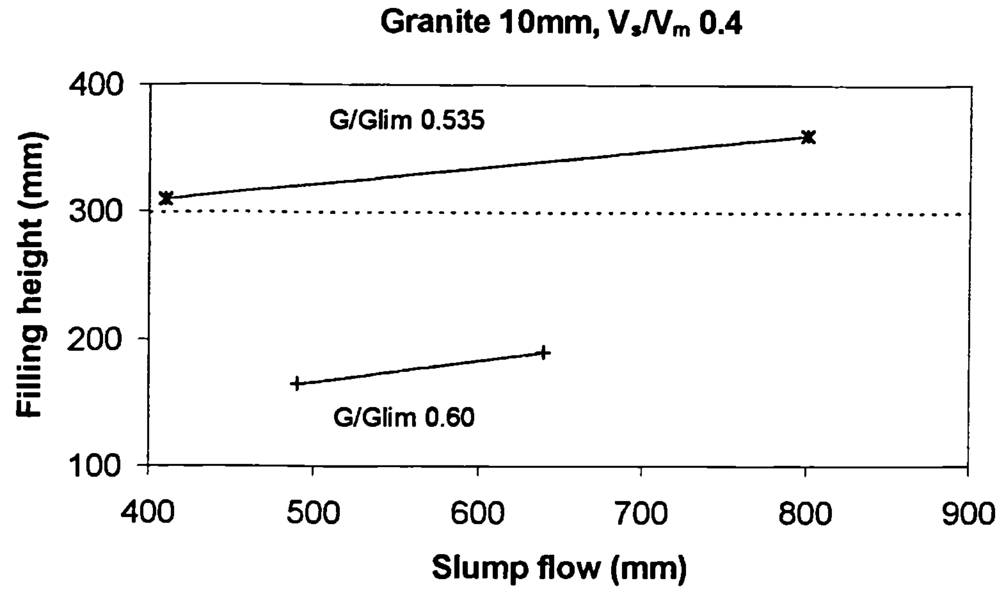


Fig 7-3 Relationship between filling height of U-test and slump flow

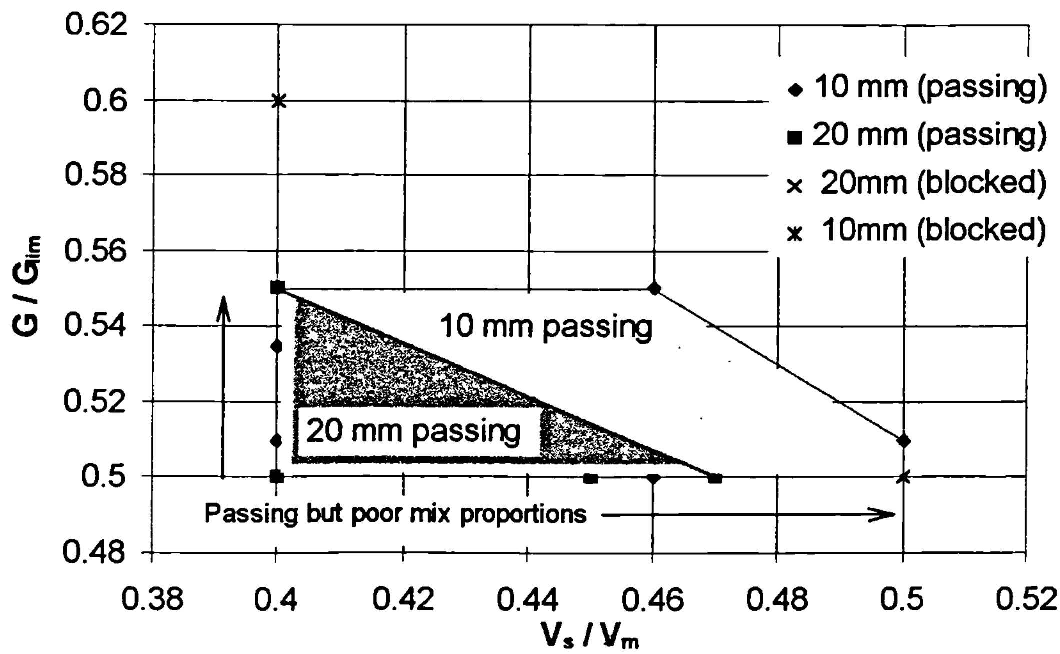


Fig. 7-4 Range of good passing ability of U-test for different size of aggregate

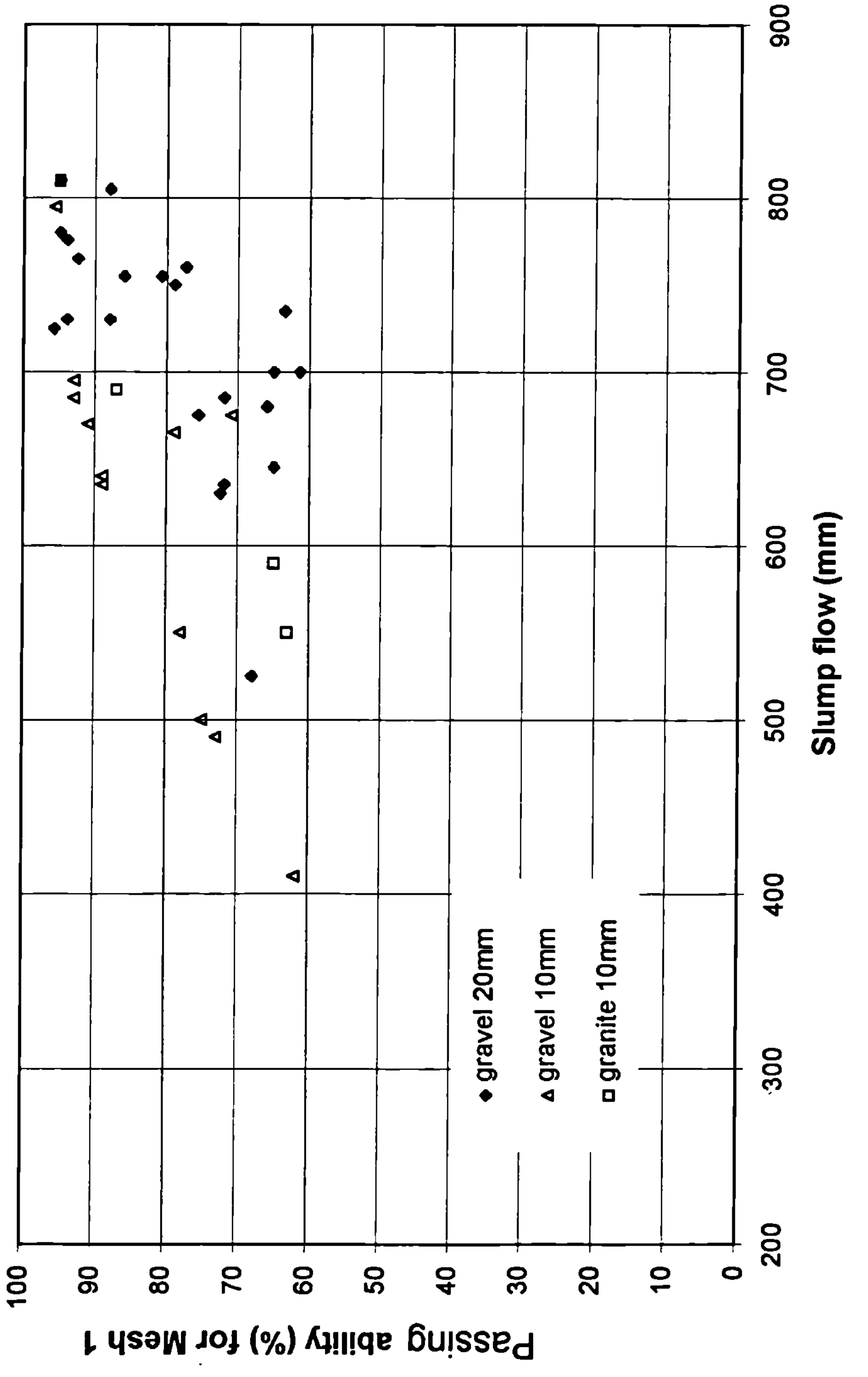


Fig. 7-5 Relationship between slump flow and passing ability from L- test

flow, the higher the passing ability. The results of L-type tests can be summarised in **Table 7-3**. It is worth noting that the L-type test also is very sensitive to the maximum size of aggregate because of its two dimensional mesh. For example, when the maximum size of aggregate is 25 mm, there is very high risk of blocking in the L-test, so that the concrete flow is often blocked.

Table 7-3 Summarised results of L-tests

D_{max} (mm)	G/G_{lim}	V_s/V_m	Slump flow (mm)	Passing ability of mesh 1 (%)
25	0.5	0.4, 0.45	!	≤ 50
20	0.50	0.40-0.47	≥ 600 ≥ 700	≥ 60 ≥ 80
10	0.50-0.52	0.4-0.51 0.4-0.46	≥ 500 ≥ 600	≥ 60 ≥ 80
10	0.52-0.55	0.40-0.46	≥ 500	≥ 60

Passing ability: ≤ 50, blocked; ≥ 60, good; ≥ 80, excellent.
! High slump flow cannot cause good passing ability in case of 25 mm aggregate

As can be seen from **Table 7-3**, the flowability requirement with 20 mm size of aggregate is higher than that with 10 mm aggregate. This result is the same as that of U-test, but the minimum requirement of slump flow for each test is different. The comparison of U-test with L-test will be discussed in the next section **7.1.3.3**.

To try to determine the major factors influencing the passing ability, a linear regression analysis technique has been used. From the L-test results for concrete with 10 mm aggregate, this gives a multi-variable relationship between the passing ability, the rheological constants g and h and the aggregate proportion V_s, V_g as follows:

$$P.A. = (2.44 - 0.437\,g - 0.024\,h - 0.429V_s - 4.136V_{g\,(5\text{-}10)}) \times 100\ \% \qquad \textbf{(7-1)}$$

Where g, h: rheological constants of two-point test

V_s: volume of sand

$V_{g\,(5\text{-}10)}$: volume of coarse aggregate (5-10 mm)

provided that the aggregate contents is in the range: G/G_{lim}: 0.50-0.55; V_s/V_m: 0.40-0.51.

The correlation coefficient for this relationship is 0.91, i.e. high. The rheological properties relate to the flowability of the concrete. The less the g value, the more flowable the concrete under its own weight. The reinforcement can be considered as a kind of barrier to concrete flow. To overcome this barrier, sufficient flowability is required, hence, the less the g value, the higher the passing ability. On the other hand, the viscosity term h relates to the velocity of flow. The higher the h value, the less the velocity and the momentum of concrete. As a result, the concrete is prone to blocking by the reinforcement. As far as the passing ability is concerned in the L-test, the less the h value, the higher the passing ability. However, as far as the segregation resistance is concerned, moderate viscosity (i.e. h value) is required. The coefficients of g and h in formula (7-1) show that the influence of g value on passing ability is much higher than that of h value.

The second group relates to the quantities of coarse aggregate and sand. As may be expected, the coefficients of V_g and V_s in formula (7-1) shown that the influence of coarse aggregate content on passing ability is much higher than that of sand content. Furthermore, it is important to note that the g and h values are sufficient to estimate the passing ability only if the aggregate contents (V_g, V_s) are known. In other words, the two-point test cannot replace the L-test or the U-test, because the two-point test cannot discern the influence of aggregate on passing ability.

7.1.3.3 Comparison of rheological properties with other types of concrete

Fig. 4-13 shows four flow curves of different types of concrete (i.e. NC, FC, SCC and anti-washout concrete). It is clear that both SCC and FC have very low g values (i.e. collapse slumps), which indicate both can flow under their own weight. On the other hand, the h value (i.e. the inverse slope of flow curve in the figure) of FC is similar to that of NC, because the addition of superplasticizer mainly reduces the g value but does not affect significantly the h value. For SCC and AWC (anti-washout concrete), higher h values are required because of the requirements of segregation resistance and anti-washout ability. In general, SCC possesses a low g value and a high h value compared to that of NC.

7.1.3.4 Comparison of U-test with L-test

Table 7-4 shows the comparison of these two tests. In the U-test, the concrete flows due to its own weight whereas in L-test, the concrete flows horizontally after a free drop of 46 cm from a V-funnel. The speed at the outlet of V-funnel has an influence on the passing ability. For instance, for V-funnel flow times of 2 sec and 10 sec, the average speed at the outlet are 89 cm/sec and 18 cm/sec respectively. Hence, the horizontal momentum of the flowing concrete will be much different. For the U-test, there is no such effect. Another important difference is the reinforcement, there is one dimensional mesh in the U-test, and a two dimensional mesh in the L-test.

Table 7-4 Comparison of U-test and L-test methods

Test	Mesh	Gap mm	Width mm	Flow direction	concrete vol. litre	Operation time min	Value assessed
U-test	1D	40	200	↳↑	18	8	Filling height
L-test	2D	40	100	↓→	10 X 2	30	Flow time+, P.A.!

+ Flow time is the time concrete flows through V-funnel test.
! P.A.: passing ability, defined in chap. 4.

The U-test is generally used and accepted by Japanese industry, because many engineering experiences have confirmed that when the filling height is 300 mm or more, the passing ability through reinforcement is good [**Okamura** (1996)]. This criterion is especially valuable for the UK, due to the lack of experience of real projects using SCC. Moreover, the test is simple, portable and quick. Experience of using this and L-test in this programme have confirmed the superiority of the U-test. However, it still has some drawbacks. It is hard to clean after testing. It cannot differentiate between mixes of high but different slump flow. For instance, **Fig. 7-1** shows that for slump flows in the range of 550 mm to 750 mm, there is little effect on the filling height of the U-tests, whereas the L-test (**Fig. 7-5**) shows continually increasing passing ability.

The main advantage of the L-test is that it gives an excellent demonstration of self compacting properties. For example, **Photo 7-1** shows the excellent passing ability of SCC through reinforcement, whereas flowing concrete (FC) could not pass through the reinforcement (**Photo 7-2**) in spite of its good flowability. After the reinforcement had been removed, **Photo 7-3** shows FC flowed and filled the mould immediately.

The main disadvantage of L-test is how to apply the results in practice. Unlike the U-test there is no experience of acceptable L-test values for practical construction. The longer operation time of the L-test is another disadvantage.

The minimum requirements of slump flow for passing ability derived from the current tests are shown in **Table 7-5**. The requirement of aggregate content are the same for both tests, whereas the requirement of flowability is higher with respect to the L-test due to the two dimensional mesh. This result is consistent with the research of **Fujiwara et al** (1996) who have concluded that for SCC with 20 mm maximum size of aggregate, the influence of a one dimensional 40 mm gap mesh on passing ability is equivalent to a two dimensional 50 mm gap mesh. Hence, for the L-test (2D, 40 mm mesh) the requirement of flowability is higher than that of the U-test (1D 40 mm mesh).

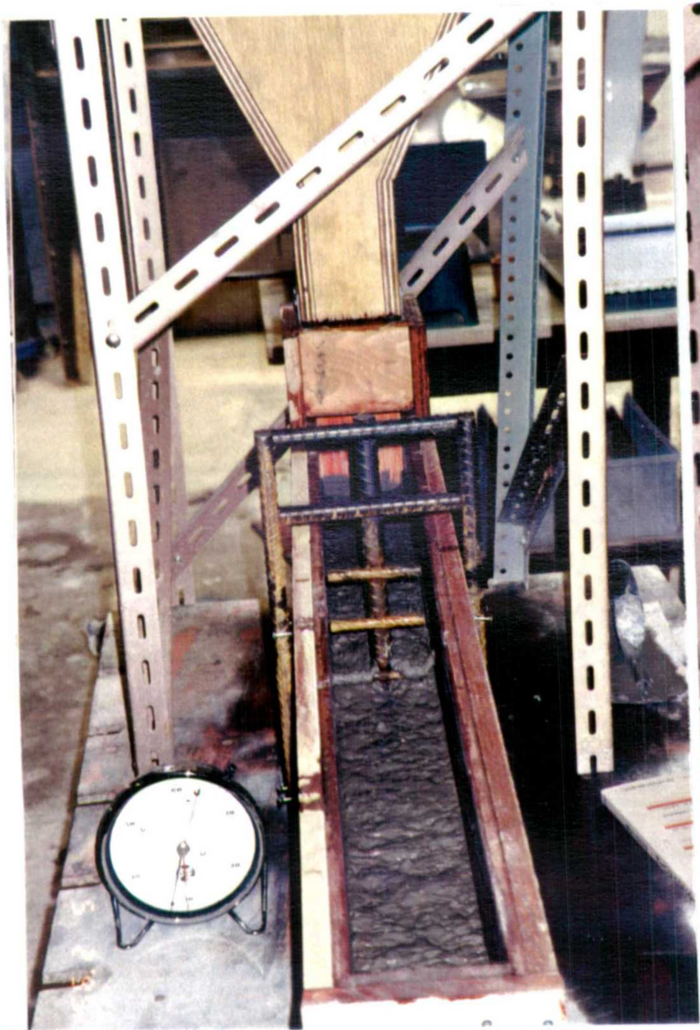


Photo 7-1 Excellent passing ability of SCC through reinforcement

Photo 7-2 Poor passing ability of FC through reinforcement

Photo 7-3 Good flowability of FC without reinforcement

Table 7-5 Minimum requirements of slump flow for passing ability

D_{max}(mm)	G/G_{lim}	V_s/V_m	Slump Flow (mm) *U-test	Slump Flow (mm) ^L-test
25	0.5	0.40-0.45	≥ 500	blocked
20	0.50	0.40 - 0.47	≥ 500	≥ 600
10	0.50-0.52	0.40-0.50	≥ 400	≥ 500
10	0.52-0.55	0.40-0.46	≥ 400	≥ 500

* filling height higher than 300 mm.
^ Passing ability higher than 60%

In conclusion, both tests have their merits and shortcomings. For the purpose of comparison with other results and industrial application, the U-test is recommended. However, for the purpose of teaching and demonstration, the L-test is preferred.

7. 2 Segregation resistance of SCC

7.2.1 Experimental objectives

The main objectives of the work reported in this section were to:

- determine the effect of different size of aggregate on the segregation resistance of SCC.
- compare the factors influencing segregation resistance between NC and SCC.

7.2.2 Experimental variables

The main experimental variables were maximum aggregate size and the concrete viscosity, which was gained by varying the water/powder ratio and the sand content, as shown in **Table 7-6**. For all these mixes, the superplasticizer dosage was such that sufficient fluidity (as measured by slump flow) was obtained. In addition, all SCC mixes except S116 had a coarse aggregate content (G/G_{lim}) in the range of 0.50 to 0.52 so that good passing ability would be achieved.

Table 7-6 Parameters for segregation resistance tests

D_{max}	W / P	V_s/V_m	Mix ref.
Gravel 20 mm	0.29	0.40	S227, M201
	0.28	0.43	S214
	0.34	0.44-0.45	S215-S219, S221, S222
	0.37	0.45-0.47	S229, S230
(For comparison)	0.50	0.45-0.48	F206, F207, N206, N210
Gravel 10 mm	0.28-0.29	0.40	M101-M103
	0.35	0.45-0.46	S111, S113
	0.38-0.40	0.48-0.50	S109, S110, S112, S114, S116
	0.50	0.45-0.50	S115 ,M105
Granite 10 mm	0.34-0.35	0.40-0.48	S107-I, M104-I

7.2.3 Results

7.2.3.1 Relationships between the rheological constants and slump flow and V-funnel flow time

The values of g and h values from the two-point test are proportional to the yield stress and plastic viscosity of the concrete respectively. The two-point tests are generally carried out in the laboratory; whereas the slump flow tests and V-funnel flow tests are easily carried out on site. It is very useful to know the relationship between the test results so that they can be properly interpreted. **Fig. 7-6** and **Fig. 7-7** show the relationship between slump flow and g and h values respectively. It is clear that there is a broad correlation between g and slump flow, whereas there is no direct relationship between h value and slump flow. Therefore, slump flow can be considered as an alternative index of g value: the higher the slump flow, the less the yield stress. On the other hand, the h values have a direct relation with V-funnel flow time, as can be seen in **Fig. 7-8,** especially in the range of V-funnel flow time from 2 seconds to 10 seconds. Hence, the V-funnel flow test can be considered as a measurement of viscosity. It is worth noting that the relationship in **Fig. 7-8** is valid only if the coarse aggregate content is in a limited range (G/G_{lim} 0.50-0.52) and the g value is small, because there are three factors influencing the V-funnel flow time, one is viscosity (**Fig. 7-8**), the others are coarse aggregate content (**Fig. 3-9**) and the g value.

7.2.3.2 Segregation resistance for different sizes of aggregate

Fig. 7-9 shows the relationship between the segregation index (defined in **Chapter 4**) and the h value of the two-point test. When the maximum size of aggregate is 20 mm, the trend of a lower segregation index with increasing h is apparent. This trend is consistent with published information and is widely accepted [**Kawai et al** (1994)]. In contrast, with a 10 mm maximum size of aggregate, there is no clear relationship. This indicates that the viscosity of the concrete is not the only factor controlling the segregation resistance, the

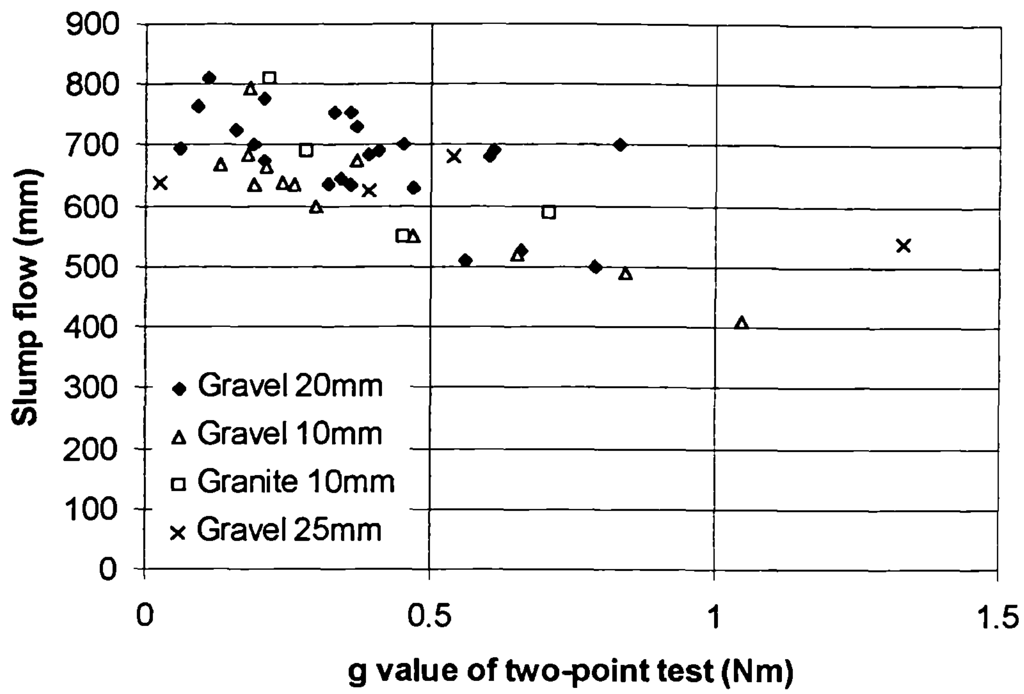


Fig 7-6 Relationship between g value and slump flow

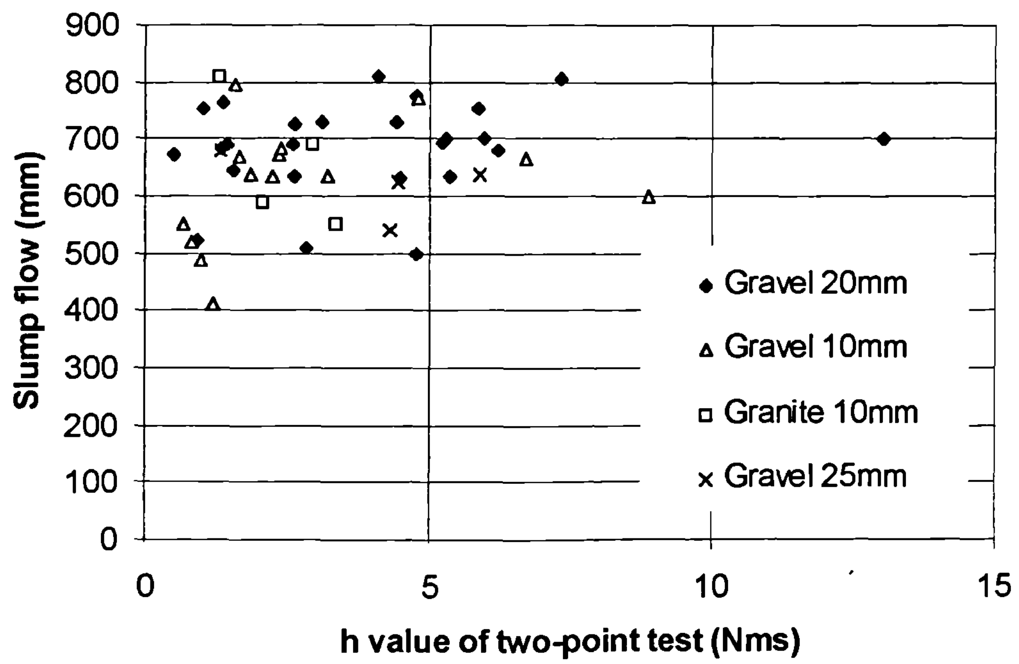


Fig 7-7 Relationship between h value and slump flow

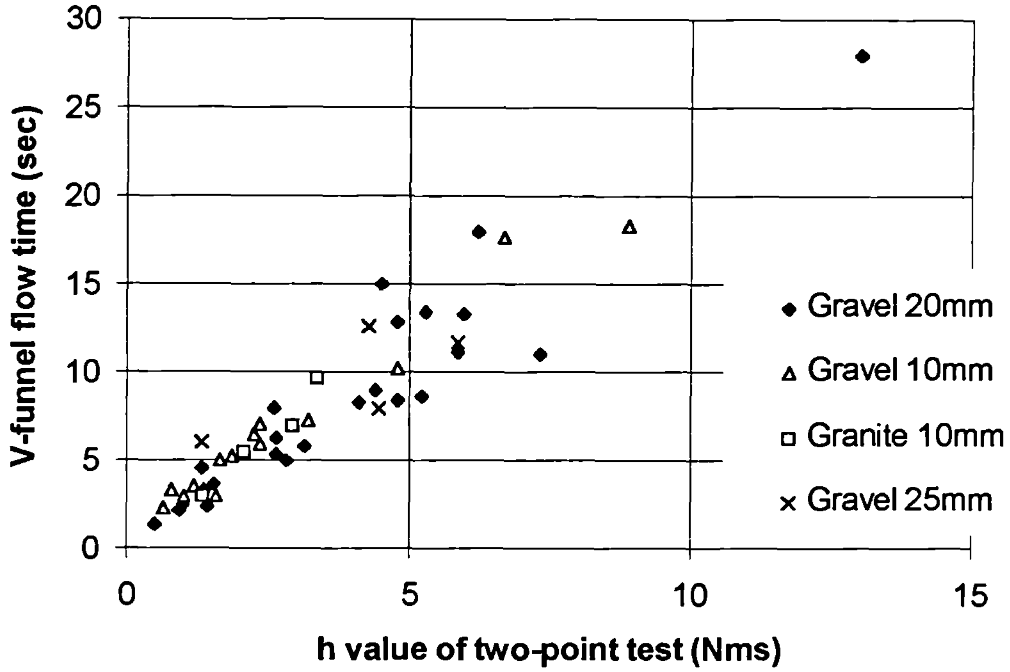


Fig. 7-8 Relationship between h value and V-funnel flow time

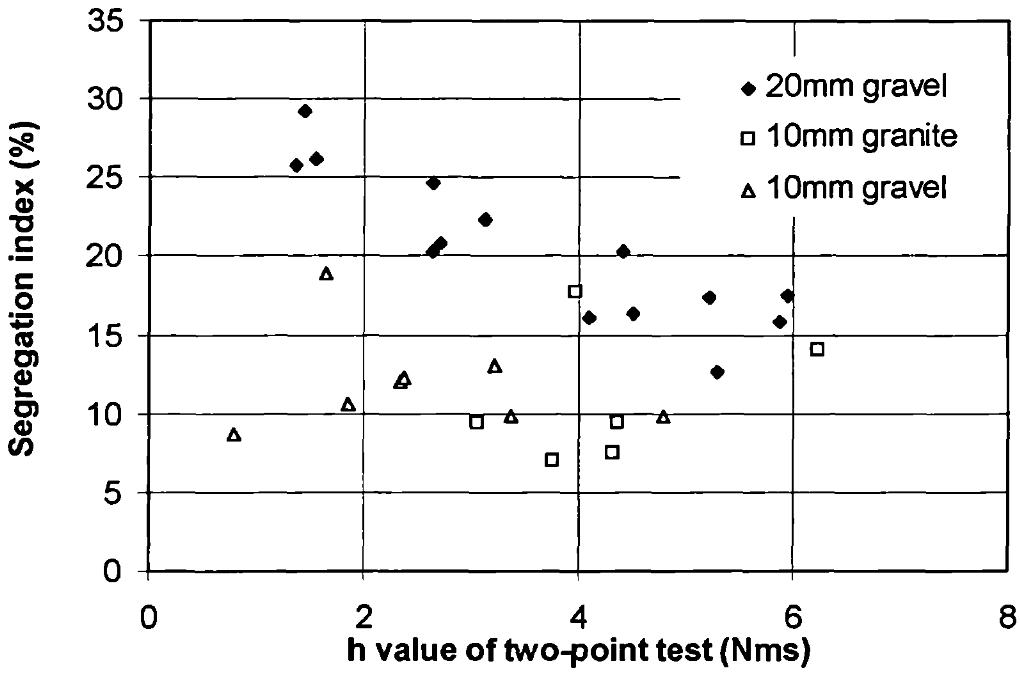


Fig. 7-9 Relationship between h value and segregation index

maximum size of aggregate must also have an influence. In addition, **Fig. 7-10** shows the relationship between the segregation index and the V-funnel flow time, in which the trend is similar to **Fig. 7-9,** as would be expected from the good relationship between V-funnel flow time and h **(Fig. 7-8)**. It can be concluded from **Fig. 7-9** and **Fig. 7-10** that the segregation resistance is improved when the maximum size of aggregate is 10 mm, and that there is no direct relationship between it and the viscosity of concrete. This trend can also be seen in **Fig. 7-11,** 10 mm aggregate concrete has a lower segregation index than 20 mm aggregate for the same g value, although there is no clear relationship between the two.

7.2.4 Discussion of factors influencing the segregation resistance

7.2.4.1 Viscosity of concrete

From the literature review, it is quite clear that when the maximum size of aggregate is 20 mm, a moderate viscosity of fresh concrete is required to prevent segregation. According to **Ozawa et al** (1995), the V-funnel (75 ×75) flow time should be between 4 and 10 sec. **Fig. 7-8** shows that the corresponding h value should be between 2.0 and 5.0 Nms. In order to obtain moderate viscosity, the sand content needs to be adjusted according to the water/powder ratio. As can be seen in the following table, the viscosity of mix S225 is too high because of its higher sand content (V_s/V_m 0.45), whereas those of mix S203 and S204 are too low due to their lower sand contents (V_s/V_m 0.40). The viscosity of every other mix is suitable because its sand content has been adjusted according to **Table 6-5.**

Table 7-7 Achieving moderate viscosity by adjusting sand content according to W/P

Mix ref.	S225	S203	S204	S215	S221	S227	S229	S230
W / P	0.26	0.34	0.34	0.34	0.34	0.29	0.37	0.37
V_s/V_m	0.45	0.40	0.40	0.45	0.45	0.40	0.47	0.45
h (Nms)	7.32	N/A	1.32	3.13	4.1	4.4	2.64	2.64
V-funnel (sec)	11.0	3.4	6.0	5.8	8.3	9.0	6.3	5.3
Viscosity	too high	too low	too low	suitable	suitable	suitable	suitable	suitable

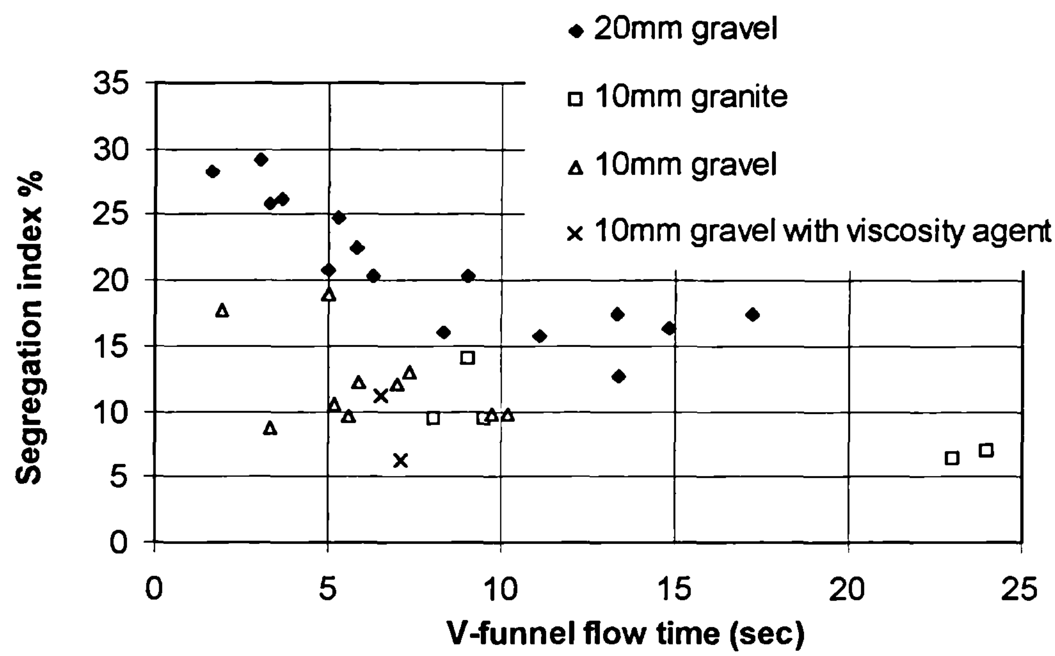


Fig. 7-10 Relationship between V-funnel flow time and segregation index

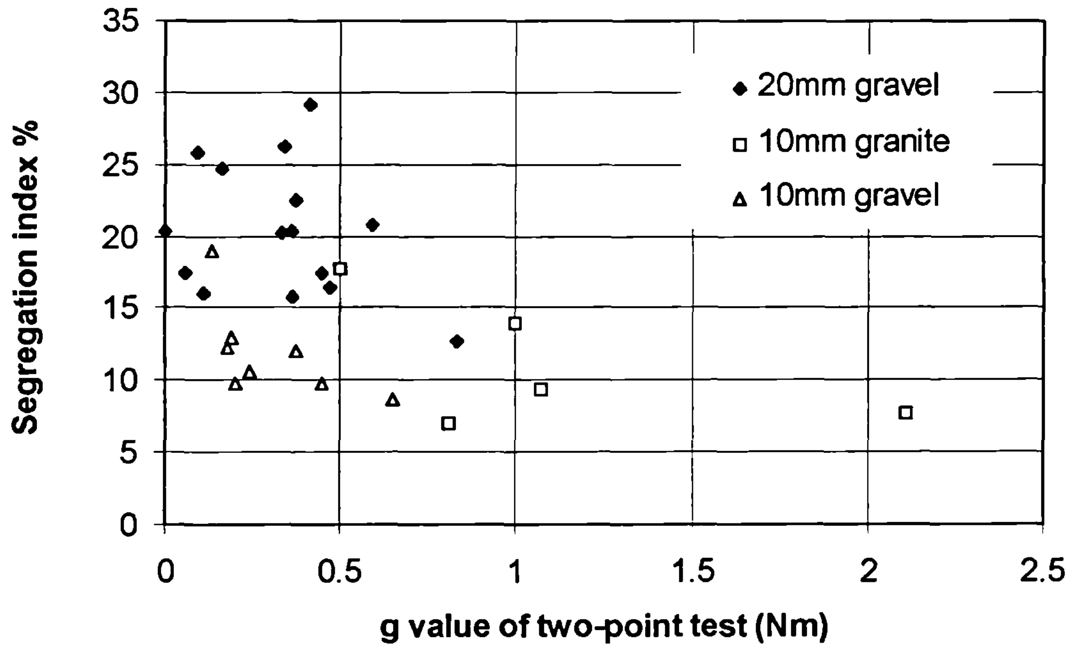


Fig. 7-11 Relationship between g value and segregation index

7.2.4.2 Surface area of coarse aggregate

The main reason that SCC with 10 mm aggregate has a low segregation index can be explained by considering the following two mixes:

Mix ref.	D_{max} (mm)	Water (Kg/m^3)	PC	PFA	CA !	CA +	F.A.	SP % *	W/P	W/T.F
F206	20	223	380	67	271	542	805	0.49	0.50	0.178
S115	10	223	380	67	813	0	805	0.60	0.50	0.178

! (5-10 mm), +(10-20 mm), * solid by wt. of powder

which were found to have the following properties:

Mix ref.	D_{max} (mm)	Slump flow (mm)	μ_p* (mPa.s)	V-funnel flow time (sec)	Segregation index (%)
F206	20	610	33	1.6	28.2
S115	10	710	33	1.9	17.7

* Calculated paste viscosity

It is obvious that both of these two mixes did not have sufficient viscosity for the requirements of SCC, because the V-funnel flow time is less than two seconds, the water / total fine ratio is higher than 0.137 and the calculated paste viscosity is less than 280 mPa.s (D_{max} 20 mm) and 70 mPa.s (D_{max} 10 mm). As expected, the segregation resistance was poor (the segregation index was 28.2%) when the maximum size of aggregate was 20 mm. In contrast, for 10 mm maximum size of aggregate, the segregation resistance was good, (the segregation index was 17.7%), even though the dosage of superplasticizer was higher and slump flow was larger. The reason is that the 10 mm coarse aggregate has larger total surface area than 20 mm coarse aggregate for the same coarse aggregate content. In fact, in this case, this surface area factor (surface area of coarse aggregate) has a larger influence on the segregation resistance of concrete than any other factor, for instance, the viscosity.

7.2.4.3 Coarse aggregate content and yield value of mortar

Consider another two mixes, one a normal concrete (NC), and the other a self-compacting concrete (SCC), both with a maximum size of aggregate of 20 mm.

Mix ref.	D_{max} (mm)	Water (Kg/m^3)	PC	PFA	CA !	CA +	FA	SP % *	W/P	W/T.F
S215	20	186	438	110	271	542	801	0.72	0.34	0.138
N206	20	244	488	0	346	691	691	0	0.50	0.207

! (5-10 mm), +(10-20 mm), * solid by wt. of powder

Which were found to have the following properties:

Mix ref.	Slump flow (mm)	g (Nm)	h (Nms)	V-funnel flow time (sec)	Segregation index (%)
S215	730	0.37	3.13	5.8	22
N206	135 (slump)	3.66	1.77	blocked	10

Although the SCC had a higher h value, higher sand content and lower water/powder ratio, surprisingly the segregation index of NC was less than that of SCC. **Table 7-8** shows the comparison of factors influencing the segregation resistance of these two mixes.

Table 7-8 Comparison of SCC with NC regarding segregation resistance

Known factors increasing segregation resistance	SCC	NC
higher h value	+	
higher sand content	+	
lower water / powder ratio	+	
Other factors:		
higher coarse aggregate content		+
higher g value		+
segregation index %	22	10

The reasons that the NC had a lower segregation index must result from the higher coarse aggregate content and the higher g value. In other words, these two factors overwhelm the first three factors with respect to segregation resistance.

To help explain this, the approach of **Kimura** et al (1990) is useful. They expressed a segregation index as:

$$S.I. = (W_{mf} - W_{ms}) / W_{mf} \times 100\% = (1 - W_{ms} / W_{mf}) \times 100\% \quad \textbf{(7-2)}$$

of which

W_{mf}: the weight of mortar in the fresh concrete

W_{ms}: the weight of mortar adhering to the coarse aggregate

The value (W_{mf} - W_{ms}) was measured by determining the amount of mortar flowing through a 5 mm sieve in 5 minutes under self weight. This is therefore a different way of assessing the segregation index to that used in the current study, but the factors influencing the segregation resistance will be the same. The weight W_{ms} is a function of the total surface area of the coarse aggregate and the adhesion of mortar to it. It is clear from Formula 7-2, that the higher the value of W_{mf}, the higher the segregation index; and the higher W_{ms}, the less the segregation index. In the example given above, W_{mf} is 1535 Kg/m^3 and 1205 Kg/m^3 for SCC and NC respectively, the weight of mortar in SCC was much higher than that of NC so that the SCC had a higher segregation index in spite of its higher mortar viscosity.

In order to understand the factors influencing the adhesion of mortar to aggregate, a glass ball test was used as described in **Chapter 4**. **Fig. 7-12** shows the relationship between the mortar adhesion to the glass balls and the relative flow area of mortar from the spread test. As can be seen, adhesion reduces with increasing flow area (obtained by increasing superplasticizer). In **Chapter 5**, it was shown that the larger the flow area, the less the yield stress. Hence, superplasticizer reduces both yield stress and adhesion significantly. As a result, the adhesion of mortar to coarse aggregate is dependant on the yield stress of the mortar. This result is consistent with the work of **Fujiwara et al.** (1992). **Fig. 7-13** shows two ways of increasing the mortar adhesion, one is suitable for SCC. i.e., increasing the viscosity; the other is not applicable for SCC, i.e., increasing the yield stress (by using less superplasticizer) which will impair the passing ability through reinforcement. Methods of increasing the viscosity of mortar have been described in **Table 6-1**. It is important to note that the viscosity of the mortar cannot be so high so that its cohesion will be lower than its adhesion, as mentioned in Chapter 6.

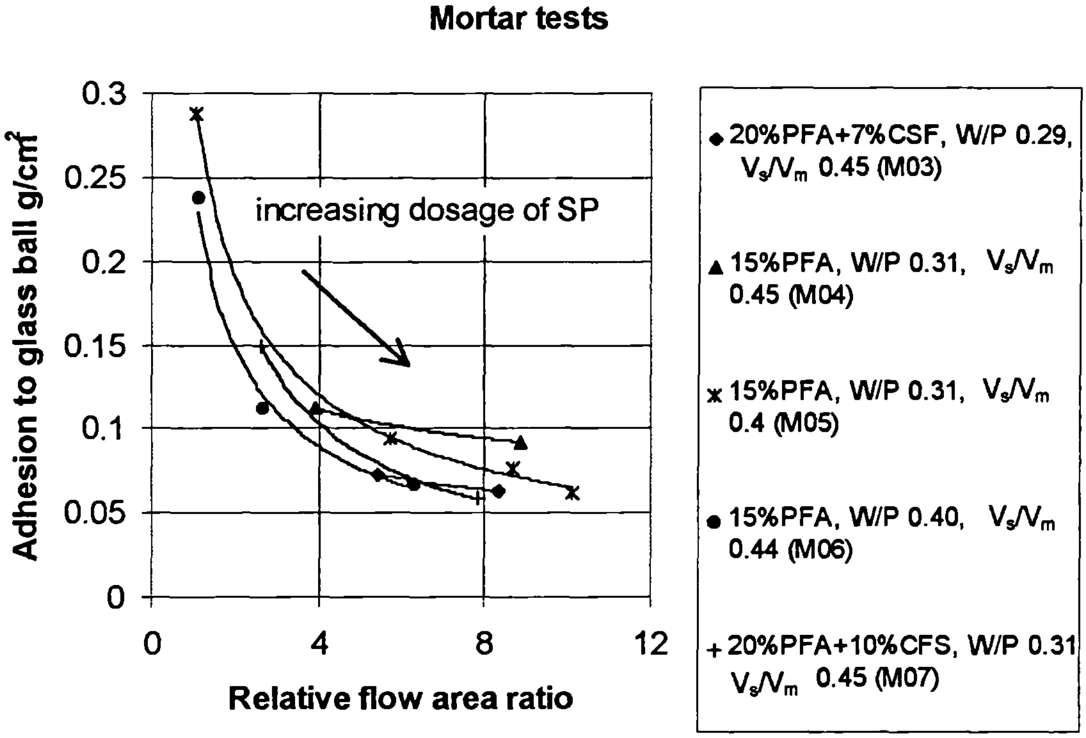


Fig 7-12 Relationship between relative flow area ratio and adhesion to glass ball

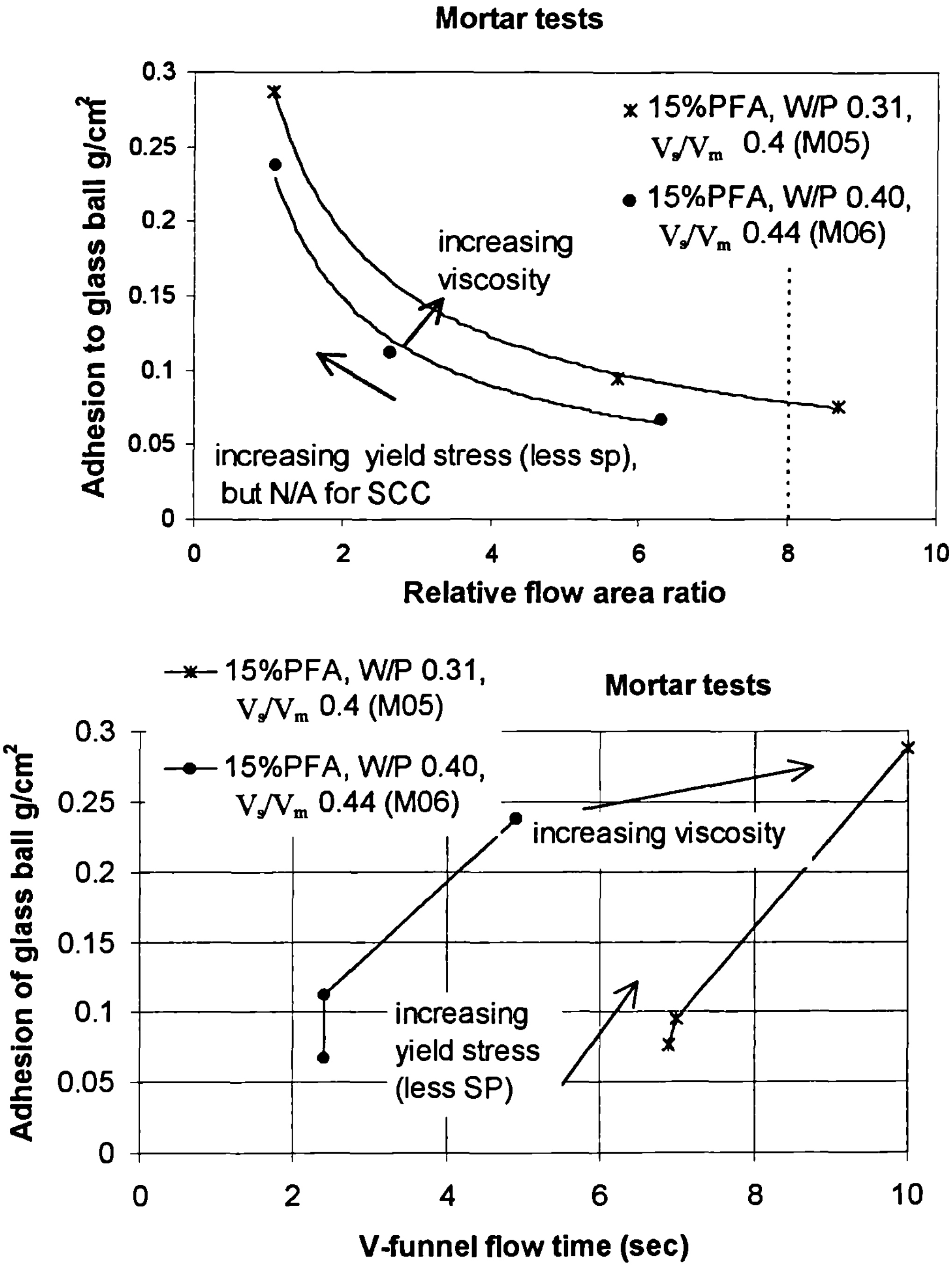
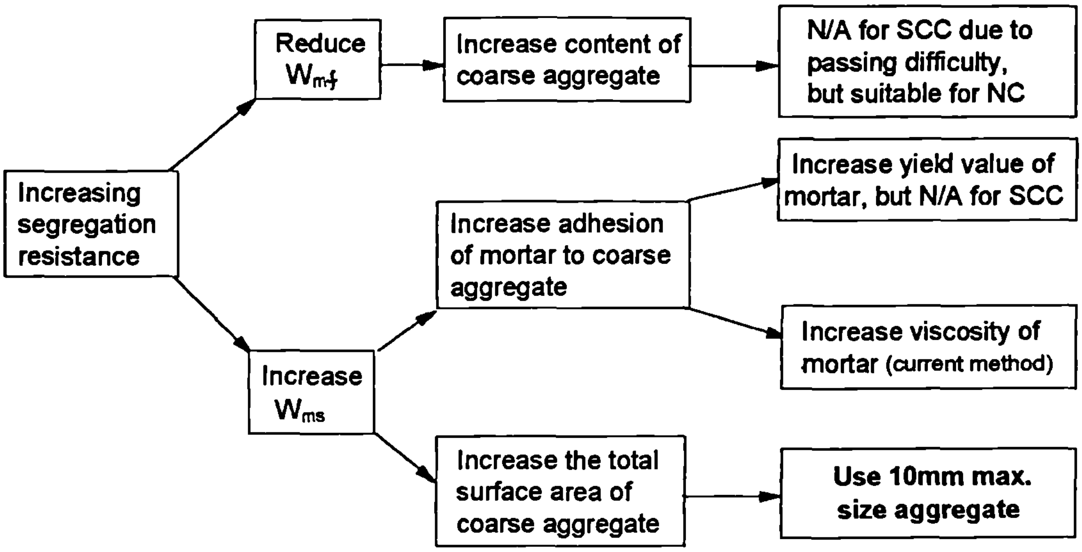


Fig. 7-13 Two methods to increase mortar adhesion.

Methods of increasing the segregation resistance are shown schematically in **Fig. 7- 14**. High segregation resistance for normal concrete (NC) results from higher coarse aggregate content and higher yield stress whereas for SCC it results from increasing the viscosity of mortar and using a smaller maximum size aggregate. So far, no published work on the latter effect has been found.



W_{mf}: the weight of mortar in the fresh concrete
W_{ms}: the weight of mortar adhering to the coarse aggregate

Fig. 7-14 Schematic representation of factors influencing segregation resistance

7.2.4.4 Overdose of superplasticizer

From observations in the experimental work, unexpected segregation often resulted from an overdose of superplasticizer. **Table 7-9** shows the change of segregation resistance for four mixes. Paste could be seen on the top surface of fresh concrete, with a sediment of aggregate at the bottom. It is clear that the adhesion of paste to aggregate is greatly reduced by the overdose. This phenomenon can be eliminated through good quality control. Also, Mix M105 shows that an increase of sand content may minimise the segregation in spite of its low value of calculated paste viscosity. Moreover, as mentioned in the literature review, incorporation of a viscosity agent also greatly reduces the influence of overdose of superplasticizer. However, this effect is beyond this study, and needs to be confirmed in the future.

Table 7-9 Influence on segregation resistance of overdose of superplasticizer

Mix ref.	M101	M102	M104-I	M105
S.I. (initial)	9	8	10	9
S.I. (overdose)	52	18	31	19
W / P	0.28	0.28	0.33	0.50
V_s / V_m	0.40	0.40	0.40	0.50
Composition	50%PFA+	50%PFA+	50%PFA+	50%PFA+
	50%LSP	50%LSP	50%GGBS	50%GGBS
μp* (mPa.s)	588	588	558	40

7.2.5 Significance of the results

The two methods of increasing segregation resistance of SCC (shown in **Fig. 7-14)** are:

1. increasing the viscosity;
2. using 10 mm maximum size of aggregate.

The second is the most economical. In Japan, the unit price of SCC is double that of NC (private communication with **Ozawa**, 1996) mainly due to the high dosage of superplasticizer or the use of viscosity agent. (Though the powder content of SCC is generally higher than NC, the price of the binder does not increase significantly due to large percentage of cheap CRM such as PFA and GGBS.) Normally, for SCC there is no need for a viscosity agent if the water/powder ratio is less than 0.37 when the maximum size of aggregate is 20 mm (Mix ref. S230, S229). However, by using 10 mm maximum size of aggregate, the viscosity requirement can be reduced as shown in **Table 7-10**. In other words, the viscosity of SCC with 10 mm aggregate can be reduced approximately to that of FC, whereas the viscosity of SCC with 20 mm aggregate is similar to that of anti-washout concrete **(Fig. 4-13)**. Furthermore, the water/powder ratio can be increased to at least 0.46 without the need for a viscosity agent. The higher the water/powder ratio, the less the dosage of superplasticizer and, of course, the cost of the SCC. Hence, this new finding can reduce the cost of SCC significantly. **Table 7-11** gives an example of this. There is further discussion of the cost of SCC in **Chapter 9**.

Table 7-10 Reducing the requirement of viscosity for SCC by using smaller size CA

D_{max}	V-funnel flow time	h-value	Possible rating for segregation resistance
20 mm	4 - 10 sec	2 - 5 Nms	Good
10 mm	2 - 10 sec	1 - 5 Nms	**Excellent**

Table 7-11 Example of a reduction in the cost of SCC

D_{max} mm	CA	FA	W	PC	PFA/ GGBS	SP	W/P	cost
20	820	809	185	372	157	6.0	0.35	£ 49
10	800	824	218	428	48	1.0	0.46	£ 42

Assume: Unit price of materials:

Aggregate	PC	PFA	GGBS	SP
£ 8 / ton	£ 60 / ton	£ 20 / ton	£ 30 / ton	£ 1.2-1.9 / litre

Another application of this new finding is that when CSF is incorporated in SCC, it is better to use 10 mm maximum size aggregate rather than 20 mm, because CSF reduces the viscosity of concrete as can be seen in Mix S216, S217, and S224, whose h values all are less than 2.0 Nms, which is the minimum requirement of viscosity for SCC with 20 mm maximum size of aggregate. As a result, the segregation resistance of these mixes are in the poor category.

7. 3 Conclusions

SCC is distinguished by its fresh properties: good passing ability through reinforcement without compaction and good segregation resistance. There are four main factors influencing the passing ability:

1. the ratio of mesh gap to maximum size of aggregate;
2. the aggregate content;
3. the flowability.
4. the segregation resistance

The first one relates to reinforcement detailing, the second one relates to its composition, the last two relate to its rheological properties. As a general guide, the coarse aggregate content should be around 50% of its dry rodded weight, the sand volume should be between 40% to 47% of the mortar volume, i.e. V_s/V_m: 0.40-0.47, the exact volume depending on the water/powder ratio and a minimum volume of paste of 38% of concrete. In addition, a slump flow between 600 mm to 700 mm and 650 mm to 750 mm will be sufficient for SCC whose maximum size of aggregate is 10 mm and 20 mm respectively.

Table 7-12 shows how to apply the results of these tests discussed in this chapter. To apply the value of V-funnel flow test, the coarse aggregate content (G/G_{lim}) should be 0.50.

Table 7-12 Test criteria of SCC

Properties of SCC	Assessing tests	Assessing value	Test criteria		
			Poor	**Fair to good**	**Excellent**
Passing ability	U-test	filling height	< 300 mm	300 - 350 mm	≥ 350 mm
	L-test	P.A.	< 60%	60% - 80%	≥ 80%
Segregation resistance	Two-point test	Segregation index	> 25%	15% - 25%	< 15%
(D_{max} 20 mm)	V-funnel test	flow time	<4.0	4.0-10.0	*
(D_{max} 10 mm)		sec	!	2.0-4.0	4.0-10.0

* SCC with 20 mm max. size aggregate hardly possesses excellent segregation resistance unless it has higher g value.
! SCC with 10 mm aggregate hardly possesses poor segregation resistance unless excessive superplasticizer is incorporated.

There are several factors influencing the segregation resistance of fresh concrete. Because of the requirement of passing ability, some are not applicable for SCC, e.g. larger quantities of coarse aggregate and high yield value of mortar. However, according to the published literature good segregation resistance of SCC can be obtained through lowering the water/powder ratio or incorporating a viscosity agent or, from the result of this study, by using the 10 mm maximum size of aggregate. The last method can effectively reduce the segregation compared with that of SCC whose maximum size of aggregate is 20 mm. Therefore, this new finding can reduce:

- the requirement of viscosity for SCC
- the cost of SCC.

As a result, it is a stimulation to the construction industry to implement its use.

Chapter 8

Some Hardened Properties of SCC

Because SCC is a new kind of high performance concrete, it is necessary to confirm that its hardened properties are similar to those of the equivalent 'normal concrete'. Of particular interests are bond strength, shrinkage and compressive strength.

- According to **Brettmann et at** (1986), a decrease in bond strength occurs when superplasticized concrete is not vibrated. Does this also apply to SCC? Since very few papers have reported data on the bond strength of SCC, further investigations are required.
- Since the paste volume of SCC is higher than normal concrete, drying shrinkage may be increased, and so needs to be measured.
- Due to the different types and high percentages of CRMs used in SCC, the conventional Abraham's law is not adequate to estimate its strength. As in any mix design method, this estimation is essential, and a modified formula is required. Also, in the construction industry the development of early strength is important, for example, for striking of formwork, and due to the large quantities of CRMs and the high dosage of superplasticizer used in SCC, its one day strength is not easy to predict. The controlling factors need to be discovered.

Tests were carried out to investigate all these of the above properties. The test methods have been described in **Chapter 4**. The test specimens were cast from the same concrete mixes as those tested for fresh properties in Chapter 7. All the mix proportions and test results are listed in **Appendix 3.**

8. 1 Bond between SCC and reinforcement

Bond mainly is made up of three components: chemical adhesion, friction, and mechanical interaction between concrete and rebars. The bond of plain bars depends primarily on the first two elements, whereas that of deformed bars depends mainly on mechanical interlocking [**Freedman** (1974)].

8.1.1 Experimental objectives

Bond strengths were measured by pull-out tests, whose purposes were:

- to compare the bond of SCC to rebars with that of fully compacted concrete;
- to find the influence of compaction on the bond of SCC to rebars;

8.1.2 Experimental variables

Table 8-1 Parameters of pull-out tests

Types of rebars	Compaction	Mixes ref.
Plain bar	none	S212-S215, S217-S219, S226-S228, S107-S109 S114, F204-F205, F207, N204, N207, N211
Deformed bar	none	S108, S110, S113, S220, S222, N209
	yes	S220, S222, N209

8.1.3 Results and discussion

Fig. 8-1 shows the typical relationship between bond and slip. As can be seen, the deformed bar has higher bond strength and slip than that of plain bar. The failure modes were also different. For the plain bars, generally after the tests the concrete was still left as a whole cube, sometimes with cracks developed from the hole from which the rebar was pulled. With the deformed bars, the concrete was split into two or three pieces, sometimes in a violent burst.

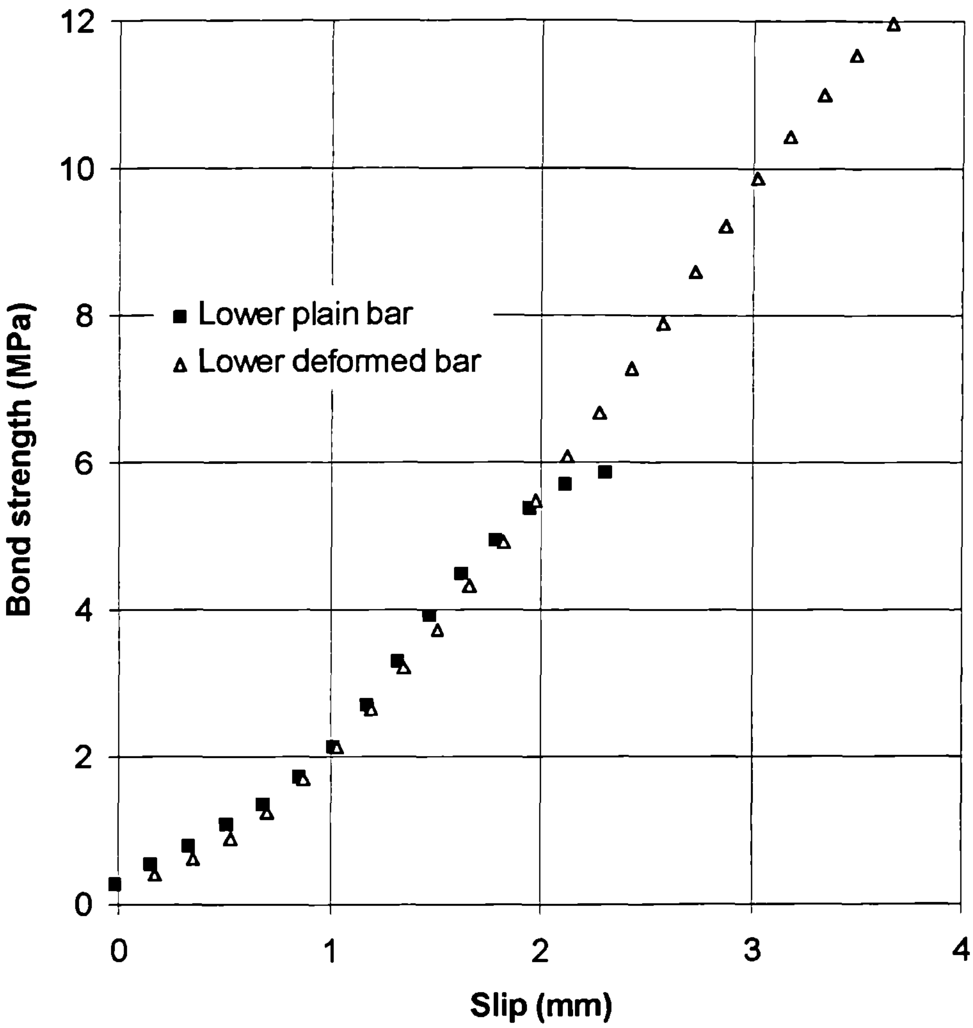


Fig. 8-1 Relationship between slip and bond strength

Table 8-2 shows the reference bond strength of fully compacted concrete [**Gj∅rv et al** (1990)] These data were obtained with the same test method and a similar range of compressive strength as in the current programme. However, Gj∅rv's data for the bond of plain bars to NC of low compressive strength seem to be unreasonably low.

Table 8.2 Bond strength results from **GjØrv et al** (1990)

Mix No	Water/binder ratio	Cube strength (MPa)^	Plain bar		Deformed bar	
			upper	lower	upper	lower
0-6000	0.46	46	0.5	0.7	8.6	11.8
0-9000	0.35	63	2.4	2.9	10.0	9.3
0-12000	0.27	75	3.7	7.1	13.7	12.3
8*-6000	0.53	48	1.0	1.5	8.9	10.9
8-9000	0.38	72	5.1	4.6	11.9	12.5
8-12000	0.28	87	5.1	9.3	16.3	16.1

! Bond strength calculated from maximum pull-out load, unit MPa
* Mixes with 8% silica fume
^ Converted from cylinder strength

Fig. 8-2 to **Fig. 8-5** show that, in most cases, the bond strengths to SCC are higher than GjØrv's data for the same compressive strength. These differences are significant, especially for the plain bar, because the adhesion of SCC to the steel is much higher than the conventional concrete.

It is worth noting that for the lower plain bars, the bond is generally higher than that for the upper bar (**Fig. 8-6**). There are two possible reasons for this: (1) bleeding water accumulates more easier beneath the upper bars than the lower ones, (2) settlement shrinkage of the concrete is proportional to the depth of fresh concrete beneath the rebars, hence the resulting loss of bond of the upper bar is higher.

However, for the deformed bars the bond is mainly due to mechanical interlocking between the concrete and the bars, and hence, the differences between the bond of upper bars and that of lower bars are less, as can be seen in **Fig. 8-7**.

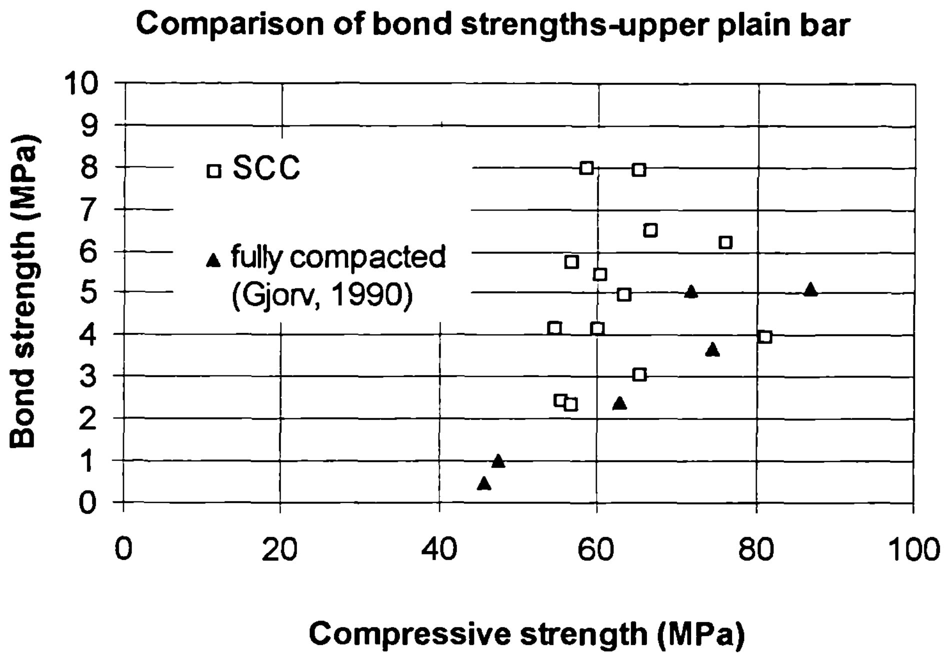


Fig. 8-2 Bond strength of SCC to upper plain bar

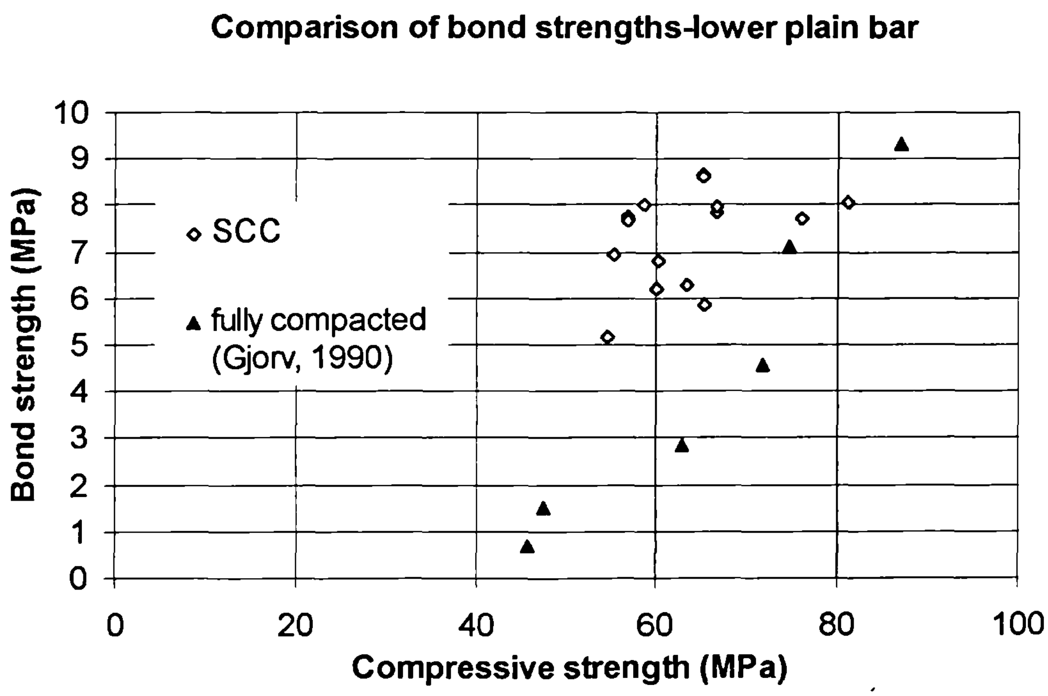


Fig. 8-3 Bond strength of SCC to lower plain bar

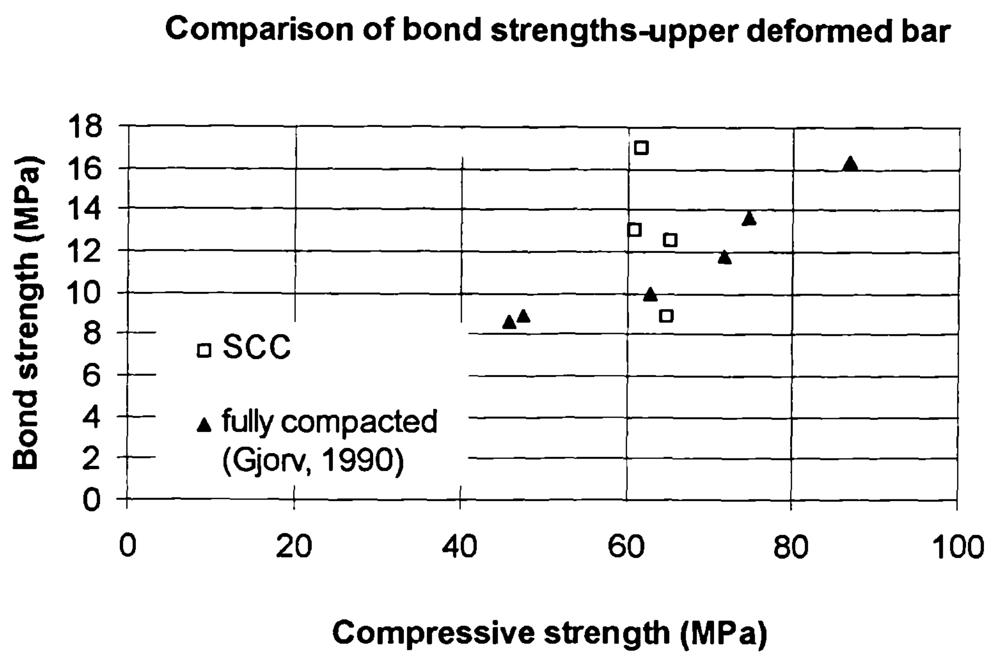


Fig. 8-4 Bond strength of SCC to upper deformed bar

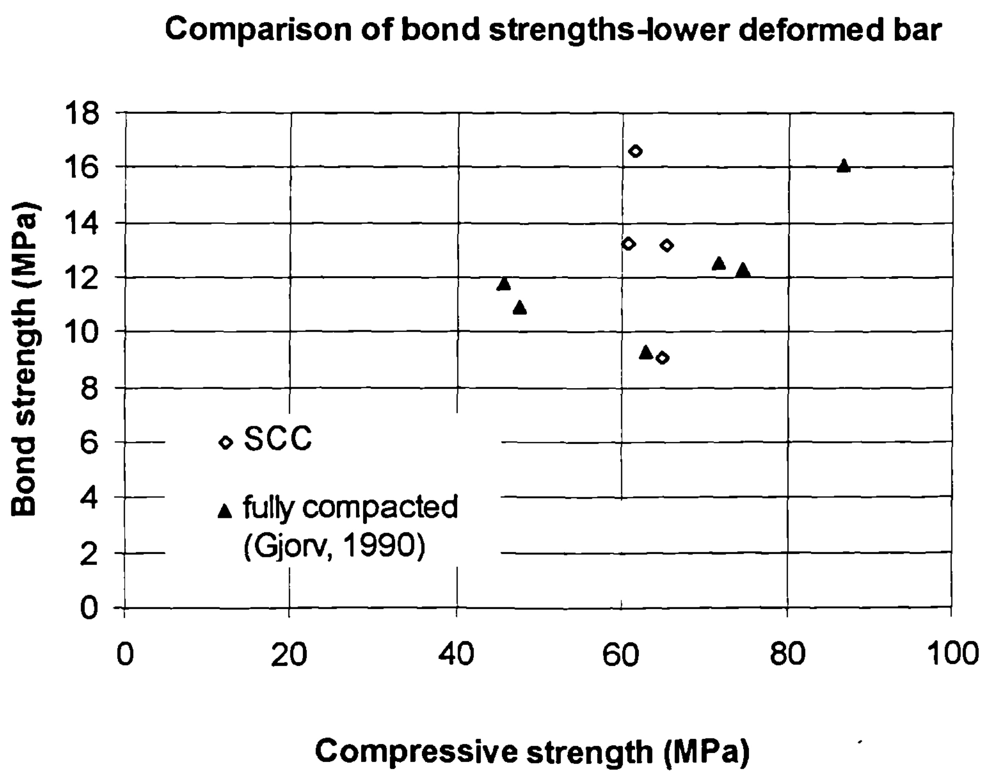


Fig. 8-5 Bond strength of SCC to lower deformed bar

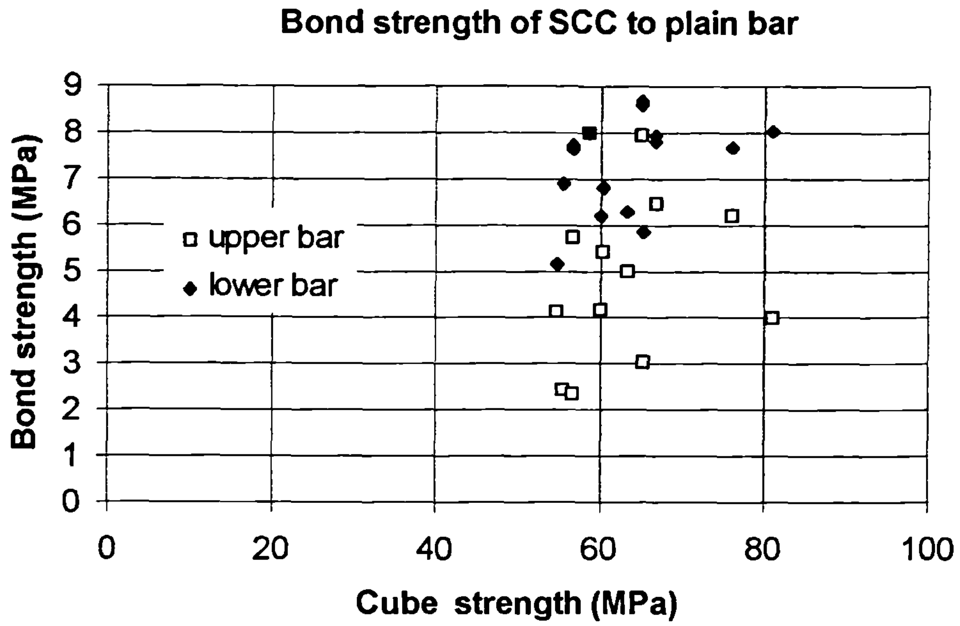


Fig. 8-6 Comparison of bond to plain bar for different bar positions

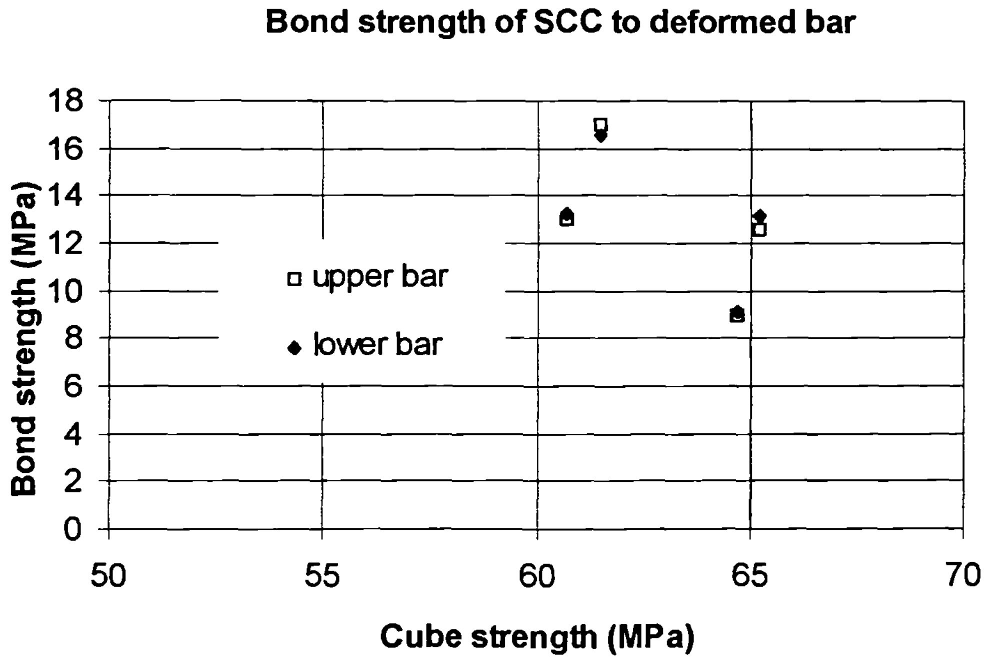


Fig. 8-7 Comparison of bond to deformed bar for different bar positions

Fig. 8-8 shows the results of tests to measure the bond strength of lower plain bars to different kinds of concrete without compaction by vibration. As expected, the NC has the lowest bond. In contrast, the bond to FC (w/c: 0.40, 0.43, 0.50) is similar to that to SCC. Therefore, according to this study, for FC of low water/powder ratio, the bond is satisfactory; whereas according to **Brettmann et at** (1986) for FC of high water/cement ratio, the bond is less than that of fully compacted concrete

For fully compacted concrete, **ENV** EC2 defines the lower location (hatched zones in **Fig. 8-9**) as good bond conditions, and the upper location as poor bond conditions. Where bond conditions are poor (top zones), the ultimate bond stress should be multiplied by 0.7. However, on an engineering site, there can be a high risk of undervibration especially for the bottom section of concrete structures, and a result, supposedly good bond conditions can become poor, particularly for NC with a slump of less than 100 mm. On the other hand, revibration, though sometimes unintentional, is almost universally detrimental to the bond strength of bottomcast bars according to **ACI 309R- 7.4.** Overall, the best way to eliminate the risk of improper vibration is to use self-compacting concrete.

To verify the influence of compaction on the bond of SCC, eight specimens were tested with and without compaction. **Fig. 8-10** shows that full bond strength of SCC to deformed bars can be achieved without compaction.

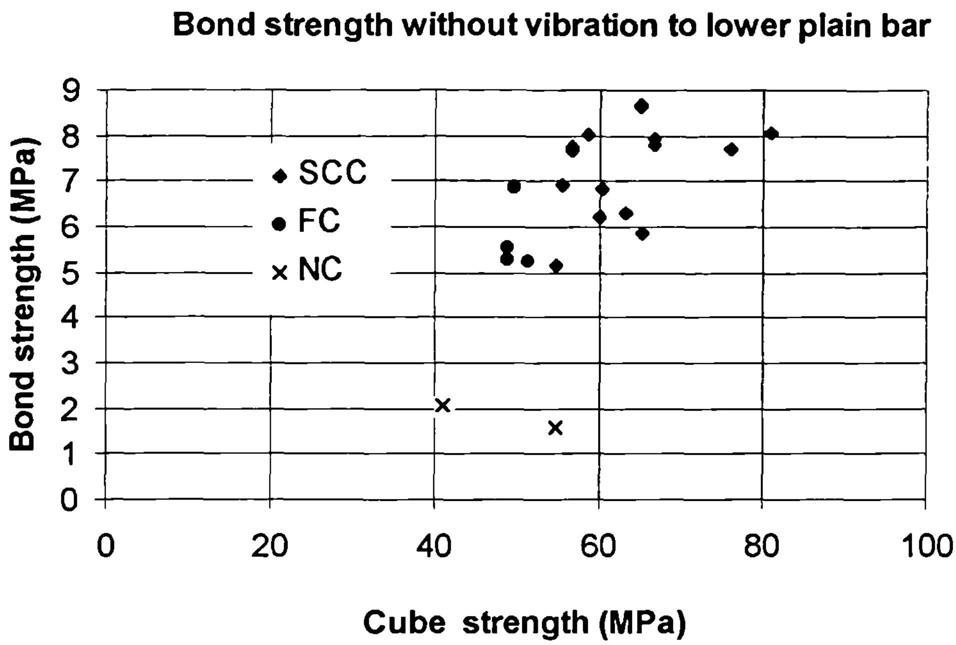


Fig-8-8 Relationship between the bond strength of different kind of concrete.

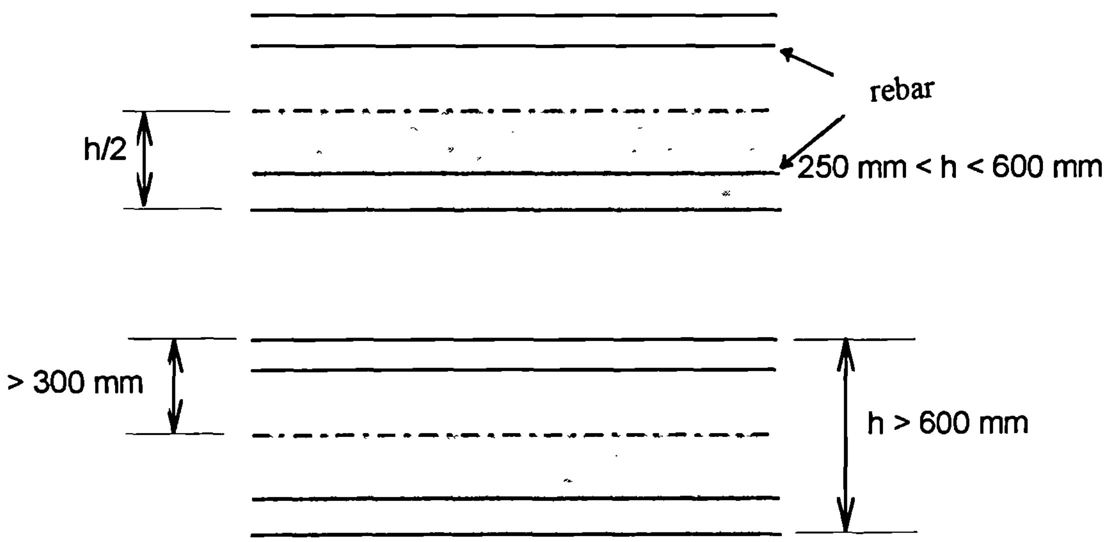


Fig. 8-9 Bond conditions: (a) good bond conditions for bars in shading zones (b) poor bond conditions for bars in non-shading zones (EC2 10.2.4)

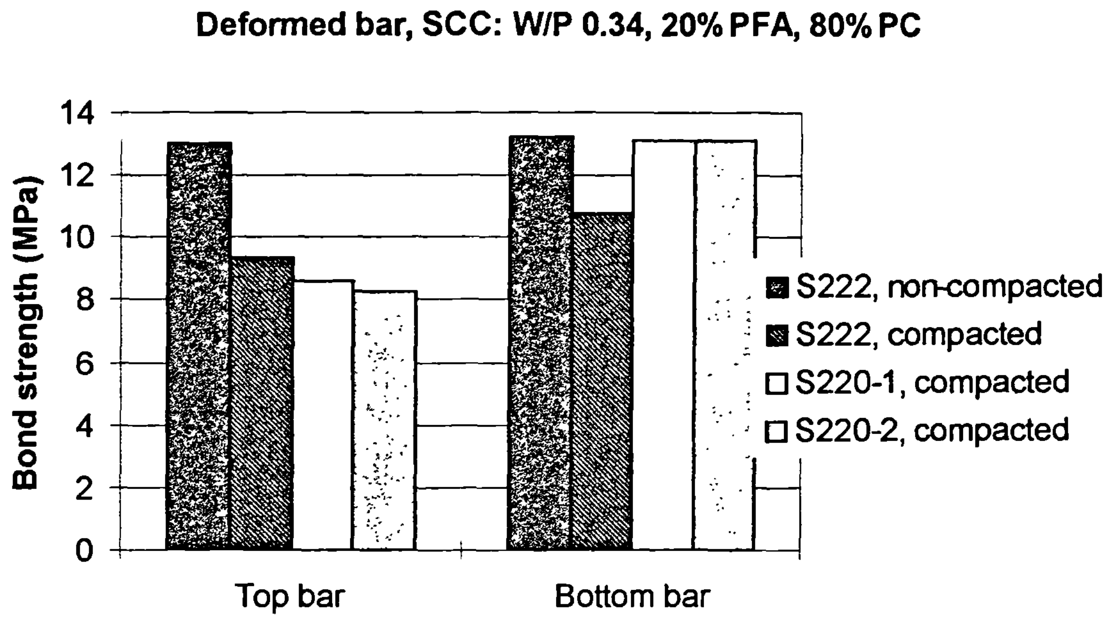


Fig. 8-10 *Comparison of bond to deformed bar with compacted and the non-compacted concrete.*

The overall conclusion is that the bond of SCC to rebars is equal to, or even higher, than that of fully compacted normal concrete for the same compressive strength. Thus, SCC can effectively eliminate the risk of poor bond which results from improper vibration.

8. 2 Shrinkage

8.2.1 Experimental objectives

The objectives of shrinkage tests in this study were:

- to compare the shrinkage of SCC with CEB-FIP code and Eurocode 2
- to find main factors influencing the shrinkage of SCC;
- to compare the shrinkage of SCC with that of NC.

8.2.2 Experimental variables

Table 8-3 Parameters for shrinkage tests

Mixes ref.	Paste volume m^3/m^3	Water/powder ratio	CRM
S109	0.35	0.40	15%GGBS
S110	0.36	0.40	15%GGBS
S112	0.35	0.40	25%PFA
S113	0.38	0.35	30%PFA
S114	0.38	0.38	50%GGBS
S116	0.36	0.36	38%PFA
S227	0.42	0.29	30%PFA
S228	0.39	0.35	25%LSP
S229	0.37	0.37	20%GGBS
S230	0.38	0.36	25%GGBS
F206	0.38	0.50	15%PFA
F207	0.32	0.50	
N208	0.35	0.40	-
N210	0.32	0.50	-

Water curing 6 to 12 days.

8.2.3 CEB-FIP shrinkage equation and EC2

The shrinkage equation of **CEB-FIP** is a function of specimen compressive strength, relative humidity of the air, specimen age after curing and its size. The influence of each item on shrinkage is as follows:

Compressive strength:

$$\varepsilon_s(f_{cm}) = [160 + 10*\beta_{sc}\,(9 - f_{cm}/10)] * 10^{-6} \qquad \textbf{(8-1)}$$

where $\beta_{sc} = 5$ for normal or rapid hardening cement

f_{cm} is the mean compressive cylinder strength at the age of 28 days

Relative humidity:

$$\beta_{RH} = -1.55*[1-(RH/100)^3] \quad \text{for } 40\% \leq RH < 99\% \qquad \textbf{(8-2)}$$

where RH: the relative humidity of the ambient atmosphere (%)

Age of concrete and its size:

$$\beta_s(t - t_s) = \left[\frac{(t-t_s)}{350(h/100)+(t-t_s)}\right]^{0.5} \qquad \textbf{(8-3)}$$

where t : the age of concrete (days)

t_s : the age of concrete at the beginning of shrinkage

h : $2*A_c/u$ (mm) A_c: cross-section;

u: perimeter of the member in contact with the atmosphere

Hence **CEB-FIP's** shrinkage equation is:

$$\varepsilon_{cs}(t, t_s) = \varepsilon_s(f_{cm}) * \beta_{RH} * \beta_s(t - t_s)$$

$$= [160 + 10*\beta_{sc}\,(9 - f_{cm}/10)] * 10^{-6} * \{(-1.55)*[1-(RH/100)^3]\}$$

$$* \left[\frac{(t-t_s)}{350(h/100)+(t-t_s)}\right]^{0.5} \qquad \textbf{(8-4)}$$

According to this equation, the influences of specimen age (after curing) and specimen size on shrinkage are shown in **Table 8-4**, expressed as the percentage of the shrinkage of a specimen with h = 50 mm, after 20 years at constant relative humidity. As can be seen, the shrinkage of a specimen at the age of 20 years can be considered as the ultimate value.

Table 8-4 Influence of specimen age and size on shrinkage

				Age after water curing					
h =2Ac/u (mm)	28d	90d	1y	2y	5y	10y	20y	30y	70y
50	49.5	71.6	90.3	95.1	98.3	99.4	100.0	100.2	100.4
150	18.6	32.2	56.6	69.8	84.1	91.2	95.6	97.2	99.1
600	4.7	8.5	16.9	23.5	35.8	47.7	60.9	68.6	82.3

d: days, y: years

The final shrinkage strains of normal weight concrete according to EC2 are shown in **Table 8-5**.

Table 8-5 Final shrinkage strains of normal weight concrete: per milli **(EC2)**

Location of the member	Typical relative humidity: (%)	h (2Ac/u) : mm	
		≤ 150	600
Inside	50	-0.60	-0.50
Outside	80	-0.33	-0.28

Ac = cross-section area of concrete, u = perimeter of that area

8.2.4 Results and discussion

Fig. 8-11 shows the developments of measured and calculated shrinkage (according to equation (8-4), based on the 28 days cylinder strength at the same age as the measured shrinkage) for mix S227. The measured shrinkage was higher than that calculated for the same compressive strength (61 MPa), but equivalent to that of lower compressive strength (39 MPa). In other words, the measured shrinkage of SCC is equivalent to the calculated value for NC of lower strength.

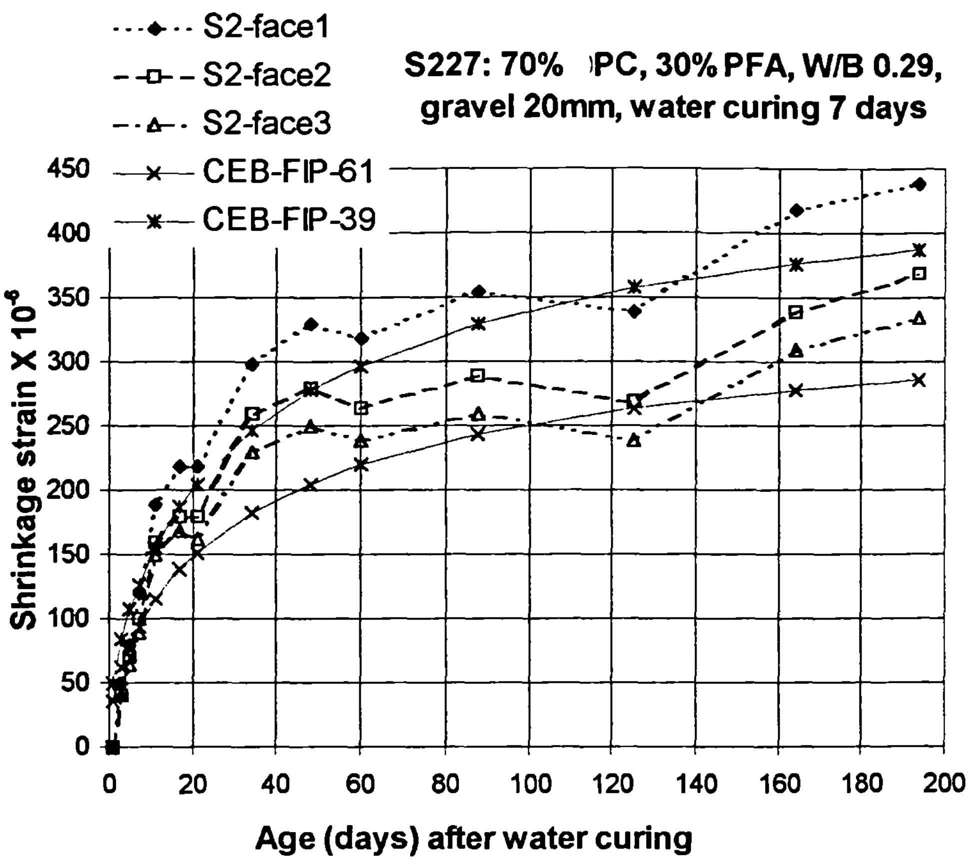


Fig. 8-11 Shrinkage of mix S227 compare with CEB-FIP equation

Table 8-6 shows the results of the measured and calculated shrinkage for different mixes. In general, measured shrinkages [col. (8)] were slightly higher than the values obtained with the CEB-FIP equation [col. (9)]. The differences between these two [col. (10)] for NC are about 20×10^{-6}. For SCC with PFA, the differences are approximately 110×10^{-6}. One possible reason is that the measured shrinkages are those at surface of concrete, and the shrinkages extend gradually from the drying surface into the interior of the concrete but do so only extremely slowly. As a result, the shrinkage of the interior of a specimen will be much less than that observed at the surface.

Table 8-6 Shrinkage results

Mixes ref.	Paste volume m^3/m^3	W / P	CRM by mass	28 days strength (cube)MPa	cylinder strength MPa	age t days	Measured shrinkage+ $\times 10^{-6}$	*Calculated shrinkage $\times 10^{-6}$	Difference (8) - (9) $\times 10^{-6}$	^Shrinkage 20 years $\times 10^{-6}$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
S109	0.35	0.40	15%GGBS	58	48	208	423	349	74	605
S110	0.36	0.40	15%GGBS	57	47	197	439	351	88	633
S112	0.35	0.40	25%PFA	53	43	182	471	365	106	688
S113	0.38	0.35	30%PFA	62	52	154	436	314	122	655
S114	0.38	0.38	50%GGBS	60	50	147	371	320	51	562
S116	0.36	0.36	38%PFA	63	53	90	389	276	113	655
S227	0.42	0.29	30%PFA	71	61	194	388	285	103	561
S228	0.39	0.35	25%LSP	57	47	175	452	344	108	664
S229	0.37	0.37	20%GGBS	63	53	163	369	313	56	549
S230	0.38	0.36	25%GGBS	66	56	151	312	295	17	470
F206	0.38	0.50	15%PFA	48	38	106	522	349	173	846
F207	0.32	0.50		49	39	85	402	327	75	687
N208	0.35	0.40		61	51	228	357	339	18	504
N210	0.32	0.50		48	38	85	352	331	21	602

+ At the age of col. (7), R.H 65%, average of three measurements on every specimen

* Based on 28 days strength: col. (6), at the age of col. (7), R.H 65%, according to CEB-FIP shrinkage equation

^ Calculated according to CEB-FIP shrinkage formula, R.H 50%, based on col. (8)

col. (11) = col. (8) x $[7300(t+87.5) / 7387.5t]^{1/2} \times (1- 0.50^3) / (1-0.65^3)$

In addition, for the comparison of the shrinkage value of EC2, the measured shrinkages were converted to the 20 years and 50% RH. values with the CEB-FIP equation. The results are shown in **Table 8-6** column (11). According to **Eurocode 2 (Table 8-5)**, the final shrinkage of normal weight concrete is **600 x 10^{-6}** for an inside member when the slump of the fresh concrete is between 50 to 150 mm. When the slump is higher than 160 mm, the value should be multiplied by 1.20. Hence, the shrinkage value **720 x 10^{-6}** can be used as a criterion for the purpose of comparison with SCC. As can be seen, the estimated shrinkage strains at 20 years are all less than this except for Mix F206.

The results in **Table 8-6** show that there are two main factors controlling the shrinkage of SCC: the water/powder ratio and the cement replacement materials (CRMs). **Fig. 8-12** shows that the shrinkage increases with the water/powder ratio. Also, SCC incorporating PFA has higher shrinkage than that with GGBS. For LSP, the effects are appear to be similar to those with PFA. Further research is, however, needed to clarify this.

Fig. 8-12 also shows that normal concrete, due to its larger quantity of aggregate, will normally have a lower shrinkage than SCC with the same water/powder ratio. However, by lowering the water/powder ratio of SCC, satisfactory shrinkage values for SCC can still be achieved. For instance, the shrinkage of NC with water/cement ratio 0.50 is similar to that of SCC with water/powder ratio 0.40 (incorporating GGBS), or with water/powder ratio 0.30 (incorporating PFA). This is consistent with data from **Odman** (1968) in **Fig. 8-13,** which shows the influence of water/cement ratio and aggregate content on shrinkage. For the same w/c ratio, the shrinkage of the concrete with 60% aggregate content (SCC) is higher than that of the concrete with 70% aggregate content (NC).

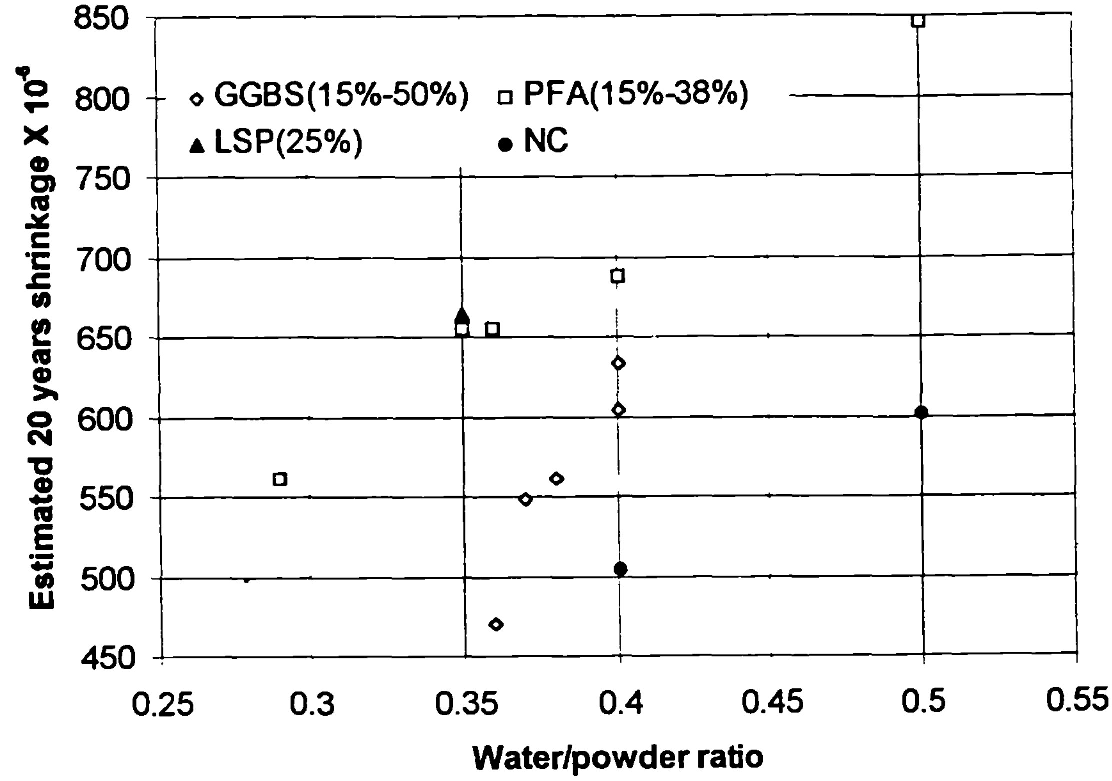


Fig 8-12 Relationship between water/powder ratio and shrinkage of SCC with different CRMs

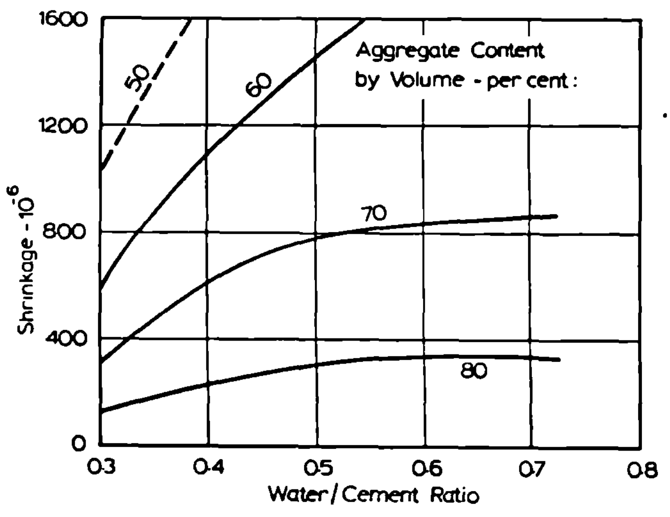


Fig. 8-13 Influence of water/cement ratio and aggregate content on shrinkage.
[Adapted from Odman (1968)]

In conclusion, although the shrinkage of SCC is slightly higher than that of NC of the same water/powder ratio, it is still satisfactory for most structures. By lowering the water/powder ratio, the shrinkage can be reduced effectively to meet the requirement for some special structures.

8. 3 Compressive strength

8.3.1 Modified Feret's rule

For normal concrete, the strength of concrete at a given age and cured at a prescribed temperature is assumed to depend primarily on two factors only: the water/cement ratio and the degree of compaction. There are two famous formulae relating the strength of concrete to these factors developed in the early years of concrete technology:

1. **Abrams' law** (1919)

   $f_c = K_1 / K_2^{w/c}$

2. **Feret's rule** (1896)

   $f_c = K(\frac{c}{c+w+a})^2$

However, in recent years, more and more CRMs are incorporated in concrete mixes, and **de.Larrard** (1993) has modified Feret's rule to a more general condition, including not only PC but also PFA, LSP, GGBS and CSF, which is in the form:

$$f_c = \frac{K_g \bullet R_c}{\left(1+3.1\frac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} \qquad \textbf{(8-5)}$$

where K_g: aggregate coefficient
R_c: cement strength measured on mortar
W: free water content (kg/m^3)
A: volume of the entrapped air (litre/m^3)
K_1: 0.4PFA/C+3SF/C ($K_1 \leq 0.5$)
K_2: 0.2LSP/C ($K_2 \leq 0.07$)

According to **Ohshita et al** (1993), the effective binder content of GGBS cannot be higher than the PC content. For instance, in mix ref. S205, GGBS 70% (404 kg/m^3), PC 30% (173 kg/m^3), water content 196 kg/m^3, the effective water/binder ratio is

196/(173+173), instead of 196/(173+404). Therefore the condition "GGBS: if GGBS > C, GGBS = C " should be added to equation (**8-5**).

It is worth noting that equation (**8-5**) relates to 28-day cylinder strength. Hence, for cube strength, according to the conversion in **Table 3-1**, this equation becomes:

$$fc = \frac{K_g \cdot R_c}{\left(1+3.1\frac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} + 10 \quad \text{if} \quad \frac{K_g \cdot R_c}{\left(1+3.1\frac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} \geq 40 \text{ MPa}$$

and

$$fc = \frac{K_g \cdot R_c}{\left(1+3.1\frac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} \times 1.25 \qquad \textbf{(8-6)}$$

$$\text{if} \quad \frac{K_g \cdot R_c}{\left(1+3.1\frac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} < 40 \text{ MPa}$$

Effective water/binder ratio: $\frac{W}{C(1+K_1+K_2)+GGBS}$ **(8-7)**

Fig. 8-14 shows the relationship between the calculated strength and the measured strength. From the regression analysis, a value of K_g of 4.60 for gravel resulted in the best fit. The prediction of the 28-day strength by using equation (8-6) is excellent, and can account for different types of CRMs, including some ternary blended mixes. Other kinds of aggregate, such as limestone and granite, are not included in this study, and are left for future research. In summary, this equation is valid for high performance concrete with compaction and SCC without compaction [**de Larrard F.**(1993), **Sedran et al** (1996)].

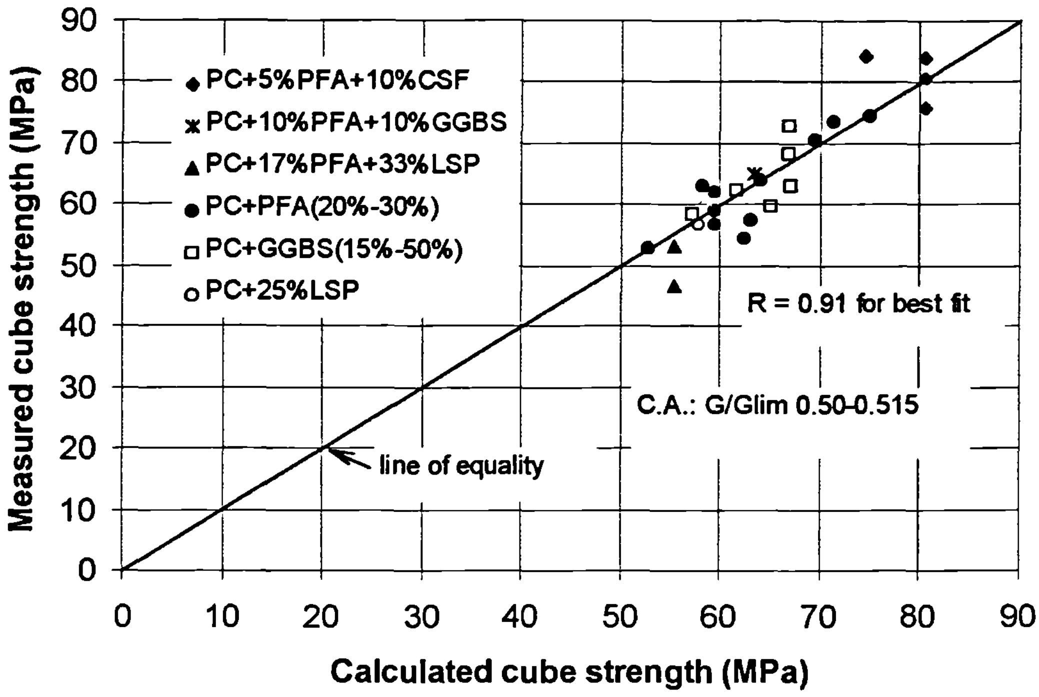


Fig. 8-14 Relationship between the calculated strength and the measured strength.

8.3.2 Influence of cube size on compressive strength

Because SCC is a new type of high performance concrete, currently there is no standard for it. To carry out compressive cube tests of SCC, which size is suitable, 150 mm or 100 mm? Should specimens be vibrated or non-vibrated? A series tests were carried out to investigate the influences of size effect and compaction on compressive strength. For most SCC mixes, the mean strength was obtained from at least four specimens for 100 mm cubes and three specimens for 150 mm cubes. **Fig 8-15** shows the influence of cube size on the variation of cube strength, and some test results are shown in **Table 8-7.**

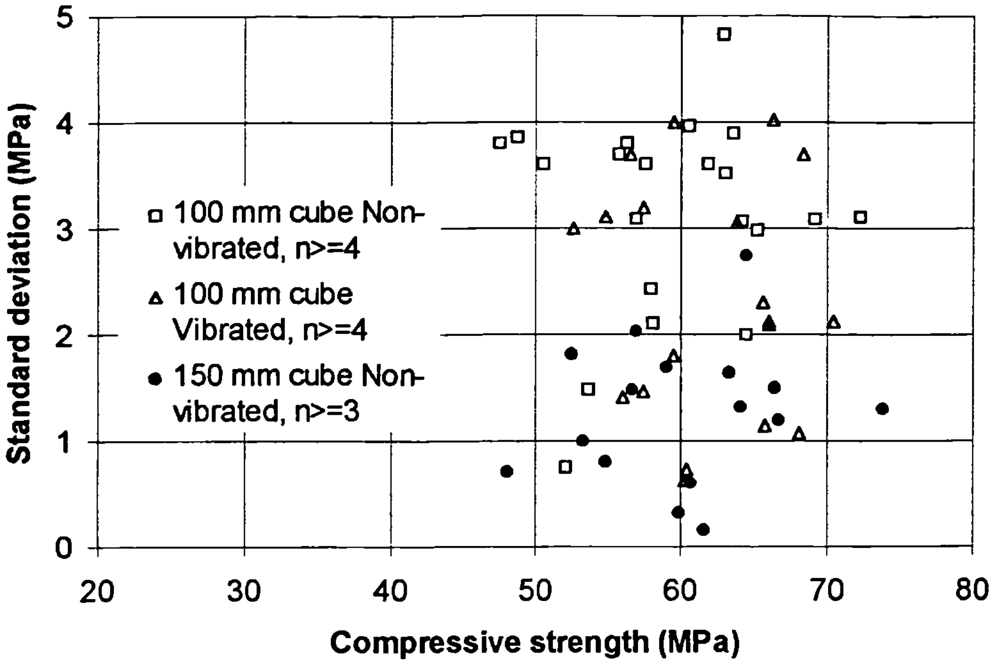


Fig. 8-15 Influence of cube size on standard deviation (within test) of compressive strength

Table 8-7 Average compressive strength of SCC for different cube sizes and compaction conditions

Mix ref.	S221	S222	S226	S109	S227	S110	S111	S112	S228	S229	S230	S113	S114	
Age (days)	14	14	16	16	28	29	28	28	28	28	28	27	28	
V100 (MPa)	59.5	59.5	65.5	56.5	70.7	66.7	68	56	60.3	66.2	63.7	65.6	57.4*	
NV100 (MPa)	57.5	56.9	64.4	50.5	67.6	60.8	64	52	58.1	62.8	63.5	60.4	57.9	
V150 (MPa)	58.9	62.1^						57	58		68.6	62.6	56.7	
NV150 (MPa)	59.8	60.63	66.6	54.7	70.9	62.3	63.7	53	56.8	63.2	66.3	61.5	59.9	Ave.
NV100 / NV150	96	94	97	92	95	98	100	98	102	99	96	98	97	97
V100 / NV150	99	98	98	103	100	107	107	105	106	105	96	107	96	102
NV100 / V100	97	96	98	89	96	91	94	93	96	95	100	92	101	95
NV150 / V150	101.5	98.0						93.2	97.9		96.6	98.2	105.6	99

Sample number: 100 mm cube, $n \geq 4$; 150 mm cube, $n \geq 3$, except * $n = 3$, ^ $n = 2$
V100: vibrated 100 mm cubes, NV150: non-vibrated 150 mm cubes.

Several conclusions can be drawn from these results:

- The large cubes (150 mm) have a lower variation of strength than the small cubes (100 mm), as shown in **Fig. 8-15**. This is similar to NC [**Neville** (1956)].

- Normally the strengths of the 100 mm cubes are a little (97% in average) less than those of 150 mm cubes in case of non-vibration, as shown in **Table 8-7**. This may be because SCC is compacted by its own weight, so that a larger size is better. This is different from compacted NC, where according to **Neville** (1959), the strength of 100 mm cubes is about 5 % higher than that of 150 mm cubes.
- The strength of vibrated 100 mm cubes are on average slightly higher than that of non-vibrated 150 mm cubes, in a range of 98% to 107%. Hence, 150 mm cubes without vibration are preferred.
- SCC can achieve nearly maximum strength without vibration. The strength ratios (non-vibrated/vibrated) are on average 99% for 150 mm cubes and 95% for 100 mm.
- It is clear that for all concrete types the large cube size has a higher strength ratio (non-vibrated/vibrated) than the small cube size, as shown in **Fig. 8-16**.

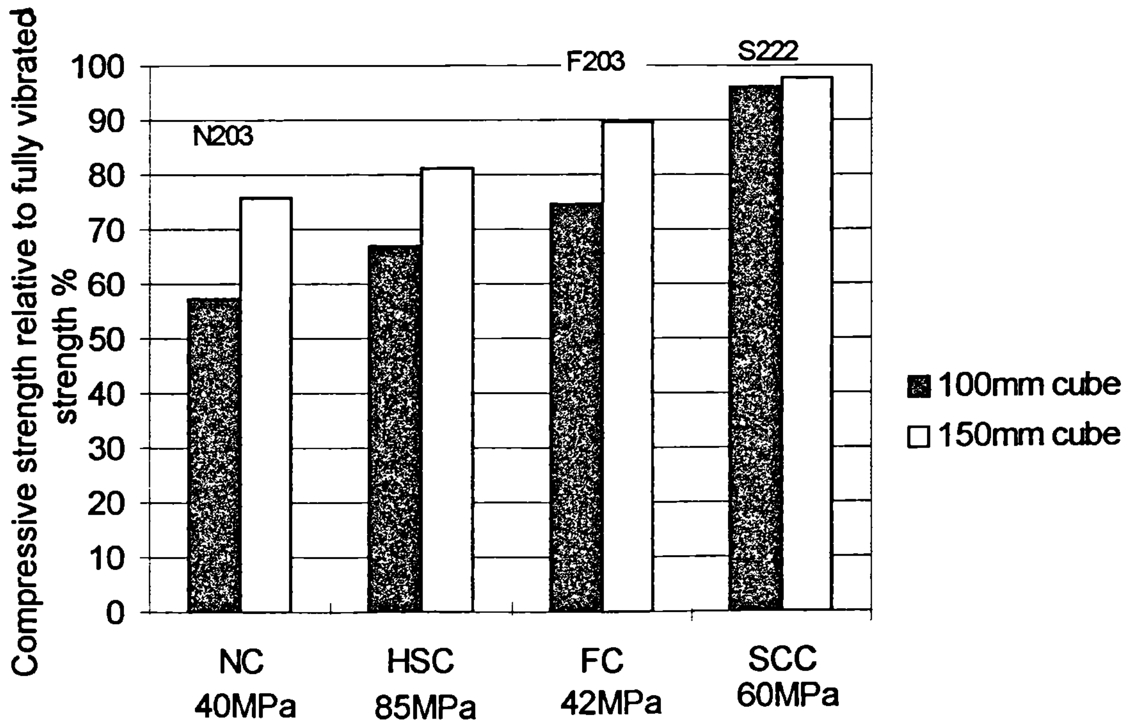


Fig. 8-16 Influence of cube size on the compaction ratio (non-vibrated/vibrated)

In addition, large cubes without compaction can provide useful information about the concrete's hardened surface. This is affected by many factors. One of these is the *wall effect*, that is the quantity of mortar required to fill the space between the particles of the coarse aggregate and the wall is greater than that required in the interior of the concrete. This wall effect is more pronounced the larger the surface/volume ratio of the specimen (**Neville** 1995). The surface/volume ratio of a 100 mm cube is 1.5 times that of a 150 mm cube, hence large cubes should contain less surface voids than small cubes in case of non-vibration. Subjective visual observations in this study confirm this. The effect of low slump flow can also be detected on non-vibrated large cubes. If the slump flow of SCC is less than 500 mm, it will often cause large voids on the hardened surface and honeycombing at the corners of the cubes. However, if the cubes are vibrated, the hardened surface will be excellent, but this is not the case in a real structure. In other words, vibration will mask the possible surface defects in a real structure, but if the hardened surface of large non-vibrated cubes are good, then that of real structure will also be good.

In consequence, for the compression testing of SCC, large cube (150 mm) without compaction are strongly recommended.

8.3.3 Influence of slump flow on compressive strength

Fig. 8-17 shows the relationship between the slump flow and compressive strength. It seems that the influence of slump flow loss on strength is not significant when slump flow is higher than 400 mm. However, if the flowability is too low, the compressive strength may drop significantly. For instance, the 150 mm cube strength of Mix S103 dropped from 72 MPa (fully vibrated) to 52.2 MPa (non-vibrated). For this reason, maintaining slump flow of SCC on engineering site is very important.

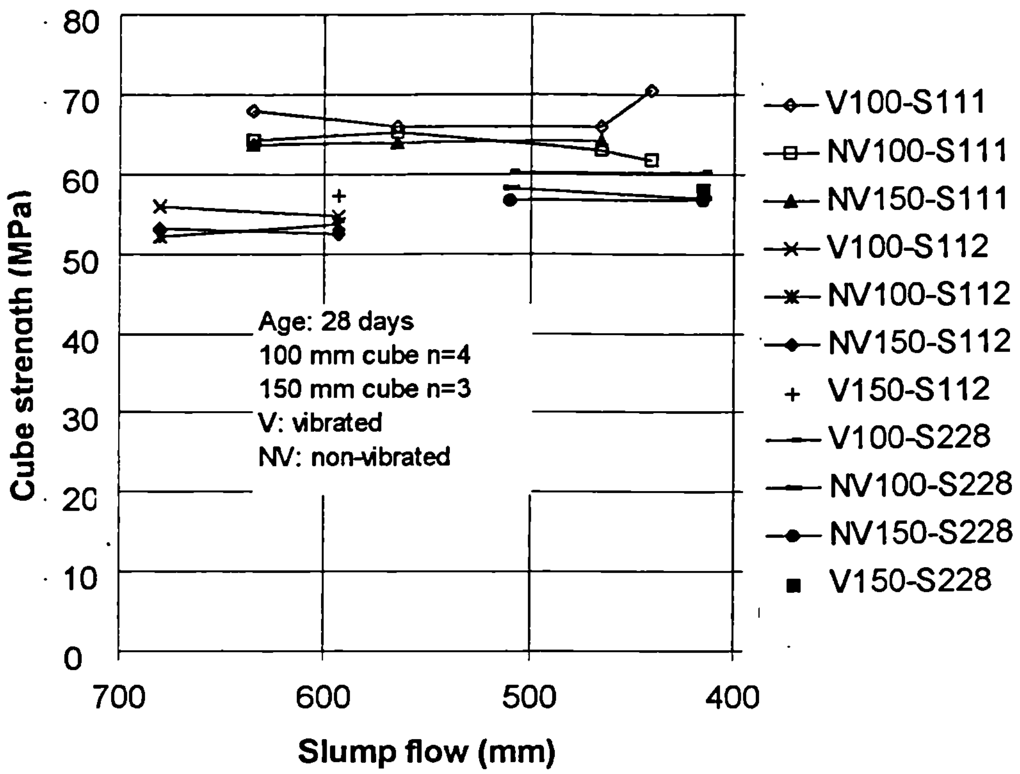


***Fig. 8-17** Relationship between slump flow and cube strength for different cube sizes and compaction conditions*
(The X axis shows the decline of slump flow with time)

In addition, as mentioned above, the slump flow influences the surface of hardened concrete. Normally when the slump flow is higher than 600 mm, the hardened surfaces of cubes have less voids, whereas voids are evident when the slump flow is less than 500 mm. Although the strength is not significantly affected by the slump flow (when slump flow is higher than 400 mm), research on its influence on durability still needs to be carried out in future studies.

8.3.4 Early strength

According to **Ozawa** (1997), a one day (cylinder) strength of 10 MPa is required for satisfactory construction. However, there are many factors influencing the early strength of concrete such as water/powder ratio, CRMs and superplasticizer. Some common methods to enhance the early strength are not applicable for SCC. For instance, an accelerating chemical admixture and rapid hardening Portland cement will cause quick loss of slump flow [**Tucker & Kinloch** (1997)] and therefore, are seldom used in SCC.

A simple method to find suitable mix proportions is through trial and error. However, this can be time consuming, and the best way is to find the controlling factors in concrete mix design. **Fig. 8-18** shows the relationship between effective water/binder ratio and early strength for four different SCC mixes.

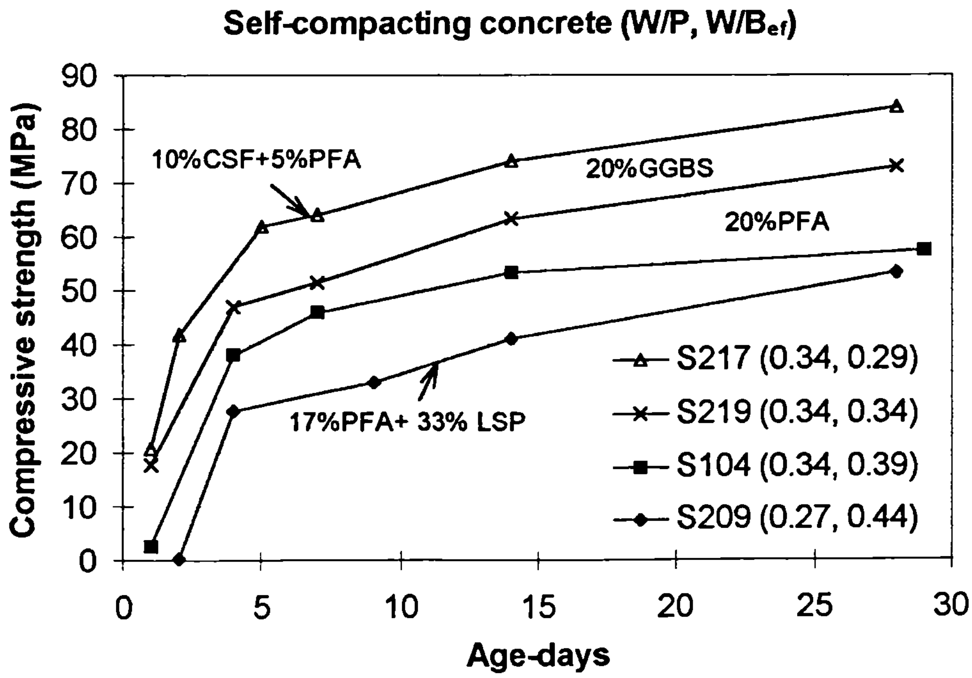


Fig. 8-18 Relationship between effective W/B and compressive strength

Although mix S104, S219 and S217 have the same water/powder ratio (0.34), the effective water/binder ratios [according to equation (8-7)] are in the sequence 0.44 (S209) > 0.39 (S104) > 0.34 (S219) > 0.29 (S217), and so the compressive strength are in the same sequence f_c (S209) < f_c (S104) < f_c (S219) < f_c (S217). It is therefore clear that the development of compressive strength depends on the effective water/binder ratios. In other words, to control the compressive strength up to 28 days, the effective water/binder ratio is better than water/powder ratio. **Fig. 8-18** also shows that silica fume can enhance early strength (as well as cost) effectively.

For mixes containing PFA and GGBS, there is little pozzolanic reaction at the age of one day, and according to **Hwang** (1997), short term compressive strength is governed by water/cement ratio, whereas medium term strength is governed by the water/binder ratio. Therefore, water/cement ratio is suitable to consider as a controlling factor for one day strength gain. **Fig. 8-19** shows a conservative relationship between compressive strength and water/cement ratio for 102 mm cubes, and it is reasonable to expect a one day cube strength of 12.5 MPa (equivalent to 10 MPa cylinder strength) if the water/cement ratio is not higher than 0.50.

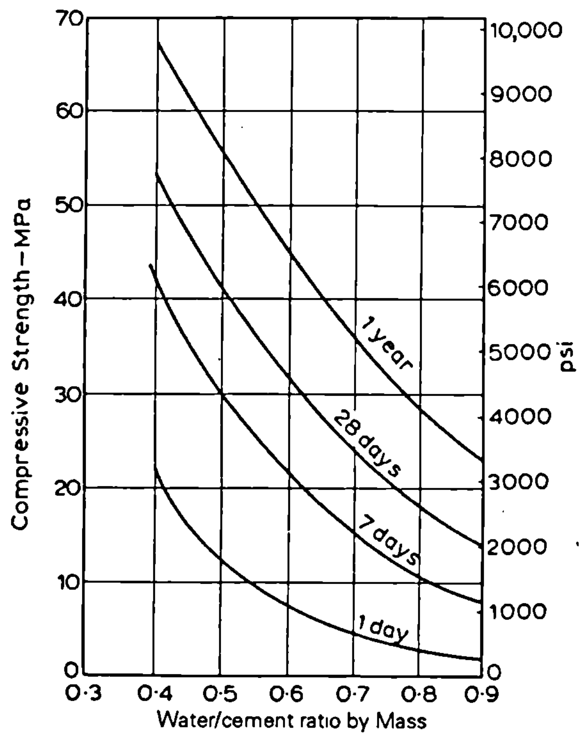


Fig. 8-19 Relationship between compressive strength and water/cement ratio for 102 mm cubes [Adapted from Neville (1995)]

The data in **Table 8-8** confirm this. For mixes S114 and S112, the effective water/binder ratios were 0.38 and 0.47, but the one day strengths were only 9.2 MPa and 8.4 MPa respectively, due to the high water/cement ratios (0.76 and 0.53). All other mixes have W/C's less than 0.50, had sufficient one day strength as long as suitable superplasticizer were used. Hence, W/C 0.50 can be used as a maximum value in SCC mix design to control the one day strength gain.

Table 8-8 Relationship between one day strength and water/powder ratio, effective water/binder ratio and water/cement ratio

Mix ref.	CRMs (by mass)	SP (%) Sika10	W/P	*W/B	W/C	^Fc(1d)
S112	25%PFA	0.31	0.40	0.47	0.53	8.4
S114	50%GGBS	0.25	0.38	0.38	0.76	9.2
S110	15%GGBS	0.29	0.40	0.40	0.47	15
S113	30%PFA	0.23	0.35	0.43	0.50	18
S219	20%GGBS	0.32	0.34	0.34	0.42	18
S217	10%CSF+5%PFA	0.60	0.34	0.29	0.36	21
S230	25%GGBS	0.23	0.36	0.36	0.49	16

* effective water/binder ratio according to equation (8-7)
^ One day cube strength (MPa)

Types and dosages of superplasticizer are also other crucial factors governing one day strength gain. **Fig. 8-20** shows the relationship between superplasticizer dosage (F-type) and one day compressive strength of mortar. It is clear that high dosages reduce one day compressive strength significantly. Silica fume is beneficial to one day strength gain, but requires increased superplasticizer dosage to obtain sufficient slump flow and this can have a negative influence on one day strength. The outcome will be the combination of these two effects.

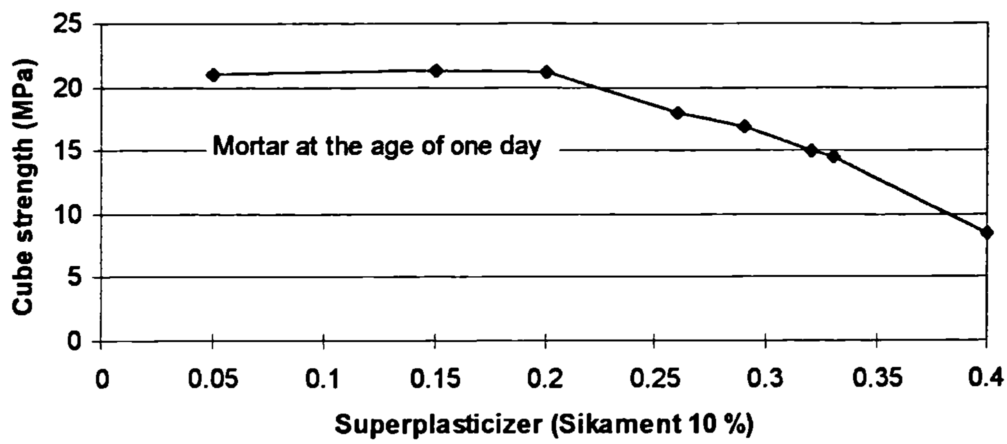


Fig. 8-20 *Relationship between superplasticizer dosage and one day compressive strength of mortar* [*Adapted from Tucker & Kinlock (1997)*]

In addition, a G-type superplasticizer (which contains a retarder) often impairs the one strength gain. This phenomenon is clearly shown in **Fig. 8-21**. For most mixes even with W/C less than 0.50, the one day strength was less than 12.5 MPa if a G-type superplasticizer was used.

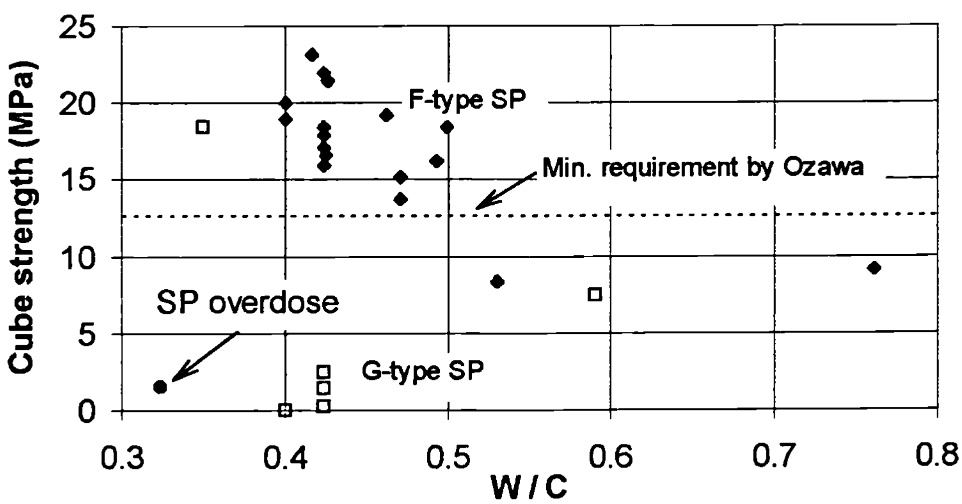


Fig. 8-21 *Relationship between water/cement ratio and one day strength with different types of superplasticizer*

In summary, based on the data from this study, a cube strength 12.5 MPa can be obtained in one day, if the following conditions are met:

- the water/cement (including CSF) ratio is less than 0.50;
- the superplasticizer contains no retarder(i.e. is not a G-type);
- there is no overdose of superplasticizer.

These criteria are valid if the water/powder ratio is in the range from 0.28 to 0.50.

8. 4 Conclusions

Although the composition of SCC is different from NC, e.g. it has a higher paste content and less coarse aggregate content, the hardened properties of SCC are satisfactory for construction purposes. The bond of SCC to reinforcement is not less than that of fully compacted NC of the same compressive strength, and SCC can effectively eliminate the risk of poor bond which can result from improper vibration of NC. Although the shrinkage of SCC is slightly higher than that of NC, by lowering the water/powder ratio and by suitable selection of the cement replacement materials, a satisfactory shrinkage can easily be achieved. The 28 day compressive strength can be predicted with a modified **Feret's** rule, and hence this is very useful in SCC mix design. For the testing of compression specimens, 150 mm cubes without compaction are recommended. Furthermore, SCC with low slump flow will result in a poor hardened concrete surface. Finally, the early strength of SCC can be controlled by adequately selecting the water/cement ratio and superplasticizer.

Chapter 9

Mix design of SCC

9. 1 Introduction

This chapter presents an SCC mix design method, based on Ozawa's method, when has been modified using the results on UK materials obtained in this study. The purpose of every mix design is to meet the requirements of a structural design, which are normally the *strength and durability* of the concrete. In addition, *workability* must be appropriate in order to gain the good hardened properties. Finally, *cost* must be considered, that is the concrete should be produced as economically as possible.

For SCC, the fresh property requirements also include good *passing ability* through reinforcement and suitable *segregation resistance*, as discussed in **Chapter 7**. These two special requirements make the procedure for SCC mix design different from that for NC. **Fig 9-1** and **Fig 9-2** show the mix design methods of BRE (1988) and ACI (211.1-91) respectively. For NC, in general, water/cement ratio and water content are selected first according to requirements of strength, durability and workability. The aggregate content is determined last. For SCC, this procedure is reversed, as can be seen in **Fig. 9-3.** Coarse and fine aggregate contents, powder combination, and water/powder ratio are selected first according to the requirements of passing ability, segregation resistance, strength and durability. Water and powder content are determined last.

9. 2 Selection of constituents

Table 9-1 shows the material constituent factors influencing the properties of SCC. Every constituent has an influence on some properties, and it is very important to know the suitable range of proportions of each constituent and the interaction between them.

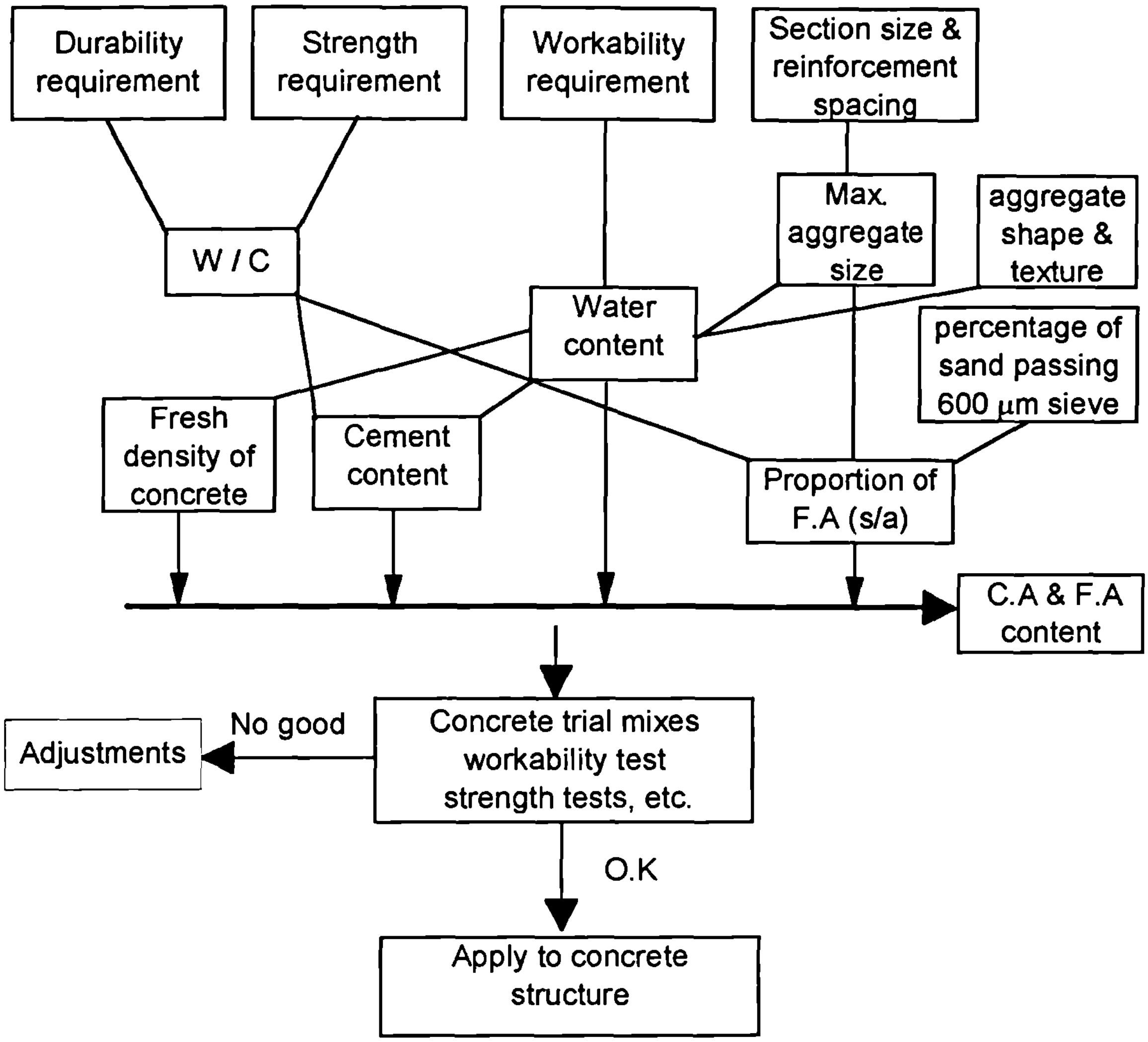


***Fig 9-1** BRE mix design procedure* [*Derived from BRE (1988)*]

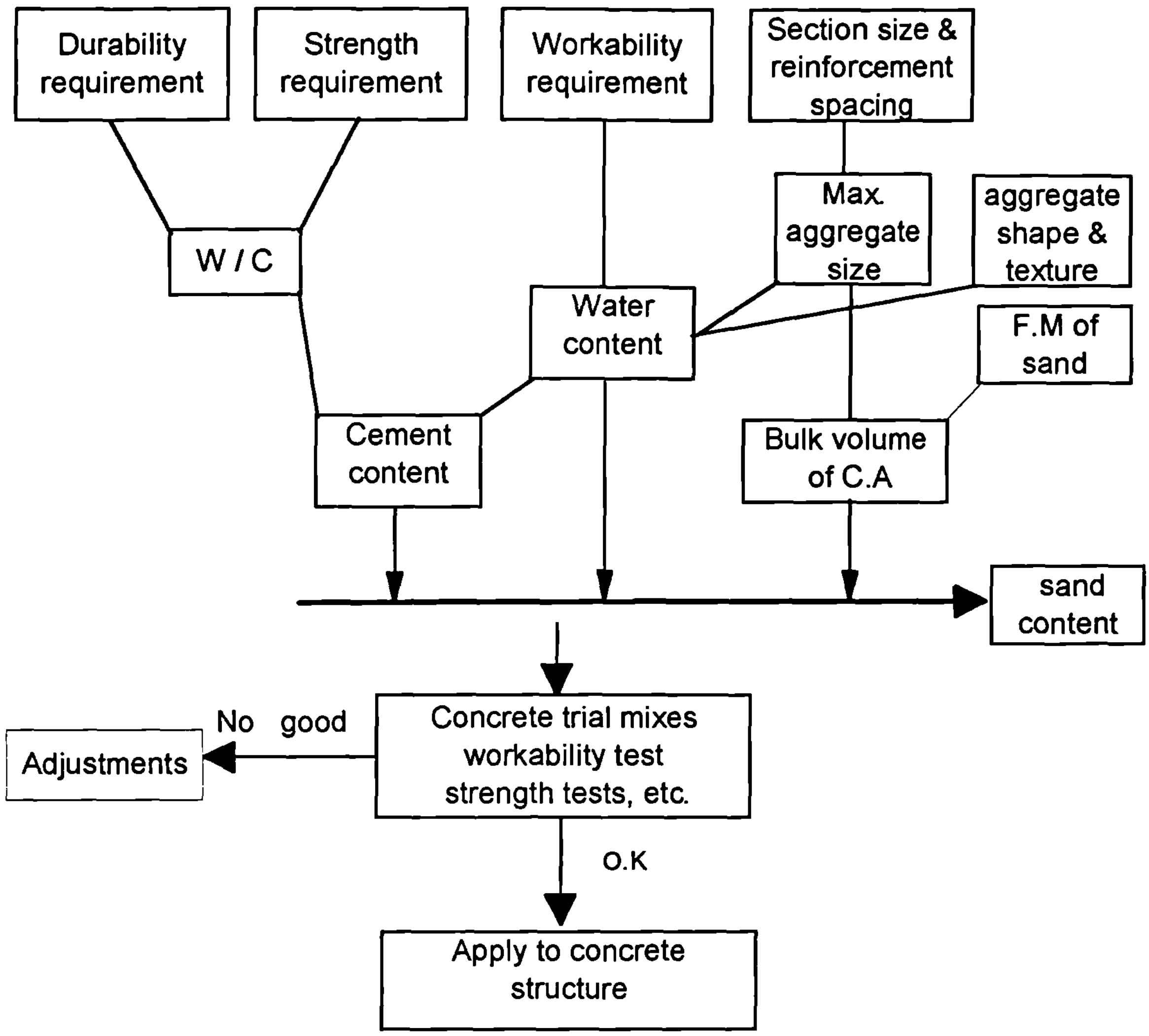


***Fig 9-2** ACI mix design procedure [Derived from ACI 211.1 (1991)]*

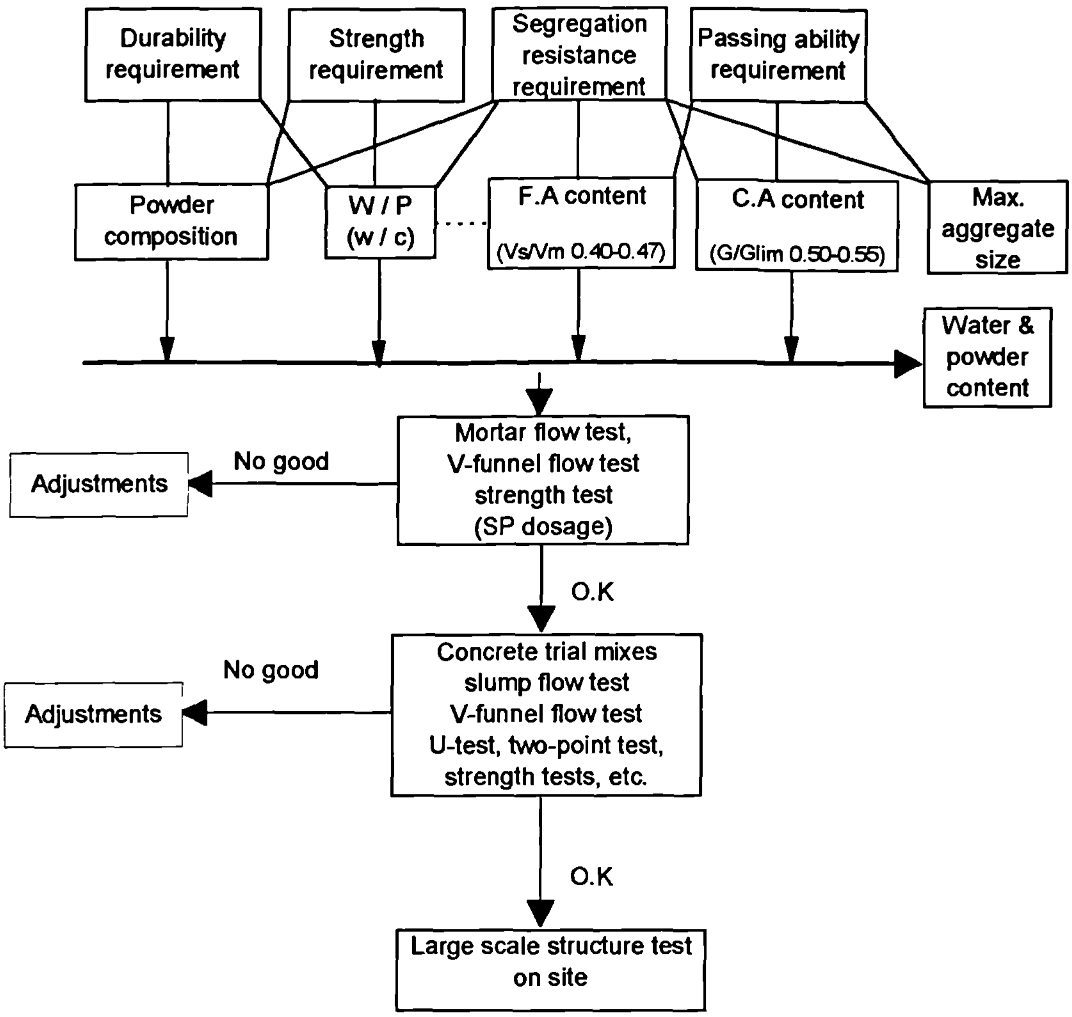


Fig 9-3 SCC mix design procedure [Modified from Ozawa's design method (1993)]

Table 9-1 Factors influencing the properties of SCC

	Durability	Strength	Segregation resistance	Passing ability	Shrinkage	Cost
W/P	O	O	O	Δ	O	O
CRM	O	O	O	Δ	O	O
Cement	O	O	O	Δ	Δ	O
Aggregate	O	Δ	O	O	O	Δ
Water	Δ	Δ	Δ	O	Δ	
Superplasticizer			O	O		O
AE agent	O	O	Δ	Δ		Δ
Viscosity		Δ	O	Δ		O

O: major factor
Δ: minor factor

9.2.1 Cement

There is no doubt that Portland cement (PC) is by far the most widely used cement in the UK. Class 42.5 N is probably the most commonly used, and corresponds to the previously defined "Ordinary Portland cement". Although the measured water retained ratio (β_P) of the Portland cement used in this study (1.08) (see **Chapter 5**) is slightly higher than the value 0.95 suggested by **Okamura et al** (1993), it proved to be satisfactory. By incorporating PFA or LSP, the value of the water retained ratio can be reduced, thus providing a better fluidity of the fresh concrete. Rapid-hardening may cause a rapid loss of slump flow (Mix 218, 406 mm/hr), hence it is not suitable for SCC. If high early strength is required, the best way is to use CSF or to lower the water/powder ratio.

Most codes or specifications have a minimum cement content requirement for durability. For example, this guarantees the alkalinity of the concrete for corrosion protection of embedded steel reinforcement. **ENV 206** specifies this as **280** or **300** kg/m^3, depending on the exposure condition. A very high cement content is also unsuitable, not only because of cost, but also because of shrinkage and thermal cracking problems. Normally, cement contents are less than 500 kg/m^3.

9.2.2 Cement replacement materials (CRMs)

The most common type of CRMs in the world are PFA, GGBS, LSP and CSF. In the UK, LSP is not as cheap as it is in Japan, because it is not in mass production. CSF is very expensive with a cost much higher than PC; it is only used for HSC or to enhance the early strength of concrete. As a result, PFA and GGBS are the popular CRMs in the UK, with the main reasons for use being:

- durability enhancement;
- reduction of thermal cracking problems;
- economical considerations;
- environmental considerations.

For SCC, in addition to the preceding reasons, CRMs are often incorporated to improve the rheology of the fresh concrete. For instance, replacing a part of PC with PFA can increase the workability, whereas replacing with GGBS can increase the plastic viscosity. **Table 9-2** shows the range of suitable percentages of each CRM by weight of total cementitious materials.

Table 9-2 Range of suitable proportions of CRMs

CRMs	Suitable percentage	Remarks
PFA	15% - 40%	**CEB-FIP** clause d.6.3.3.2, **Keck et al** 1997
GGBS	up to 80%	**CEB-FIP** clause d.6.3.3.2
CSF	5% - 10%	**Neville** 1995
LSP	up to 35%	**Neville** 1995

For GGBS, 50% is preferred, because this may result in the highest medium-term strength (**Neville** 1995).

9.2.3 Aggregate

The maximum aggregate size (D_{max}) has a great influence both on the passing ability through reinforcement and the segregation resistance of SCC. The clear gap between reinforcement and between reinforcement and formwork should be at least double the maximum aggregate size (see **3.4.1.1**). On the other hand, a small aggregate size provides better segregation resistance than a larger one. Crushed aggregate produces a higher compressive strength than the uncrushed one for the same mix proportion, but needs more water or superplasticizer to produce the same workability.

9.2.4 Water / cementitious ratio

For NC, the water/cementitious ratio is mainly governed by durability and strength requirements. For reinforced concrete, **ENV 206** requires a maximum water/cementitious ratio in the range **0.65-0.45**, depending the exposure condition. For concrete with high resistance to water penetration, the water/cement ratio should not exceed **0.55** or **0.60**, depending on the thickness of the structural component (**CEB-FIP** clause d.6.6.1). For SCC, because of the segregation resistance requirement, the water/cementitious ratio should not be higher than **0.40** with 20 mm maximum size of aggregate if no viscosity agent is being used. With 10 mm maximum size of aggregate, the maximum water/cementitious ratio should not exceed **0.50**. Based on the data in this study, **Table 9-3** shows a general guide to SCC mix proportion with UK materials. SCC meets the requirements of durability in most cases in terms of water/powder ratio and minimum cement content.

Table 9-3 Guide to SCC mix proportions without viscosity agent

W / P	CRMs	D_{max} (mm)	V_s/V_m	Remarks
< 0.30	PFA, LSP	20, (10)	0.40	too viscous for GGBS
0.30-0.34	PFA, LSP, GGBS	20, 10	0.40-0.45	
0.34-0.40	PFA, LSP, GGBS	20, 10	0.45-0.47	
0.40-0.50	GGBS	10	≥ 0.45	high shrinkage for PFA segregation for D_{max} 20 mm
	CSF	10		segregation for D_{max} 20 mm

9.2.5 Water content

For most SCC mixes in Japan, the water content is within the range 160-185 kg/m^3, due to the requirement of Japanese Architectural Standard (1986) JASS 5. Air entrainment is also essential. This is not the case either in England or in Taiwan. **Fig. 9-4** obtained by calculation shows the common range of water/powder ratio for a water content of 185 kg/m^3. As can be seen, when the paste volume is in the range 0.38-0.42 m^3, for an air content 5%, the water/powder ratio is in the range of 0.32-0.45 whereas for air content 1%, the water/powder ratio is in the range of 0.26-0.35. In other words, with non-air entrained concrete, if the water/powder ratio is chosen to be higher than 0.35, the water content will be unavoidably higher than 185 kg / m^3. Hence, this criterion cannot be applied in a region where air entrainment is not required. However, the higher water content will result in low viscosity, and also increase the shrinkage. From the available literature, the highest water content used for SCC has been **200** kg/m^3.

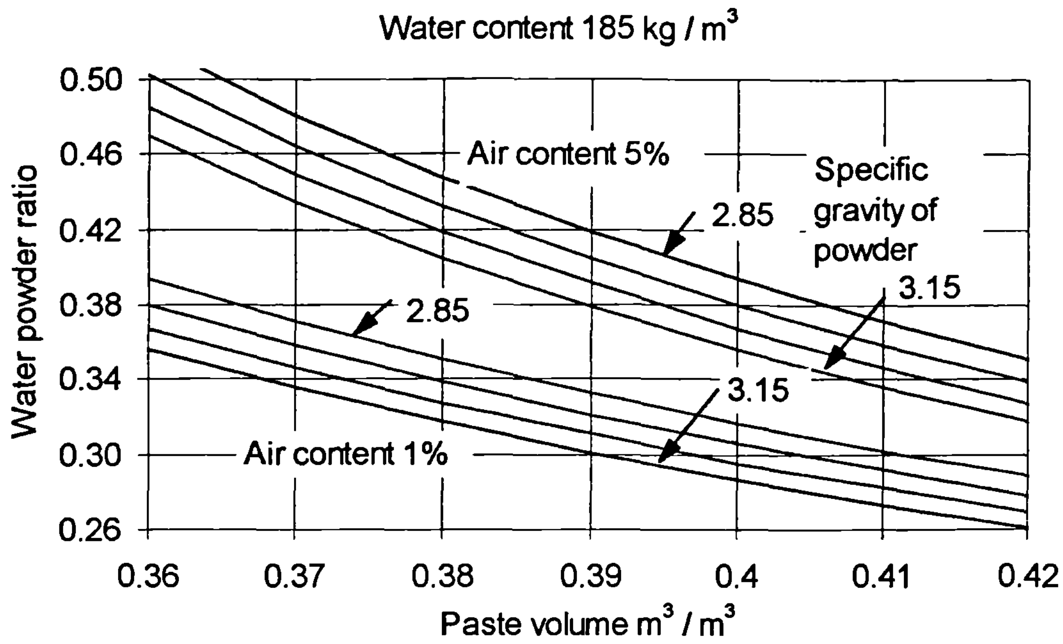


***Fig. 9-4** Relationship between paste volume and water/powder ratio for different air contents*

9. 3 Mix design procedure

Based on the data in this study and **Ozawa**'s approach (see **3.5.1**), this section describes a SCC mix design procedure, which covers a wider range (compared to Ozawa's) of W/P and V_s/V_m (see **Table 9.3**). This method also includes using 10 mm maximum size aggregate which has not been used in Japan for SCC.

9.3.1 By calculation

Step 1: Coarse aggregate content

$$W_{c.a} = (1\text{-}A) \times G/G_{lim} \times \gamma_d \qquad \textbf{(9-1)}$$

where A: air content; γ_d: dry rodded bulk density of coarse aggregate
G/G_{lim}: usually 0.50

For concrete without air-entrainment, the air content is assumed to be 1% with 20 mm maximum aggregate size or 1.2% with 10 mm maximum aggregate size.

Step 2: Fine aggregate content

Select a value of V_s/V_m according to passing ability and segregation resistance requirements.

$$V_s = (1\text{-}A\text{-}V_g) \times V_s/V_m \tag{9-2}$$

Step 3: Check paste volume

$$V_{paste} = 1 - V_s - V_g \qquad (V_{paste} \text{ includes air content}) \tag{9-3}$$

The paste volume should be within 0.38-0.42 m^3 per cubic metre of concrete

Step 4: Selection of water / powder ratio and powder composition

According to the requirements of strength, durability and segregation resistance, select an appropriate water/powder ratio and powder composition. Then calculate the specific gravity of the blended powder.

$$S.G_p = \left(\frac{100}{P_1 / S.G_1 + P_2 / S.G_2 + \ldots}\right) \tag{9-4}$$

where P_1: proportion of powder_1 by weight of total powder,
$S.G_1$: specific gravity of powder_1; P_2, $S.G_2$: etc.

Then calculate the water/powder ratio by volume

$$V_w/V_p = (W / P) \times S.G_p \tag{9-5}$$

Step 5: Water content

$$V_w = V_{paste} - V_p - V_a \tag{9-6}$$

Solve equations **9-5** and **9-6**

$V_w = (V_{paste} - V_a) \times (V_w/V_p) / (1 + (V_w/V_p))$ **(9-7)**

$W_w = V_w \times \rho_w$ **(9-8)**

Step 6: Powder content

Calculate the amount of the individual powders, using

$V_p = V_w / (V_w/V_p)$ **(9-9)**

$W_p = V_p \times S.G_p \times \rho_w$ **(9-10)**

weight of $powder_1 = P_1 \times W_p$

weight of $powder_2 = P_2 \times W_p$ **(9-11)**

It is worth noting that step 2 and step 3 can be carried out in reverse order. The paste volume can be chosen first, for instance 0.38 m^3, then the fine aggregate content calculated. The value of V_s/V_m should then be checked. A spreadsheet can easily be used for all the calculations.

Example

A SCC mix of characteristic strength C50 is required, and its one day strength should not less than 12.5 MPa. Durability requirements are: water/powder ratio not higher than 0.45, minimum cementitious material content 300 kg/m^3. Uncrushed aggregate with a maximum size of 10 mm (Rodded bulk density 1590 kg/m^3) and Thames Valley sand (F.M 2.6, S.G 2.64) are provided. No air entrainment is required. PC and PFA are to be used.

Step 1: coarse aggregate content

Assume air content 1.2%, G/G_{lim} 0.50

$W_g = (1-0.012) \times 0.50 \times 1590$ kg/m^3 = 785 kg/m^3

Step 2: fine aggregate content

The value of V_s/V_m is in the range of 0.40 -0.47 (See **Table 6-6**).

Let $V_s/V_m = 0.45$

$V_s = (1 - 0.012 - 785/2600) \times 0.45 = 0.309$

$W_s = 0.0309 \times 2640\ kg/m^3 = 816\ kg/m^3$

Step 3: Check paste volume

$V_{paste} = 1 - 785/2600 - 816/2640 = 0.389 > 0.38$ (O.K)

Step 4: Selection of water / powder ratio and powder composition

Assume the proportion of PFA to be 30%, then according to equation **(9-4)** the specific gravity of this powder combination is 2.88.

- Strength requirement:

  Target cube strength = 50 + 8 = 58 MPa

  From equation (8-6)

$$f_c = \frac{K_g \bullet R_c}{\left(1+3.1\dfrac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} + 10 \geq 58 \text{ MPa}$$

  Let $K_g = 4.60$ (for gravel), $R_c = 57$ MPa (28 days mortar strength)

$$\text{Hence, } \frac{W+A}{C(1+K_1+K_2)+GGBS} = 0.43$$

$$\frac{W}{C(1+K_1+K_2)+GGBS} \text{ (the effective binder ratio)} + \frac{A}{C(1+K_1+K_2)+GGBS} = 0.43$$

  Assume the amount of effective binder 450 kg/m^3

$$\text{Then } \frac{(w/p)}{0.7(1+0.4\times 0.3/0.7)} + \frac{12}{450} = 0.43$$

  Hence w/p = 0.33

- Durability requirements: w/p < 0.45 ∴ O.K.
- Segregation resistance requirements

  From **Table 6-9** and equation **(5-9)**

$$\mu = \frac{23.6}{E_p}\left(\frac{(w/p)\bullet S.G_p}{\beta_p}\right)^{-6.38} \geq 70 \text{ mPa.s} \qquad \text{for } D_{max} \text{ 10 mm...}$$

From **Table 5-1**, for the powder combination 70%PC + 30%PFA

$\beta_p = 0.93$, $E_p = 0.050$

then w/p = 0.43

From the requirements of strength, durability and segregation resistance, the lowest w/p is 0.33.

$V_w/V_p = (W/P) \times S.G_P = 0.33 \times 2.88 = 0.95$

Step 5: Water content

According to equation (9-7)

$$V_w = (0.389 - 0.012) \times 0.95 / (1 + 0.95) = 0.184$$

Step 6: Powder content

$V_p = 0.184 / 0.95 = 0.194$

$W_p = 0.194 \times 2.88 \times 998.5 = 558$ (kg)

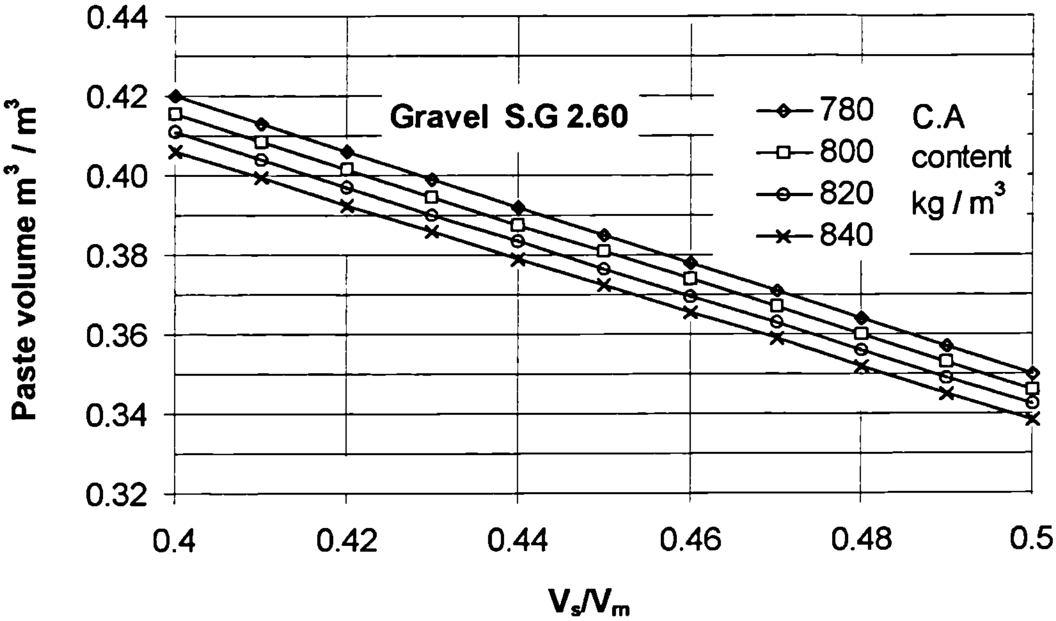
Hence the mix proportions are:

	C.A	F.A	PC	PFA	Water	Air	Total
Weight (kg/m^3)	785	816	391	167	184	0	2343
Volume (m^3)	0.302	0.309	0.124	0.069	0.184	0.012	1.000

The superplasticizer dosage is then determined by mortar flow spread and V-funnel tests. Finally, a slump flow test and V-funnel flow time as checked on a concrete trial mix.

9.3.2 By tables and charts

Step 1 and 2 are the same as in **9.3.1**. Step 3 (paste volume) can be checked using **Fig. 9-5.** Step 4 (water/powder ratio by volume) can be determined from **Table 9-4.** The water content can be found using **Fig. 9-6** (Step 5). Finally, step 6 (powder content) is the same as in **9.3.1.**



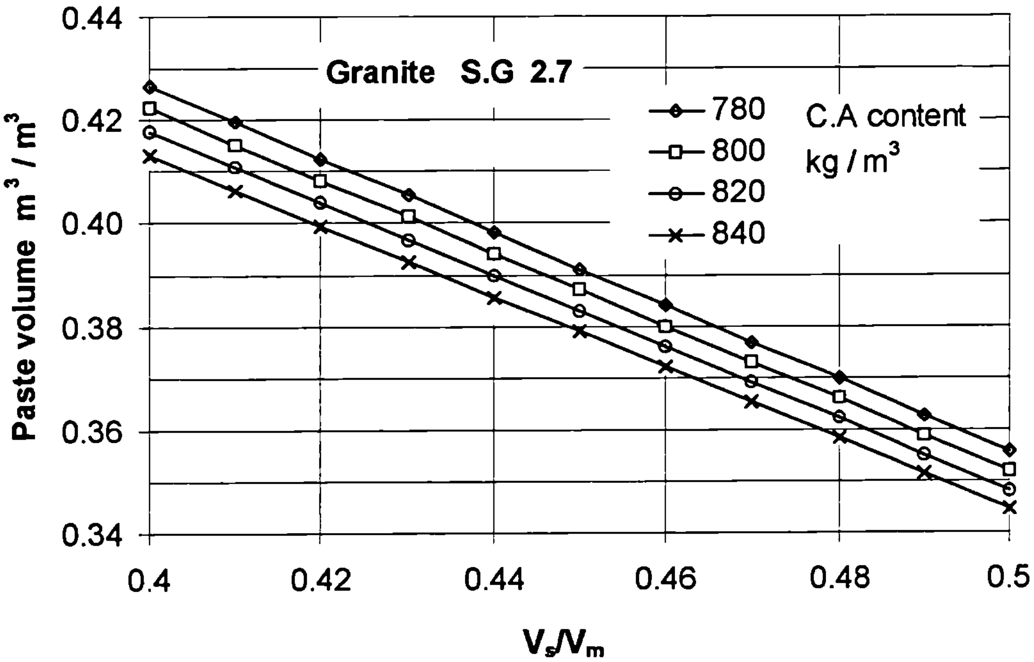


Fig. 9-5 Paste volume vs. V_s/V_m for different coarse aggregate content for SCC mixes

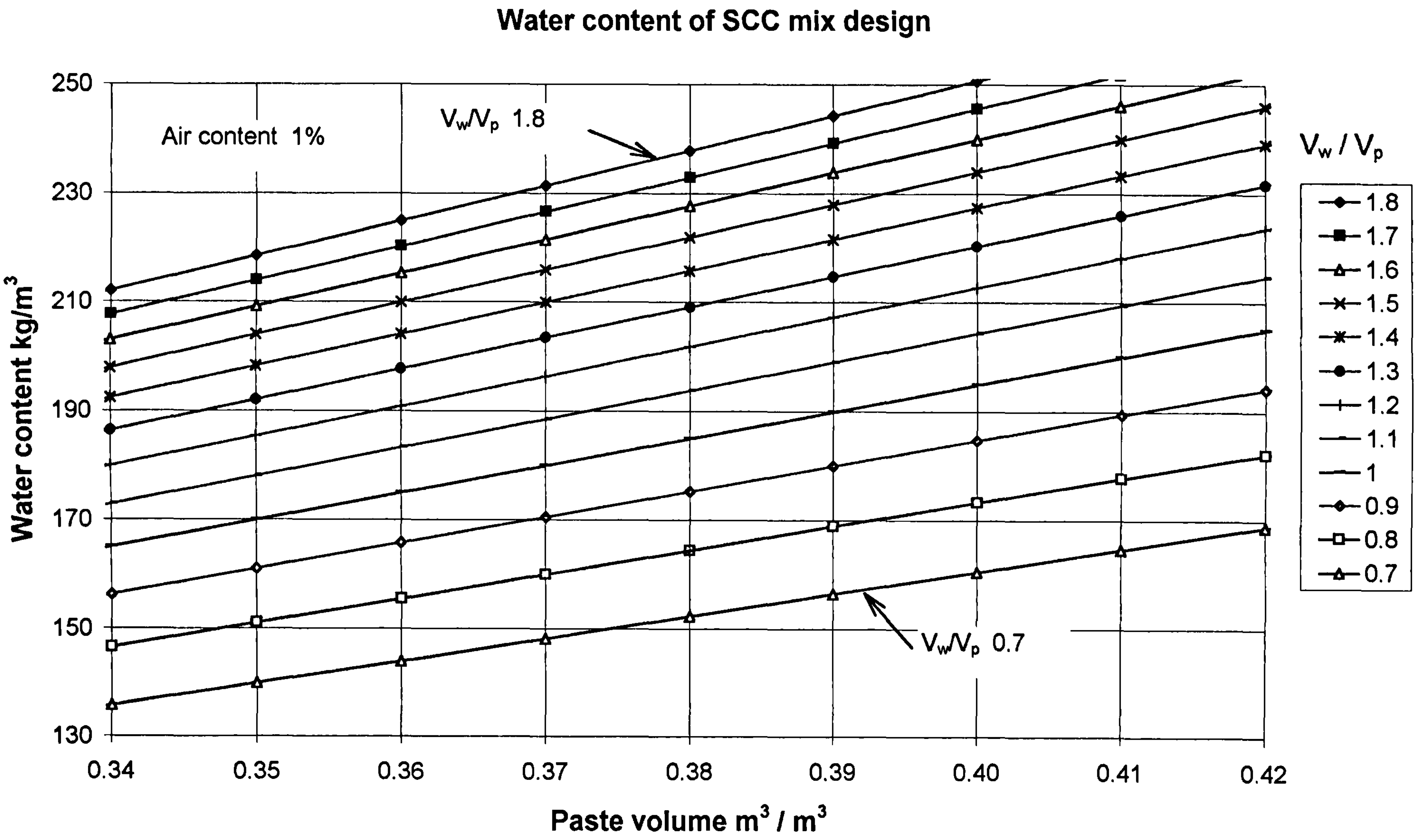


***Fig. 9-6** Water content vs. past volume for different V_w/V_p for SCC mixes*

Table 9-4 Conversion of water / powder ratio by weight to by volume

	PFA / (PFA+ PC), % by wt.					$S.G_{pfa}$	2.400
Vw / Vp	0	15	20	25	30	35	40
W / P | $S.G_p$	3.150	3.009	2.965	2.922	2.880	2.839	2.800
0.28	0.882	0.843	0.830	0.818	0.806	0.795	0.784
0.30	0.945	0.903	0.889	0.877	0.864	0.852	0.840
0.32	1.008	0.963	0.949	0.935	0.922	0.909	0.896
0.34	1.071	1.023	1.008	0.993	0.979	0.965	0.952
0.36	1.134	1.083	1.067	1.052	1.037	1.022	1.008
0.38	1.197	1.143	1.127	1.110	1.094	1.079	1.064
0.40	1.260	1.204	1.186	1.169	1.152	1.136	1.120
	GGBS / (GGBS+ PC), % by wt.					$S.G_{ggbs}$	2.900
Vw / Vp	0	20	30	40	50	60	70
W / P | $S.G_p$	3.150	3.097	3.071	3.045	3.020	2.995	2.971
0.32	1.008	0.991	0.983	0.974	0.966	0.958	0.951
0.34	1.071	1.053	1.044	1.035	1.027	1.018	1.010
0.36	1.134	1.115	1.105	1.096	1.087	1.078	1.069
0.38	1.197	1.177	1.167	1.157	1.148	1.138	1.129
0.40	1.260	1.239	1.228	1.218	1.208	1.198	1.188
0.42	1.323	1.301	1.290	1.279	1.268	1.258	1.248
0.44	1.386	1.363	1.351	1.340	1.329	1.318	1.307
0.46	1.449	1.424	1.412	1.401	1.389	1.378	1.367
0.48	1.512	1.486	1.474	1.462	1.450	1.438	1.426

V_w/V_p: water/powder ratio by volume

Repeating the same example as in **9.3.1**

Step 1, step 2, step 4 and step 6 are unchanged. From **Fig. 9-5**, C.A 785 kg/m^3, V_w/V_m 0.45, paste volume can be determined as 0.384 m^3. From **Table 9-4**, the w/p 0.33 can be converted to V_w/V_m by take the average of 0.979 (from w/p 0.34) and 0.922 (from w/p 0.32), i. e. 0.95. From **Fig. 9-6**, for a paste volume of 0.384 m^3 and V_w/V_p 0.95, the water content is found to be 182 kg/m^3. The mix proportions shown below are nearly identical to those found by calculation.:

	C.A	F.A	PC	PFA	Water	Air	Total
Weight (kg/m^3)	785	816	386	165	182	0	2334
Volume (m^3)	0.302	0.309	0.123	0.069	0.182	0.012	0.997

These table and figures are therefore useful for quick check.

9. 4 Optimisation of SCC mix design - Economical considerations

The mix design procedure as described is easy and simple, with the exception of step 4, the selection of the water/powder ratio and powder composition. This is a key part of SCC mix design. The composition of the powders as well as the water/powder ratio have a great influence on many important properties such as strength, durability and segregation resistance. Moreover, optimum use of CRMs can reduce the cost significantly. When cost is taken into account, a lengthy trial-and-error process is inevitable. In fact, there may be more than one solution, and second alternatives may need to be assessed.

This burdensome work can be simplified by using a linear programming optimisation technique. Many commercial software versions of this are available, and among the most popular is Microsoft Excel. Solver, one of the most powerful tools within Excel, can find the optimum solution to complex problems involving multiple variables and constraints. To run Solver, one should know the function of the following items [**Chester** (1994)]:

- *Target cell* is the specific objective of the problem - the cell whose value Solver will set to be a minimum, maximum, or a specific value. In this study, the target cell is the cost (which is to be minimised) of the mix. For many engineering considerations, cost often is the first and decisive factor. Although the accurate current unit price of each constituent is often changeable, the relative cost is sufficient.
- *Changing cells* are cells whose values Solver will manipulate to meet the target cell objective. In other words, they are variables. In this study, the changing cells are the water content, water/powder ratio, and the proportion of CRMs.
- *Constraints* are the limits set on the values in any of these cells - there can be constraints on changing cells, the target cell, or any cells involved in the calculations. In this study, the constraints are the requirements for strength, durability, and

segregation resistance etc. Also, the limits of the proportions of each of the constituents can also be entered.

The general constraints of SCC are listed as follows:

Strength requirements:

$$fc = \frac{K_g \bullet R_c}{\left(1+3.1\dfrac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} + 10 \geq \text{target mean strength} \qquad \textbf{(9-12)}$$

W / C ≤ 0.50, if one day cube strength of 12.5 MPa is required.

Durability requirements:

W/P ≤ 0.45 to 0.65 (maximum ratio) according to the exposure condition

Minimum cementitious materials requirements:

cementitious materials content ≥ 300 or 280 kg/m^3

Segregation resistance requirements:

Plastic viscosity of the cementitious paste should be higher than 280 or 70 mPa.s (see **Table 6-9**), according to the maximum size of aggregate, i.e. the following conditions should be met.

$$\mu = \frac{23.6}{E_p}\left(\frac{(w/p) \bullet S.G_p}{\beta_p}\right)^{-6.38} \geq 280 \text{ mPa.s} \qquad \text{for } D_{max} \text{ 20 mm...} \qquad \textbf{(9-13)}$$

$$\mu = \frac{23.6}{E_p}\left(\frac{(w/p) \bullet S.G_p}{\beta_p}\right)^{-6.38} \geq 70 \text{ mPa.s} \qquad \text{for } D_{max} \text{ 10 mm...} \qquad \textbf{(9-14)}$$

In the case of no values of β_p and E_p being available, the following limits to water/total fines ratios can be used: (see **6.3.3**)

For D_{max} 20 mm

PC+GGBS $W/T.F \leq 0.147$

PC+PFA $W/T.F \leq 0.137$

PC+LSP $W/T.F \leq 0.137$

For D_{max} 10 mm

$W/T.F \leq 0.170$

To prevent the concrete from being too viscous, the following formula should be applied.

$W/T.F \geq 0.125$

Limits of CRMs proportion:

In addition to the constraints given in **Table 9-2,** the percentage of each CRM cannot be negative. Therefore,

PFA% ≥ 0,

GGBS% ≥ 0

LSP% ≥ 0

CSF% ≥ 0

Paste content:

$V_p \geq 0.38$ m³

$V_p \leq 0.42$ m³

Cost per cubic metre of concrete: no negative value

Cost ≥ £25

The price £25, as quoted by Pioneer Concrete Ltd in 1991 for 20 MPa concrete, is used as a lower limit.

Sand content:

$V_s/V_m \geq 0.40$

$V_s/V_m \leq 0.47$

From the experience of this study, the dosage of superplasticizer can be estimated by the powder content and water/powder ratio in order to calculate its cost. The final dosage will be obtained by trial mixes.

As with all software used in engineering design, the most important step for Solver is to check its results. Are all the results reasonable? Is the water/powder ratio a proper value? Is the powder composition adequate? Abnormal and peculiar results are not difficult to recognise, in the *Answer report* produced by the Solver.

In brief, for concrete mix design, most specification requirements can be expressed as constraints. Solver can search for the optimum mix proportions to meet the requirements. It is flexible, available and hence economical.

9. 5 Design example

Example 1

A SCC mix of characteristic strength C55 is required, and its one day strength should not less than 12.5 MPa. Durability requirements are: water/powder ratio not higher than 0.45, minimum cementitious material content 300 kg/m^3. Uncrushed aggregate with a maximum size of 20 mm and sand (F.M 2.6) are provided. No air entrainment is required. PC and GGBS are to be used.

According to CEB-FIP:

target mean strength = characteristic strength + 8 (MPa)
= 55 + 8 = 63 (MPa)

The constraints and results can be seen in the following Answer Report

Microsoft Excel 5.0c Answer Report
Worksheet: [SCCMIX10.XLS]Sheet1
Report Created: 11/28/97 11:02

Target Cell (Min)

Cell	Name	Original Value	Final Value
P41	Cost of SCC	57.7	51.7

Adjustable Cells

Cell	Name	Original Value	Final Value
C39	W	185	196.8000996
L39	W/P	0.34	0.373533626
S39	GGBS%	20	25.29325443

Constraints

Cell	Name	Cell Value	Formula	Status	Slack
O40	Vs/Vm	0.459068295	O40>=0.4	Not Binding	0.059068295
AB39	Up(mPaS)	279.9999969	AB39>=280	Not Binding	3.06011E-06
X39	Fc 28d	66.0	X39>=X41	Not Binding	3.0
P41	Cost of SCC	51.7	P41>=25	Not Binding	26.7
N39	W/TF	0.145631921	N39<=0.17	Not Binding	0.024368079
N39	W/TF	0.145631921	N39>=0.125	Not Binding	0.020631921
P40	Vp	0.380	P40>=0.38	Binding	0.000
M39	W/C	0.499999864	M39<=0.5	Binding	0
W32	Weight Kg binder(eq)	532.4	W32>=300	Not Binding	232.4
S39	GGBS%	25.29325443	S39>=10	Not Binding	15.29325443
S39	GGBS%	25.29325443	S39<=80	Not Binding	54.70674557
L39	W/P	0.373533626	L39<=0.45	Not Binding	0.076466374
L39	W/P	0.373533626	L39>=0.26	Not Binding	0.113533626

All the results are reasonable, the binding conditions are water/cement ratio (which control one day strength), paste viscosity and paste content. In other words, these three critical conditions controlled the mix proportions. From the results of Solver, the mix proportions for the concrete trial mix are:

Mix proportions (kg/m^3)

W / P	V_s/V_m	C.A 20-10	C.A 10-5	F.A	PC	GGBS	Water	Sikament 10
0.37	0.45	410	410	805	399	133	197	6.9

The next step is to carry out mortar tests to obtain the superplasticizer dose to give required properties of mortar as described in section **6.2**. Finally, a concrete trial mix is produced and tested for the slump flow, V-funnel flow time, and U-test (or L-test) and two-point test to check its passing ability and segregation resistance respectively.

Tests results: (see mix S230 in Appendix 3)

From mortar tests the superplasticizer dosage was adjusted from 6.9 kg/m^3 (obtained by Solver) to 6.0 kg/m^3, which was 0.23% solid by weight of powder. Results of mortar flow tests and concrete slump flow tests can be seen in **Fig. 6-3.** The one day cube strength for mortar and concrete were 13.3 and 16.2 MPa respectively. The mean compressive strength at 28 days was 66.3 MPa. When the slump flow was 725 mm, the passing ability of the L-test was 96%, the rheological constants g and h were 0.16 Nm and 2.64 Nms. The segregation index was 24.7%. The V-funnel flow tests for mortar and concrete were 5.2 and 5.3 sec respectively. When the slump flow was reduced to 585 mm, the filling height of U-test was 315 mm. All the results satisfied the performance requirements.

In conclusion, the main cost of SCC results from cement and superplasticizer. To minimise the cost the following rules should be taken into account:

- the water/powder ratio, sand content and CRM content should be used as high as possible. This minimises the cement content and superplasticizer dosage.
- For characteristic strength C50 or below (cube strength), 10 mm maximum size of aggregate is recommended. This obviates the need for a viscosity agent.

9. 6 Cost comparison with NC

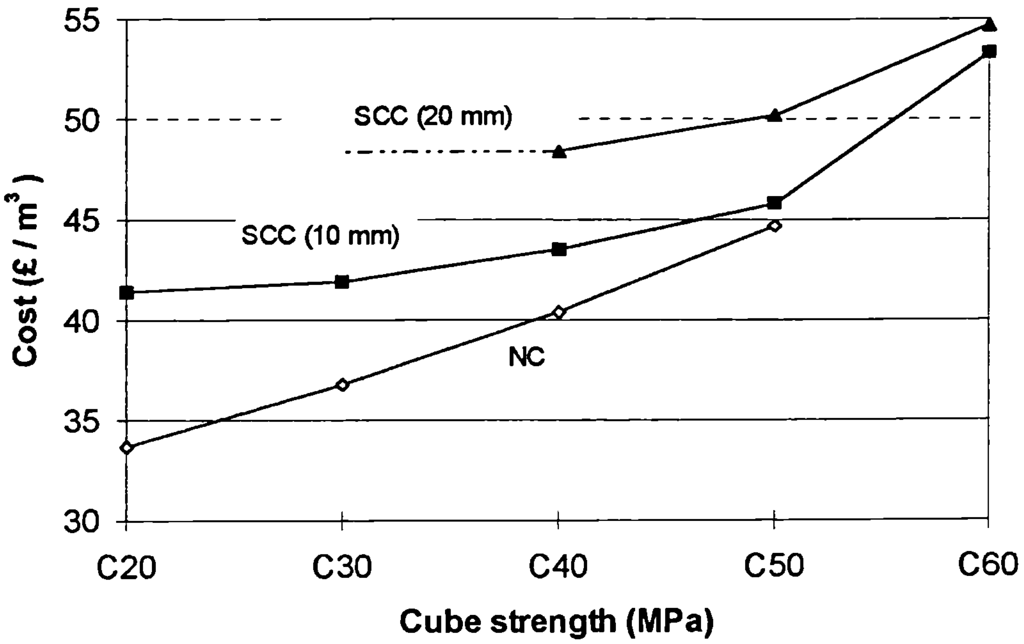
The material cost of SCC is inevitably higher than that of NC, mainly because superplasticizer is essential. For NC, the cost of the superplasticizer can sometimes be offset by a reduction in cement content, and therefore, an increase in the aggregate content, as can be seen in the **Table 9-5**. However, this is not the case for SCC, because a high aggregate content will impair the passing ability though reinforcement. The use of CRMs does reduce the cost to some extent, but the cost is still higher than NC. The main profit with SCC results from the saving of labour cost during concrete casting and the reduction of construction time.

Table 9-5 The advantage of using superplasticizer in NC

PC	Water	Agg. (kg/m$^{3)}$	SP (kg/m$^{3)}$	Paste Vol. (m^3)	W / C	A / C	Cost
450	225	1705	---	0.35	0.50	3.8	£40.6
360	180	1910	2.2	0.27	0.50	5.3	£39.1

Fig. 9-7 shows the material cost of SCC compared with that of NC designed according to BRE (1988). As can be seen, the cost of SCC with 10 mm maximum size aggregate is about £5/m^3 higher than that of NC. It is worth noting that if a one day strength of 12.5 MPa is not required, the cost of SCC can be reduced significantly. Moreover, it is clear

that the cost of SCC with 20 mm aggregate cannot be reduced further for cube strengths of under C40. This is due to the segregation resistance requirement which limits the maximum value of water/powder ratio in the absence of a viscosity agent.



Assume: Unit price of materials

Aggregate	PC	PFA	GGBS	SP
£ 8 / ton	£ 60 / ton	£ 20 / ton	£ 30 / ton	£ 1.2-1.9 / litre

Fig 9-7 *Cost comparison of SCC and NC*

9. 7 Conclusions

SCC, due to its specific properties, requires a different mix design procedure to other concretes. The aggregate content can first be chosen. Then the key step is to select an appropriate water / powder ratio and powder composition. Next, the water and powder contents can be calculated. A suitable dosage of superplasticizer is then obtained by mortar tests. Finally, it is very important to carry out a concrete trial mix to examine its fresh properties. After the various tests, as discussed in Chapter 7, some adjustments to the mix may be needed.

To obtain the relevant mix design for a structure, the performance requirements of concrete have to be studied comprehensively. For instance, the requirement of segregation resistance of a retaining wall may be different from that of a girder. The requirement of passing ability for a mat foundation will also be different to that for a high column. These all come from engineering experiences, and therefore, large scale concrete tests on site are often needed for SCC. This subject is beyond the scope of this study.

Neville, in his famous book, *Properties of concrete 4th ed.* stated "the various methods of mix selection may seem simple and, indeed, they do not involve any complex calculations. However, a successful implementation of the selection requires *experience*, coupled with the *knowledge* of the influence of various factors upon the properties of concrete; this knowledge must be based on an *understanding* of the behaviour of concrete. When these three desiderata -experience, knowledge, and understanding -are all present, the first trial mix is likely to be approximately satisfactory, and can be rapidly and successfully adjusted so as to achieve a mix with the desired properties" This is absolutely right for normal concrete, and especially true for SCC.

Chapter 10

Conclusions and recommendations for future work

10.1 Conclusions

This work has continually examined the tests and mix design methods for SCC reported in the literature, and then has developed a mix design procedure and relevant tests for paste, mortar and concrete. A novel viscosity equation has proved useful in the mix design. SCC has been produced successfully in the laboratory with readily available UK materials. An effective and novel method has been used to assess the segregation of concrete and has resulted in an economical way of enhancing the segregation resistance. The main factors controlling the early strength of SCC have been discovered. Consequently, the research aims have been achieved.

The principal individual conclusions from the experimental study can be summarised as follows:

1. The simple flow spread test can be used to obtain the retained water ratio, β_p, and the deformation coefficient, E_p, of powders, (see 5.4) which are important parameters characterising their rheological performance. It is also possible to predict with reasonable confidence the values of β_p and E_p for the blended powders from results of powders tested singly. Comparison of the results of the flow spread test with yield stress and plastic viscosity measured in a concentric cylinder viscometer gives confidence that the flow spread test is measuring a useful rheological characteristic. The relative flow area ratio of the flow spread test has an inverse linear relation with yield stress. The plastic viscosity of cementitious paste can be calculated from the values of β_p, E_p and water/powder ratio using the novel viscosity equation. This is extremely useful, because the selection of cementitious powders and the water/powder ratio is a key step in SCC mix design.

2. The mortar tests offer substantial information that can be used in the adjustment of concrete trial mixes, (see chapter 6) including:
   - the cement/superplasticizer compatibility
   - a suitable dosage of superplasticizer,
   - the workability and stability of the mixes,
   - early strength gain.

3. As a general guide to the composition of SCC,: the coarse aggregate content should be limited to 50% of its dry rodded weight with 20 mm maximum size of aggregate, which confirms Ozawa's recommendation, and not higher than 55% of its dry rodded weight with 10 mm maximum size of aggregate. The sand volume should be between 40% to 47% of the mortar volume, the exact volume depending on the water/powder ratio and a minimum volume of paste (see **7.1.3**, **9.2 4** and **9.3**).

4. From literature review, there are four main factors influencing the passing ability through reinforcement:
   - the ratio of mesh gap to maximum size of aggregate
   - the aggregate content;
   - the flowability.
   - segregation resistance

   The experimental work has confirmed that both the U-test and the L-test are good for assessing the passing ability. For the purpose of comparison with other results and industrial application, the U-test is recommended, but for the purpose of teaching and demonstration, the L-test is preferred. A slump flow between 600 mm to 700 mm and 650 mm to 750 mm will be sufficient for SCC whose maximum size of aggregate is 10 mm and 20 mm respectively (see **7.1**).

5. The V-funnel flow test can be considered as a measurement of the concrete viscosity provided that the coarse aggregate content is in the range (G/G_{lim} 0.50-0.52) and the yield value (g) is small. For SCC with a 20 mm maximum size of aggregate, the V-funnel flow time and the h value should be in the range of 4-10 sec. and 2-5 Nms respectively whereas for SCC with 10 mm aggregate they should be in the range of 2-10 sec. and 1-5 Nms respectively (see **7.2**).

6. A novel and effective method has been developed to assess the segregation of concrete by utilising the two-point workability test. By stirring with the helical impeller at a speed of 0.31 rps for one minute, the difference of coarse aggregate content between the top and bottom part of the concrete can be used as an index to measure the degree of segregation resistance. This method has successfully differentiated between the segregation resistances of SCC with different maximum sizes of aggregate, and therefore has lead to a novel economical way of enhancing the segregation resistance (see **4.3.3.6** and **7.2.4**).

7. There are several ways of increasing the segregation resistance of fresh concrete, but because of the additional requirement of passing ability, some are not applicable to SCC, e.g. larger quantities of coarse aggregate or a higher yield value of the mortar. For SCC, the current practice is to increase its viscosity through lowering the water powder ratio or incorporating a viscosity agent so that the requirement of segregation resistance can be satisfied. However, this study has shown that the segregation can effectively be reduced by using a smaller maximum size of aggregate (10 mm) compared to the more normal 20 mm. As a result, this can reduce:
   - the requirement of concrete viscosity
   - the concrete cost, in particular with strength C40 and below (see **7.2.4**)

8. The bond of SCC to reinforcement is not less than that of fully compacted NC for the same compressive strength. Hence, SCC can effectively eliminate the risk of poor bond which results from improper vibration of NC (see **8.1**).

9. Although the shrinkage of SCC is slightly higher than that of NC, by lowering the water/powder ratio and by selecting the cement replacement materials properly, a satisfactory shrinkage can easily be achieved (see **8.2**).

10. The modified **Feret's** rule can predict the 28-day compressive strength of SCC containing different types of cement replacement material with reasonable accuracy. For compressive strength testing of SCC, large cubes (150 mm) without compaction are recommended. The influence of slump flow on compressive strength is not significant provided it is higher than 400 mm, but low slump flow will result in a poor hardened concrete surface (see 8.3).

11. A cube strength 12.5 MPa can be obtained in one day, if the following conditions can be met (see **8.3.4**):
    - the water/cement (including CSF) ratio is less than 0.50;
    - the superplasticizer contains no retarder (i.e. is not a G-type);
    - there is no overdose of superplasticizer.

12. Solver, a useful tool within Microsoft Excel, can be used in SCC mix design to minimise the material cost. Most requirements of SCC performance can be transformed into constraint conditions so that the optimum mix proportions can be found by Solver. For example, in order to ensure segregation resistance, the calculated plastic viscosity of cementitious paste should be higher than 280 and 70 mPa.s, when maximum size of aggregate are 20 and 10 mm respectively. If the water/powder ratio is in the range 0.40-0.50, 10 mm maximum size of aggregate and GGBS are preferred if no viscosity agent is to be used (see **Chapter 9**).

10.2 Recommendations for future work

From the results obtained and the knowledge gained about SCC, the following areas for future work are suggested:

1) More trial mixes are needed with water/powder ratios are in the range of 0.40 to 0.50, both for 10 mm maximum size of aggregate without a viscosity agent, and for 20 mm aggregate, with a viscosity agent.

2) It is very critical for SCC to have a low loss of slump flow. It may be beneficial to split the dosage of superplasticizer; and add the first part when the concrete is mixing and then add the rest on site just before the pouring of the concrete. Another alternative is to use new types of chemical admixtures such as super-superplasticizer, high range water reducing air-entraining agent, etc.

3) For SCC when slump flow declines with time to a value between 600 mm and 400 mm, there is little influence on its compressive strength, however, the influence of low slump flow on durability is not clear. In particular, when the slump flow is under 500 mm, its hardened surface contained many large voids, which might increase the concrete permeability.

4) From this study, the large voids on the hardened surface have been found to depend on the slump flow, the paste content and surface/volume ratio of the specimen. Each of these factors needs further study. For example, if the paste content is less then 0.38 m^3, can a smooth hardened surface be achieved with confidence?

5) Feret's modified formula for strength is very useful, and the values of K_g for aggregate other than Thames gravel are required.

6) Although some research on the application of packing factors for aggregate and powder to SCC performance have been carried out in France and other countries, the relationships between packing and passing ability and segregation resistance are not yet very clear.

7) Different structural components have different requirements for passing ability and segregation resistance. It is a great challenge to quantify these requirements so that they can be taken into account in SCC mix design. Large scale real structure tests on site are essential for this.

8) From the practical point of view, it is very important to translate the production of SCC from the laboratory to the ready mixed concrete plant. Methods of the quality control and assurance of SCC in mass production are also required.

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APPENDICES

APPENDIX 1.

RESULTS OF TESTS ON PASTE

APPENDIX 2.

RESULTS OF TESTS ON MORTAR

APPENDIX 3.

RESULTS OF TESTS ON CONCRETE

APPENDIX 4.

SOURCE PROGRAMME

APPENDIX 1.

RESULTS OF TESTS ON PASTE

Table A.1 Results of tests on paste

Rugby cement*			S.G	βp	Ep	Date
			3.15	1.064	0.0574	3-Jul-95
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
0.69	0.349	1.1	1.034	123.8	331	19.01
2.17	0.381	1.2	1.128	68.6	210	12.03
4.38	0.413	1.3	1.222	45.5	96	5.53
5.71	0.444	1.4	1.316	32.7	70	4.04
	0.500	1.575	1.480	12.7	32	1.85
PFA*			S.G	βp	Ep	Date
			2.404	0.5863	0.0242	5-Jul-95
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
0.76	0.255	0.614	1.047	27.0	995	24.08
3.62	0.277	0.665	1.134	20.3	416	10.08
5.76	0.298	0.717	1.223	14.3	227	5.50
9.24	0.340	0.818	1.395	6.4	104	2.53
GGBFS*			S.G	βp	Ep	Date
			2.9	1.097	0.0457	12-Jul-95
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
0.56	0.379	1.1	1.003	33.4	527	24.10
2.06	0.414	1.2	1.094	29.3	276	12.60
3.84	0.448	1.3	1.185	20.7	160	7.29
7.12	0.483	1.4	1.276	13.7	87	3.95
LSP*			S.G	βp	Ep	Date
			2.68	0.7655	0.0368	9-Aug-95
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
1.10	0.299	0.8	1.045	56.6	581	21.40
3.20	0.336	0.9	1.176	47.3	223	8.21
6.40	0.373	1.0	1.306	27.2	111	4.08
9.66	0.410	1.1	1.437	16.1	63	2.33
14.21	0.485	1.3	1.698	7.6	35	1.30
PC +1.0% SP			S.G	βp	Ep	Date
			3.15	0.862	0.0342	4-Aug-95
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
1.25	0.286	0.9	1.044	54.35	460	15.72
3.62	0.317	1.0	1.160	18.77	189	6.47
7.67	0.349	1.1	1.276	8	108	3.70
9.43	0.381	1.2	1.392	5.87	68	2.31

Yield stress and plastic viscosity measured in a concentric cylinder viscometer (Rheomat 115).
R: relative flow area ratio

Table A.1 continued (1)

50%PFA+50%LSP			S.G	βp	Ep	Date
			2.533	0.718	0.047	9/2/96
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
0.082	0.276	0.700	0.975	65.0	947	44.58
1.403	0.316	0.800	1.114	52.0	419	19.73
3.41	0.355	0.900	1.253	29.0	170	8.01
6.29	0.395	1.000	1.392	16.5	71	3.34
0.35PC+0.30PFA+0.35GGBS*			S.G	βp	Ep	Date
			2.8027	0.9476	0.056	4-Aug-95
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
1.10	0.359	1.01	1.066	62.17	507	28.39
2.80	0.395	1.11	1.171	44.6	210.9	11.81
5.00	0.431	1.21	1.277	29.9	105.5	5.91
6.26	0.467	1.31	1.382	24.2	73	4.09
0.70PC+0.30PFA*			S.G	βp	Ep	Date
			2.88	0.9375	0.0487	1-Sep-95
R		Vw/Vp	Vw/Vp/Bp	Yiel stress Pa	Viscosity (mPas)	viscosityxEp
1.42	0.347	1.0	1.067	82	284	13.83
3.35	0.381	1.1	1.173	54	133	6.48
5.03	0.416	1.2	1.280	33	81	3.94
7.64	0.451	1.3	1.387	21	57	2.78
Rugby cement*		S.G		βp	Ep	Date
		3.15		1.096	0.0653	15-Aug-95
R	W/P	Vw/Vp	Vw/Vp/βp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
0.37	0.349	1.1	1.004	140.0	426	27.81
1.43	0.381	1.2	1.095	95.8	183	11.92
2.69	0.413	1.3	1.186	62.6	114	7.42
5.25	0.444	1.4	1.277	37.4	77	5.02
5.86	0.476	1.5	1.369	29.8	60	3.92
GGBS			S.G	βp	Ep	Date
			2.9	1.074	0.0607	24/11/95
R	W/P	Vw/Vp	Vw/Vp/Bp	Yiel stress Pa	Viscosity (mPas)	viscosityxEp
0.53	0.379	1.1	1.024	40	554	33.63
1.92	0.414	1.2	1.117	31	385	23.37
3.73	0.448	1.3	1.210	26	184	11.17
5.40	0.483	1.4	1.304	20	114	6.92
*Silverson mixer, mixing time 5min						

Table A.1 continued (2)

0.25PC+0.25PFA+0.50GGBS!			S.G	βp	Ep	Date
			2.8094	1.009	0.0357	12-Mar-95
R	W/P	Vw/Vp	Vw/Vp/Bp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
2.90	0.392	1.1	1.090	41.6	372	13.27
5.11	0.427	1.2	1.189	26	179	6.37
7.81	0.463	1.3	1.288	15.4	97	3.47
11.25	0.498	1.4	1.388	8.9	55	1.96
0.35PC+0.20PFA+0.45GGBS!			S.G	βp	Ep	Date
			2.8603	0.988	0.0416	22-Mar-95
R		Vw/Vp	Vw/Vp/Bp	Yield stress (Pa)	Viscosity (mPas)	viscosityxEp
3.00	0.385	1.1	1.113	36.6	331	13.78
5.00	0.420	1.2	1.215	25.0	157	6.52
6.95	0.454	1.3	1.316	16.0	81	3.37
10.22	0.489	1.4	1.417	11.3	65	2.70
! Hobart mixer						

APPENDIX 2.

RESULTS OF TESTS ON MORTAR

Table A.2 Results of tests on mortar

time (min.)	Dia (mm)	*SP % wt. of pow	V-funnel (sec)	W : P: S by wt.	Strength size(mm)-age(d)	Fc MPa	Remark	Adhesion Glass ball
06-Feb-96	*16.7%PFA, LSP 33% Vs/Vm 0.40 W/P 0.268 SP333 0.83%*						M01	
14	201	0.83	15					
76	195		22					
163	147		36					
06-Feb-96	*17%PFA, 33%LSP, W/P 0.268, Vs/Vm 0.40, SP333*						M02	g/cm^2
2	316	1.00	9.4	0.27 : 1: 1.09			Fig. 6-16	0.067
78	318		10					0.069
18-Jun-96	*20%PFA+7%CSF, W / P 0.29, Vs/Vm 0.45, SP 333*						M03	
	117	1.11		0.29 : 1 : 1.38			Fig. 7-12	
	192	1.22	5.9					
	253	1.32	3.8					0.073
	305	1.4	3.6					0.063
21-Jun-96	*15%PFA, W/P 0.31, Vs/Vm 0.45*						M04	
	222		9.1	0.31 : 1 : 1.39			Fig. 6-12	0.112
	314		7.4				Fig. 7-12	0.092
	W/P 0.31, 15%PFA, Vs/Vm 0.4, SP 333						M05	
	110	0.59		0.31 : 1 : 1.13			Fig. 7-12	
	144	0.69	10				Fig. 7-13	0.288
	259	0.77	7					0.095
	311	0.83	6.9					0.076
	333		4.8					0.062
	W/P 0.40, 15%PFA, Vs/Vm 0.44						M06	
	145		4.9	0.40 : 1 : 1.52			Fig. 7-12	0.238
	191		2.4				Fig. 7-13	0.112
	270		2.4					0.067
25-Jun-96	*20%PFA+10%CFS, 0.31 Vs/Vm 0.45, SP 333*						M07	
	110	0.85		0.40 : 1 : 1.42			Fig. 7-12	
	190	0.96	6.5					0.149
	297	1.05	4					0.058
12-Nov-96	*20%PFA, Vs/Vm 0.45 W/P 0.34 SP435 0.6%*						M08	
14	205	0.60	4.6	0.34 : 1 : 1.46			Fig. 6-5	
118	140		8.9					
12-Nov-96	*20%PFA, Vs/Vm 0.45 W/P 0.34 Sika 0.3%*						M09	
13	315	0.30	5.9	0.34 : 1 : 1.46			Fig. 6-5	
86	305		6.5					
18-Nov-96	*15%PFA, 10%GGBS, Vs/Vm 0.45 W/P 0.34 Sika10 0.3%*							
11	342.5	0.30	5.8	0.34 : 1 : 1.46	50-1	9.0	M10	
110	340		7.7		100-1	9.1		
					50-2	31.4		
					50-2	34.9		

Flow spread test was carried out first, followed by V-funnel test. If mortar stood for a period of time, remixed 5 sec for every 30 min before repeated the tests.

* SP dosage: solid by wt. of powder.

W : P : S = water : powder : sand

Table A.2 continued (1)

time (min.)	Dia (mm)	SP % wt. of powd	V-funnel (sec)	W : P: S by wt.	Strength size(mm)-age(d)	Fc MPa	Remark	Adhesion Glass ball
19-Nov-96	*20%GGBS, Vs/Vm 0.45 W/P 0.34 Sika 0.25%*						M11	
12	320	0.25		0.34 : 1 : 1.43	50-1	18.8		
43	310		10.4		100-1	17.4		
100	307.5		13.3		50-2.3	40.4		
					50-2.3	39.4		
19-Nov-96	*20%GGBS, Vs/Vm 0.45 W/P 0.34 Sika (0.2%+0.03)*						M12	
10	240	0.20		0.34 : 1 : 1.43	50-1	20.6		
43	210		12.4		100-1	20.6		
76	295	0.23			50-2	42.8		
109	270		11.1		50-2	42.4		
28-Nov-96	*10%PFA, 10%GGBS, W/P 0.34, Vs/Vm 0.45, Sika*						M13	
13	235	0.23		0.34 : 1 : 1.45	50-1	16.8		
23	330	0.25			100-1	17.8		
61	310		8		50-4	52.1		
110	277.5		9.5		50-4	53.2		
11-Dec-96	*10%PFA, 10%GGBS, Vs/Vm 0.50 W/P 0.34 Sika (0.25+0.03)%*						M14	
10	273	0.25		0.34 : 1 : 1.77	50-1	12.6		
19	310	0.28			50-1	13.1		
50	297.5		11.8					
90	278.5		15.8					
13-Jan-97	*30%PFA, Vs/Vm 0.40 W/B 0.29 Sika10 (0.45)%*						M15	
5	357.5	0.45		0.29 : 1 : 1.12	100-1.6	25.4		
40	360		9		50-1.8	30.1		
90	350		13.2		50-1.8	30.5		
					50-2.9	36.6		
13-Jan-97	*20%PFA, 15%GGBS, Vs/Vm 0.40 W/P 0.29 Sika10 (0.56)%*						M16	
5	358	0.56	18	0.34 : 1 : 1.11	50-2.1	32.8		
42	345				100-2.1	32.8		
					50-3.1	49.9		
					50-3.1	50.5		
14-Jan-97	*20%PFA, Vs/Vm 0.45 W/P 0.34 SP333 (0.72+0.24)%*						M17	
10	118.5	0.72		0.34 : 1 : 1.46				
15	330	0.96	4.8					
79	255		7.9					
14-Jan-97	*20%PFA, Vs/Vm 0.45 W/P 0.34 SP333 (0.72+0.24)%*						M18	
5	109	0.72		0.34 : 1 : 1.46	100-1.1	0.6		
12	330	0.96	4.8					
72	255		7.9					
15-Jan-97	*20%PFA, Vs/Vm 0.45 W/P 0.34 SP333 0.96%*						M19	
10	297.5	0.96		0.34 : 1 : 1.46				
35	257.5		10.5					
89	194		14.4					

* SP dosage: solid by wt. of powder

Table A.2 continued (2)

time (min.)	Dia (mm)	SP % wt. of pow	V-funnel (sec)	W : P: S by wt.	Strength size(mm)-age(d)	Fc MPa	Remark	Adhesion Glass ball
15-Jan-97	*20%PFA, Vs/Vm 0.45 W/P 0.34 SP435 0.96%*						M20	
11	333.5	0.96		0.34 : 1 : 1.46	50-1.2	20.3	Fig. 6-5	
35	336		5.1		100-1.2	20.6		
116	325		5.8					
130	312.5							
15-Jan-97	*20%PFA, Vs/Vm 0.45 W/P 0.34 SP337 0.80%*						M21	
13	240	0.80		0.34 : 1 : 1.46	50-1	14.5		
41	195		9.1		50-1	15		
					100-1	14.5		
20-Jan-97	*20%PFA, W / P 0.34, Vs/Vm 0.45 SP333 0.72% water Temp. 21C*						M22	
7	295	0.72	10.5	0.34 : 1 : 1.46	50-1	0	Fig. 6-7	
25	297.5		9		50-2	18.5		
42	305		9		50-2	18.6		
57	301		9		50-2	18.8		
73	280		10					
93	255		11					
20-Jan-97	*20%PFA, W / P 0.34, Vs/Vm 0.45 SP333 0.72% water Temp. 14C*						M23	
5	277.5	0.72	9	0.34 : 1 : 1.46	50-1	0	Fig. 6-7	
20	182.5		12		50-2	23.3		
37	150		16		50-2	22.7		
54	120		18		50-2	21.2		
71	105		24					
20-Jan-97	*20%PFA, W / P 0.34, Vs/Vm 0.45 Sika 0.30% water Temp. 22C*						M24	
11	330	0.3		0.34 : 1 : 1.46	50-1	11.6	Fig. 6-3	
48	320		6.9		50-1	10.8	Fig. 6-7	
97	300		7.6		50-2	34.8		
20-Jan-97	*20%PFA, W / P 0.34, Vs/Vm 0.45 Sika 0.30% water Temp. 15C*						M25	
10	340	0.3		0.34 : 1 : 1.46	50-1	11.6	Fig. 6-7	
50	327.5		6.6		50-1	12.7		
99	317		7.1		50-2	36.2		
					50-2	35		
22-Jan-97	*40%GGBS, W / P 0.40, Vs/Vm 0.46 Sika (0.56+0.11)%*						M26	
5	218	0.56	7.6	0.40 : 1 : 1.64	50-1	7.4		
20	321	0.67	5.1		100-1	7.5		
95	250		6.6					
27-Jan-97	*15%GGBS, W/P 0.40, Vs/Vm 0.50 Sika10, water temp. 21C*						M27	
11	220	0.23	9.1	0.40 : 1 : 1.90	50-2	29.4		
25	297	0.27	6.7		50-2	29		
83	242.5		9.1					
132	180		20.6					

* SP dosage: solid by wt. of powder

Table A.2 continued (3)

time	Dia	SP %	V-funnel	W : P: S	Strength	Fc	Remark	Adhesion
(min.)	(mm)	wt. of powd	(sec)	by wt.	size(mm)-age(d)	MPa		Glass ball
27-Jan-97	*15%GGBS, W/P 0.40, Vs/Vm 0.50 Sika10, water temp. 19.5C with viscosity*						M28	
13	170	0.23	37.5	0.40 : 1 : 1.90	100-1	10.1		
24	278	0.28	11.1		50-2	30		
48	285		10.5		50-2	30		
109	265		14.2					
149	245		17					
03-Apr-97	*30%PFA, W/P 0.28, Vs/Vm 0.40 Sika 10*						M29	
4	355	0.45	8.2	0.28 : 1 : 1.10	100-1	3.5		
62	357		9.2					
16-Apr-97	*25%PFA, Vs/Vm 0.50, Sika 0.23%*						M30	
5	311	0.23	3.3	0.40 : 1 : 1.96				
24	295	+vis	4.6					
73	303		5.7					
103	277	+vis	9.1					
113	265							
123	280							
25-Apr-97	*20%LSP, Vs/Vm 0.45, W / P 0.34, Sika 0.23%*						M31	
6	335	0.23	4.2	0.34 : 1 : 1.44			Fig. 6-21	
85	312.5		5.4					
25-Apr-97	*20%PFA, Vs/Vm 0.45, W / P 0.34, Sika 0.23%*						M32	
5	320	0.23	4.3	0.34 : 1 : 1.46			Fig. 6-21	
90	282.5		5.9					
25-Apr-97	*20%GGBS, Vs/Vm 0.45, W / P 0.34, Sika 0.23%*						M33	
9	303	0.23	5.3	0.34 : 1 : 43			Fig. 6-21	
90	272.5		7.1					
29-Apr-97	*20%GGBS, Vs/Vm 0.47, W / P 0.37, Sika 0.20%*						M34	
5	300	0.2	4.1	0.37 : 1 : 1.62	100-1	17.3		
90	250		5.5		50-29	72.8		
					50-29	72.8		
					50-29	73.2		
08-May-97	*25%GGBS, Vs/Vm 0.45, W / P 0.37, Sika 0.26%*						Segregation	
6	335	0.23	4.3	0.37 : 1 : 1.50	100-1	13.2	M35	
86	325		4.6				Fig. 6-22	
08-May-97	*25%GGBS, Vs/Vm 0.45, W / P 0.37, Sika 0.23%*						M36	
6	318	0.23	5.2	0.37 : 1 : 1.50	100-1	13.3	Fig. 6-3	
90	305		6.8		50-5	49.2		
122	293		6.8		50-5	51.2		
					50-5	50.4		

* SP dosage: solid by wt. of powder

Table A.2 continued (4)

time (min.)	Dia (mm)	SP % wt. of pow(	V-funnel (sec)	W : P: S by wt.	Strength size(mm)-age(d)	Fc MPa	Remark	Adhesion Glass ball
14-May-97	*30%PFA, W / P 0.35, Vs/Vm 0.46 Sika 0.23%*						M37	
10	320	0.23	4.8	0.35 : 1 : 1.57	100-1	11.1	Fig. 6-3	
67	315		5.3		50-5	38.3	Fig. 6-15	
					50-5	39.4		
					50-5	38.6		
19-May-97	*50%GGBS, W / P 0.38, Vs/Vm 0.46 Sika 0.23%*				Segregation		M38	
5	330	0.23	5	0.38 : 1 : 1.60			Fig. 6-22	
19-May-97	*50%GGBS, W / P 0.38, Vs/Vm 0.46 Sika 0.20%*						M39	
10	310	0.20	5.4	0.38 : 1 : 1.60	100-1	7.5	Fig. 6-4	
90	165		9.6		50-2.3	21.2	Fig. 6-8	
					50-2.3	21.6		
					50-9	49.2		
04-Jun-97	*20%PFA, 39%GGBS, Vs/Vm 0.46, w / P 0.38, Sika 0.23%*						M40	
5	320	0.23	4.9	0.38 : 1 : 1.64	50-1	5.4	Fig. 6-8	
65	275				50-6	36.5		
110	228		7.8		50-6	33.5		
04-Jun-97	*30% PFA, Vs/Vm 0.40, Sika 0.40%*						M41	
	298	0.40	9.5		100-6	59.6		
					50-6	65.2		
					50-6	60.5		
					50-6	62.5		
09-Jun-97	*30% PFA, Vs/Vm 0.40, W / P 0.29, Sika 0.40%*						M42	
5	350	0.40	6.8	0.29 : 1 : 1.12	100-1	19.6		
70	340				50-1	19.3		
119	330		9.9					
25-Jul-97	*35%PFA, Vs/Vm 0.46, W / P 0.38, Sika 0.20%*						M43	
7	320	0.20	3.4	0.38 : 1 : 1.65				
77	270		5.6					

* SP dosage: solid by wt. of powder

APPENDIX 3.

RESULTS OF TESTS ON CONCRETE

Table A.3.1 Mixes and tests carried out

Gravel 25 mm		MIXES					Coarse agg.											TEST								
ref	mix	binder^	W/P	Vs/Vm	Vg	G/G_{lim}	20-10	10-5	sand	PC	PFA	GGBS	LSP	CSF	W	SP	AE	SF	g,h	L	U	V	Fc	S.I	Bond	Shr.
S203	SE291195	35%GGBS, 30%PFA	0.34	0.40	0.302	0.50	393	392	695	198	170	198			192	SP435	PA21	x	x	x		x	x			
S204	SE131295	45%GGBS, 20%PFA	0.34	0.40	0.302	0.50	393	392	695	200	115	258			194	SP435	PA21	x	x	x		x	x			
S205	SE151295	70%GGBS	0.34	0.40	0.314	0.50	544	272	688	173		404			196	SP435	PA21	x	x	x		x	x			
S206	SE160196	35%LSP	0.26	0.40	0.323	0.50	421	420	688	425			229		170	SP435	PA21	x	x	x		x				
S222	SC290197	20%PFA	0.34	0.45	0.315	0.50	410	410	801	438	110				186	Sika10		x	x	x	x	x	x	x	x	
Gravel 20 mm																										
S201	SC300395	45%GGBS, 20%PFA	0.29	0.40	0.3	0.50	314	471	707	225	129	289			187	SP435		x	x	x		x				
S202	SC020595	45%GGBS, 20%PFA	0.29	0.40	0.302	0.50	314	471	684	218	125	280			179	SP436	PA21	x	x	x		x	x			
S207	SC240196	29%GGBS, 36%LSP	0.26	0.40	0.323	0.50	337	505	693	234		191	224		170	SP435		x	x	x		x	x			
S208	SC070296	17%PFA, 33%LSP	0.27	0.40	0.323	0.50	337	505	693	319	106		210		170	SP333		x	x	x		x	x			
S209	SC120296	17%PFA, 33%LSP	0.27	0.40	0.323	0.50	337	505	693	319	106		210		170	SP333		x	x	x		x	x			
S210	SFC02059(	15%PFA	0.40	0.44	0.313	0.50	542	271	764	427	75				201	SP333		x	x	x		x	x			
S211	SFC03079(	15%PFA	0.50	0.45	0.313	0.50	542	271	812	384	68				226	SP333		x	x	x		x	x			
S212!	SC141096	20%PFA	0.34	0.45	0.315	0.50	410	410	801	438	110				186	SP333		x		x		x	x		x	
S213!	SC211096	5%PFA5%, 10%CSF	0.34	0.44	0.315	0.50	410	410	784	475	28			56	190	SP435		x		x		x	x		x	
S214!	SC281096	20%PFA	0.28	0.43	0.315	0.50	328	492	766	498	125				174	SP435		x	x	x		x	x	x	x	
S215	SC301096	20%PFA	0.34	0.45	0.315	0.50	410	410	801	438	110				186	SP333		x	x	x		x	x	x	x	
S216	SFC31109(	5%PFA, 10%CSF	0..34	0.44	0.315	0.50	410	410	784	475	28			56	190	SP333		x	x	x		x	x	x		x
S217	SFC06119(	5%PFA, 10%CSF	0.34	0.44	0.315	0.50	410	410	784	475	28			56	190	Sika10		x	x	x		x	x	x	x	
S218!	SFC13119(	20%PFA20, 80%RHP(	0.34	0.45	0.315	0.50	410	410	801	438	110				186	SP333		x	x	x		x	x	x	x	
S219	SC211196	20%GGBS	0.34	0.45	0.315	0.50	328	492	801	448		112			190	Sika10		x	x	x		x	x	x	x	
S220!	SC130197	20%PFA	0.34	0.45	0.315	0.50	328	492	801	437	109				185	SP333		x	x	x		x	x		x	
S221	SC160197	20%PFA	0.34	0.45	0.315	0.50	273	547	801	438	110				186	Sika10		x	x	x		x	x	x		
S223!	SC030297	20%PFA	0.34	0.45	0.315	0.50	328	492	801	438	110				186	Sika10		x		x		x	x			
S224!	SC100297	5%PFA, 10%CSF	0.34	0.45	0.315	0.50	328	492	801	466	27			55	186	Sika10										
S225!	SC110297	20%PFA	0.26	0.45	0.315	0.50	328	492	801	497	126				161	Sika10		x	x	x	x	x	x			
S226	SC050397	20%PFA	0.34	0.45	0.315	0.50	328	492	801	438	110				186	Sika10		x	x		x	x	x		x	
S227	SC040497	30%PFA	0.29	0.40	0.315	0.50	328	492	712	452	194				180	Sika10		x	x	x		x	x	x	x	x
S228	SC230497	25%LSP	0.34	0.47	0.315	0.50	410	410	835	412			137		190	Sika10		x	x			x	x		x	x
S229	SC300497	20%GGBS	0.37	0.47	0.315	0.50	410	410	837	413		103			191	Sika10		x	x	x	x	x	x	x		x
S230	SC120597	25%GGBS	0.37	0.45	0.315	0.50	410	410	805	399		133			197	Sika10		x	x	x	x	x	x	x		x

^ Rest portion : PC

*Dosage of SP: solid by wt of powder. SP 435, SP 333: 40% solid; Sikament 10 20% solid

SFC: V-funnel flow time < 4.0 Sec; MC: Modified concrete without PC; SE: SCC with AE; FC: flowing concrete; NC: normal concrete

! tests carried out by Tucker & Kinloch

SF: slup flow, g,h: two-point test, L: L-test

U: U-test, V: V funnel test, Fc: comp. streng

S.I: segregation index, Bond: pull-out test.

shr: shrinkage test

Table A.3.1 continued (1)

Gravel 10 mm		MIXES				Coarse agg.										TEST								
ref	mix	binder^	W/P	Vs/Vm	Vg	G/G$_{lim}$	10-5	sand	PC	PFA	GGBS	LSP	CSF	W	SP	SF	g.h	L	U	V	Fc	S.I	Bond	Shr.
F101	FC020695		0.42	0.41	0.412	0.67	1071	629	465					195	SP435	x	x	x		x				
M101	MC231096	50%PFA, 50%LSP	0.28	0.4	0.3	0.51	809	729	0	307		307		172	SP435	x	x		x	x		x		
M102	MC131196	50%PFA, 50%LSP	0.28	0.40	0.3	0.51	809	729	0	307		307		172	SP435	x	x			x		x		
M103	MC060397	50%PFA, 50%LSP	0.29	0.40	0.315	0.515	820	712	0	300		300		168	SP435	x	x		x	x		x		
M105	MC130397	50%PFA, 50%GGBS	0.50	0.50	0.315	0.515	820	890	0	191		191		191	SP435	x	x	x	x	x		x		
S101	SC210396		0.50	0.48	0.299	0.495	777	863	439					219	SP435	x	x	x		x	x			
S102	SC170496		0.50	0.51	0.302	0.5	785	899	400					200	SP435	x	x	x		x	x			
S103	SC240496	15%PFA	0.40	0.45	0.300	0.5	780	796	428	75				201	SP333	x	x	x		x	x			
S104	SC090596	20%PFA	0.34	0.45	0.300	0.49	780	796	435	109				185	SP333	x	x	x		x	x			
S108	SC121296	10%PFA, 10%GGBS	0.33	0.45	0.307	0.51	800	811	448	56	56			190	Sika10	x	x	x		x	x		x	x
S109	SC170397	15%GGBS	0.40	0.50	0.315	0.515	820	891	397		70			187	Sika10	x	x	x	x	x	x	x	x	x
S110	SC070497	15%GGBS+vis	0.40	0.48	0.315	0.515	820	855	413		73			196	Sika10	x	x	x	x	x	x	x	x	x
S111	SC110497	20%PFA	0.36	0.45	0.315	0.515	820	801	438	110				195	Sika10	x	x	x		x	x	x		
S112	SC160497	25%PFA+vis	0.40	0.50	0.315	0.515	820	891	341	114				182	Sika10	x		x		x	x	x		x
S113	SC140597	30%PFA	0.35	0.46	0.308	0.5	800	829	370	159				185	Sika10	x	x	x	x	x	x	x	x	x
S114	SC200597	50%GGBS	0.38	0.46	0.308	0.5	800	824	256		256			195	Sika10	x	x	x		x	x	x	x	x
S115	SFC09079	15%PFA	0.50	0.45	0.313	0.50	813	805	380	67	0			223	SP333	x			x	x	x	x		x
S116	SC250797	38%PFA	0.36	0.46	0.339	0.55	880	785	306	187				181	Sika10	x		x	x	x	x	x		x
Granite 10mm																								
M104-I	MC100397	50%PFA,50%GGBS	0.35	0.40	0.316	0.535	852	712		284	284			188	SP435	x	x	x	x	x		x		
M106-I	MC140397	50%PFA,50%GGBS	0.40	0.40	0.354	0.6	955	672		244	244			195	SP435	x			x	x		x		
S105-I	SC230596	20%PFA	0.34	0.45	0.294	0.5	794	810	443	111				188	SP333	x	x	x		x	x			
S106-I	SC270696	15PFA%	0.30	0.40	0.323	0.55	873	699	534	94				188	SP333	x	x	x		x	x			
S107-I	SC031296	10%PFA, 10%GGBS	0.34	0.48	0.308	0.52	830	856	428	53	53			182	Sika10	x	x	x		x	x	x	x	x

^ Rest portion : PC

*Dosage of SP: solid by wt of powder. SP 435, SP 333: 40% solid; Sikament 10 20% solid

SFC: V-funnel flow time < 2.0 Sec; MC: Modified concrete without PC; SE: SCC with AE; FC: flowing concrete; NC: normal concrete

SF: slup flow, g,h: two-point test, L: L- test
U: U-test, V: V funnel test, Fc: comp. strength
S.I: segregation index, Bond: pull-out test.
shr: shrinkage test

Table A.3.1 continued (2)

Gravel 20 mm		MIXES					Coarse agg.										TEST								
ref	mix	binder	W/P	Vs/Vm	Vg	G/G_{lim}	20-10	10-5	sand	PC	PFA	GGBS	LSF	CSF	W	SP	SF	g.h	L	U	V	Fc	S.I	Bond	Shr.
F201	FC180595		0.42	0.38	0.444	0.69	770	385	545	465					195	SP435	x	x	x		x	x			
F202	FC130995		0.42	0.38	0.444	0.69	770	385	545	465					195	SP435	x	x							
F203	FC 110396		0.42	0.38	0.444	0.69	770	385	545	465					195	SP435	x	x			x	x			
F204	FC241096		0.43	0.44	0.4	0.63	691	346	691	488					210	SP435						x		x	
F205	FC291196		0.40	0.43	0.35	0.55	607	303	739	520					208	SP435						x		x	
F206	FC090797	15%PFA	0.50	0.45	0.313	0.50	542	271	805	380	67				223	SP333	x			x	x	x	x		x
F207	FC280797		0.50	0.48	0.392	0.62	680	340	770	375					195	SP435	x					x	x	x	x
M201	MC040397	50%PFA, 50%LSP	0.29	0.40	0.315	0.50	547	273	712		300		300		168	SP435		x		x	x		x		
M202	MC120397	50%PFA, 50%GGBS	0.50	0.50	0.315	0.50	547	273	890		191	191			191	SP435	x	x	x	x	x		x		
N201	NC200395		0.43	0.44	0.4	0.63	699	349	700	460					196		x	x			x				
N202	NC180595		0.42	0.38	0.444	0.69	770	385	545	465					195										
N203	NC110396		0.42	0.38	0.444	0.69	770	385	545	465					195		x	x	x		x	x			
N204	NC221096		0.45	0.42	0.4	0.63	691	346	663	488					219							x		x	
N205	NC241096		0.45	0.44	0.4	0.63	691	346	691	488					219							x			
N206	NC251096		0.5	0.44	0.4	0.63	691	346	691	488					244		x	x					x		
N207	NC251196		0.49																			x		x	
N208	NC250297		0.40	0.44	0.4	0.63	691	346	691	488					195							x			x
N209	NC280597		0.59	0.50	0.43	0.68	746	373	746	400					236							x		x	
N210	NC280797		0.50	0.48	0.392	0.62	680	340	770	375					195		x					x	x		x
N211	NC080797	10%CSF																				x		x	

^ Rest portion : PC

*Dosage of SP: solid by wt of powder. SP 435, SP 333: 40% solid; Sikament 10 20% solid

MC: Modified concrete without PC; SE: SCC with AE; FC: flowing concrete; NC: normal concrete

SF: slup flow, g.h: two-point test, L: L- test
U: U-test, V: V funnel test, Fc: comp. streng
S.I: segregation index, Bond: pull-out test.
shr: shrinkage test

Table A.3.2 Results of strength tests

Gravel 25 mm		Sample No.																						size-age	
ref	size-age(d)	x1	x2	x3	x4	x5	x6	Ave	S.D	size-age(d)	x1	x2	Ave	size-age(d)	x1	x2	Ave	size-age(d)	x1	size-age(d)	x1	x2	Ave	NV/V	%
S203	NV100e-105	52	51	48	49	53	54	51.1	2.2	NV100e-536	64	58	61.2												
S204	NV100e-91	54	55	53				54.2	1.1																
S205	NV100e-150	43	48					45.5		NV100e-521	50	56	52.7												
S222	NV100-14	52	60	59	54			58.2		NV150-14	60		60	NV150-14-T	61			100-1	16					100-14	94.4
	V100-14	60	62	57	59			59.5		V150-14	62	62	62	NV150-14-B	61									150-14	96.7
Gravel 20 mm																									
ref	size-age(d)	x1	x2	x3	x4	x5	x6	Ave	S.D	size-age(d)	x1	x2	Ave	size-age(d)	x1	x2	Ave	size-age(d)	x1	size-age(d)	x1	x2	Ave		
S202	NV100e-56	52	49	43	45			47.4	3.8															100e-56	90.1
	V100e-56	50	51	53	57			52.8	3																
S207	NV100-33	56	59					57.5		NV100-2	11			NV100-7	39			NV100-110	71						
S208	NVcy-9	33								NVcy-28	44		44	NV100-28	49		49							100-28	94.4
	Vcy-9	34								Vcy-28	43		43	V100-28	52	55	53.4							CY-28	102.3
S209	NV100-28	50	45	45				46.7	2.7	NV100e-30	47	43	45	NV100-4	28			NV100-14	41	NV100-60	55	53	54	100e-30	91.8
										V100e-30	49	49	49	V100-461	81	81	81.2								
S210	NV150-7	42								NV150-36	53													150-7	97.0
	V150-7	43								V150-36	53							V100-1	8	V100-350	68			150-36	100.0
S211	?100-28	37								?100-1	7.5			?150-9	32										
S215	?100-1	0.3																							
S216	NV100-14	69	76	71	73			72.2	3.1	NV100-28	81	81	80.9												
	NV100-14-T	80	82	83	80			81.3	1.4	?100-7	58	60	58.9												
	NV100-14-B	78	75	75	77			76.2	1.7	?100-1	0														
S217	NV100-14-T	74	60	73				69.1	7.8	NV100-14	68														
	NV100-14-B	55	54	62				56.7	4.3																
S219	NV100-14-T	60	58	70	69			64.3	6.2	NV100-14	59	65	61.6	NV100-28	70	73	71.3	NV100-1	18	NV100-7	51.4				
	NV100-14-B	69	57	63				63.1	5.9	NV100-4	47			NV150-28	73	75	74.1	V150-28	73	NV150-7	53.5			150-28	101.7

V: vibrated NV: non-vibrated T; top part of segregation test B: bottom part of segregation test * abnormal value cy: cylinder strength e: equivalent cube strength

Table A.3.2 continue (1)

Gravel 20 mm ref	size-age(d)-sf(mm)	Sample No. x_1	x_2	x_3	x_4	x_5	Ave	S.D	size-age(d)	x_1	x_2	Ave	size-age(d)	x_1	size-age(d)	x_1	size-age(d)-sf NV/V	%
S221	NV100-14>630	59.6	60	52.1	58.6		57.5	3.6	?100-1.1	18.5								
	V100-14>630	63.2	54	60.2	60.65		59.4	4.0	V100-28	59.1	65.3	62.2					100-14>630	96.7
	NV100-14-2	55.4	59	57.7	50.5		55.6	3.7										
	V100-14-2	55	61	55.9	32*		57.3	3.2									100-14-2	97.0
	NV150-14>630	60.8	59				59.8											
	V150-14>630	58.9					58.9											
	NV150-14-2	56.8	59				58.1											
	V150-14-2	58.3	61				59.5										150-14	97.7
S226	NV100-16	67.1	63	64.7	65.15	62.1	64.4	2.0	?100-1	22								
	V100-16	67.9	67	63	64.25		65.5	2.3									100-16	98.3
	NV150-16	67.4	67	65.3			66.6	1.2										
S227	NV100-28	70.3	68	75.2	57.5*		71.0	3.9	NV100-14	61.5					100-1.2	23		
	V100-28	72.6	65	70.4	74.8		70.7	4.2	V100-14	65.8			V100-21	68.5	100-3	50	100-28	100.4
	NV150-28	70.3	73	68.9			70.6	1.9										
S228	NV100-28-510	60.3	55	57.4	59.1		58.1	2.1	?100-1	21.5								
	NV100-28-415	54.8	61	58.3	53.85		56.9	3.1	?100-42	62								
	V100-28-470	50.2*	61	59.7	60.25		60.3	0.7									100-28-510	96.2
	V100-28-410	59.5	61	60.5	59.95		60.2	0.6									100-28-415	94.4
	NV150-28-510	59.1	55	56.1			56.8	2.0										
	NV150-28-415	54.9	58	57.4			56.6	1.5										
	V150-28-415	53.7	61	59.2			58.0	3.8									150-28-415	97.6
S229	NV100-28-493	56.7	66	67.4	61.35		62.8	4.8	?100-1	19.3								
	V100-28<425	70.5	63	62.6	68.7		66.2	4.0									100-28	94.9
	NV150-28-425	62.3	62	65.1			63.2	1.6										
S230	NV100-28-585	64.3	60	68.7	60.85		63.5	3.9	V100-1	16.2								
	V100-28-585	65.7	59	64.8	65.25		63.7	3.1	V100-3	40.6	42.9	41.8					100-28-585	99.6
	NV100-28-495	64.7	71	69.5	70.9		69.1	3.1	V100-7	49.3								
	V100-28-495	72.4	64	66.3	70.3		68.3	3.7									100-28-495	101.2
	NV150-28-495	65.2	68	65.8			66.3	1.5										
	V150-28-495	69.3	69	67.5			68.6	1.0									150-28-495	96.7

V: vibrated NV: non-vibrated T; top part of segregation test B: bottom part of segregation test * abnormal value

Table A.3.2 continue (2)

Gravel 10mm ref.	size-age(d)-sf	x_1	x_2	x_3	x_4	x_5	x_6	Ave	S.D				Ave						Ave			size-age-sf NV / V	%
S101	NV100-22	40.0	40.4					40.2		NV100e-56	43	44	43.5	NV150-28	40.9	NV100e-599	53	54	53.7			100-22	100.5
	V100-22	40.0						40.0		V150-144	52.7			V150-28	42.2	?100e-424	49	53.4	51.1			150-28	96.9
S102	NV150-28	38.2	40.0					39.1		NV150-8	34.2	31.6	32.9									150-8	87.5
	V150-28	44.5	45.8					45.2		V150-8	37	38.2	37.6	V100-117	55							150-28	86.6
S103	NV150-7	36.4						36.4		NV150-110h	52.2											150-110	72.5
	V150-7	41.6						41.6		V150-110	72			V100-358	81.8	100-23hr	7					150-7	87.5
S104	NV150-14	52.4	52.2					52.3		NV150-7	46			NV150-29	59.6	NV100e-550	84	83	83.4	100-1	2.5	150-14	95.7
	V150-14	54.7						54.7		V150-7	47.1			V150-29	55.6	V100e-546	81	82.8	81.8	V100-4	38	150-29	107.2
S108	NV100-28	58.9	66.8	64.0	71.1			65.2	5.1	NV100-1	16			NV100-5.3	54.5								
S109	NV100-16	54.6	47.3	52.9	45.5	49 8	53.1	50.5	3.6														
	V100-16	53.6	51.6	58.7	59.3	59.5		56.5	3.7	V100-28	63.5	53.5	58.5	V100-1	13.7							100-16	89.4
	NV150-16	55.1	55.2	53.7				54.7	0.8														
S110	NV100-29	59.6	61.1	61.8	60.6			60.8	0.9	NV150-29	61.8			NV150-29-T	61.3	?100-1	15			NV100-92	65	100-29	91.2
	V100-29	65.4	63.5	67.8	69.9			66.7	2.8	V150-29	64.4			NV150-29-B	63.7					V100-92	74	150-29	96.1
S111	NV100-28-635	65.3	61.9	61.4	68.0			64.1	3.1	?100-96	81.5	84.5	83										
	NV100-28-565	68.7	64.7	65.7	61.5			65.1	3.0														
	NV100-28-465	62.9	59.0	62.7	67.6			63.0	3.5														
	NV100-28<440	56.5	64.0	64.2	62.3			61.8	3.6														
	V100-28-635	69.0	68.9	67.3	66.9			68.0	1.1													100-28-635	94.3
	V100-28-565	63.7	64.9	68.5	66.8			66.0	2.1													100-28-565	98.8
	V100-28-465	63.0	67.7	67.3	65.6			65.9	2.1													100-28-465	95.6
	V100-28<440	70.8	73.2	69.6	68.1			70.4	2.1													100-28<440	87.7
	NV150-28-565	62.4	64.9	64.5				63.9	1.3														
	NV150-28-465	64.0	61.8	67.2				64.3	2.7													150-28-465	99.4
S112	NV100-28-595	50.3	44.0	53.0	47.4			48.7	3.9	100-1	8.4												
	NV100-28-680	51.8	53.1	52.1	51.3			52.1	0.8	100-2	27.4	27	27.2										
	NV100-28-593	52.3	55.1	54.7	52.4			53.6	1.5	100-91	71.6	66.2	68.9										
	V100-28-680	55.8	56.5	57.3	54.0			55.9	1.4													100-28-680	93.2
	V100-28-593	57.7	54.1	56.4	50.6			54.7	3.1													100-28-593	98.0
	NV150-28-680	52.4	53.0	54.4				53.2	1.0														
	NV150-28-593	51.1	54.5	51.7				52.4	1.8														
	V150-28-593	57.3	56.1	57.8				57.1	0.9													150-28-593	91.9
S113	NV100-27-535	64.1	58.9	63.2	55.6			60.4	4.0	NV100-1	18.5											100-1	101.1
	V100-27-490	66.6	64.0	65.7	66.3			65.6	1.1	V100-1	18.3											100-27-535	92.1
	NV150-27-535	61.6	61.3	61.6				61.5	0.2	V100-5	48.1	45.2	46.7										
	V150-27-490	61.0	63.6	63.0				62.6	1.4	V100-7	50	40.7*										150-27-535	98.3
S114	NV100-28-735	54.4	59.9	59.1	58.1			57.9	2.4	NV100-1	9.4											100-1	104.4
	V100-28-540	58.4	55.7	58.0				57.4	1.5	V100-1	9											100-28-735	100.9
	NV150-28-735	59.6	59.8	60.2				59.9	0.3	V100-2	20.8	21.3	21.1										
	V150-28-540	56.9	53.7	59.4				56.7	2.9	V100-8	47.3	45.4	46.4									150-28-735	105.6
S115	NV150-28	48.0	47.2					47.6	0.5	NV150-28-T	48.9			NV150-28-B	47.6	NV100-1	11						
S116	NV150-28	58.8						58.8		NV150-28-T	62.2			NV150-28-B	63.6	?100-1	17	16.6	16.6				
	V150-28	60.1	65.7	52.8*				62.9														150-28	93.5

V: vibrated NV: non-vibrated T; top part of segregation test B: bottom part of segreg: * abnormal value

Table A.3.2 continue (3)

Granite 10mm		Sample No.																		150-15	94.7
ref.	size-age(d)-sf	x_1	x_2	x_3	x_4	Ave	S.D				Ave				Ave				Ave	NV / V	%
S105-I	NV150-39	76.2						NV150-15	55.6			NV150-81	93.3			NV100-1	1.5			150-39	96.1
	V150-39	79.3						V150-15	58.7			V150-81	93.3							150-81	100.0
S106-I	NV150-29	73.8						NV150-7	55.6			?100-1	18.5							150-15	91.9
	V150-29	76.5						V150-7	60.4			?100-4	55							150-29	96.4
S107-I	NV100-14-T	64.9	55.1	65.3		61.8	5.8	NV100-14	49.9	45	47.4	NV100-1	16.6			NV100-3.2	39.7				
	NV100-14-B	59.8	58.5	57.9		58.7	1.0	NV100-35	55.4	61	58.3	NV100-2.2	34.7			NV100-7.2	43.8	50.25	47		
Gravel 20mm																		size-age			
ref	size-age(d)	x_1	x_2	x_3	x_4	Ave	S.D	size-age(d)	x_1	x_2	Ave	size-age(d)	x_1	x_2	Ave	size-age(d)	x_1	size-age(d)	x_1	NV / V	%
F201-1	NV100e-56	51.6	52.2	49.4	46.8	50.00	2.4														
	NV100e-56	49	46.3	52	52.8	50.00	3														
F203	NV100-7	32.4	31.6	32.7		32.20	0.6	NV100-32	32.6												
	V100-7	44.3	42.7	42.8		43.30	0.9	V100-32	46.2	51	48.5	V100-63	54	57.5	55.8	V100-402	60.1	V100-1	12.5	100-7	74.4
	NV150-7	37.3	37.5			37.40														100-32	67.2
	V150-7	41.6	41.8			41.70														150-7	89.7
F204	V100-29	50.6	50.6	47.6		49.60	1.7														
F205	V100-14					51.20															
F206	NV150-28	49.2	47.5			48.36		V150-28-T	46.8			V150-28-B	43.3								
F207	V100-31	48.4	48.6	49.2		48.73	0.4	V100-1	19	21	19.8										
N203	NV100-7	23.8	22.6	20.4		22.30	1.7														
	V100-7	?	?	?		38.90														100-7	57.3
	NV150-7	30.2	30.7	29.6		30.20	0.6														
	V150-7	39.3	40.1			39.70														150-7	76.1
N204						54.60															
N205	V100-28	45	47.1	44.5		45.53	1.4														
N207	V100-14	41.4	40.4			40.88															
N208																					
N209	V100-28	34	34	32		33.33	1.2														
N210	V100-28	47.1	47.9	50		48.33	1.5														
N211	V100-29	63	63	57		61.00	3.5														

V: vibrated NV: non-vibrated T; top part of segregation test B: bottom part of segregation * abnormal value e: equivalent cube strength

Table A.3.3 Results of slump flow, L-test, two-point test, V funnel test and segregation index

Gravel 20mm					L-test		Two-point test				
Mixes	time	SP dose % solid	sf	sf-loss	Passing ability %		g	h	V-funnel	S.I	Mortar
ref	min	by wt. of powder	mm	mm/hr	mesh1	mesh 2	Nm	Nms	Sec	%	flow*(mm), V-f^
S201	15	SP435, 0.59	700	391	N.G		0	7.27			
	71		335						14.8		
S202	45	SP435, 0.53	>700	393	Excel.		-0.53	5.56	9.1		
	100		340						45.5		
S207	17	SP435, 0.72	700		65	38	0.19	13.01	28		
	125	AE 0.16, SP 0.76							16.7		
S208		overdose, SP333 1.34	776		94	92	0.21	4.77	8.4		
S209	15	SP333, 0.95	705	27			0.64	4.77	17.5		
	70		680	78	66	36	0.6	6.2	18		
	116		620				0.8	6.53	17.4		
S210	19	SP333, 0.21	390						4.8		
	35	0.31	425								
	47	0.41	525		68	46	0.66	0.93	2.3		
S211	20	SP333, 0.24	675		75.6	62.6	0.21	0.51	1.35		
S212!		SP333, 0.60	780		95				4		
S213!		SP435, 1.25	520								
		1.42	750		79	76.6			4		
S214!	10	SP435, 0.92	630								
	99	1.17	700	233	61.4	33	0.83	5.29	13.4	12.7	
	126		595								
S215		SP333 0.60									
	20	0.72	730		88	84.8	0.37	3.13	5.8	22.4	
S216	12	SP333, 1.38	500								
	24	1.61	765	57	92.5	93.2	0.09	1.36	3.3	25.8	
S217	15	Sika 10, 0.60	645	38	65	57.3	0.34	1.55	3.65	26.2	
	105		588								
S218!		SP333, 0.60	395								
		0.78	755		86	86	0.33	1.01	2.55	20.2	
S219	15	Sika 10, 0.28	660								
	50	0.32	755		80.8	78	0.36	5.86	11.1	15.8	
S220!	15	SP333	735	500	63.5	41.4			9.2		(low temp.)
	45		485								
S221	12	Sika 10 * 0.30	595								285,
	31	0.36	810	152	95	97	0.11	4.1	8.3	16.1	
	102		630		72.5	61.9	0.47	4.5	15	16.4	
S223!	12	Sika 10, 0.30	760	205	77.4	74.9			6		
	50		630								
S224!	5	Sika 10, 0.45	505								
	18	0.53	685	158	72	67	0.39	1.32	4.5		
	53		593								
S225!	10	Sika 10, 0.43	805	60	88	88	-0.59	7.32	11		
	75		740								
S226	10	Sika 10 * 0.23	500				0.79	4.78	12.8		275, 8.5
	63	0.27	635				0.32	5.37	12.3		
S227	6	Sika 10 * 0.40	675								310, 22.4
	25	water 0.454kg	730	107	94		-0.18	4.41	9	20.3	
	84		625								
S228	7	Sika 10 * 0.23	510								300, 9.7
	18	0.24	580								
	33	water 0.422kg	550								
	48	water 0.502kg	510				0.56	2.83	5		
S229	4	Sika 0.20	635	183	72		0.36	2.64	6.3	20.3	
	41		515	169							
	73		425								
S230	10	Sika 0.23	780								
	23	+PFA 1kg	725	200	95.8		0.16	2.64	5.3	24.7	
	65		585	216							
	90		495								

* Mix mortar first with all water , powder, F.A and SP, then add C.A mix two more minutes.

^ V-f : mortar V-funnel flow time (sec)

Table A.3.3 continued(1)

Gravel 10mm					L-test		Two-point test				
Mixes	time	SP dose % solid	sf	sf-loss	Passing ability (		g	h	V-funne	S.I	Mortar
ref	min	by wt. of powder	mm	mm/hr	mesh1	mesh 2	Nm	Nms	Sec	%	flow*(mm), V-f^
M101		SP435,	800							52	
			620				1.07	4.36	9.5	9.4	
			790				1	6.24	9	14	
									23	6.4	
M102		SP435, 0.45	415				1.35	5.13	24	7	
M103	10	SP435*, 0.52	773	207			-0.19	4.79	10.2	9.8	340, 8.6
	60		600				0.3	8.88	18.3		
M105	10	SP435*, 0.44	520	133	61		0.65	0.79	3.3	8.7	310,
	55		420								
	132	0.74	670	93	91		0.13	1.65	5	18.9	
	203		560								
M104-I	7	SP435* 0.56	550	140	63		0.45	3.37	9.7	9.8	305, 7.5
	67		410						21		
	215	0.63	800						13.9	31.2	
S101	18	SP435, 0.48	550		78	60	0.47	0.66	2.3		
S102	33	SP435, 0.36	410		62	29	1.05	1.19	3.5		
	125	0.63	500		75	63					
S103	8	SP333, 0.2	380						4.5		
	35	0.31	410								
	42	0.41	490		73		0.84	0.98	3		
S104	14	SP333, 0.33	305								
	28	0.67	795		95.7	89	0.18	1.59	3		
S108	5	Sika * 0.25	395								
	15	0.31	665	158	79	73	0.21	6.69	17.6		
	72		515								
S109	7	Sika * 0.28	635	16	52		0.19	3.22	7.3	13	300, 5.1
	66		620								
S110	5	Sika * 0.25	550						12.2		288, 7.2
	40	+vis, Sika 0.29	675	80	71		0.37	2.34	7	12	
	89		610								
S111	10	Sika * 0.25+W 0.65kg	635	84	89		0.26	2.24	6.5	11.2	273, 10.9
	60		565	167					10.8		
	96		465								
S112	5	Sika *+vis 0.23	595								315, 4.9
	16	0.31	695	19	93				7.1	6.3	
	64		680	100							
	116		593								
S113	10	Sika 0.23	640	134	89		0.24	1.85	5.2	10.6	
	48		555						8.3		
S114	9	Sika 0.22	685	432	93		0.18	2.37	5.9	12.3	
	43		440								
	69	0.25	735	290							
	99		590								
S115	8	SP333 0.36	593								
	30	0.6	740						1.9	17.7	
S116	6	Sika, 0.23	730		85				5.6		
	33	+PFA 0.5kg	445								
	76	0.27	635								
	144	0.3	680							9.6	

* Mix mortar first with all water , powder, F.A and SP, then add C.A mix two more minutes (Method 2)

^ V-f : mortar V-funnel flow time (sec). Mixing method 3: S113, S114, S116

Table A.3.3 continued(2)

Gravel 25mm					L-test		Two-point test				
Mixes	time	SP dose % solid	sf	sf-loss	Passing ability %		g	h	V-funnel	S.I	glass ball
ref	min	by wt. of powder	mm	mm/hr	mesh1	mesh 2	Nm	Nms	Sec	%	g/cm^2
S203	9	SP435 0.52	435						8		
	90	0.76	>>700		48	50			3.4		0.066
S204	10	SP435 0.70	680				0.54	1.32	6		
	105	0.8	>>700		76	63			3.35		0.071
S205	10	SP435 0.60	540		blocked		1.33	4.3	12.6		
	81	0.71	625				0.39	4.45	8		0.256
S206	18	1.3	>>700		49	50	0	2.26	5.7		
	72	GGBS 1.4kg,	640		50	24	0.03	5.87	11.7		
S222	19	Sika10*, 0.3	573		blocked				25.1		
	84	0.35	703	89	46		0.45	5.95	13.3	17.5	
	136		625		46	28					
Granite 10mm											
S107-I	15	Sika, 0.25	690	115	87	82	0.28	2.94	6.9	9.4	
	54		615		63	53	0.5	3.04	8.2		
S105-I	10	SP 333, 0.50%	455								
	60	0.73%	810		95	97	0.22	1.31	3		
S106-I	6		590		64.9	45.2	0.71	2.08	5.4		
Gravel 20mm											
Mixes	time	SP dose % solid	sf	sf-loss	Passing ability %		g	h	V-funnel	S.I	Mortar
ref	min	by wt. of powder	mm	mm/hr	mesh1	mesh 2	Nm	Nms	Sec	%	flow*(mm), V-f^
F203	14		170!		blocked		1.92	1.74	blocked		
	114	SP435 0.4	625				0.29	1.28	9.1		
F204		SP435	400							21.2	
F206	5	SP333 0.24	505								
	16	0.34	615								
	26	0.42	640						1.6	28.2	
	65	0.50	615								
F207	55	SP435 0.18	200!								
	86	0.22	220!							11.5	
M201	10	SP435* 0.45	695				0.06	5.21	8.6		355, 10.3
	84	0.52	570						17.2	17.4	
M202	10	SP435* 0.34	625								304, 1.1
	31	0.5	690	100	blocked		0.41	1.43	2.4		
	70		625								
N206			135!				3.66	1.77		10.2	
N210	43		90!							5.7	
* Mix mortar first with all water , powder, F.A and SP, then add C.A mix two more minutes											
! Slump (mm) ^V-f: mortar V-funnel flow time (sec)											

Table A.3.4 Results of U-tests

Mix ref.	date	SF(mm)	box-H(mm)	C.A	F.A	Vs/Vm
F206	FC090797	640	338	813	805	0.45
M201	MC040397	645	332	820	712	0.40
M202	MC120397	625	305	820	890	0.50
M202		580	180	820	890	0.50
S222	SC290197	572.5	330	820	801	0.45
S222		702.5	355			
S224	SC100297	595	340	820	801	0.45
S225	SC110297	785	355	820	801	0.45
S226	SCC050397	500	305	820	801	0.45
S227	SC040497	730	365	820	712	0.40
S228	SC230497	460	280	820	835	0.47
S229	SC300497	635	350	820	837	0.47
S230	SC120597	585	315	820	805	0.45
M103	MC060397	600	350	820	712	0.40
M104-I	MC100397	410	310	851.7	712	0.40
M104-I		800	360			
M105	MC130397	420	320	820	890	0.50
M105		560	365			
M106-I	MC140397	640	190	955	672	0.40
M106-I		490	165			
S109	SC170397	620	345	820	891	0.50
S110	SC070497	610	350	820	855	0.48
S112	SC160497	606	360	820	891	0.50
S112		695	365			
S113	SC140597	524	315	800	829	0.46
S115	SF090797	740	357	813	805	0.45
S116	SF250797	450	325	880	785	0.46
S116		635	353			

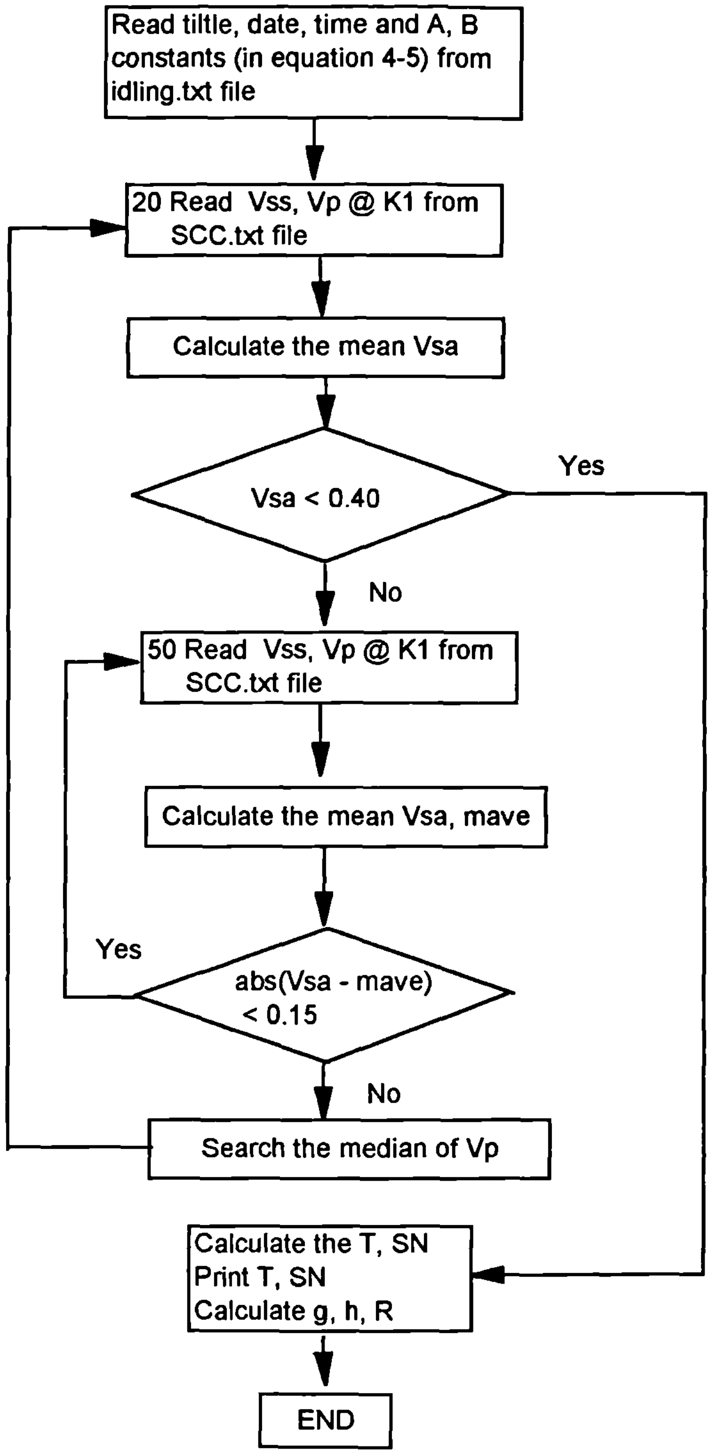
Table A.3.5 Results of pull out tests

Plain Bar					
Mixes	FC (MPa)	bond stress	(MPa)	bond stress	(MPa)
Ref.		SCC bottom bar	SCC top bar	bottom bar	top bar
		non-vibrated	non-vibrated	vibrated by vibration table	
F204	49.6	6.87	4.19	2.81	1.94
S212	54.6	5.17	4.15	5.54	4.00
S214	81	8.06	3.99	8.10	5.98
S215	55.3	6.92	2.44	3.71	0.56
S217	76	7.70	6.23	8.46	6.24
S218	56.7	7.72	2.34	4.70	2.53
S219	63.3	6.29	4.99	6.49	5.23
		non-vibrated	non-vibrated	Compacted by rod	
N211	63			8.09	7.75
				8.54	6.95
Mixes	FC (MPa)	non-vibrated	non-vibrated	vibrated by poker	
N207	40.9	2.08	5.00	6.18	2.76
F205	51.2	5.23	4.59	5.04	2.56
N204	54.6	1.6	1.7		
F207	48.7	5.29	5.49		
F207	48.7	5.54	6.44		
S107-I	60.23	6.83	5.44	4.30	2.33
S108	65.2	5.86	3.05		
S226	66.6	7.83	6.50		
S109	58.5	8.01	7.98		
S227	65	8.68	7.96		
S228	56.7	7.75	5.73		
S114	60	6.21	4.18		
S226	66.6	7.96			
S227	65	8.63			
S228	56.7	7.66			
S109	honeycomb	5.92			
Deformed bar					
Mixes	FC (MPa)	bond stress	(MPa)	bond stress	(MPa)
Ref.		SCC bottom bar	SCC top bar	bottom bar	top bar
		non-vibrated	non-vibrated	compacted by rod	
S108	65.2	13.18	12.57		
S222	60.7	13.24	13.02	10.76	9.35
S220	55.1			13.08	8.29
S220				13.13	8.62
S110	64.7	9.1	8.94		
S113	61.5	16.6	17		
N209	33.3	7.69	6.76	6.29	5.57

APPENDIX 4.

SOURCE PROGRAMME OF DATA ANALYSIS FOR TWO-POINT WORKABILITY TEST: MC.EXE

Flow Chart of MC.EXE



Vss: flywheel voltage
Vp: pressure voltage
Vsa: mean of flywheel voltage per K1 samples
mave: total mean of flywheel voltage
T: torque
SN: impeller shaft speed
g and h: rheological constants
R: correlation coefficient

```
      integer n,i,j,k,nm,jp,tjp(30),tnm(30),inp,ib,np
      real vp(30000), vss(30000), vsa(100), vsd(100),mave,tmave,mean
      real sigma,sn(300),sp(300),mp,tmp,vpa(100),vpd(100),psum,t(30)
      real a,b,r,ip(30),fsv(30),ipv(30),med
      character*20 f1,f2,title
      character*31 date
      character*22 time
      character*72 ititle,inr
      parameter (k1=100)
      write(*,*) 'By Paul Hsi-Wen Chai, Civil Eng. of UCL, Nov. 1995'
      write(*,*)
      print *, 'Enter the name of the data file'
      read '(a)', f1
      print *, 'Enter the name of the out file'
      read '(a)', f2
      open(1,file=f1,status='old')
      open(2,file=f2,status='unknown')
      open(3,file='iab.dat',status='old')
      read(3,17) ititle
      read(3,17) inr
   17 format(1x,a71)
      read(3,*)ai,bi


      read (1,6) title
    6 format(a17)
      do 10 i=1,7
      read(1,*)
   10 continue
      read (1,7) date
    7 format(a31)
      read (1,9) time
    9 format(t10,a22)
      do 15 i=1,8
      read(1,*)
   15 continue

      write(2,*) 'Run mc.exe under DOS system(<0.15,k1=100,<0.40 out
     + T=0.0215P,use median,19/Sept/96)'
   25 write(2,8) title,date,time
      write(2,17) ititle
      write(2,17) inr
      write(2,23) 'Idling pressure ai bi==>',ai,bi
   23 format(1x,a24,8x,f7.5,8x,f7.5)
    8 format(1x,a17,t20,a31,a22)
      write(2,*) ' n    flywheel speed voltage  pressure voltage
     +idling pressure voltage'
      write(*,*) ' n    flywheel speed voltage  pressure voltage
     +idling pressure voltage'

      j=1

   20 read(1,*)(vss(n),vp(n), n=1,k1)
      i=1
      nm=1
      vsa(i)=mean(vss,1,k1)
      if (vsa(i) .lt. 0.40) then
      go to 200
      endif
      mave=vsa(i)
```

```
      tmave=mave
   50 i=i+1
      do 100 n=1+(i-1)*k1,i*k1
      read(1,*) vss(n),vp(n)
  100 continue
      vsa(i)=mean(vss,1+(i-1)*k1,k1)

      if (abs(vsa(i)-mave) .le. 0.15) then
      tmave=tmave+vsa(i)
      nm=nm+1
      mave=tmave/nm
      write(*,150) vsa(i),mave,i
  150 format(1x,t7,f8.3,t21,f8.3,t35,i3)
      else
      write(*,*) '****************************************************'
      write(*,*) vsa(i),mave, abs(vsa(i)-mave),j
      write(*,*) '****************************************************'
      call median(n-1,vp,med)
      sn(j)=mave
      sp(j)=med
      tnm(j)=n-1
      mave=vsa(i)
      j=j+1
      go to 20
      endif

      go to 50
  200 do 300 n=1,j-i
      write(2,310) tnm(n), sn(n),sp(n),sn(n)*bi+ai
      write(*,310) tnm(n), sn(n),sp(n),sn(n)*bi+ai
  300 continue
  310 format(1x,i4,t15,f8.3,7x,t38,f8.3,15x,f8.3)
      write(2,*) '---------------------------------------------'
      write(*,*) '---------------------------------------------'
      write(*,*) '                    Torque(Nm)      Shaft speed(rps)'
      write(2,*) '                    Torque(Nm)      Shaft speed(rps)'
      do 400 i=1,j-1
      p=(176.44*sp(i)-155.5)-(176.44*(sn(i)*bi+ai)-155.5)
      t(i)=0.0215*p
      sn(i)=sn(i)/0.5/4.681486
      write(2,290) t(i),sn(i)
      write(*,290) t(i),sn(i)
  400 continue
  290 format(1x,t15,f8.3,t38,f8.3)
      call rab(j-1,sn,t,a,b,r)
c     call gra(j-1,sn,t,title)
      close(1)
      close(2)
      close(3)
      end



      function mean(x,j,n)
      real mean, x(30000), sum
```

```
      integer n,i,j
      sum=0
      do 1000 i=1,n
      sum=sum+x(j)
      j=j+1
 1000 continue
      mean=sum/n
      end


      function sigma(x,k,n)
      real sigma, x(30000), sumr,r,av1,mean
      integer n,i,k
      sumr=0
      av1=mean(x,k,n)
      k=k-n
      do 1010 i=1,n
      r=x(k)-av1
      sumr=sumr+r*r
      k=k+1
 1010 continue
      sigma=sqrt(sumr/(n-1))
      end

      function irun(x)
      real x
      integer irun
      if( mod(x*10,10) .gt. 4 ) then
      irun=x+1
      else
      irun=x
      endif
      end

      subroutine median(n,x,med)

      real x(6000),tmax,med
      integer n,i,j,m

      do 1012 i=1,n
      do 1014 j=i+1,n
      if (x(j) .gt. x(i)) then
      tmax=x(j)
      x(j)=x(i)
      x(i)=tmax
      endif
 1014 continue
 1012 continue
      if (mod(n,2) .eq. 0) then
      m=n/2
      med=(x(m)+x(m+1))/2
      else
      m=(n+1)/2
      med=x(m)
      endif
      return
      end

      subroutine rab(n,x,y,a,b,r)
```

```
      real x(300),y(300),a,b,r,tx,ty,txy,ty2,tx2,tz(350),hcl
      integer n,nn,k

c tz:The t distribution 90% confidence limit    tz(n)    d.f=n-2

      do 1020 i=1,350
      tz(i)=0
 1020 continue
      nn=n

      tz(4)=2.920
      tz(5)=2.353
      tz(6)=2.132
      tz(7)=2.015
      tz(8)=1.943
      tz(9)=1.895
      tz(10)=1.860
      tz(11)=1.833
      tz(12)=1.812
      tz(13)=1.796
      tz(14)=1.782
      tz(15)=1.771
      tz(16)=1.761
      tz(17)=1.753
      tz(18)=1.746
      tz(19)=1.740
      tz(20)=1.734
      tz(21)=1.729
      tz(22)=1.725
      tz(23)=1.721
      tz(24)=1.717
      tz(25)=1.714
      tz(26)=1.711
      tz(27)=1.708
      tz(28)=1.706
      tz(29)=1.703
      tz(30)=1.701
      tz(31)=1.699
      tz(32)=1.697
      tz(34)=1.6942
      tz(37)=1.690
      tz(40)=1.6864
      tz(42)=1.684
      tz(45)=1.681
      tz(47)=1.679
      tz(50)=1.6772
      tz(52)=1.676
      tz(57)=1.6735
      tz(62)=1.671
      tz(67)=1.669
      tz(72)=1.667
      tz(77)=1.6655
      tz(82)=1.664
      tz(87)=1.663
      tz(92)=1.662
      tz(97)=1.661
      tz(102)=1.660
      tz(112)=1.659
      tz(122)=1.658
      tz(132)=1.657
```

```
      tz(142)=1.656
      tz(152)=1.655
      tz(162)=1.654
      tz(182)=1.653
      tz(202)=1.653

1030  if (tz(nn) .eq. 0) then
      nn=nn-1
      go to 1030
      endif

      tz(n)=tz(nn)
      tx=0
      ty=0
      txy=0
      tx2=0
      ty2=0
      k=0

      do 1100 i=1,n

      if (x(i) .eq. 0) then
      k=k+1
      endif

      tx=tx+x(i)
      ty=ty+y(i)
      txy=txy+x(i)*y(i)
      tx2=tx2+x(i)*x(i)
      ty2=ty2+y(i)*y(i)
1100  continue

      n=n-k
      b=(n*txy-tx*ty)/(n*tx2-tx*tx)
      a=(ty-b*tx)/n
      r=(n*txy-tx*ty)/sqrt((n*tx2-tx*tx)*(n*ty2-ty*ty))
      write(2,*) '-----------------------------------------------'
      write(*,*) '-----------------------------------------------'
      write(2,76) 'n=',n
      write(*,76) 'n=',n
      write(2,77) 'Two point test constant g(Nm)=',a
      write(*,77) 'Two point test constant g(Nm)=',a
      write(2,78) 'Two point test constant h(Nm s)=',b
      write(*,78) 'Two point test constant h(Nm s)=',b
      write(2,79) 'Linear regression correlation coefficient r=',r
      write(*,79) 'Linear regression correlation coefficient r=',r
      hcl=tz(n)*sqrt((1-r*r)/r/r/(n-2))*100
      write(2,80) '90% confidence limits on g(%)=',sqrt(tx2/n)*b/abs(a)*
     +hcl
      write(*,80) '90% confidence limits on g(%)=',sqrt(tx2/n)*b/abs(a)*
     +hcl
      write(2,80) '90% confidence limits on h(%)=',hcl
      write(*,80) '90% confidence limits on h(%)=',hcl
      write(*,*)
   76 format(1x,a2,i2)
   77 format(1x,a30,f5.2)
   78 format(1x,a32,f5.2)
   79 format(1x,a44,f6.4)
   80 format(1x,a30,f6.2)
      return
```