PROPERTIES OF MORTAR FOR SELF-COMPACTING CONCRETE

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

by

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Abstract

The effect of types and amount of powder materials, admixtures, sand and water content on the properties of self-compacting concrete (SCC) have been investigated by tests on the mortar fraction. Tests on concrete have also been a carried out to confirm the most important effects.

The component materials used were

- eight types of powder – PC and SRC, GGBS, PFA, CSF and three types of LSP,
- six superplasticizers - a naphthelene (Conplast430) and melamine type, two co-polymers, one polycarboxylic ether (Glenium51) and one formulated for SCC,
- two viscosity agents - Welan gum and a cellulose product ,
- one fine and coarse aggregate, generally at volumetric proportions of 40-47.5% of the mortar and 31.7% of the concrete respectively.

Testing has concentrated on workability and workability retention of mixes with a single powder, binary and ternary powder combinations, with and without a viscosity agent. Tests have included spread/slump flow, V-funnel flow time, and two-point workability tests for mortar and concrete, a U-box test for concrete, and some strength tests on concrete.

The most important outcomes include:

- Glenium 51, the most efficient superplasticizer, was selected for most of the programme, added at 1 minute after the start of mixing.
- Excellent workability and workability retention was obtained in binary and ternary mixes containing CSF, and in SRC single powder mixes.
- Yield stress and plastic viscosity are two distinct and independent properties.
- Welan gum has better compatibility with Conplast430 than Glenium51; its use improved workability retention but slightly decreased strength.
- There are strong relationships between
  - the properties of concrete and its mortar component,
  - the rheological constants and single point test results for mortar and concrete.
- The rheology of some mortar mixes may be better described by the Herschel-Bulkley model than by the Bingham model.

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All symbols are used as defined unless they are defined immediately after being used in the text.

- A — air content
- A/C — aggregate/cement ratio by weight
- AE — air entraining agent
- C — cement content by weight
- C.A. — coarse aggregate
- CRMs — cement replacement materials
- CSF — condensed silica fume
- $D_{D.R.}$ — dry drodded bulk density of aggregate
- D_m — spread of mortar in diameter
- D_{max} — maximum size of aggregate
- E_p — deformation coefficient of a powder
- F.A. — fine aggregate
- f_c — compressive strength
- G, K — calibration coefficient for two - point machine
- GGBS — ground granulated slag
- g — rheological constant by two-point test, related to τ_0
- h — rheological constant by two-point test, related to μ
- LSP — limestone powder
- LSP100 — limestone powder with particle size nominally smaller than 150 microns
- LSP50 — limestone powder with particle size nominally smaller than 75 microns
- LSP15 — limestone powder with particle size nominally smaller than 15 microns
- N — impeller speed in two-point test
- NC — normal concrete
- PC — portland cement
- PFA — pulverised fly ash
- s/a — sand /total aggregate ratio
- SCC — self-compacting concrete
- SF — slump flow
- sp — superplasticizer
- SRC — sulphate-resisting cement
- SSD — superplasticizer saturation dosage
- T_V — V-funnel flow time in mortar and concrete tests
- T_{250} — time for a mortar spread to 250 mm in diameter in spread test
- T_{500} — time for a concrete flow to 500 mm in diameter in slump flow test
- $T_{u\text{-}box}$ — time for concrete flow to 250 mm filling height in U box test
- V_a — volume of air
- $V_{C.A.}$ — volume of coarse aggregate

V_m volume of mortar

V_{GGBS} volume of GGBS

V_{LSP} volume of LSP

V_P volume of powder

V_{PFA} volume of PFA

V_s volume of sand

V_s/V_m sand/mortar ratio by volume

V_w volume of water

V_w/V_p water/powder ratio by volume

U_H U box filling height (mm)

W water content by weight

w/c water/cement ratio

$W_{C.A.}$ proportion of coarse aggregate by weight in concrete

$W_{C.A.}/D_{D.R.}$ the ratio of coarse aggregate weight to dry rodded bulk density

WG Welan gum

w/p water powder ratio by weight

Γ_m mortar spread ratio,

$$\Gamma_m = \left(\frac{Dm}{100}\right)^2 - 1$$

R_m relative V-funnel flow speed for mortar, $R_m = \frac{T_V}{10}$

τ_0 yield stress

τ shear stress

$\dot{\gamma}$ shear rate

μ plastic viscosity

β_p retained water/powder ratio of a powder,

η apparent viscosity

η_{re} relative viscosity of a suspension to its liquid medium

ϕ volume concentration of solid phase

ϕ_M maximum volume concentration of solid phase

$[\eta]$ intrinsic viscosity of the suspension related to characteristic of particle shape

Glossary of terms

In many workability studies including those on SCC, much confusion has been caused by the careless use of terminology. Therefore, some terminology used in this thesis is clarified at this stage.

Apparent viscosity (η_{app})

The viscosity of a non-Newtonian material at the particular shear rate under consideration, given by the of the slope of the straight line drawn from the origin to the appropriate point on the flow curve.

Filling ability

Used to describe the ability of SCC to fill a container with or without obstacles. It is evaluated by the quantity of concrete flowing into a container, or the height of filling. Many test methods have been used, most of them imitating part of a real structure.

Flowability or Fluidity or Deformability

A property of fresh concrete indicating the ease of flowing under gravity and external forces [1]. This is evaluated by the amount of deformation after a concrete ceases to flow, i.e. **flowing capacity**, and the **flowing speed**. In an RILEM report [2] "filling ability" was used to describe this property for no specific reason, but in this project "flowability" will be used. The meaning of filling ability in this project is more specific.

Ionic strength (I_0)

A function expressing the effect of the charge of the ions in a solution, equal to the sum of the molality of each type of ion present (m_i) multiplied by the square of its charge (Z_i). $I_0 = \sum m_i Z_i^2$ [3]

Passing ability or non-blocking property

This describes the ability of SCC to pass through obstacles or narrow openings, such as gaps between reinforcement. It is evaluated by measuring the quantity of concrete passing through the obstacles, the filling height on the downstream side or flowing speed.

Powder

Fine materials that have particle sizes the same as or finer than PC, such as cement replacement materials and inert fillers.

Pseudoplastic material

A material which can be represented by a power-law model of the form

$$\tau = k\dot{\gamma}^n$$

where k,n are constants.

Retained water/powder ratio (β_P), deformation coefficient (E_P)

The retained water/powder ratio is that at which flow of paste is about to commence under self weight in a flow-spread test (This is the same as the spread test for mortar, which will be introduced in chapter 2). This water is physically and chemically retained by powder and so has no contribution to flow. The deformation coefficient is a measure of sensitivity to increasing water content as shown in **Figure T-1.**

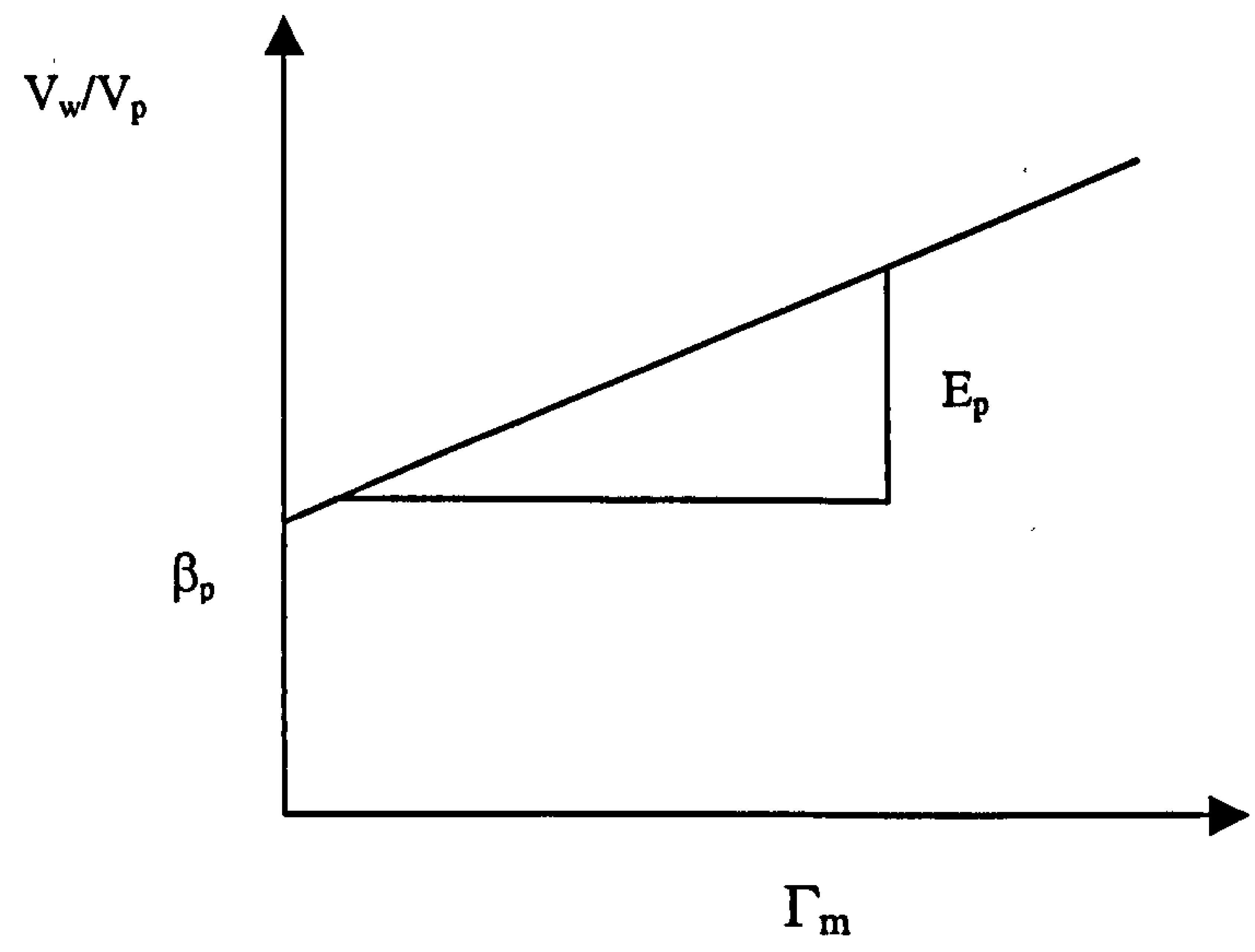


Figure T-1 The definition of retained water/powder ratio (β_p) and deformation coefficient (E_p) ($\Gamma_m = (\frac{D_m}{100})^2 - 1$)

Rheology

Rheology is defined as 'the science of the deformation and flow of matter', which means that it is concerned with relationship between stress, strain rate, and time (BS 5168: 1975). It can result in quantitative fundamental terms, associated with models describing the relationship between stress and strain. For example, the Bingham model is

$$\tau = \tau_0 + \mu\dot{\gamma}$$

where τ_0, μ constants.

Another example is Herschel-Bulkely model which describes a flow curve of the power-law pseudoplastic type but with the addition of a yield value:

$$\tau = \tau_0 + k\dot{\gamma}^n$$

where τ_0, k, n are constants.

Shear thickening material

A material whose flow curve is concave towards the stress axis because the shear stress is increasing more rapidly than the shear rate.

Shear thinning material

A material whose flow curve is concave towards the shear rate axis because the stress is increasing less rapidly than the shear rate.

Superplasticizer saturation dosage (SSD), optimum superplasticizer dosage (OSD)

In a cement paste or slurry, there is a superplasticizer saturation dosage (SSD) for each type of superplasticizer after which any addition of superplasticizer does not significantly reduce the viscosity of the mix [4]. It is also called optimum superplasticizer dosage (OSD) since it is the point at which an increase in superplasticizer dose not affect the slurry rheology [5]. In mortar and concrete, similar definitions are used; in this programme the saturation superplasticizer dosage for mortar was determined by the spread test.

Thixotropy

This describes a material which becomes thinner when it is disturbed and thickens again when it is subsequently left alone, i.e. the behaviour is reversible.

Wall-effect

With granular suspensions like fresh concrete, a layer forms in the vicinity of the wall of the container, with a lack of coarse particles, which makes the material locally more flowable than in the bulk of the suspension.

Workability

Workability is a very complex, general term which describes the dynamic properties of fresh paste, mortar, and concrete. It could include many specific properties such as flowability, passing ability, filling ability, compactability *etc.* In some cases it refers to a specific property, such as slump or slump flow.

Chapter 1

Introduction

This chapter introduces the concept of self-compacting concrete (SCC) and its application, the background to the research project presented in this thesis and the thesis structure.

1.1 Concept and applications of SCC

Self-compacting concrete is concrete which under its own weight will flow into place through and around reinforcement and form a compact, uniform, void free mass without the need for any vibration. It was first developed in Japan in 1988, since then it has had continually increasing use worldwide.

SCC was initially called "High Performance Concrete". It was defined as concrete that had the following properties at three stages [6],

1) fresh stage: self-compactability,
2) early age: avoidance of initial defects,
3) hardened stage: protection against external factors.

At almost the same time, "High Performance Concrete" was defined by Gagne *et al* [7] as a concrete with high durability due to a low water/cement ratio. Self-compacting concrete therefore became the name given to concrete with self-compactability in the fresh stage, with no specific requirement for early age or hardened properties.

There are three key properties that distinguish SCC from other types of concrete:

- It must flow under self-weight at a reasonable rate; high flowing capacity and proper flowing speed are thus required, i.e. **high flowability**.

- It must be stable and not segregate during flow (and also after it is in place), i.e. **high segregation resistance.**
- It must flow through and around reinforcement without blocking, i.e. **good passing ability.**

The methods of achieving self-compactability, illustrated in **figure 1-1,** are:

- a limited aggregate content,
- a low water/powder ratio and/or the addition of viscosity agent,
- the use of a superplasticizer.

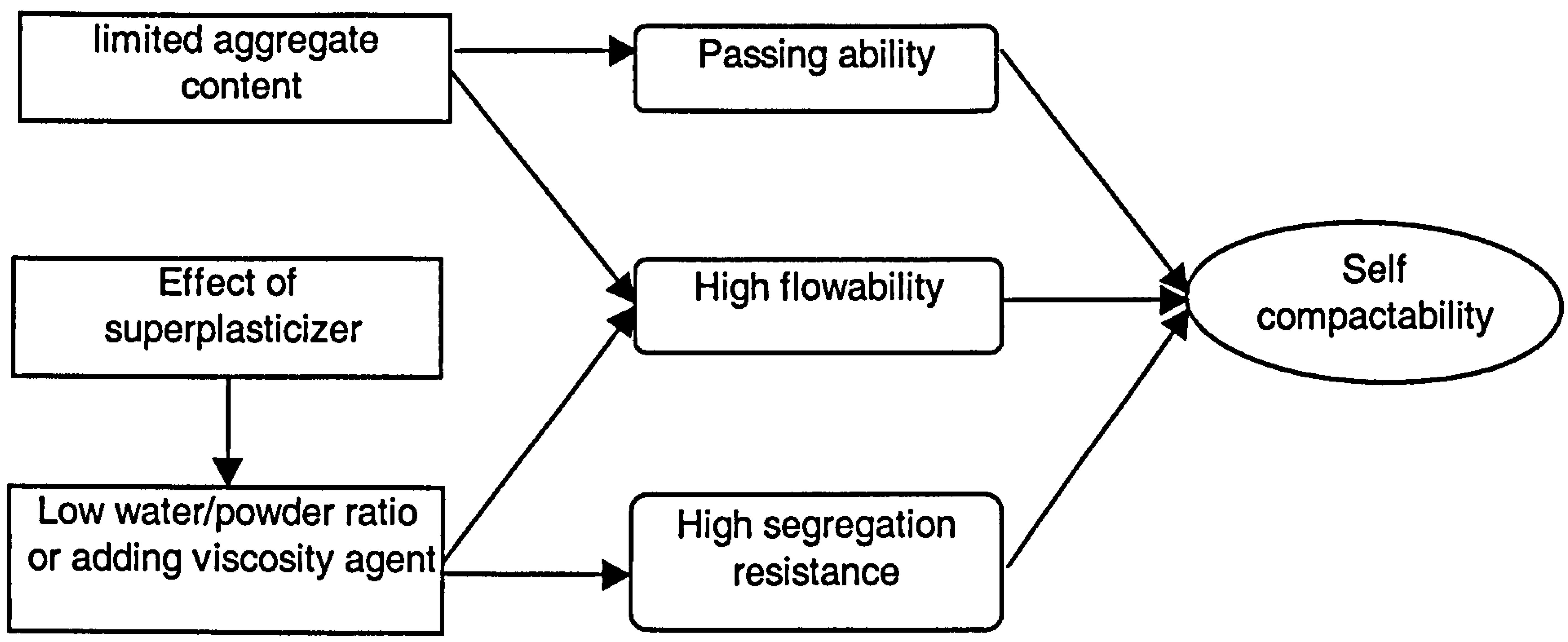


Figure 1-1 The methods of achieving self-compactability (modified from Ouchi *et al.* [6])

SCC is broadly classified into three types in Japan according to the method of preventing segregation, i.e. by the method of increasing plastic viscosity of paste [8]:

- A **powder based SCC** in which a large amount of powder is used to obtain sufficient viscosity without using viscosity agent.
- A **viscosity agent-based SCC** in which a viscosity agent is used to obtain sufficient viscosity.
- A **combined type SCC** where the two types above are combined. The purpose of adding viscosity agent in this kind of concrete is to improve the stability to allow for variations during construction.

It can be seen that in terms of components it can be classified into two types: SCC with and without viscosity agent.

The proven advantages of SCC include [9]:

- reduced concrete placing time,
- reduced labour costs,
- improved concrete durability, especially in the cover zone,
- lower noise levels during placing,
- elimination of the harmful effects of vibration,
- automation of construction.

The disadvantages of SCC include [9]:

- increased cost of materials because of higher cementitious and admixture content than normal concrete, normally 25 to 50% higher [10],
- the need for more rigorous production and quality control,
- a greater tendency to plastic shrinkage on exposed surfaces,
- the lack of suitable standardised test methods to assess the fresh properties,
- the need for efficient mixing procedures,
- the possibility of increased formwork pressures,
- difficulties of surface finishing on exposed flat slabs,
- increased blowholes in vertical faces of wall.

Many of these disadvantages can and have been overcome by attention to details of and modifications to production and construction procedures.

After its initial development, SCC was used in the first half of 1990s in heavily reinforced structures, in massive structures, and for architectural concrete, in all of which the quality of concrete and/or the speed of construction were particularly important. In other words, in situations where [11]:

- the full compaction of concrete with vibration is not possible or extremely difficult;
- a greatly improved reliability of the structure is expected;
- rationalization of work including labour savings, energy savings and shortening of the construction period is anticipated.

Table 1-1 Examples of applications of SCC

Case No.	Date	Structure	Details	Strength required (MPa)	Concrete volume (m^3)	Benefit
1	1996-1998	Sandwich composite [12]	An immersed tunnel, the components are steel shell and SCC	30	6000 per month	Saves reinforcing bar arrangement and form work, reduces site work
2	1994	Concrete filled steel tube [13]	A composite structure consisting of steel tubes filled with concrete	60		Avoids defects due to poor vibration in a complex structure
3	11/92-03/94	Anchorage of Akashi kaikyo bridge [14,15]	Mass concrete, placing rate 1900 m^3 per day	24	290,000	Saves construction time and labour
4	08/97-06/98	Tank for LNG storage [16]	Mass concrete placing into prestressed concrete structure	60	12,000	Increases in the height of each concrete lift, reduces construction periods, saves labour.
5	1996 (?)	Precast concrete [17]	Complicated and thin concrete panels			Production of various shape and size products
6	1998	Bridge [18]	Reinforced concrete structure	70	230	Very high quality
7	1999	Millennium point [19]	Complex and congested reinforcement in 400 steel tubes	60	400	Easy of use and reduced placing times
8	1997	Railway bridge [20]	Long span bridge beam	50		High quality concrete construction

1-5 in Japan, 6 in Sweden, 7 in UK. 8 in China

More recently several attempts have been made to use SCC as an alternative to normal workability concrete for normal structural applications. **Table 1-1** shows some examples of applications, from which it is clear that SCC embraces nearly all of the range of early age and hardened properties of conventional workability concrete – strength and durability *etc*; therefore it should not be thought of as a specialist concrete with a narrow range of properties.

1.2 Research background

As outlined above, the development of SCC has assisted improvement in processes within the construction industry. Worldwide interest has spread rapidly since it was first produced in 1988, particularly after the ACI workshop on high-performance concrete in November 1994 in Bangkok [21]. Research and development studies are now being carried out in many countries, such as the UK (Paisley University, University College London), Sweden, France, Thailand, Taiwan, Canada and USA as well as Japan. In January 1997, RILEM's committee on self-compacting concrete was formed, and in August 1998, the first workshop on SCC was held in Kochi, Japan [22]. The first RILEM international symposium on SCC was held in Stockholm, Sweden in September 1999 [23]. In 2000, RILEM published first state-of-the art report on self compacting concrete [2].

The research programmes include investigation into mix design methods, test methods, the mechanism of SCC from manufacturing and rational construction system.

In particular, in Europe, a three and half year Brite-Euram project on 'Rational production and improved working environment through using self-compacting concrete' started in January 1997, with a consortium of ten partners from five countries, including the Advanced Concrete and Masonry Center, University of Paisley. The aims were [9]:

- to develop an SCC with local materials, and quantify its fresh and hardened properties,
- to develop a steel fibre reinforced SCC,
- to carry out full-scale experiments on the use of SCC in civil engineering and in housing, with the focus on developing production and transport methods and optimising site operations.

The programme will therefore lead to expansion of the use of SCC not only as special concrete, but also in normal structures as a standard concrete.

This programme also highlighted the necessity of establishing standard test methods for SCC; therefore a three-year European project on 'Testing SCC' started in November 2001 with a consortium of twelve partners from eight countries. The objective [24] is to establish a test, or tests, which will enable concrete producers and users throughout Europe to identify with confidence whether or not SCC has the three key properties mentioned above.

Research on SCC at University College London has been carried out since 1993, initially on SCC production using the materials available in UK, which has led to establishment of a rational mix design method [25].

The investigation reported in this thesis followed on from this, and concentrated on the effect of types and amount of powder materials, admixtures, sand and water content on the fresh properties of SCC. These were studied initially by mortar tests, and then some important results were confirmed on concrete. Mortar was tested because it has properties similar to those of the concrete itself; it contains all of the materials except coarse aggregate, and the effect of the test variables will be similar to those in the concrete; it is also more convenient than testing concrete, and hence a large range of variables can be assessed efficiently.

The research consisted of three stages:

1. Establishment of the experimental conditions including examination of physical and chemical properties of the constituent materials, selection of test methods and development of a two-point workability test for mortar.

2. Determination of mixing procedure and selection of a superplasticizer. Investigation of workability and workability retention, setting time and hardened properties of various SCC mixes by mortar tests, with the main effects then examined by tests on concrete. The types of SCC mixes included,
   - a powder type SCC including single type of powder mix, binary and ternary blends of powder mixes,
   - an SCC with viscosity agent including single type of powder mix and binary powder mix.

3. An analysis of the results from the second stage to establish predictability of fresh properties of concrete from correspondent mortar properties, and the relationships between the measured properties for mortar and concrete, rheological behaviour of some mixes.

1.3 Thesis structure

Chapter 2 is a detailed review of the relevant literature. This is followed by chapter 3 which presents the aims and scope of research, and chapter 4 which describes the materials and test methods. The majority of experimental results are reported in chapters 5 to 9 with supplementary experiments for the necessity of discussion presented in chapter 10. These are,

- mixing procedures and selection of superplasticizer, in chapter 5;
- fresh properties of the mixes with single type of powder, in chapter 6;
- fresh properties of the mixes with binary blends of powder, in chapter 7;
- fresh properties of the mixes with ternary blends of type of powder, in chapter 8;
- properties of mixes with viscosity agent, in chapter 9,

Chapter 10 presents the analyses and discussions of the test results from stage 2, this includes,

- rheology model of some mortar mixes,
- relationships between the fresh properties for mortar and concrete,
- modified Feret's rule for strength prediction.

Chapter 11 gives conclusions and recommendation for future work.

Chapter 2

Literature review

The first international paper on SCC was presented by Ozawa at the second East-Asia and Pacific Conference on Structural Engineering and Construction (EASEC-2) in January 1989, a year after the first SCC was produced [26]. It attracted worldwide interest and led to a number of development programmes, initially in Japan, and more recently in Europe and other countries. Many papers have subsequently been published on this subject, and the number of papers collected in UCL until 1999 is shown in **figure 2-1**. Clearly SCC research development and use has increased rapidly in recent years throughout the world (with an exception in 1997).

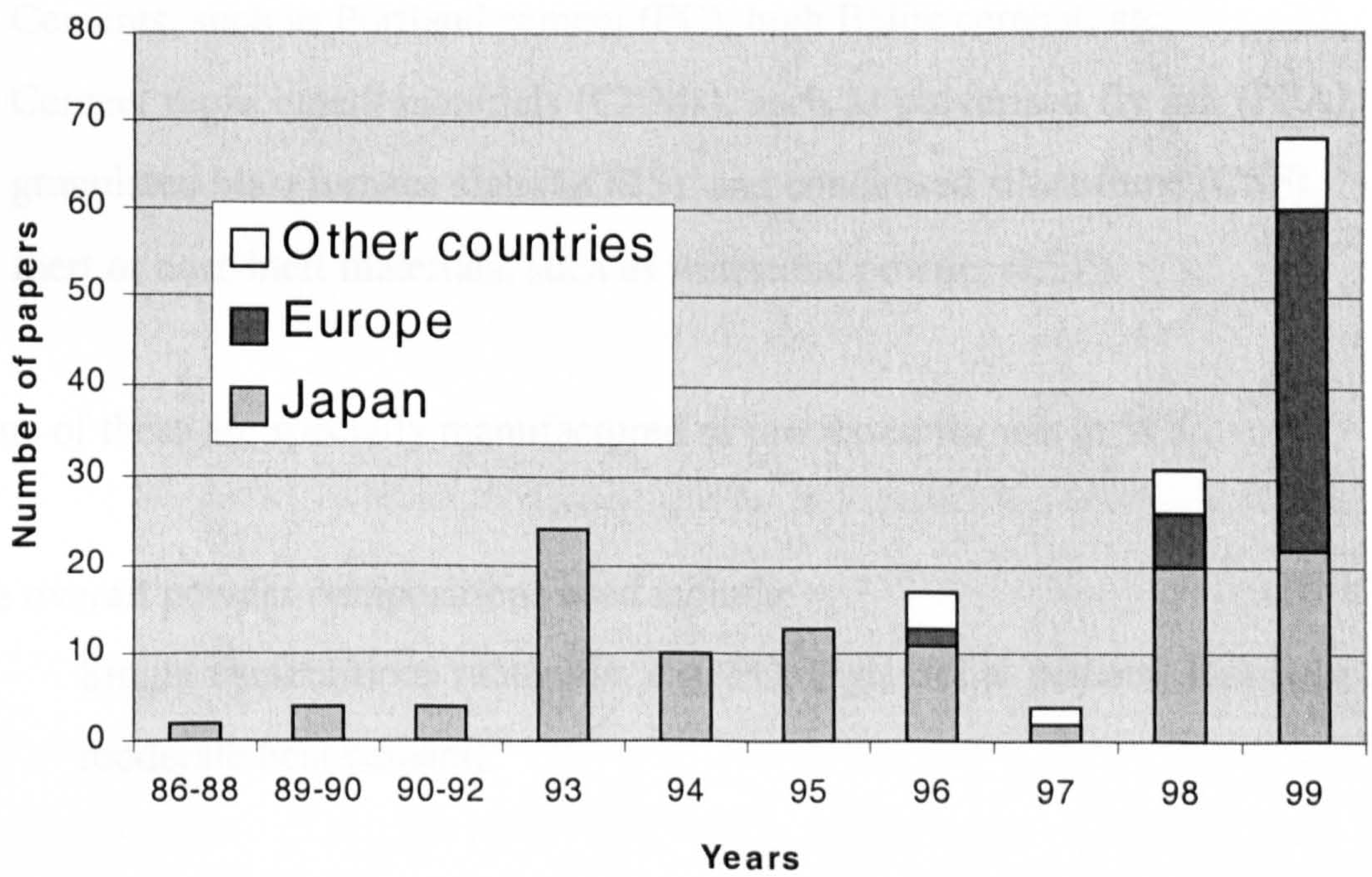


Figure 2-1 Published papers on SCC collected in UCL until 1999

For this chapter, much of the published literature was reviewed, concentrating on materials, test methods, mix design, fresh properties, rheology, hardened properties and durability, and mixing procedures. Because the focus of this project is on the properties obtained in the laboratory, discussion of literature on topics such as manufacturing and construction procedures is not included in this chapter. Some of the papers reviewed were published during the course of the research and have influenced the subsequent experimental work.

2.1 Materials used in SCC

Generally, almost any material that is suitable for normal concrete can be incorporated in SCC. The number of types of materials used in an SCC mix is normally more than that in a normal concrete.

2.1.1 Powders

A variety of powder materials have been used in SCC because of the advantages of being able to select the powder composition. Three main types of powder are used,

- Cements, such as Portland cement (PC), high Belite cement, *etc.*
- Cement replacement materials (CRMs), such as pulverised fly ash (PFA), ground granulated blast furnace slag (GGBS), and condensed silica fume (CSF).
- Inert or near-inert materials, such as limestone powder (LSP).

None of these are specially manufactured or processed for use in SCC.

The overall powder compositions used include:

1. Single cementitious materials: e.g. PC, high Belite cement, low heat cement, moderate heat cement;

2. Binary or ternary blends of PC with CRMs or fine filler; e.g.

PC +
- GGBS
- PFA
- LSP
- GGBS + PFA
- GGBS + LSP
- GGBS + PFA + LSP

3. Combinations of alternative types of cement (other than PC) with CRMs or fine fillers.

Table 2-1 The types of powder composition applied in 43 SCCs in Japanese construction (up to 1999)

composition of the binder	applications (%)
100% PC	13
GGBS cement	24
High Belite cement/moderate or low heat cement	8
Early strength cement	2
Binary mixes (cement + pfa, cement + ggbs, or cement + lsp)	30
Ternary mixes	23

Table 2-1 shows a summary of different powder compositions used in SCC in Japan from the references collected at UCL. These figures depend to a certain extent on the availability of the various materials, for example, GGBS is widely used, and several different finenesses are available in Japan. However, it still shows two distinguishing features in respect of the use of powder in SCC compared to normal concrete.

Firstly, cement other than normal Portland cement such as high Belite cement, low heat or moderate heat cement is often used. It is claimed that superplasticizer can disperse low C_3A, and C_4AF content cements such as high Belite cement and low heat cement more effectively [27]; however, this may be not the case when the superplasticizer is added at sometime after the mix water. High Belite cement reduces the heat of hydration and is ideal for use in high strength self compacting concrete [8].

Secondly, binary and ternary blends of powders, such as those shown above are often used for the following benefits:

- improved flowability, e.g. with PFA or LSP at low water/powder ratios;
- improved plastic viscosity, e.g. with GGBS at higher water/powder ratios;
- reduced heat of hydration in large pours.

Microsilica has had limited amount of use, mainly because it has much less amount of replacement to reduce heat of hydration than other CRMs, but may have other benefits therefore may be worth investigation.

It is important to note that binary or ternary blended cements differ from the powders mixed on site. They are ball-mill blended by mixing high-fineness granulated blast furnace slag powder and fly ash at low temperatures. These cements have a higher packing ratio, and therefore give better fluidity of the paste [8].

The effect of powder composition and the chemical-physical properties of particles on the fresh properties of SCC is reviewed in section 2.4.1.

2.1.2 Admixtures

All SCC contains a superplasticizer to provide high flowability. Those successfully used are mainly based on naphthalene sulfonates, melamine sulfonates, vinyl copolymers, amino sulfonates, and polycarboxylic acids [8]. Recently, admixtures possessing both superplasticizing and viscosity modifying properties have been produced, such as Viscocrete (a Sika product).

In Japan an air entraining water reducing agent (AE) is often used to improve freeze-thaw resistance as well as in fluidity. Many other countries have no particular requirement for air content, and therefore an AE is not necessarily used.

Many different kinds of viscosity agent have been used e.g. cellulose-based water soluble polymers, acrylic-based water-soluble polymer and inorganic viscosity agents etc. Those can be classified into three types, according to their mechanism of action [8]:

1) adsorption on the surface of particles, forming bridge structures between the particles, hence imparting viscosity;
2) absorbing water and swelling to impart viscosity;
3) dissolving in water with links between its own molecules to increase viscosity (this type is also called non-adsorptive viscosity agents.).

The first two types reduce flowability while increasing plastic viscosity, but the third type can increase plastic viscosity without any effect on yield stress. The first type includes cellulose–based water-soluble polymers and acrylic-based water-soluble polymers. The second type includes bio-polymers polysachharide polymers, microorganisms, and inorganic compounds. Glycol-based water-soluble polymer belongs to the third type, which have more benefit to SCC, but an example of this was not available at the time of research, and one of second type, Welan gum, common in the UK, was used. This is a heavy, linear polysaccharide produced by a fermentation process. It can adsorb mixing water and has an impact on the overall rheology of the mix by modifying the rheology of mix water, hence it is also known as a rheology-modifying admixture (RMA).

Recently, a new viscosity agent, based on colloidal silica, has also been used, however, detailed information about its mechanism has not been obtained.

2.1.3 Aggregates

All types of aggregate used in normal concrete can be used in SCC. The maximum size of coarse aggregate varies from 10 to 40 mm according to the minimum clearance between reinforcements and the reinforcement and the formwork. It has been reported that the ratio of clear space between rebars to maximum aggregate radius should be higher than $(2+\sqrt{3})$ for a one-dimensional mesh or $(2+2\sqrt{2})$ for a two-dimensional mesh [28]. In general, aggregate smaller than 20 mm is often used, especially 10-15 mm, because the concrete is more stable [29]. There is also a requirement for the maximum quantity of coarse aggregate, which is normally 50-

55% of its dry rodded bulk density.

Similarly there is no specific requirement for type of fine aggregate. However, the definition of fine aggregate is different in different countries; for example, countries such as Japan, China, UK and America consider it as particles with no more than 10% of particles by weight larger than 5 mm while in Sweden and Norway [35] this size is 8 mm. This can cause the confusion when comparing the properties of SCC produced from different countries. The effect of coarse and fine aggregate on fresh properties is reviewed in section 2.4.1.

2.1.4 Comments

It can be concluded that any materials used for normal concrete can also be used for SCC, although some materials or blends of powder may be preferable. No particular specification is needed for the selection of materials, and therefore SCC should not be treated as special concrete in terms of materials.

2.2 Test methods

As outlined in chapter 1, a successful SCC must have three distinct fresh properties: **high flowability, high segregation resistance** and **good passing ability.** The test methods to evaluate the fresh properties of SCC must therefore be capable of measuring these.

Existing workability tests, particularly those in standards, were inappropriate for the assessment of these properties. Not surprisingly, this subject continues to be pursued by a number of groups. In 1994, Japan Society of Civil Engineers (JSCE) reported 47 test methods as having been studied [30]. Some methods developed in Europe for evaluating the rheology of medium to high flowing concrete, such as the BTRHEOM rheomoter (France), BML viscometer (Sweden) and two-point test (UK) have also been used for SCC. The number of methods indicates the difficulty in establishing and standardising tests.

Most of the test methods that have been developed involve evaluating a combination of two or three properties simultaneously. However, a test method can not be used to evaluate one property independently if the other properties do not satisfy the SCC criteria. For instance, the U-Box test (described below) can evaluate passing ability and flowability but it can not evaluate passing ability of a SCC with a poor flowability or flowability with a poor passing ability. Also, there is still no widely accepted test method to measure segregation resistance directly. Therefore a combination of several test methods is essential, such as a combination of a flowability, a segregation resistance and a passing ability test.

In 1998, JSCE established a standard for the methods of testing SCC [31]. This includes the slump test, the V-funnel test and the U-box test. In Europe the rheology test is also used in addition to the slump test in laboratory, and the L-box test is used instead of the U-box test in some countries.

In this section some widely accepted and typical test methods used are introduced and the main properties measured are discussed.

2.2.1 Flowability tests

These include flow capacity and flow velocity tests. The slump flow test as shown in **figure 2-2 (a)**, which is simply a standard slump test without tamping, is widely used to examine the flow capacity. It gives slump flow value by measuring the average of final spread diameter of the sample deforming under self weight. Total spread values in excess of 600 mm are generally required. It can also give a flow velocity by measuring the time to a spread of 500 mm, but this value is affected by slump flow value [2]. There is no consensus of preferred values for the time although the JSCE has suggested a range of 3-20 seconds [31].

The flowability of mortar can also be measured by a similar test, called the spread test (**figure 2-2 (b)**). This is similar but smaller than the slump flow test. Spread time is not often measured, but as discussed in chapter 4, the time to 250 mm was measured in this project.

The slump flow test is very simple and easy to operate, and therefore can be used both in the laboratory and on construction sites. It is however important to recognise that operator experiences may affect the result [32].

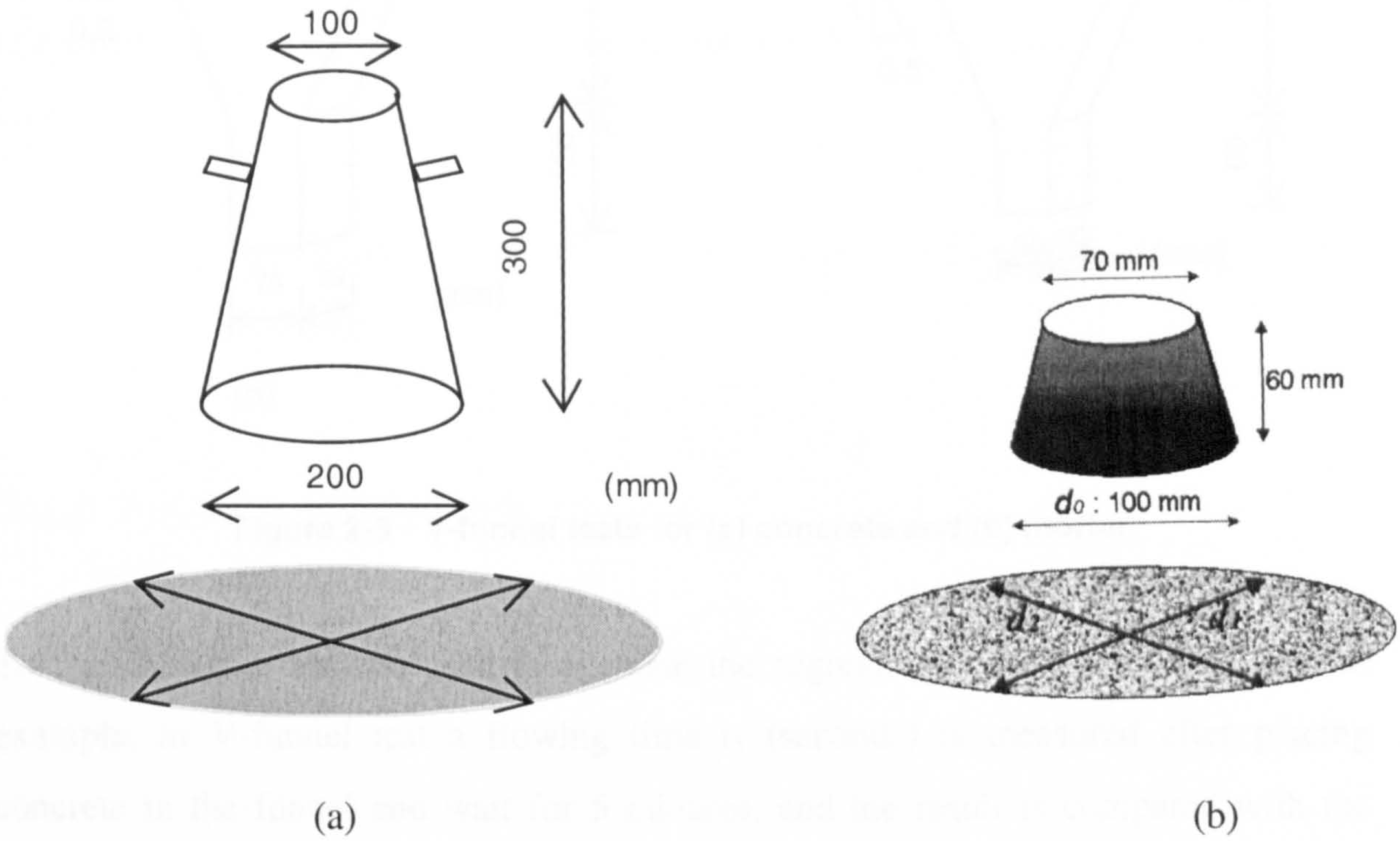


Figure 2-2 Flowability tests: (a) slump flow test for concrete, (b) spread test for mortar

A funnel flow test, such as V-funnel and O-funnel tests, is the most common method of testing flow velocity when passing through narrow space that intimate space between reinforcements. In the V-funnel test concrete commences two dimensional flow, which is same as when concrete passes through reinforce bars in structure, while it has three dimensional flow in O-funnel test, therefore V-funnel test is more commonly used. This method evaluates the flowing speed through narrow opening, which involves passing ability and viscosity of fresh SCC, and to evaluate this, the time t_0 (sec) from opening the orifice to the first daylight appearing when looking vertically down through the funnel is measured and recorded.

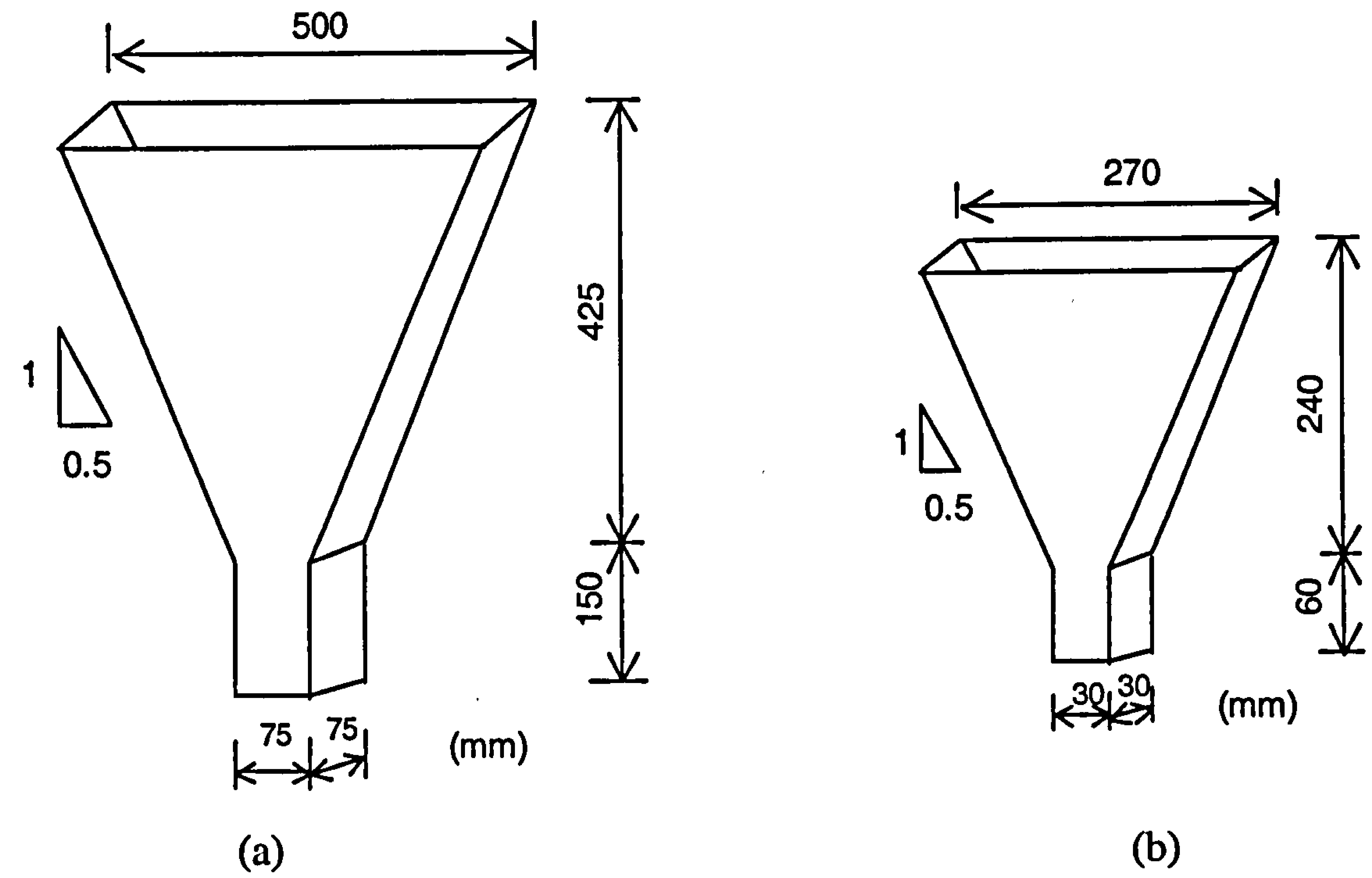


Figure 2-3 V-funnel tests for (a) concrete and (b) mortar

This method can also be used to evaluate the segregation resistance of SCC. For example, in V-funnel test a flowing time t_5 (seconds) is measured after placing concrete in the funnel and wait for 5 minutes, and the result is compared with the flowing time t_0 (seconds) measured immediately after placing concrete in the funnel. A segregation index S_f can be expressed by $S_f = (t_5-t_0)/t_0$ (if $t_5 < t_0$, then $S_f = 0$.)

V-funnel flow time is also affected by flowing capacity, concrete with larger slump flow tends to result in a shorter flow time even when plastic viscosity is unchanged [2].

Many different types of funnel have been proposed, for example, for a V-funnel, the size of the opening at the bottom of V-funnel can be varied, such as 55×75 mm, 65×75 mm, 75×75 mm openings. The V-funnel with 75×75 mm opening, which was proposed by Ozawa *et al* [33] for SCC with maximum coarse aggregate size 20 mm, is used in UCL (**figure 2-3**) since 1995; the one with 65×75 mm opening is used a standard apparatus by JSCE since 1998 [31].

The suggested V-funnel flow time is 4-20 seconds by the JSCE [31] for 65×75 mm opening and 4-10 seconds by Chai [23] for 75×75 mm opening. Lower flow times may indicate a mix with insufficient viscosity for adequate stability; higher flow times with discontinuous flow may show a segregated concrete where aggregate particles separate and bridge at the orifice.

A smaller scale V-funnel test is also used for mortar (**figure 2-3 (b)**). The difference is that the opening size is 6 times of the maximum size of sand, suggesting that it is not measuring passing ability and segregation but flowing speed related to apparent viscosity.

This test method is simple and easy to operate and, as with the slump flow test, care is needed when operating.

2.2.2 Passing ability tests

As well as the V-funnel test designed above, a number of passing ability tests have been used, such as the U-box test, the L-box test and the J-ring test. Unlike the funnel test, these methods measure the passing ability through a mesh of bars.

One of the commonly used methods is the U-box test. It was first developed by Matusuoka and Shindo, who called it the U-shape box test. There were several versions of this. Okamura and Ozawa modified it by changing the curved bottom to flat (as shown in **figure 2-4**) after finding out that it is then more sensitive to concrete with low segregation resistance [34].

Three different obstacles can be used in the U-box. Obstacle 1 (R1) is made of D10 mm bars with four 35 mm clear gap between bars, obstacle 2 (R2) of 13 mm bars and 45-35-35-45 mm clear spacing, and obstacle 3 (R3) has no bars.

The concrete flowing can be observed through a transparent wall on one side of the compartment. A fill the height of over 300 mm in compartment B is judged as satisfaction self compactability. Concrete with low flowing ability or plastic viscosity will not reach this height due to low deformation or high segregation. This has found to be an effective and convenient test, with the measurement of final height being readily interpreted in terms of an acceptance criterion.

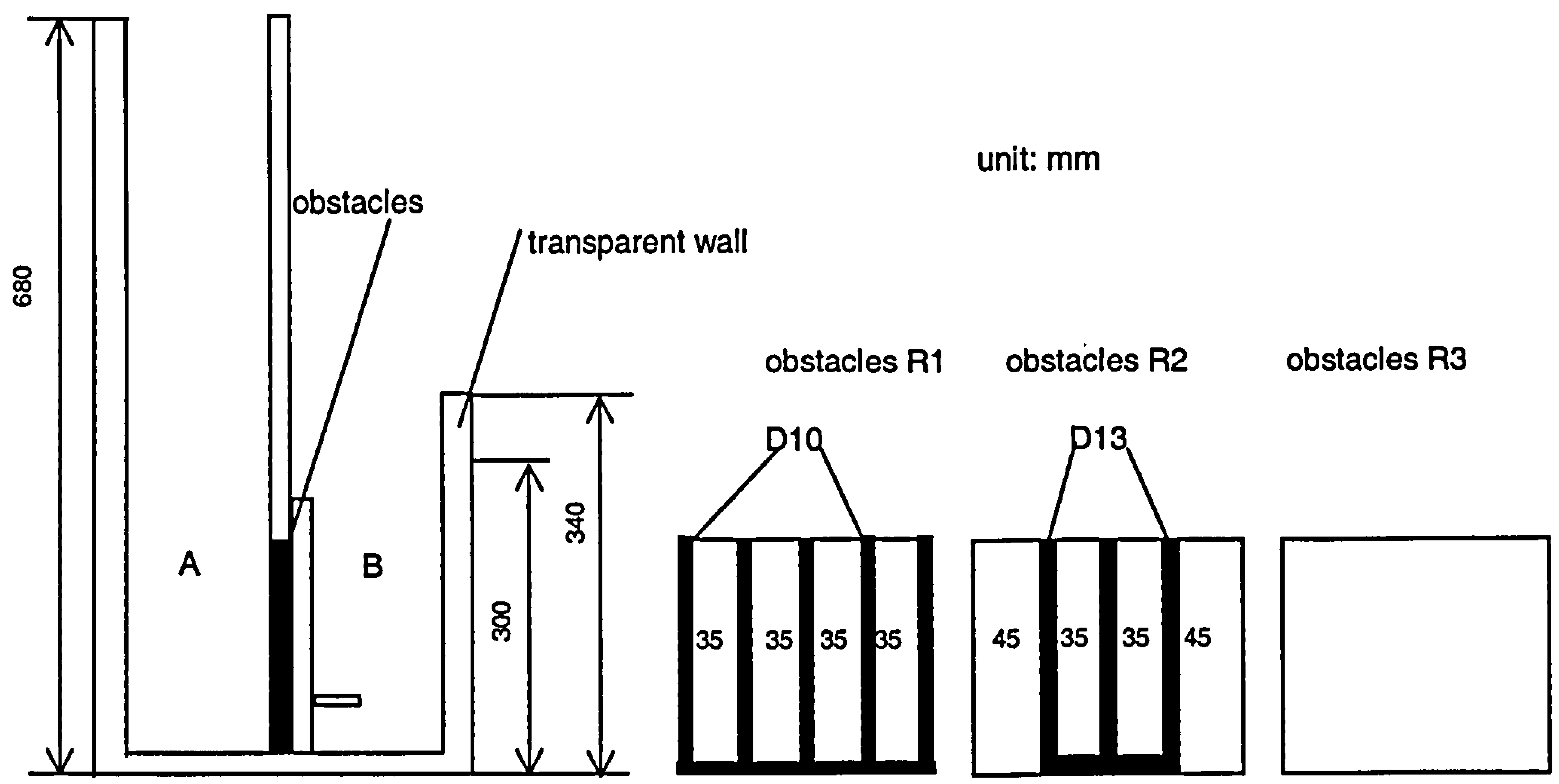


Figure 2-4 U Box test

An L-shaped box with reinforcement at the opening is also used in some countries such as Sweden (**figure 2-5**). Measurements that have been used include flow times to 200 and 400 mm flow, and the ratio of the final heights H2/H1 as shown in the figure. Also, some workers record flow distance by measuring the distance between the gate and edge of the flow. An advantage of such a test is that the flow can easily be visually assessed, and any tendency to block or segregate is immediately apparent. It is also easily dismantled and reassembled for cleaning. However, a general agreed criterion is more difficult to define than the U-box type test (an acceptable values for H2/H1, is according to Swedish experience 0.80-0.85.)

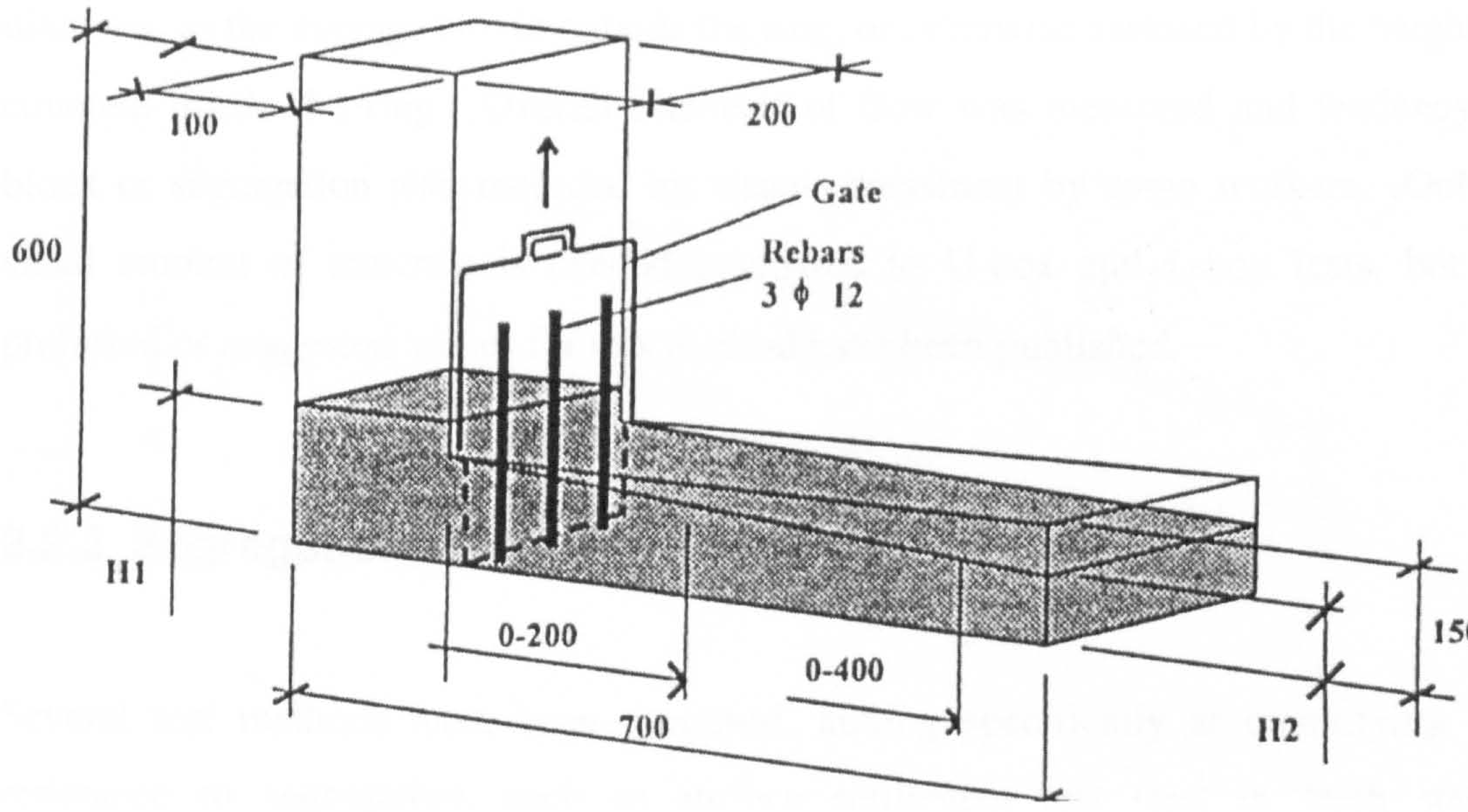
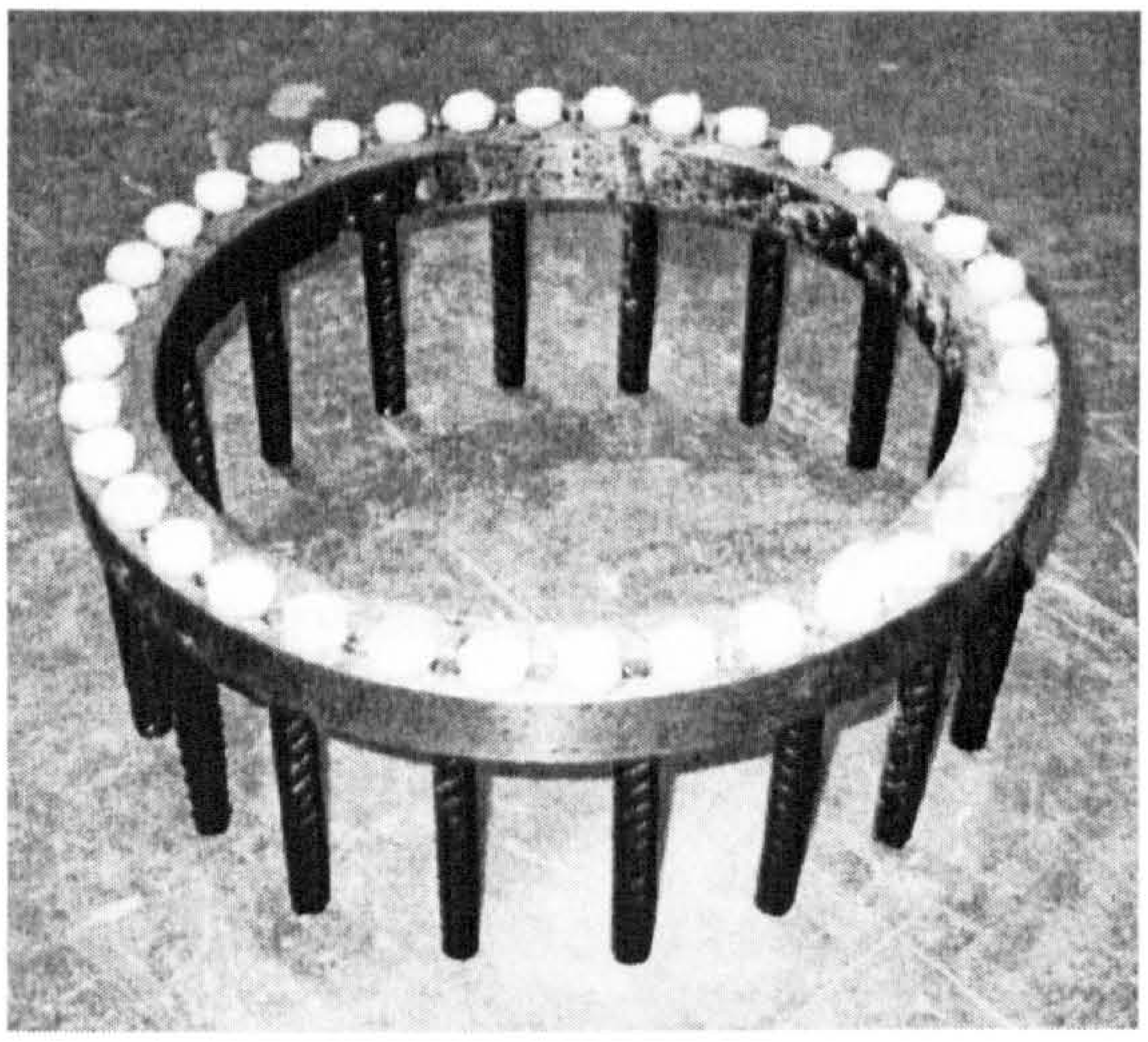
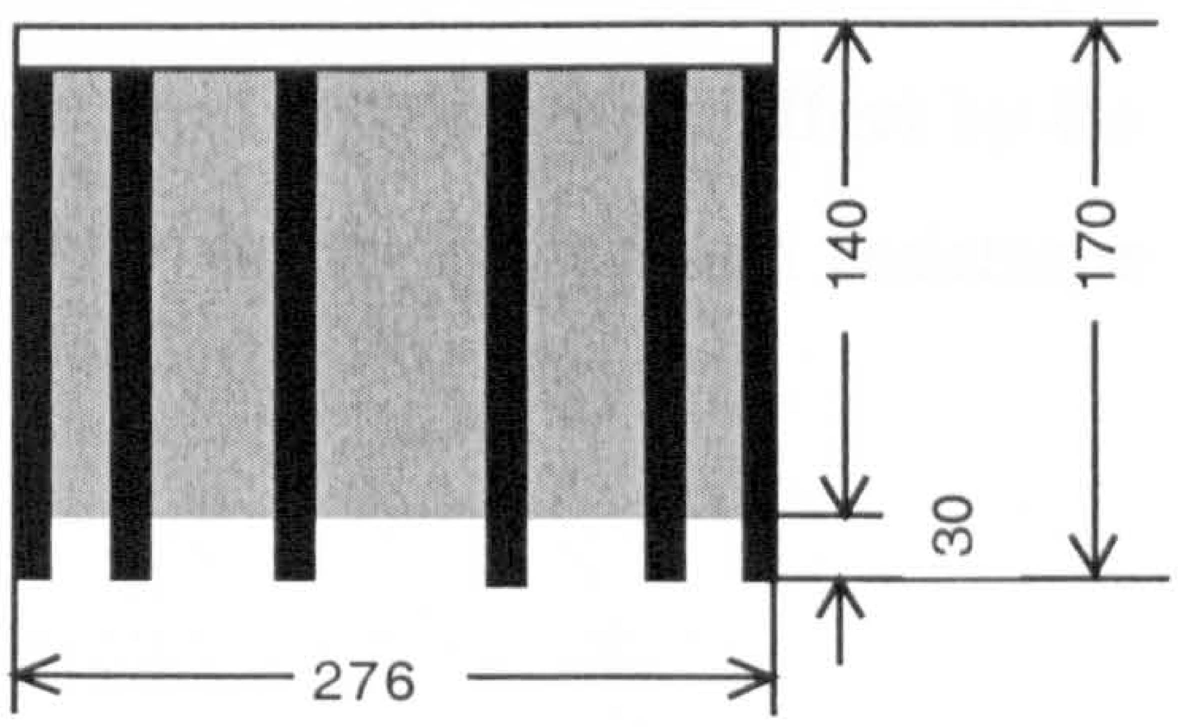


Figure 2-5 L-shape test (adapted from [35])



J-ring in Paisley (300 mm in diameter)
(adapted from [37])



J-ring in Japan
(adapted from [38])

Figure 2-6 J-ring tests

A J ring test is simpler than both these tests. **Figure 2-6** shows the two types of J ring – one from Paisley [36,37] and one from Japan [38]. The major difference between them is that the top part of the J ring in Japan is blocked; therefore the function of openings is equal to a two dimensional mesh. A fixed quantity of concrete is introduced into the ring, e.g. from a slump test carried out inside the ring, and allowed to flow through the bars until flow ceases. The passing ability is assessed by the average ratio of the height of concrete retained inside the ring at approx. 200 mm diameter, to the average height outside the ring, or otherwise assessed by the height of concrete inside the ring. Overall diameter of flow was measured and tendency to block or segregation also recorded by visual assessment by some workers. Only a small amount of concrete is needed compared to U-box and L-box tests, but no preferred or suggested values for this method have been published.

2.2.3 Segregation tests

Several test methods have been proposed, aiming specifically at quantifying the resistance to segregation, such as surface settlement test (test in fresh state), penetration test for rapid evaluation of resistance to segregation (test in fresh state) and segregation test (test in hardened state). The detailed method description can be found in reference [2]. However, there are no general agreed criteria for these tests, and as mentioned earlier, none of these segregation test methods has been generally accepted and no routine methods are available at present. As discussed the segregation can be examined by other test methods qualitatively such as the V-funnel test, L-box test and the U-box test in which the measured properties are affect by the degree of segregation, but an effective test to directly assess segregation resistance would be very useful.

2.2.4 Filling capacity tests

The filling capacity test is normally used to examine the quality of self–compactability after the SCC is proved to satisfy the properties mentioned above. The test examines a combination of properties and predicts the flowing behaviour in the real structure. Several versions have been used, some of which are models of parts of real structure [39]. **Figure 2-7** shows a typical test. It represents the bottom part of an I-section beam, and has a higher requirement of self-compactability than in the full scale structure [40]. The method is comprehensive, with a lot of work needed for each test, so it is only suitable for use in the laboratory.

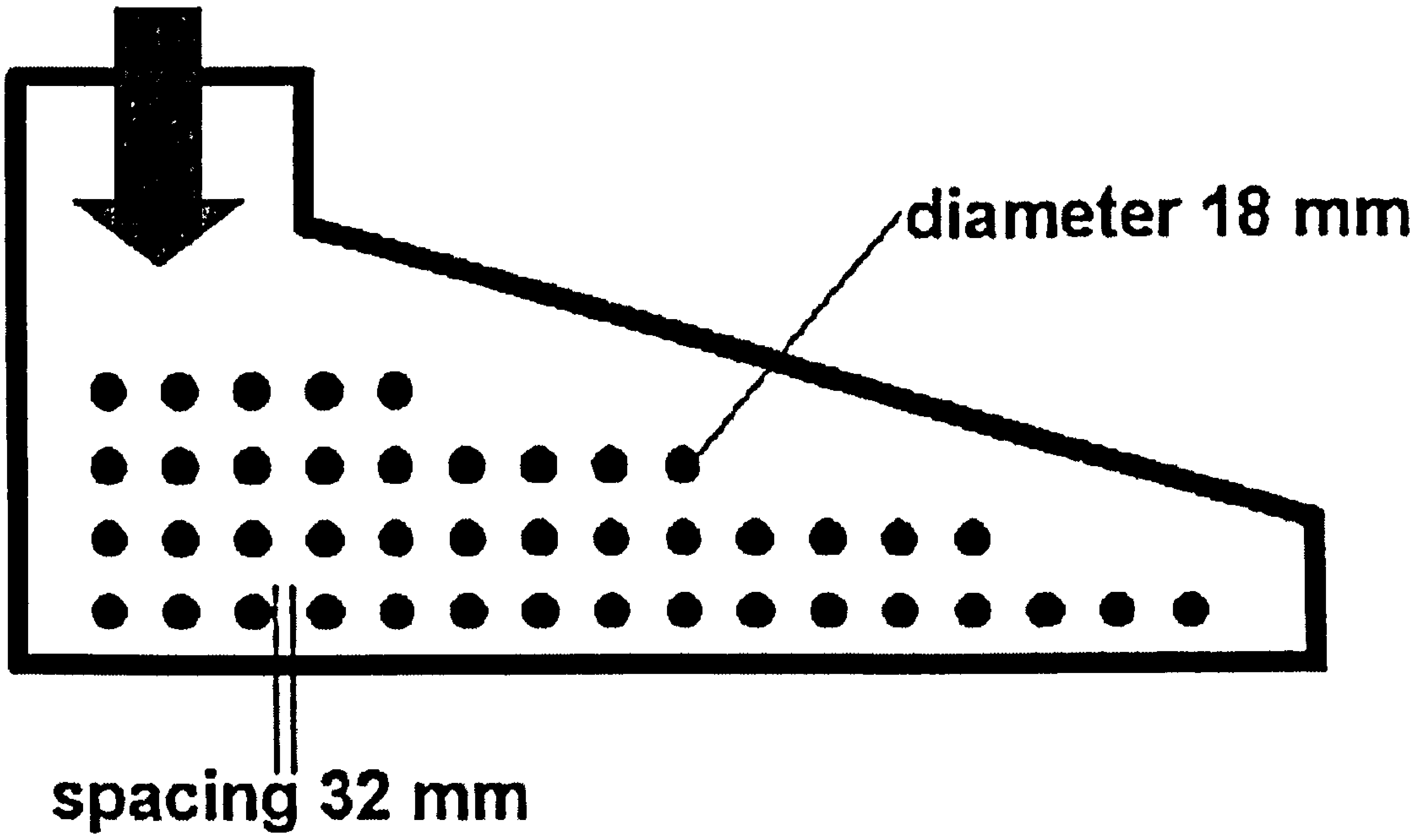


Figure 2-7 Filling capacity test used in Japan (Adapted from [40])

2.2.5 Rheology tests

The rheology of mortar and concrete is generally considered to follow the Bingham model,

$$\tau = \tau_0 + \mu\dot{\gamma}$$

Therefore rheological tests are generally used to measure the values of yield stress and plastic viscosity, although, as will be discussed in chapter 10, some authors claim that it would be more suitable to describe SCC with the Herschel-Bulkely model;

$$\tau = \tau_0 + k\dot{\gamma}^n$$

Tests on mortar

There are two main types of devices used to test the rheology of mortar, one is a coaxial cylinder viscometer, such as the HAAKE Rotovisco CV20 [96], the other is a two-point rheometer, such as the ViscoCorder [140,141]. The latter needs calibration to obtain yield stress and plastic viscosity in fundamental units.

In theory these two types of devices should give the same numerical results for the mortar properties. This has been confirmed by Banfill [143], who found that the yield stress and plastic viscosity of the same mortar tested with a Viscocorder and coaxial cylinder viscometer had acceptable agreement.

In this project, a smaller version of the two-point apparatus for concrete with a helical impeller was established to test mortar. Comparison was also made with the ViscoCorder and a coaxial cylinder viscometer. This is described in chapter 4.

Tests on concrete

Several test devices have been used to assess SCC, including a coaxial cylinder rheometer (Japan) [110,111], the BTRHEOM (France) [42], the BML viscometer (Sweden) [35], and the two-point test (UK, Japan) [29, 41], *etc.* The BML viscometer works on the same principle as a coaxial cylinder viscometer, while the BTRHEOM is a parallel plate rheometer. Most of them are mainly used in the laboratory because of the inconvenience of their use on site.

If the values of yield stress and plastic viscosity are obtained in fundamental units, then the test results obtained with the different apparatuses should be consistent. However, this is not the case. For example, for a successful SCC, Kawai *et al* [41], using a two-point test, proposed a yield stress about 50 Pa and the plastic viscosity 20-80 Pa.s, and Wallevil and Nielsson, using BML viscometer, proposed 50-70 Pa and 20-30 Pa.s respectively [2], while Sedran *et al* [42], using BTRHEOM, suggested the yield stress less than 500 Pa and the plastic viscosity 100-200 Pa.s. Clearly, more study is needed on this subject. The results of the corporation study carried out in LCPC, Nante, in October 2000, will be a great help in this respect [43].

In this project, a two-point apparatus with helical impeller developed at UCL was used to test concrete. Discussion of this is left until chapter 4.

2.2.6 Tests on the job site

All the SCC should be checked before it is placed since the compaction is entirely dependent on its self-compactibility. Strict quality control is therefore necessary, including such properties as slump flow, air content, concrete temperature, segregation, water content and chloride content. The test methods that have been used to control fresh properties include slump flow, V-funnel and O-funnel tests, and visual observation *etc.* Clearly, these tests cannot be used to check all the concrete casting into structure, and an acceptance test for this has been developed by Ouchi *et al* [44] (**figure 2-8**) which has been used in several applications.

The apparatus is installed between agitator truck and pump at the job site. All the concrete is passed through the apparatus, and if it flows through it is considered as satisfactory. If the concrete flow blocks, it has insufficient self-compactability and the concrete is rejected.

This apparatus was successfully used in the construction site of the LNG tank of Osaka Gas in 1996-1998 and saved labour compared to the use of other acceptance tests [44].

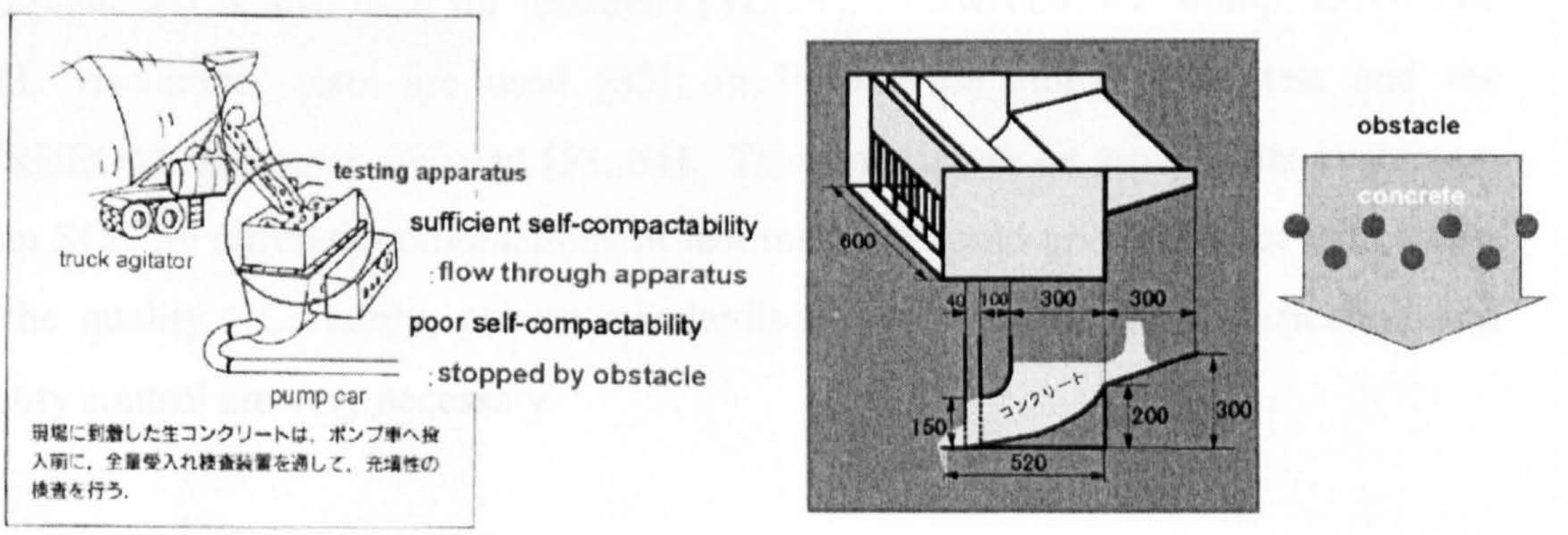


Figure 2-8 Test on job site (adapted from [44])

2.2.7 Comments

Each test method has its own distinguishing features. Even when several tests measure the same property they may show different results because of different sensitivities. **Table 2-2** shows the results of a comparison of several test methods described earlier by testing 8 SCC mixes, which is extracted from the report by Japan Society of Civil Engineering (JSCE), 1994 [45]. It can be seen that the mix D had much higher slump flow than mix E although they showed similar results in V-funnel flow time. As a result, the mix D was ranked 1 and 3 in the L-box passing ability test and the U-box passing test respectively. This suggests that the L-box test is more sensitive to slump flow than to flowing speed compared with the U-box test, therefore higher flowing concrete shows better property in the L-box test than relatively low slump flow concrete. Among 8 mixes only 2 mixes (D, E) were marked different ranks by U-box passing ability test compared to the filling capacity test, suggesting that U-box test (with R1 bars) and the filling capacity test gives similar indication to the quality of concrete, but the ranks given by L-passing ability test were generally higher than those marked by filling capacity test.

As mentioned earlier, the fresh properties of an SCC must be evaluated by a combination of several test methods, such as the flowability, passing ability, segregation and filling ability tests. Many different combinations of test methods have been used in different countries. For example, in Japan (and UCL), a combination of the slump flow test, the V-funnel test and the U-box test is used (the two-point test is also used for research) [31, 29]; in Sweden, the slump, L-box and BML viscometer tests are used [35]; in France the slump flow test and the BTRHEOM rheometer are used [53, 54]. Therefore it can be argued that evaluation of an SCC by different combinations of test methods could give different indications of the quality. Certainly, proven standardised test methods for specification and quality control are very necessary.

Table 2-2 A comparison of test methods reported in Japan (translated from [45])

	Concrete quality*								
concrete mixes	A	B	C	D	E	F	G	H	speed
Standard filling capacity test (Figure 2-7)	2	3	2	2	3	1	4	3	
U-box passing capacity test (R1 bars) (Figure 2-4)	2	3	2	3	2	1	4	3	
L-box passing ability test (Figure 2-5, the gap between bars 35 mm)	2	2	1	1	2	1	3	1	
V-funnel flow test ($V_{6.5\times7.5\ cm}$)	2	1	3	3	3	2	3	1	High
V-funnel flow test ($V_{5..5\times7.5\ cm}$)	1	3	2	2	2	1	3	1	High
O-funnel test	3	2	4	4	3	3	4	1	High
slump flow test (cm)	64	69	65	70	54	65	64	68	

*The quality of SCC is marked with different ranks according to the test results. The best quality is marked as 1, followed by 2,3 and 4.

2.3 Mix design methods

There is no unique solution to a SCC mix for a particular application since the material availability and quality requirements for the SCC vary from region to region. For example, GGBS finer than 10,000 cm^2/g can be produced in Japan [8], and types with a specific surface area of about 6000 cm^2/g is normally used in SCC because this gives good flowability, but this is not available in Europe. Also, concrete in Japan is required to have an air content greater than 4% for durability requirement, consequently an AE water reducing agent is normally used in Japan, although this is not required in other countries.

A number of mix design methods have been developed, based on different approaches, the detailed methods are described in **Appendix 1.** **Table 2-3** provides a summary of the different mix design methods. It can be seen that each method has been developed for its own specific conditions and environment, and has its own distinguishing features and some inherent limitations. This also makes it difficult to compare one method to another. Therefore, understanding the specific conditions seems to be very important when applying these methods. A trial mix for a particular application during mix design is always very necessary along with an understanding of the effect of each component on the properties.

There have also been other mix design methods developed for particular applications, such as Hwang's mix design for columns of a 347m high rise building in Taiwan [57], Hon's mix design used for several applications in China [39] and Walraven experiences with Netherlands materials [58]. Special SCC mix design, such as steel fiber reinforced concrete and SCC with expansive additives have also been studied [59-61].

The number of mix design methods indicates the difficulty of establishing a method embracing all range of mixes and easy to follow, this limited the use of SCC to special concrete with the instruction of SCC specialist. Further study will be needed to establish a method which can be easily followed and broadly used in various different environments.

Table 2-3 Summaries of the different mix design methods

Mix Design	Brief description of methods and Distinguishing features	Comment
Japan: Okamura & Ozawa [46,47]	It is a step by step method, following determination of air content→ coarse aggregate content→, fine aggregate content→ water/powder ratio→ dosage of superplasticizer. In this method moderate-heat Portland cement or belite-rich Portland is assumed to be the only source of powder materials. Also the volume of coarse aggregate and fine aggregate is predetermined to 50% of the dry rodded volume and 40% of mortar by volume respectively.	Very simple and very easy to follow. Concrete is often over designed at high material cost.. Not always useful when other than moderate-heat Portland cement or belite-rich Portland is used as powder. The number of tests to determine water/powder ratio and superplasticizer dosage depends on the familiarity with the material properties and experimental experience. It can not be used for designing of mixes containing viscosity agent.
Japan: JSCE [8,31,43]	It is also a step by step method by recommending limits of parameters in each step. The procedure follows: coarse aggregate content→ water content → water/powder ratio → powder content → air content → fine aggregate content → dosage of superplasticizer. This is a **general** recommendation to any construction work with materials in Japan.	Very easy to follow. Requires a good understanding of materials properties. Construction experience is important. This is the only one that can be used for designing of mixes containing viscosity agent.
Thailand & CBI [48-52]	The important difference between this method and general step by step method is that it is aimed to obtain minimum paste content with satisfying SCC requirement. The minimum paste content is determined by blocking criteria and minimum void content, and water/powder ratio and superplasticizer dosage by study of fine mortar rheology.	An SCC can be obtained with minimum paste content and good passing ability. A database is need for each single size aggregate and various structural conditions in order to establish blocking criteria. This method can be complicated. The design for SCC containing viscosity agent was not considered.
LCPC (France) [53, 54]	It uses a 'Compressible Packing Model' which considers all ranges of material from powder to coarse aggregate to obtain initial mix proportion. BTRHEOM rheometer is also used to test rheology of the mix and water content and superplasticizer dosage are adjusted to achieve proposed criteria for SCC.	An SCC can be obtained with minimum powder content and good passing ability. Because the RENE-LCPC^{TM} is based on granular skeleton packing model, sometimes it may result in too low paste content, causing a rapid slump loss and blockage while pumping. It is only for designing of mixes without containing viscosity agent.
UCL (UK) [25,29, 55, 56]	It is also a step by step test method with giving limits for those parameters in each step, which was obtained on a extensive laboratory test programme using UK material. Two important equations are used to determine powder composition and water/powder ratio. Mortar tests to determine superplasticizer dosage.	It is simple and easy to follow. Little mix design experience is needed. Not many concrete trial mixes are needed because of mortar test. Particularly suitable for UK materials. The proposed criteria are only for designing of mixes without containing viscosity agent.

2.4 Fresh properties

The fresh properties and their retention in SCC are very important since the compaction is thoroughly dependent on the self-compactibility of the concrete. In this section the effect of each constituent of the mix on those properties and their retention is reviewed, as mortar and concrete. The relationship of properties between mortar and concrete is also reviewed because of the important role of mortar properties in SCC.

2.4.1 Effect of constituents on fresh properties

2.4.1.1 Powder

The powder type and content is very effective in controlling the plastic viscosity and inhibit the segregation of concrete. Almost all types of binders and cements used in normal concrete have been used in SCC for various reasons. The effects of the chemical composition and physical properties of each component of the powder are first reviewed.

Chemical composition

Cement

Cement particles in SCC are highly dispersed by the superplasticizer, which gives rise to high flowability. The composition of cement affects the efficiency of the superplasticizer and therefore the mix properties. It has been reported that the adsorption of superplasticizer by each chemical component is very different. **Table 2-4** shows a comparison of the amount of adsorbed naphthalene and polycarbonate acid superplasticizer by various powders including cements, binders and chemical components of cement, the dosage of superplasticizer was 1% of powder by weight [62,63]. The powders are grouped into three types according to the size: fine, medium and coarse, with particle size less than 20 μm, 100 μm and 200 μm respectively.

It can be seen that C_3A and C_4AF adsorb more superplasticizer than C_2S and C_3S. This means that higher C_3A and C_4AF content cement may require more superplasticizer in order to achieve the same flowability. For this reason the recommended cement chemical composition for SCC is $C_3A + C_4AF < 10\%$, C_2S = 40-50%, C_3S = 50-40% [62]. This also falls in the range of the composition for moderate heat, low heat and sulfate resisting cement.

Table 2-4 Comparison of the superplasticizer adsorbed by various type of cement, binder and constituents of cement (translated from [62])

Size	Cement and Binder	BET Specific Area (m^2/g);	Specific gravity (g/cm^3)	Adsorption (mg/g)	
				Naphthalene	Polycarbonate acid
Fine	Limestone powder	4.99	2.76	5.3	7.4
	Slag powder	3.2	2.91	6.9	6.3
	Fly ash (<7 μm)	3.97	2.53	4.4	7.2
	Fly ash (<10 μm)	5.65	2.55	5.2	7.5
	Fly ash (<20 μm)	2.31	2.46	6.5	8.4
	Silica Fume	21.53	2.48	0.3	5.9
Medium	OPC	0.74	3.22	8.1	6.9
	Moderate heat cement	0.96	3.25	7.7	6.6
	High β-C_2S cement	0.89	3.29	6.1	6.4
Coarse	Moderate heat cement	0.31	3.23	6.3	4
	Coarse fly ash (<20 μm)	0.37	2.11	2.6	3.1
	Coarse slag	0.57	2.92	0.9	1.6
Constituent of cement	C_3S			2.6	3.9
	C_2S			5.8	3.1
	C_3A			9.8	8.2
	C_4AF			9.8	
	F.Cao			9.2	

CRMs and LSPs

Table 2-4 also shows the superplasticizer adsorption on different powders. It can be seen that the adsorption by PFA and GGBS was much lower than cement with a similar particle size. LSP had slightly lower adsorption of Naphthalene and higher adsorption of Polycarbonic acid than a similar size GGBS. Similar results have been obtained by Sudo *et al*, who found that SCC containing GGBS required much lower superplasticizer than PC [64]. It is surprising that silica fume adsorbed very low amount of Naphthalene; this contradicts many results obtained by others and the reason is not clear.

Physical characteristics of powders

The physical characteristics of a powder can be specified by particle size distribution, shape, mean size, and specific surface area. It also can be described by retained water/powder ratio (β_p) and deformation coefficient (E_p), two constants used in some SCC mix design methods.

There have been many investigations on the effect of the powder physical characteristics on fresh properties. These can be summarized as follows:

Fujiwara *et al* [65]

The plastic viscosity of paste increases with specific surface area of cement; the yield stress is closely related to the particle size distribution which can be represented by N-value calculated using Rosin-Rammler equation:

$$R(D_P) = 100\times.\exp(-bD_p^N), \qquad (2\text{-}1)$$

Where,

- $R(D_P)$: cumulative percentage retained on sieve
- D_P : particle diameter
- b, N : constants.

Figures 2-9 & **2-10** show a typical result measured on the mortar with PC/LSP blends of powder. It can be seen that plastic viscosity increased with the increase of specific surface area but it is also affected by N-value, and yield stress is low when N-value is about 0.7-0.9.

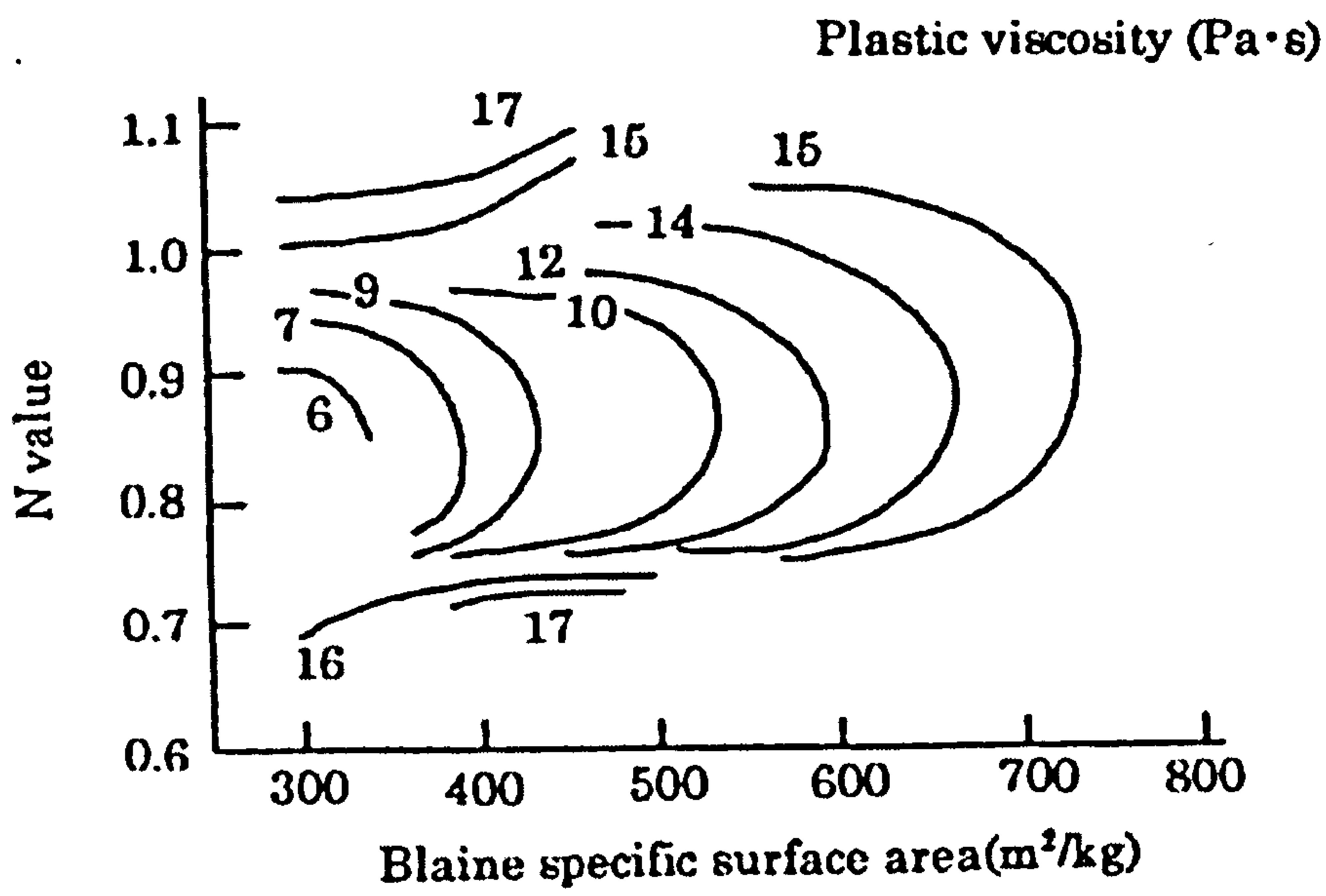


Figure 2-9 Effect of Blaine specific surface area and N-value on plastic viscosity for the mortar with PC/LSP blends of powder (adapted from [65]).

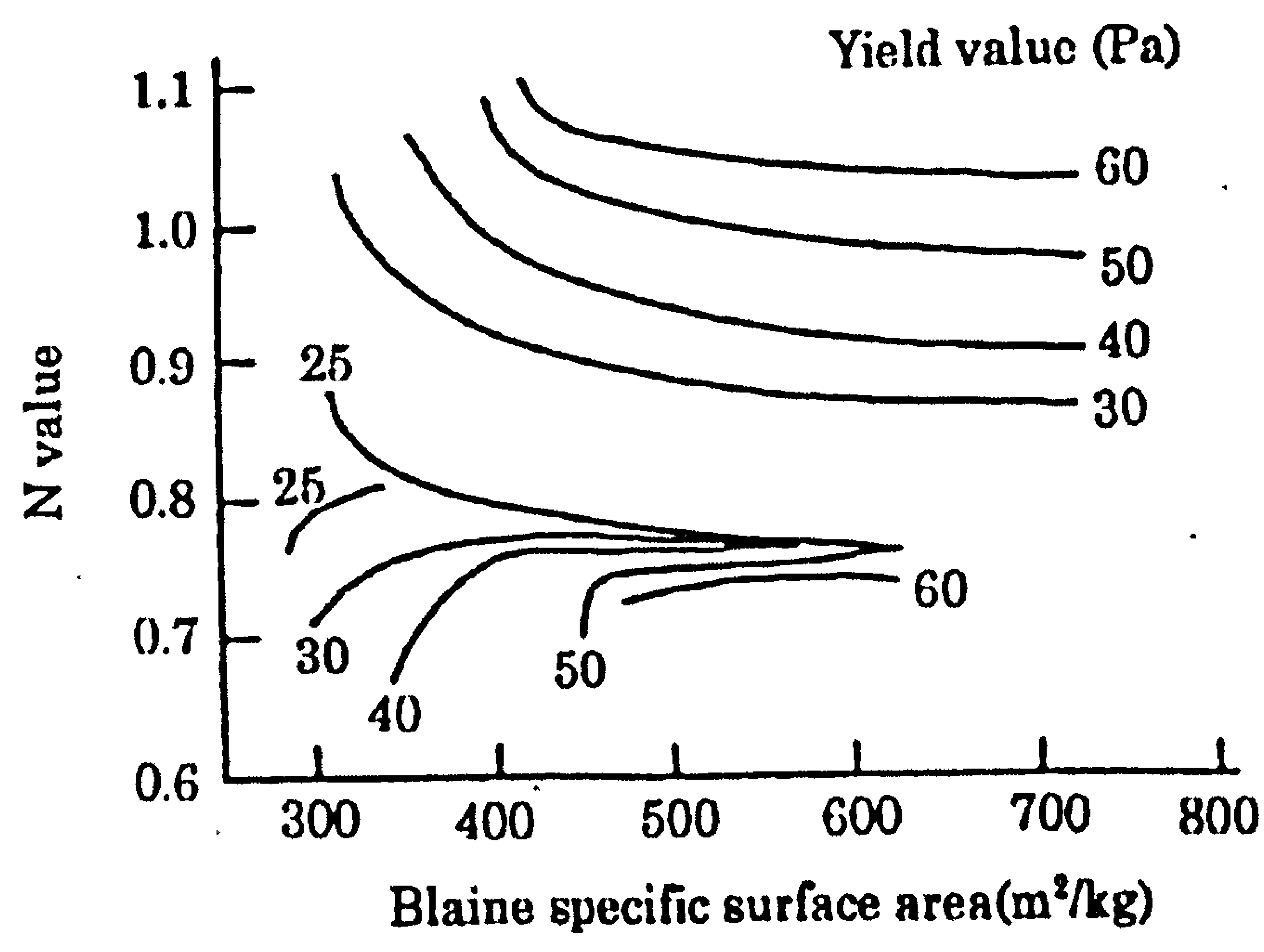


Figure 2-10 Effect of Blaine specific surface area and N-value on yield stress for the mortar with PC/LSP blends of powder (adapted from [65]).

They also found possible minimum powder content by adjusting N-value and fineness of powder to achieve a mortar with 20-50 Pa yield stress and 6-12 Pa.s plastic viscosity measured with rotation viscometer (It may be a cylinder viscometer), a requirement for the mortar component of SCC. For example for a PC/LSP binary mix the minimum powder can be 370 kg/m^3 OPC with 159 kg/m^3 water when Blaine fineness is 3500~5200 cm^2/g and N-value is 0.8~0.9 [65].

This very interesting finding could reduce the powder volume in SCC significantly; the understanding of physical significance of N value would be very helpful for applying this equation but insufficient information was published.

Uchikawa *et al* [62]

Concrete mixed with powder containing approximately 30-40% of coarse particles, 40-50% of medium particles and 10-20% of fine particles as shown in **table 2-4** may achieve good flowability [62].

Domone *et al* [51]

Each type of powder has its own characteristic retained water/powder ratio (β_P) and deformation coefficient (E_P). **Table 2-5** shows an example of these characteristics of some powders [51]. It can be seen that PC and GGBS have the highest retained water powder ratio and this is followed by LSP100 and PFA, and the properties are also affected by superplasticizer.

Table 2-5 Retained water/powder ratio and deformation coefficient (adapted from [55])

Powder/mixture	βp	Ep
OPC	1.08	0.061
PFA	0.59	0.024
GGBS	1.10	0.046
LSP100	0.77	0.037
OPC + 1.0% sp	0.86	0.034

The flow spread (Γ_m) and plastic viscosity (μ) of a paste can be predicted by the retained water/powder ratio (β_p), deformation coefficient of the powder (E_P) and water/powder ratio (V_W/V_P) by the equations (2-2) and (2-3) [55]:

$$\mu = \frac{a}{E_p}\left(\frac{V_w/V_p}{\beta_p}\right)^{-k} \qquad (2\text{-}2)$$

$$\Gamma_m = (V_w/V_p - \beta_p)/E_p \qquad (2\text{-}3)$$

Where a, k are constants obtained from experiments.

These equations have been used in UCL mix design method to predict initial mix proportions.

2.4.1.2 Water

Water in paste can be divided into two parts: one is that filling the voids between particles and physically and chemically retained by the powder (denoted by β_p), and remainder is the free water. **Equations (2-2)** and **(2-3)** show that the flowing capacity (as expressed by Γ_m) of a paste is controlled by free water, and plastic viscosity of a paste is related to the ratio of retained water to total water.

Edamatsu *et al* [66] carried out two series of concrete tests with 100% high belite cement. Series 1 included several types of mixes with various sand content and constant coarse aggregate content, i.e. 50% of dry rodded bulk density; and series 2 were with various coarse aggregate content and constant sand/mortar ratio 0.49 by volume. In each type of mix the water/powder ratio varied at 0.7-1.3, and the dosage of superplasticizer in each concrete was adjusted to obtain the maximum filling height in U-box test. They found that there was a range of water/powder ratio for each type of SCC to obtain a filling height more than 300 mm (**figure 2-11**). This range varied with the sand content and coarse aggregate content. For example, for a mix type with sand/mortar ratio 0.45 and a coarse aggregate content 50% of its dry rodded bulk density, the optimum water/powder ratio ranged from 0.83 to 0.94 by volume, which equals to 0.26-0.29 water/cement ratio by weight. This is in the low part of the range of water/powder ratio proposed by JSCE for SCC mixes without viscosity agent, i.e. 0.28-0.37 water/powder ratio by weight [6], and the range proposed by Chai, i.e. 0.28-0.4 by weight [29]. This suggests that although a water/powder ratio lower than 0.4 by weight is normally required for SCC without a viscosity agent, individual limits of water/powder depends on the type of mix. There is little information on mixes with viscosity agent, and further study is needed.

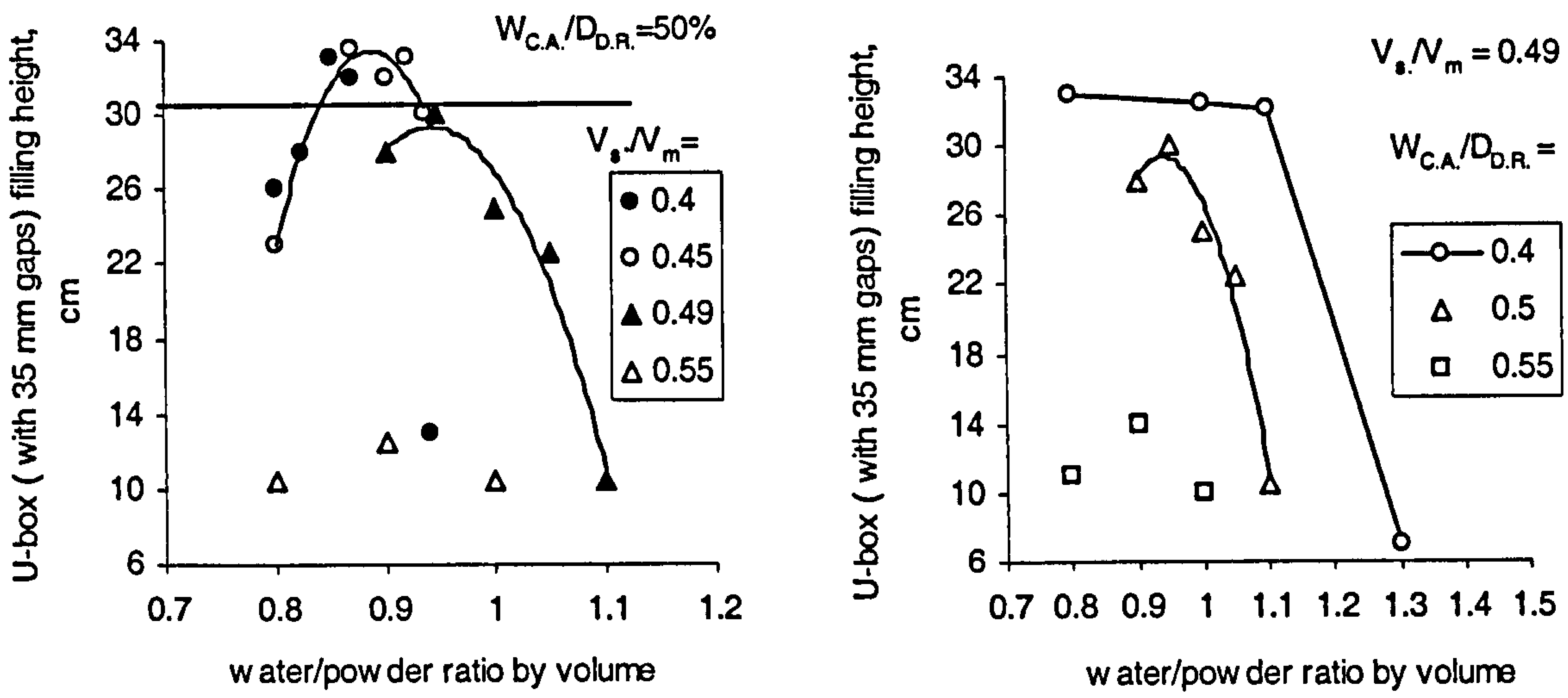


Figure 2-11 Effect of water/powder ratio on the maximum filling height of concrete (adapted from [66])

2.4.1.3 Superplasticizers

Superplasticizers are very important in SCC because they improve flowability by lowering the yield value of concrete without seriously decreasing the plastic viscosity.

It is known that the plastic viscosity of a solid suspension such as paste is related to the volume concentration of particles and the extent to which the particles are flocculated. Plastic viscosity decreases with decreasing solids concentration and deflocculation, both of which occur when water is added, although the deflocculation may only be partial. However, a superplasticizer releases the water retained by flocs of powder particles without decreasing the solids concentration, and so the plastic viscosity is less reduced. **Figure 2-12** demonstrates these effects.

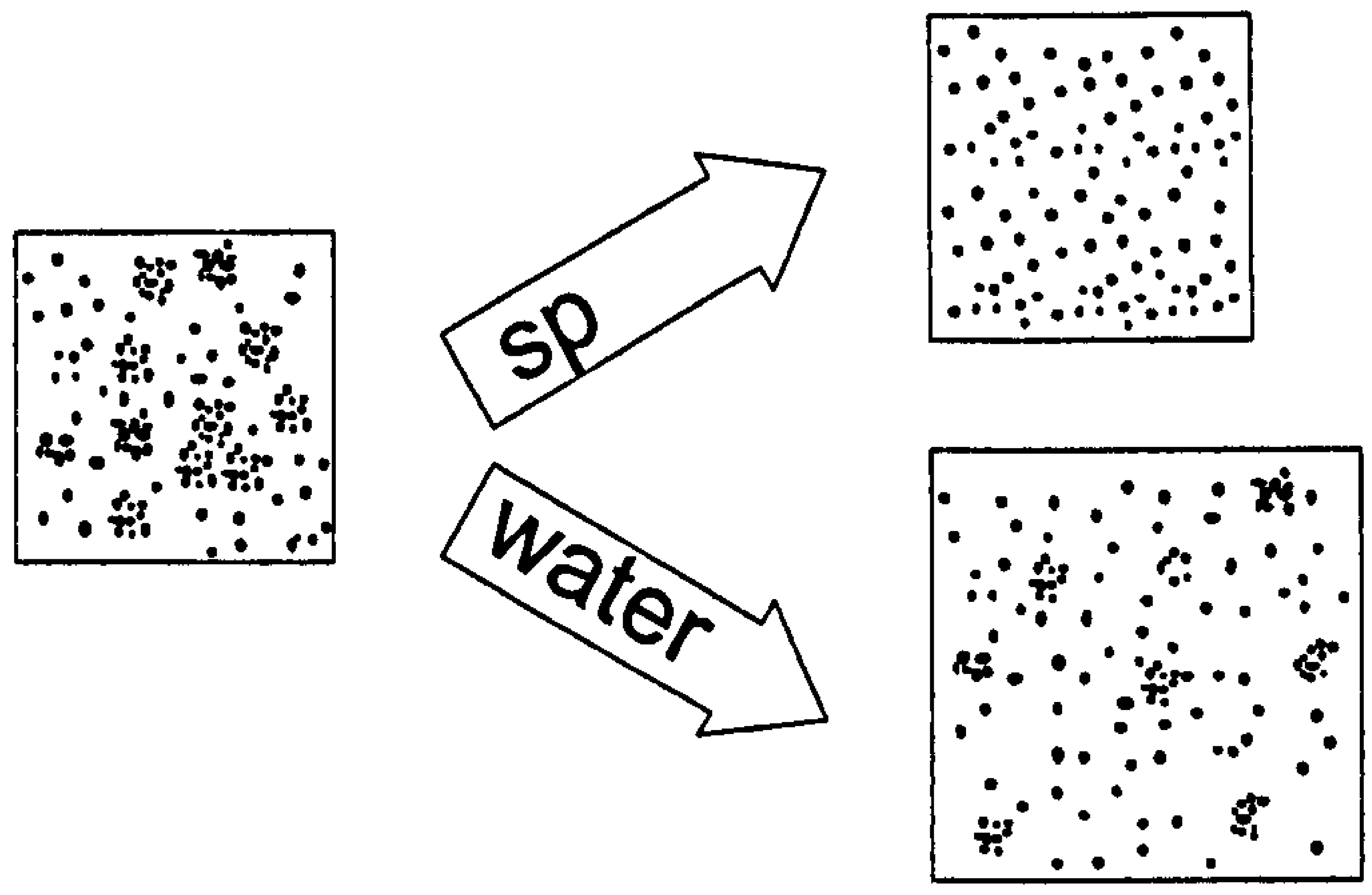


Figure 2-12 The effect of superplasticizer and water on deflocculation of cement particles

Table 2-6 shows the viscosities of pastes with and without superplasticizer calculated from data **table 2-5** using **equations 2-2 & 2-3**. The coefficients (a = 0.024 and K= -6.2×10^{-3}) were obtained from reference [29]. It can be seen that the addition of 1.0% of Naphthalene superplasticizer to a paste with 0.45 water/cement ratio resulted in the spread increasing to 418 mm, and the plastic viscosity reduced by 2.4 times. When water was added to achieve the same spread increase, the plastic viscosity decreases by 12 times. The superplasticizer therefore allows a large increase in flowability with a relatively small decrease in plastic viscosity compared to that obtained by adding water.

Table 2-6 The comparison of calculated plastic viscosity of pastes using data in table 2-5

w/c	Vw/Vp	Sp % (by wt. of powder)	spread (mm)	plastic viscosity (mPa.s)
0.45	1.42	0.0	256	68.20
0.66	2.09	0.0	418	5.75
0.45	1.42	1.0	418	28.50

As was mentioned earlier many different types of superplasticizer have been used in SCC, some which have been specially produced for SCC. The dispersion mechanism is dependent upon the chemical structure of the components, and consequently the dispersion efficiency is very different in each case.

Traditional superplasticizers such as sulfonated naphthalene polymers are anionic surface-active agents. They are adsorbed on cement particles to provide negative potential. It is reported that the efficiency is significantly affected by the soluble alkali content which has an optimum content for a given cement [67].

Polycarboxlic acid-based admixtures (such as Glenium51) are nonionic surface active agents with zero potential. The side chains of polyethylene oxide (EO) extend from the surface of cement particles in the form of brush on a comb, and the cement particles are dispersed by steric hindrance of these side chains. It has been reported that a high content of soluble alkaline sulfate reduces the efficiency because of the shrinking of the side chains [68].

According to the manufacturer, there are three advantages of Glenium51 compared to conventional superplasticizers such as those based on naphthalene sulfonates (NSFC) [69].

- the dosage is linearly related to the flow of concrete mix;
- it provides better workability retention than NFSC;
- It improves compressive strength.

Viscocrete is a new type of superplasticizer specially produced for SCC. It is a blend with a property enhancing polymer to improve the flowing stability of the concrete, but no further information was available on its properties.

There is a general lack of detailed information on the effect of superplasticizers on the plastic viscosity of SCC.

2.4.1.4 Viscosity agents

There are two reasons for adding a viscosity agent to SCC:

- To increase the tolerance to variations in the quality of materials with small amount of viscosity agent without other changes to the original mix proportions.
- To increase the segregation resistance and produce types of SCC that are tolerant

of a wide range of water/powder ratios. A larger amount of viscosity agent is required.

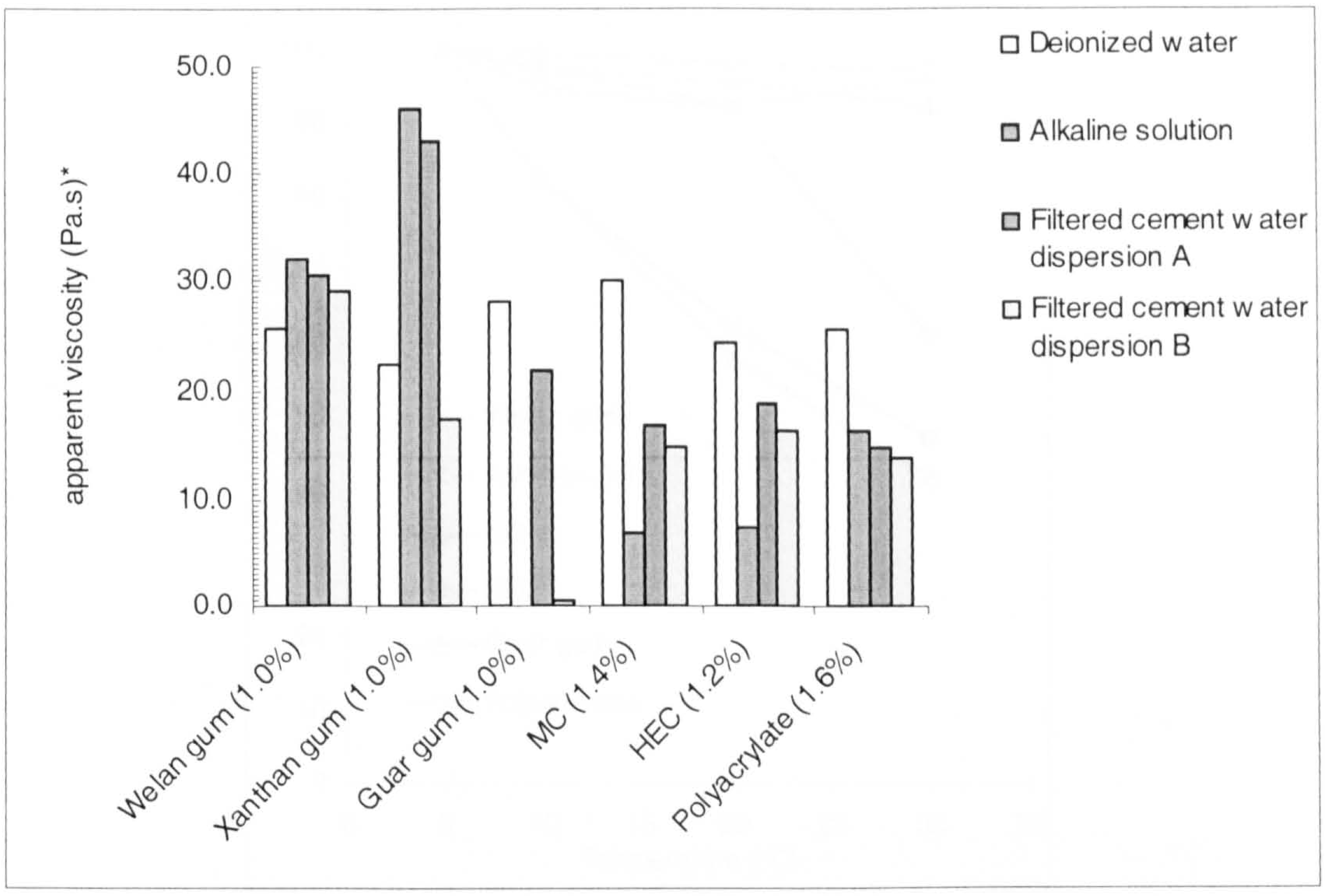
As mentioned earlier many types of viscosity agent have been used in SCC. Welan gum is popular, and in this section its properties, and those of some similar viscosity agents, their effect on the properties of cement paste, mortar and concrete are reviewed.

Solution properties of various agents

Several other natural polysaccharide based viscosity agents other than Welan gum have been used in cement paste and concrete. These are generally called polysaccharide gums (PSG), and include Xanthan Gum, Guar Gum and Curdlan Gum. Cellulose based viscosity agents such as Methyl cellulose (MC), Hydroxy Ethyl Cellulose (HEC) have also been used.

The effect of water

Figure 2-13 shows the apparent viscosity of the solutions with each viscosity agent in deionized water, an alkaline solution (2% sodium hydroxide and saturated calcium hydroxide), and filtered cement water dispersion A (100g of cement in 1000g of deionized water) and B (300g of cement in 1000g of deionized water) [70]. It can be seen that Welan gum gives almost the same viscosity in all four, except that it tends to have a slightly higher viscosity in the alkaline solution and the filtered cement water dispersion than in deionized water. In contrast, the rheological properties of the other viscosity agents varied significantly with different kinds of water.



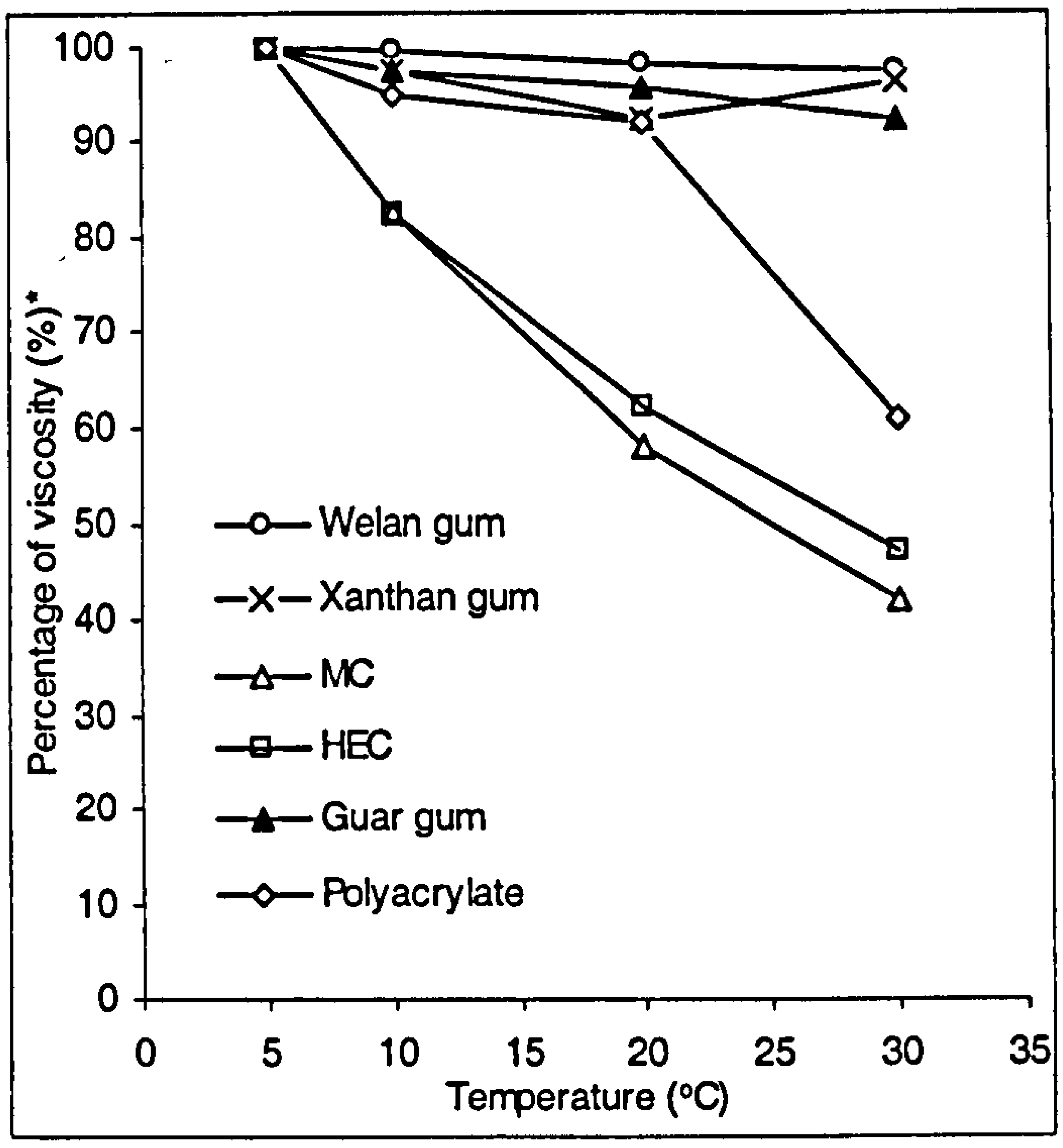
* measured at 60 rpm by BM type viscometer

Figure 2-13 Apparent viscosity of different viscosity agents in four different water solutions (reproduced from [70])

From these results, it might be expected that Welan gum may produce relatively consistent rheological properties in various cement pastes while the performances of other viscosity agents in cement pastes are affected by cement concentration.

Effects of temperature

Figure 2-14 shows the effect of temperature on viscosity relative to that at 5 ^{o}C [70]. The viscosity of the solutions containing Welan gum, Xanthan Gum and Guar gum were independent of temperature and identical for the range 5~30 ^{o}C. Consequently the fresh properties of SCC containing Welan gum vary very little with temperature.



* measured at 60 rpm by BM type viscometer

Figure 2-14 Relationship between apparent viscosity and temperature (reproduced from [70])

The relationship between shear rate and viscosity

Figure 2-15 shows the shear rate – apparent viscosity relationship. For Welan gum and Xanthan gum, the viscosity of the solution decreased sharply as the shear rate increased, i.e. pseudoplastic behaviour, which is thought to contribute to stabilization of the flow property of SCC:

- impart good suspension properties because of fast increase in apparent viscosity with decrease of shear rate, and hence improve sedimentation, segregation and bleeding resistance;
- impart good flowability because of sharp decrease in apparent viscosity with increase of shear rate, and hence ease mixing, pumping, placing and levelling.

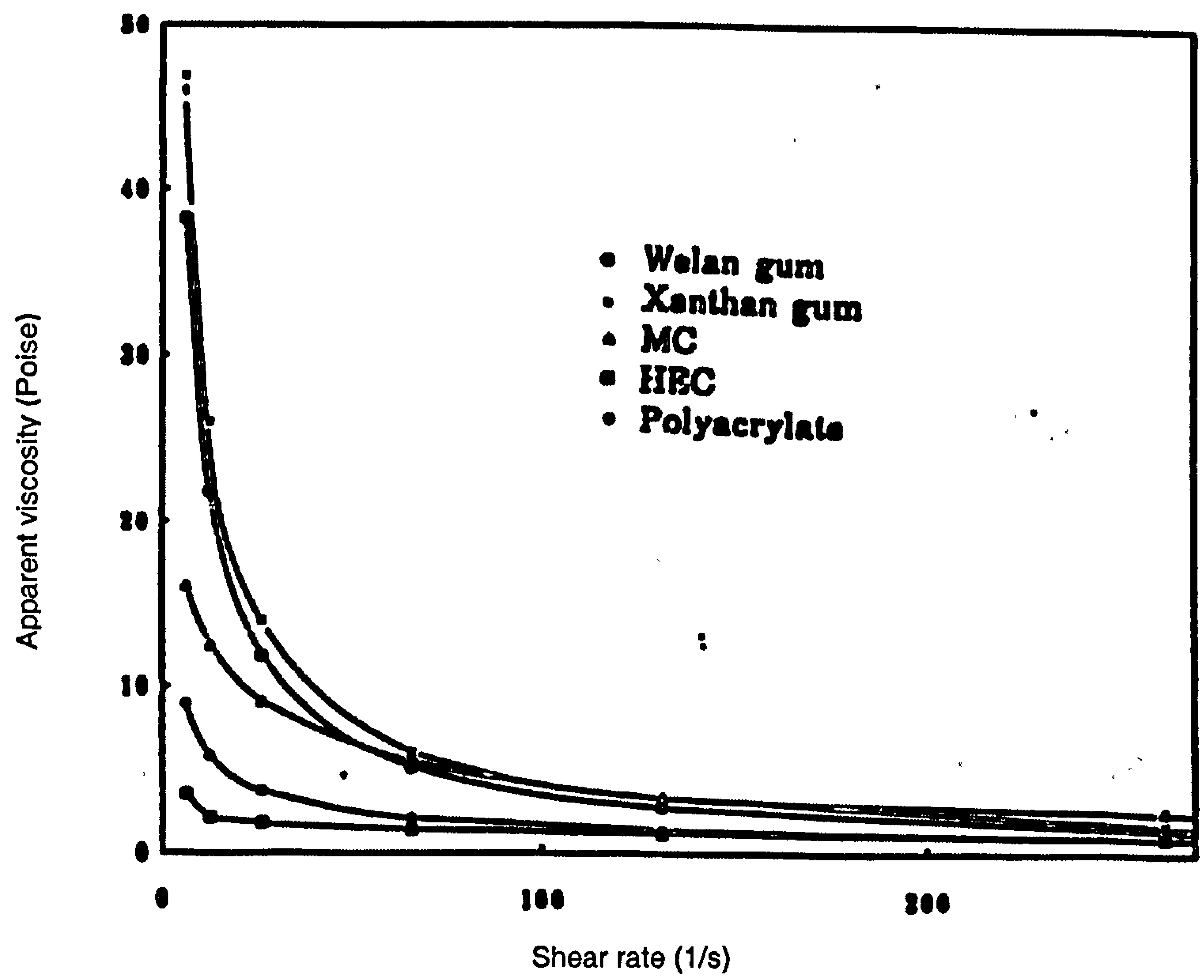


Figure 2-15 The relationship between apparent viscosity and shear rate (adapted from [70])

Effect of Welan gum on the fresh properties of cement paste

The effect of Welan gum on the properties of cement paste has been studied by several researchers. Both advantages and disadvantages have been discussed.

It has been agreed that the addition of Welan gum to cement paste increases the degree of pseudo-plasticity, or shear thinning. This means a greater relative increase in apparent viscosity at a low shear rate than at a high shear rate, as shown by the results in **figure 2-16** [71]. As a result, addition of Welan gum to cement paste not only significantly increases the plastic viscosity but also the stability. K.H. Khayat *et al* examined stability of cement grout mixes with various Welan gum and naphthalene superplasticizer dosages by testing washout loss and bleeding [72], and the results are shown in **figure 2-17**. Clearly both properties are reduced with the increase in Welan gum dosage; and the bleeding can be eliminated with a suitable combination of Welan gum and superplasticizer. Superplasticizer also reduced bleeding because it causes a dispersion of cement particles in the grout which enhances the ability of such grains to achieve better packing against the filter in the test setup [72].

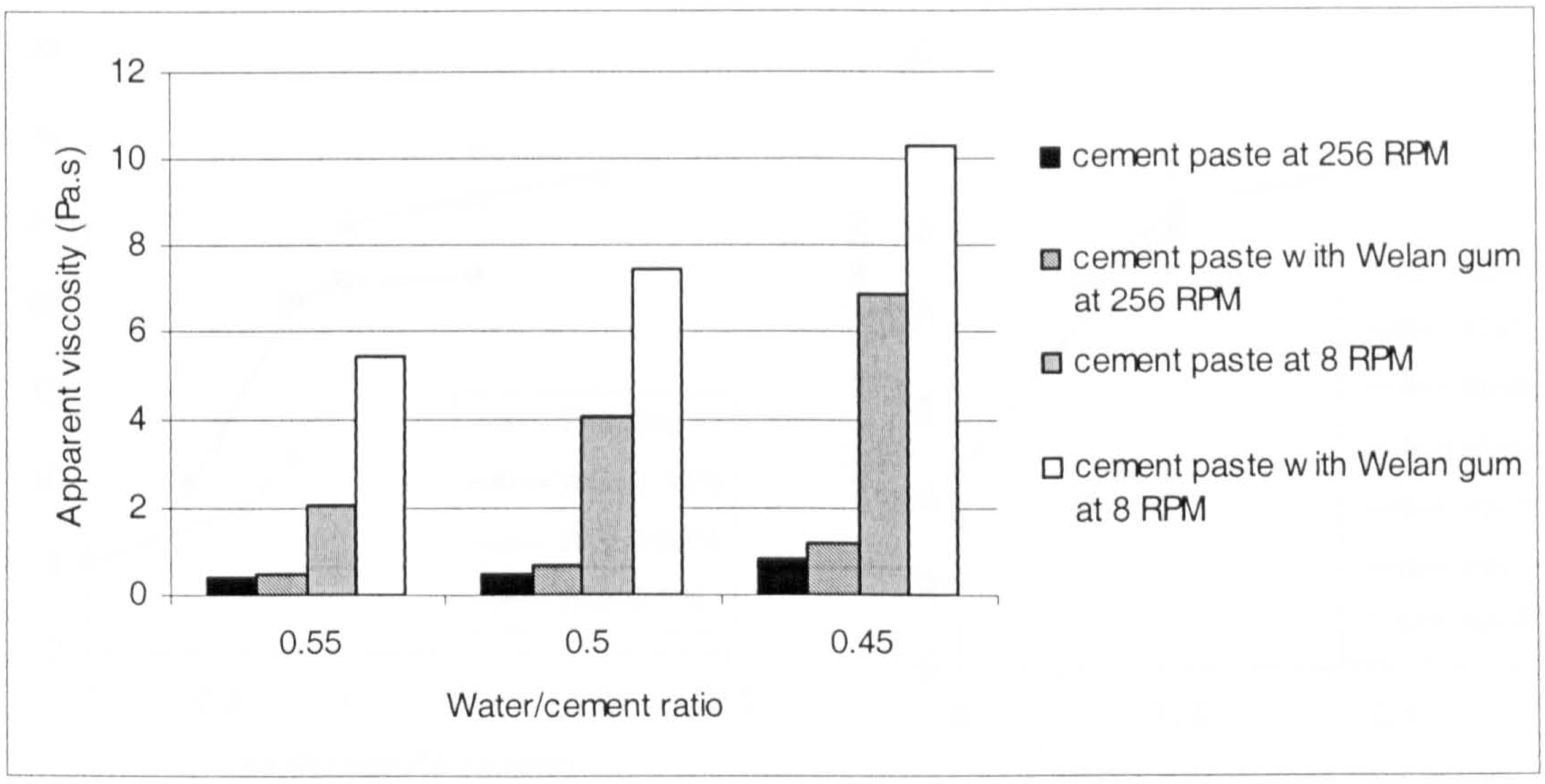


Figure 2-16 Apparent viscosities of two cement paste mixes with and without Welan gum at low and medium shear rates (reproduced from [71])

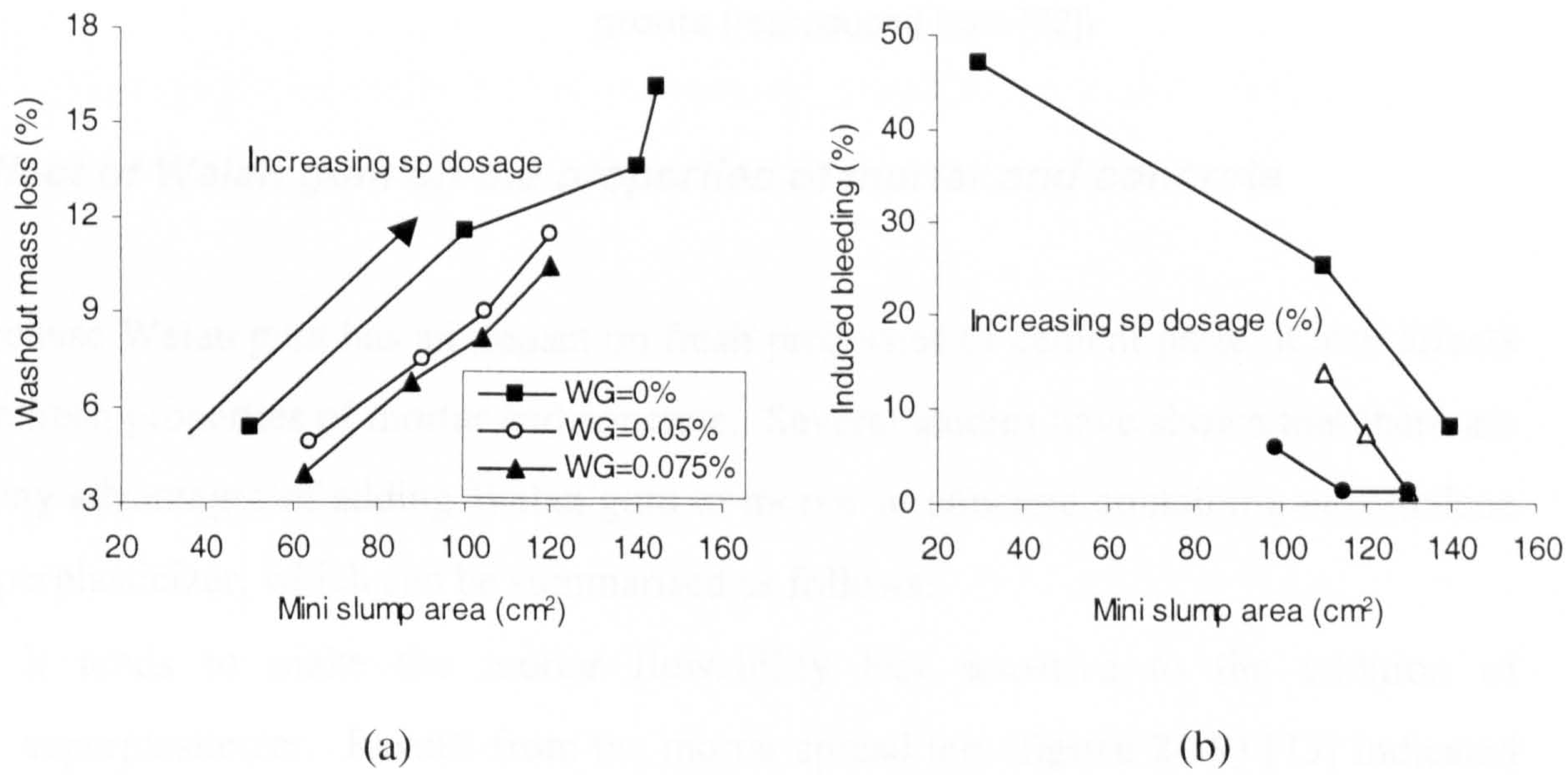


Figure 2-17 Effect of Welan gum and superplasticizer on (a) washout loss and (b) forced bleeding for cement grout mixes (reproduced from [72])

However, with the increase in Welan gum content, the effectiveness of adding superplasticizer to enhance fluidity reduces, hence necessitating greater superplasticizer addition. The coupled effect of Welan gum plus superplasticizer delays the onset of initial setting of cement paste, as shown in **figure 2-18** [72], but the delay seems to be more affected by Welan gum.

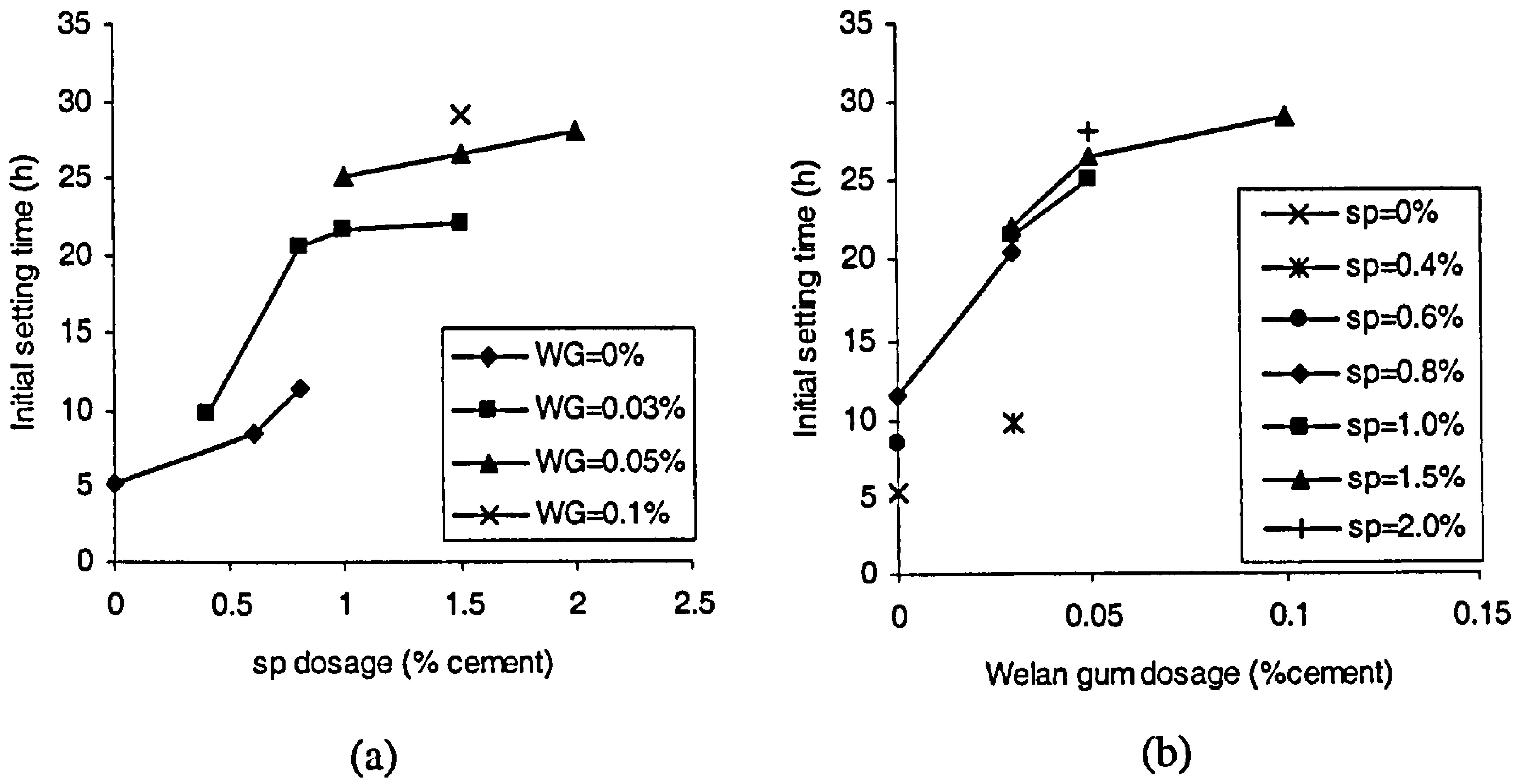


Figure 2-18 Effect of superplasticizer and Welan gum on initial setting time of cement grouts (reproduced from [72])

Effect of Welan gum on the properties of mortar and concrete

Because Welan gum has an impact on fresh properties of cement paste, it also affects the fresh properties of mortar and concrete. Several studies have shown that there are many advantages of adding Welan gum to mortar or concrete containing naphthalene superplasticizer, which can be summarised as follows:

1) It tends to make the mortar flowability less sensitive to the addition of superplasticizer. Results from the mortar spread test (**figure 2-19**) [73] indicated that

   (a) a small amount of Welan gum made the mortar flow stable even with a high dosage of superplasticizer,

   (b) Although bleeding was observed in mortar having a high flow value (> 270mm) without a viscosity agent, no bleeding was observed when the dosage of viscosity agent exceeded 0.03%, but a significantly increased dose of superplasticizer was required to achieve the flow.

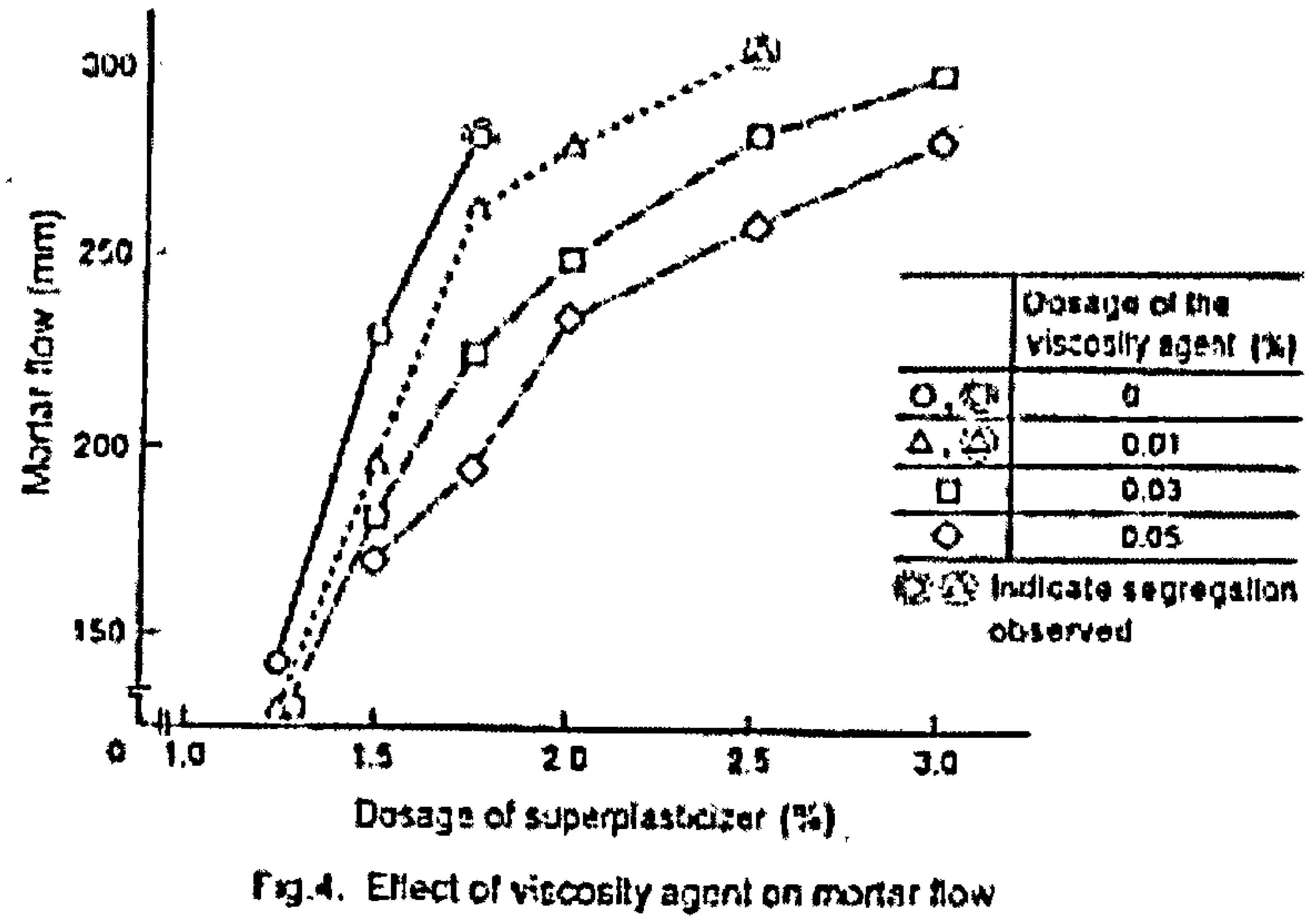


Figure 2-19 Effect of viscosity agent on mortar flow (adapted from [73])

2) Welan gum can improve the workability retention of mortar especially when cement is blended with CRMs [74]. This is reviewed in section 2.4.2.

3) The fresh properties of SCC with Welan gum are more constant under a variety of conditions :

- Temperature varying in the range of 10-30 °C (**figure 2-20**) [73].
- Variation of the quality of PC. **Figure 2-21** shows there is a large variation in the slump flow of concrete with PC obtained from different companies when the viscosity agent was not used but only a little change in slump flow of concrete when viscosity agent was added into mixes [73].
- Variation of the fineness modulus of sand. **Figure 2-22** shows that the variations of both slump flow and V-funnel value are much smaller for the concrete with the viscosity agent [73].
- Variation of water content (**Figure 2-23,2-24 & 2-25**) [70].

Moreover, Welan gum mix significantly reduces bleeding, settlement and segregation [75]. Therefore, high quality SCC is more easily produced by using Welan gum.

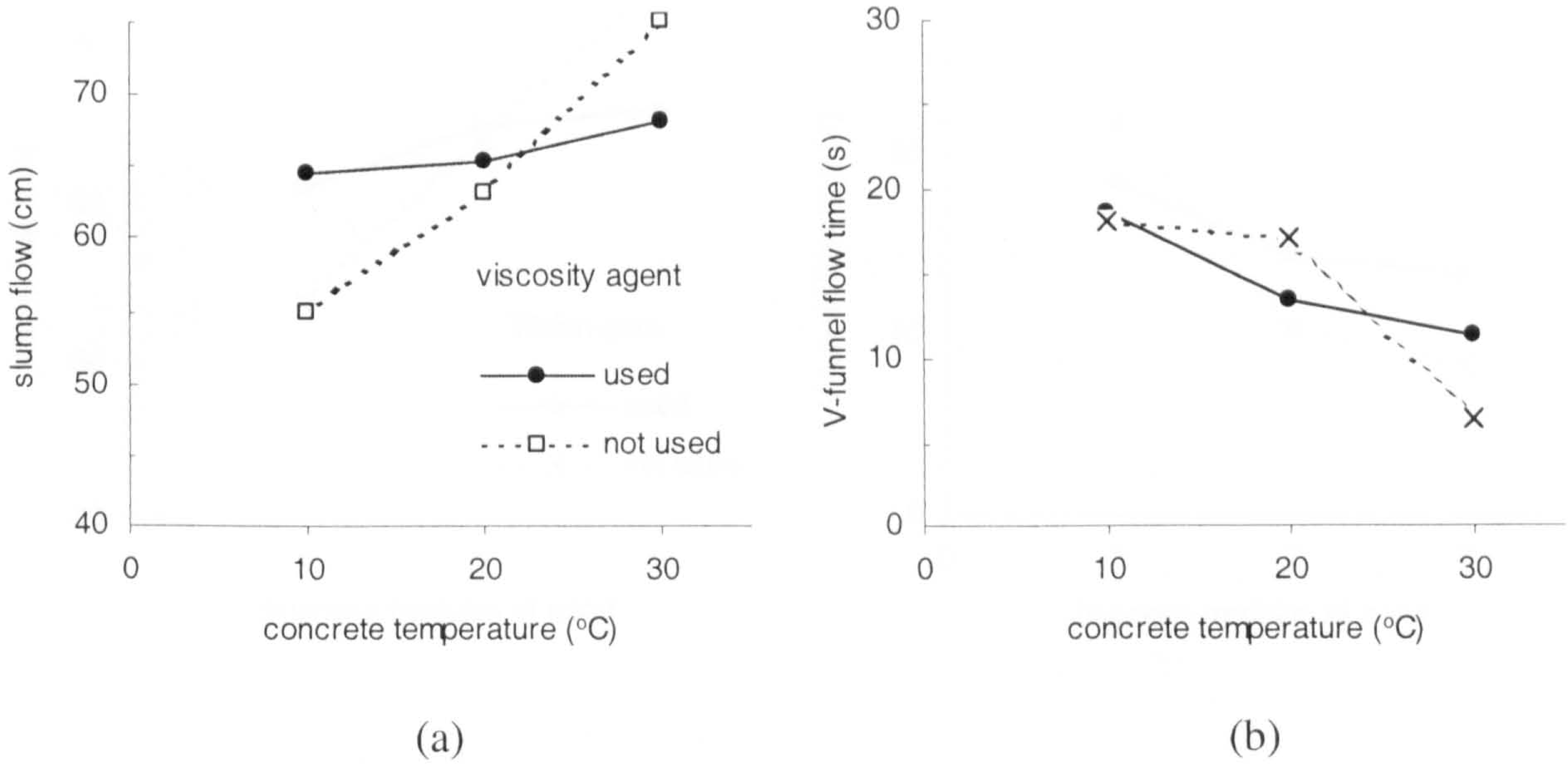


Figure 2-20 Effect of temperature on flowability (a) slump flow, (b) V-funnel flow time of mixes with and without Welan gum (reproduced from [73])

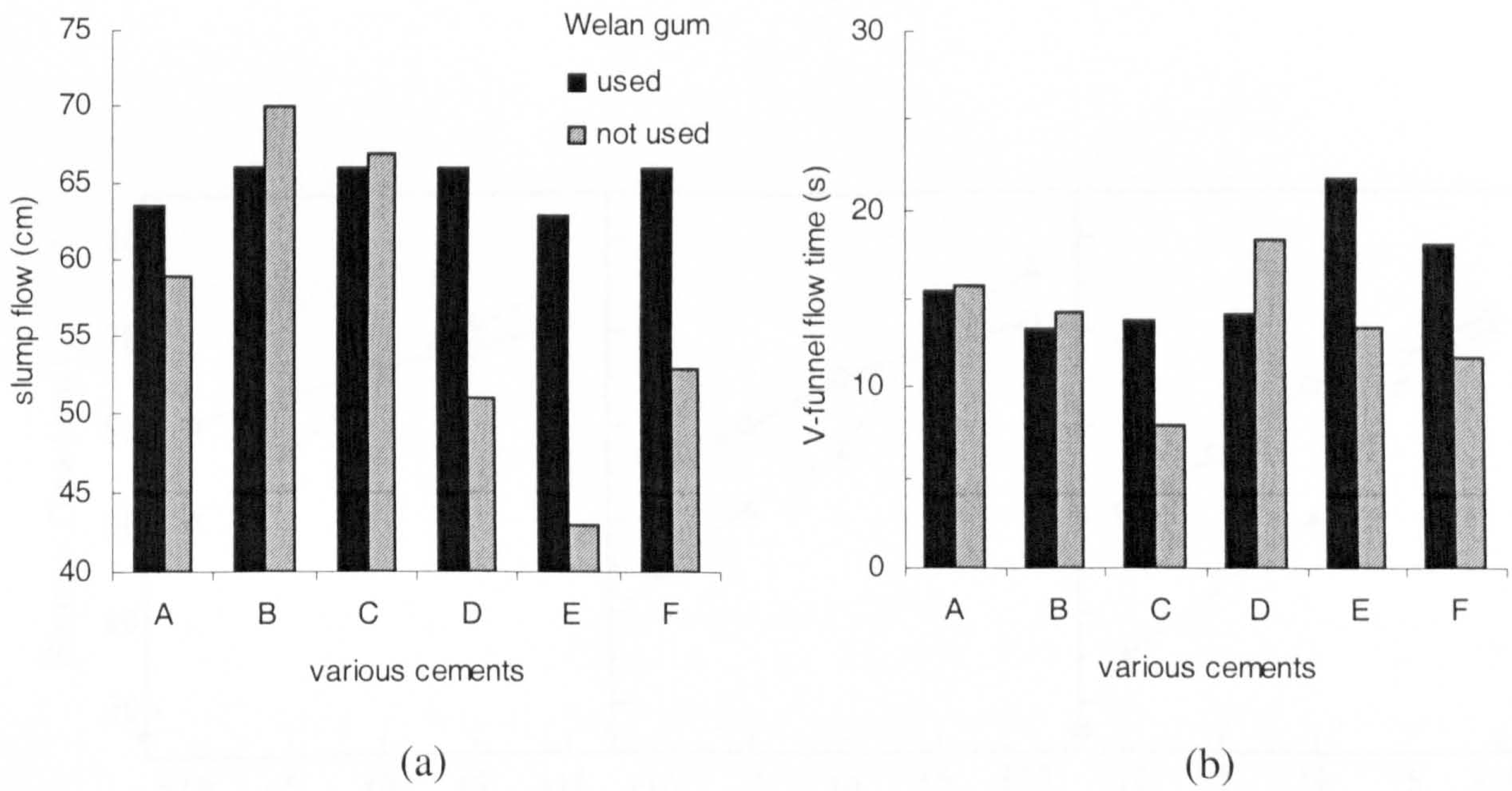


Figure 2-21 Effect of cement quality on flowability (a) slump flow, (b) V-funnel flow time of mixes with and without Welan gum (reproduced from [73])

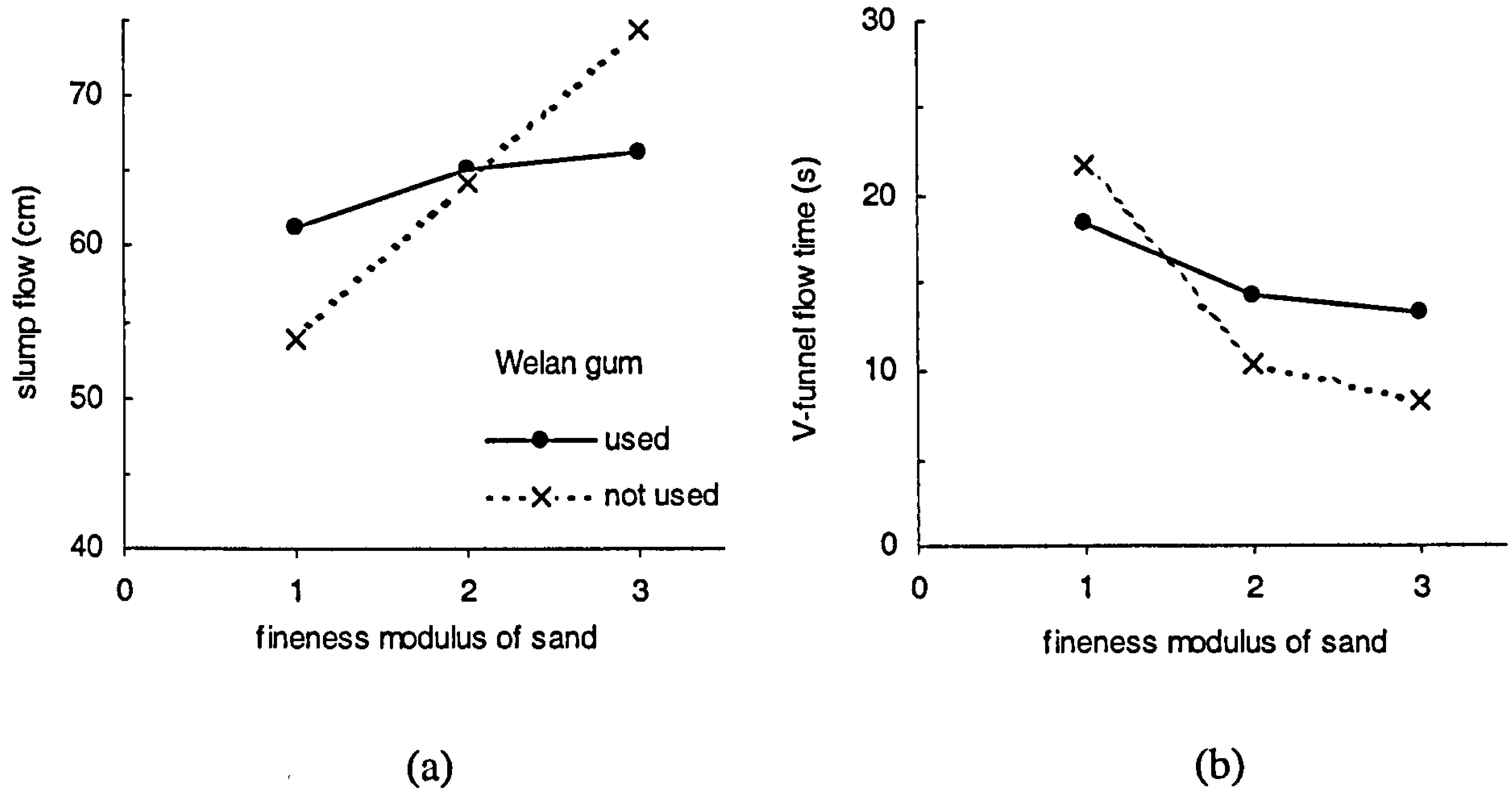


Figure 2-22 Effect of fineness modulus of sand on flowability (a) slump flow, (b) V-funnel flow time of mixes with and without Welan gum (reproduced from [73])

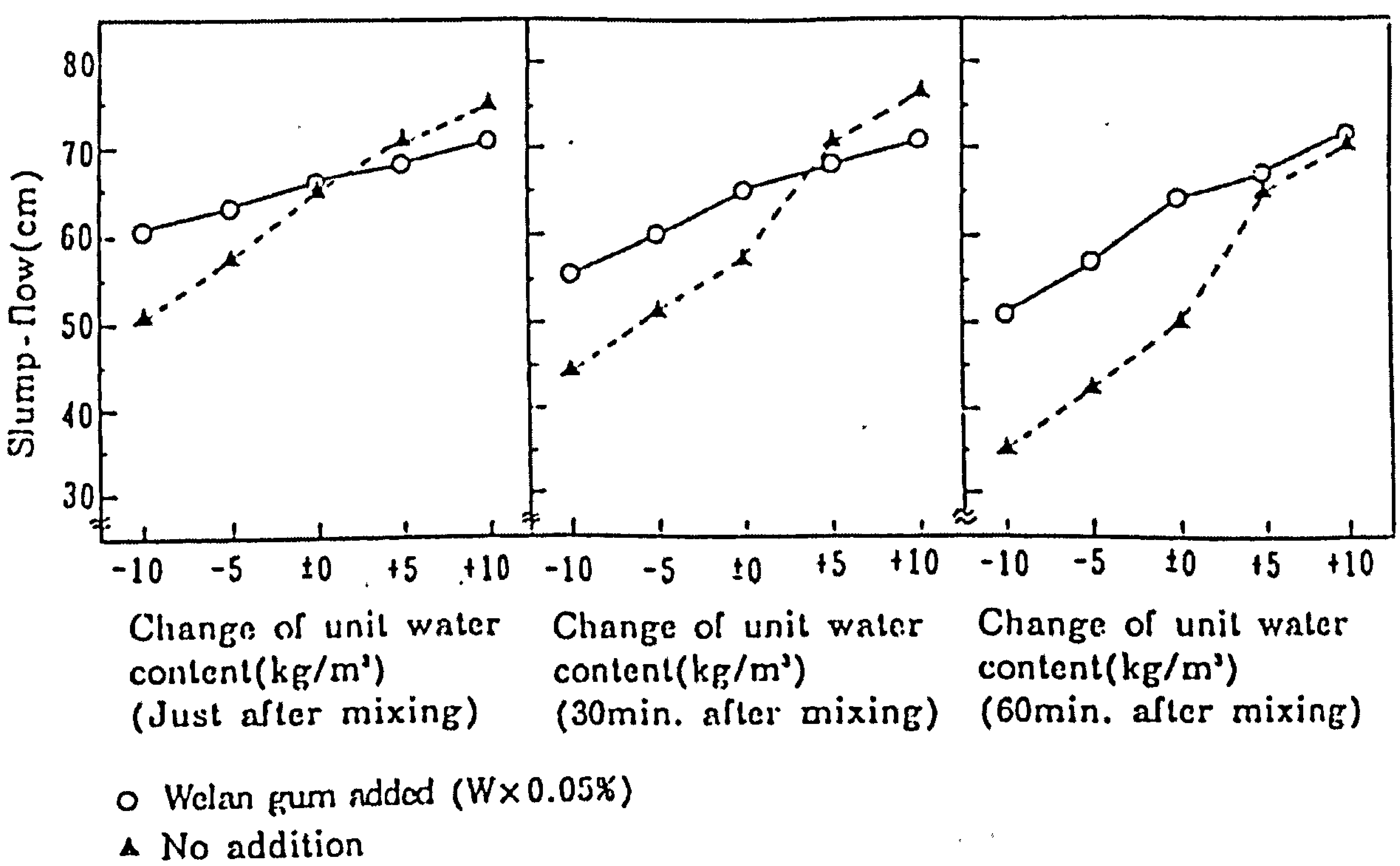


Figure 2-23 Effect of variation of water content on the slump flow of fresh concrete for mixes with and without Welan gum (adapted from [70])

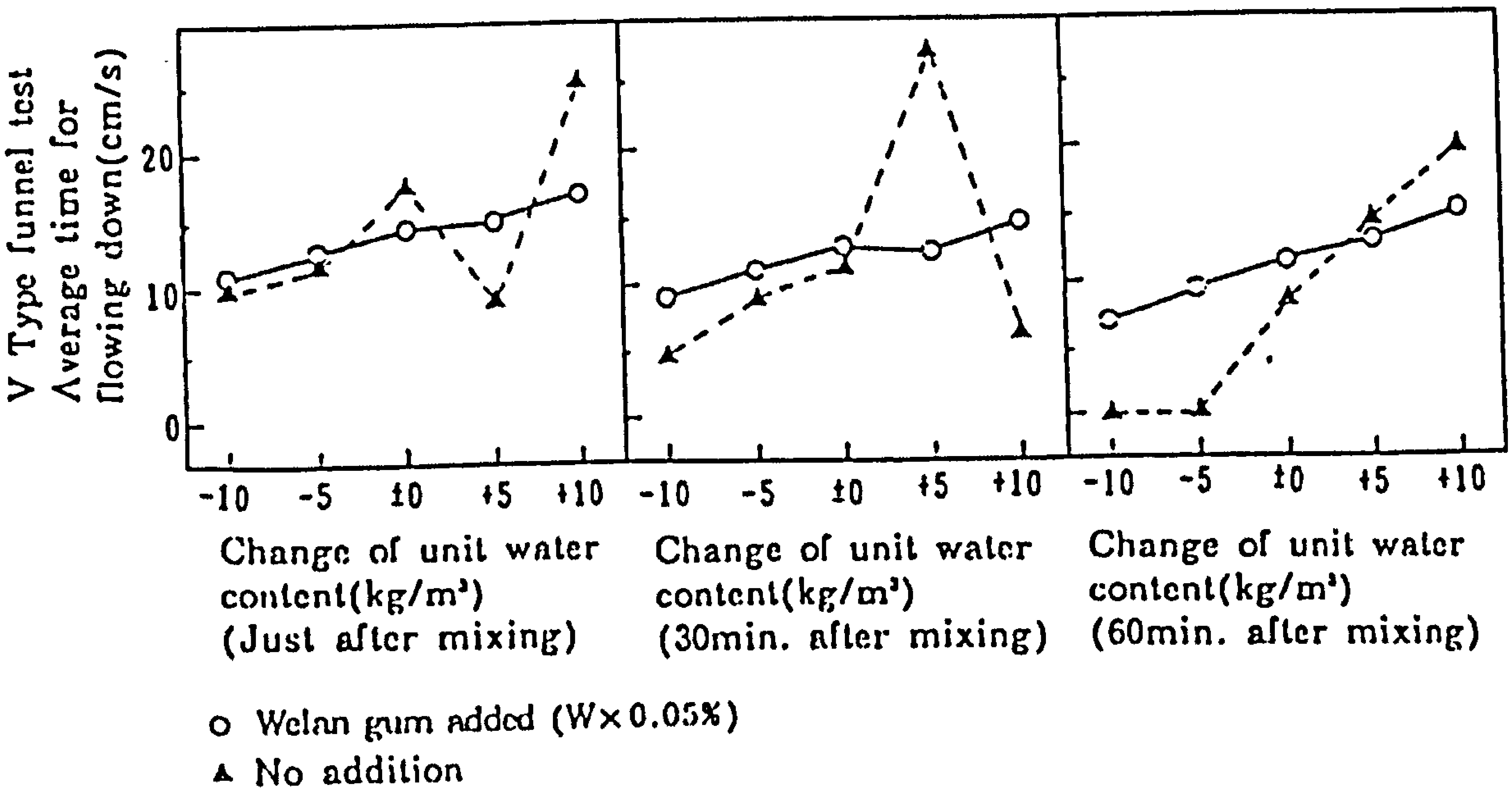


Figure 2-24 Effect of variation of water content on the V-funnel flow time of fresh concrete for mixes with and without Welan gum (adapted from [70])

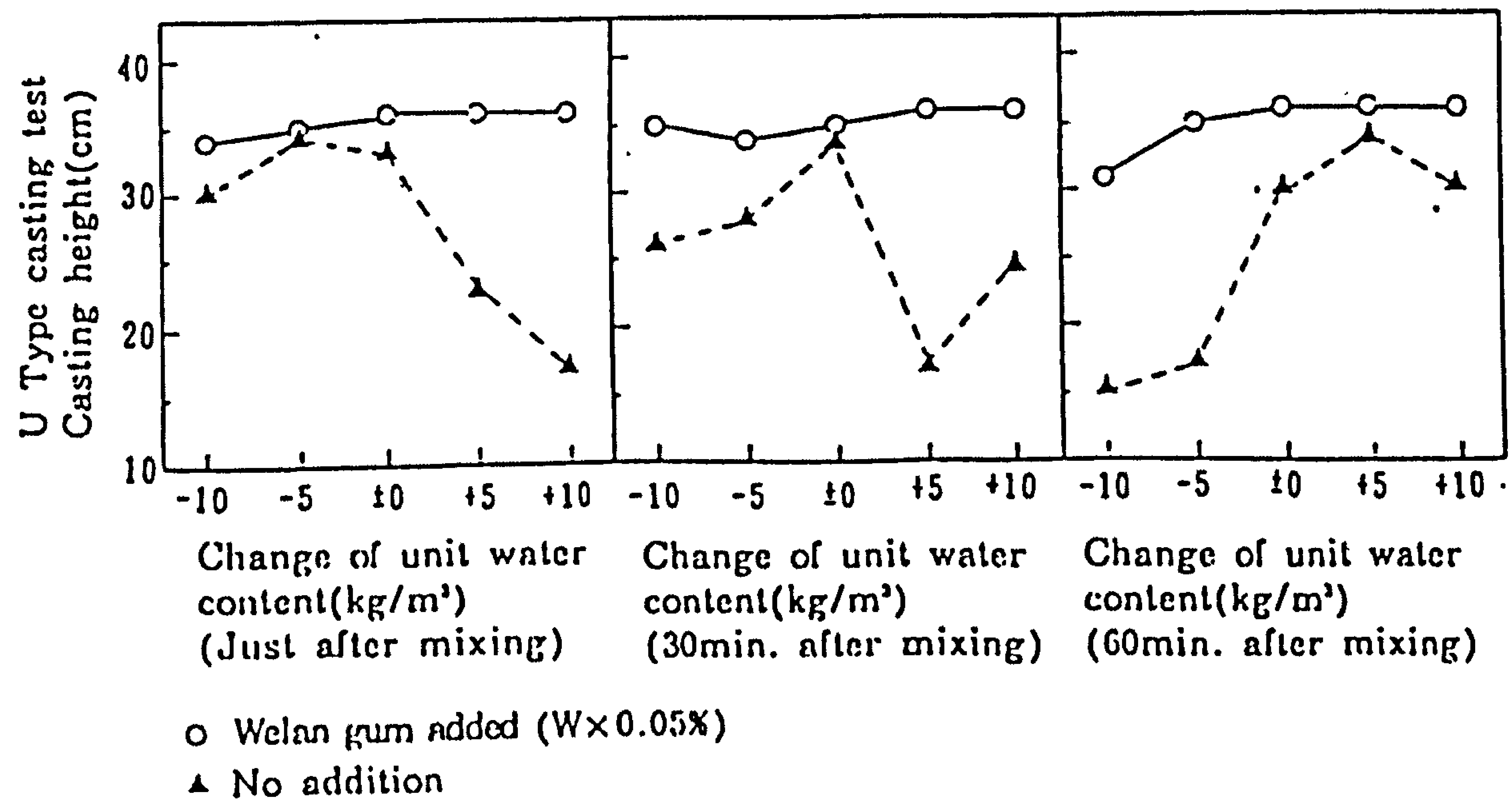


Figure 2-25 Effect of variation of water content on U-box filling height of fresh concrete for mixes with and without Welan gum (adapted from [70])

However, there are also disadvantages of using Welan gum, including,

1) The maximum spread (spread ceiling) of mortar decreases when a very high dosage of Welan gum is added. (**figure 2-26**) [76].

2) The delayed setting time in paste suggests a similar property for mortar and concrete.
3) The 28 day strength decreases when the dosage of superplasticizer required by the use of Welan gum is very high [76],
4) There may be compatibility problem between Welan gum and another ingredients, but little information has been published.
5) The use of Welan gum also means an increase of complexity of the mixing procedure and cost.

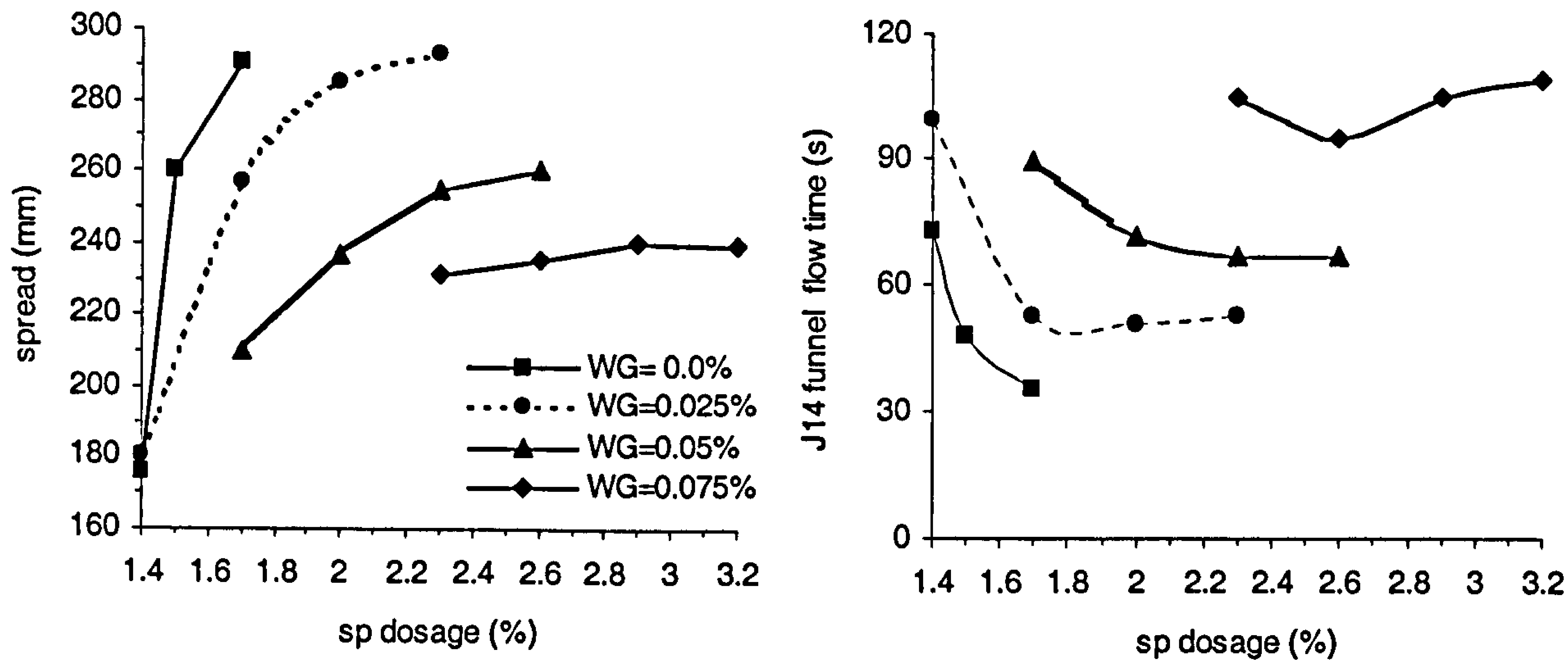


Figure 2-26 Effect of Welan gum dosage on mortar properties (reproduced from [76])

Rheological properties of concrete with Welan gum

Unlike cement paste, there seems to be little research carried out on the rheological properties of concrete with Welan gum. Results with normal concrete [77], shown as **figure 2-27 & 2-28**, have given some explanation of the benefit of using Welan gum in concrete at water/cement ratios higher than 0.55. At moderate to high rates of shear, i.e. 0.1-0.55 revolutions per second (rps), concrete with Welan gum followed the Bingham model, and the increasing dosage of Welan gum generated an increase in the flow resistance of fresh concrete. However, at shear rates lower than 0.1 rps the flow resistance increased compared to that calculated from the Bingham model and this increase was higher for higher concentrations of Welan gum **(figure 2-27)**. However, no similar indication was shown at water/cement ratio 0.5. Although the flow resistance was also increased with increasing concentration of Welan gum, it was still lower than the flow resistance calculated from the 'Bingham model' at very low shear rates (**figure 2-28**). No explanation was given; further investigation will be useful.

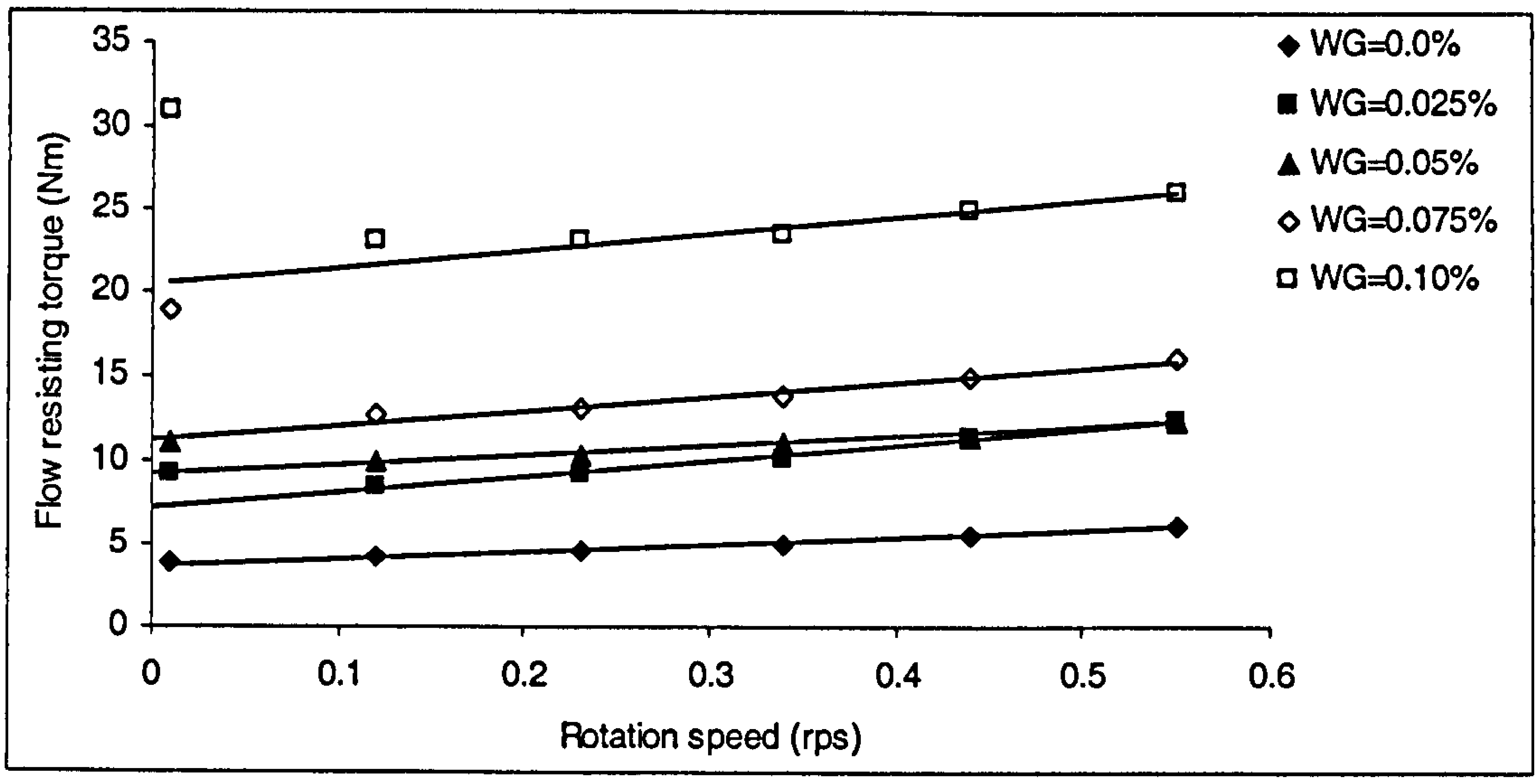


Figure 2-27 Effect of Welan gum on rheology of concrete mixes (w/c=0.55) (reproduced from [77])

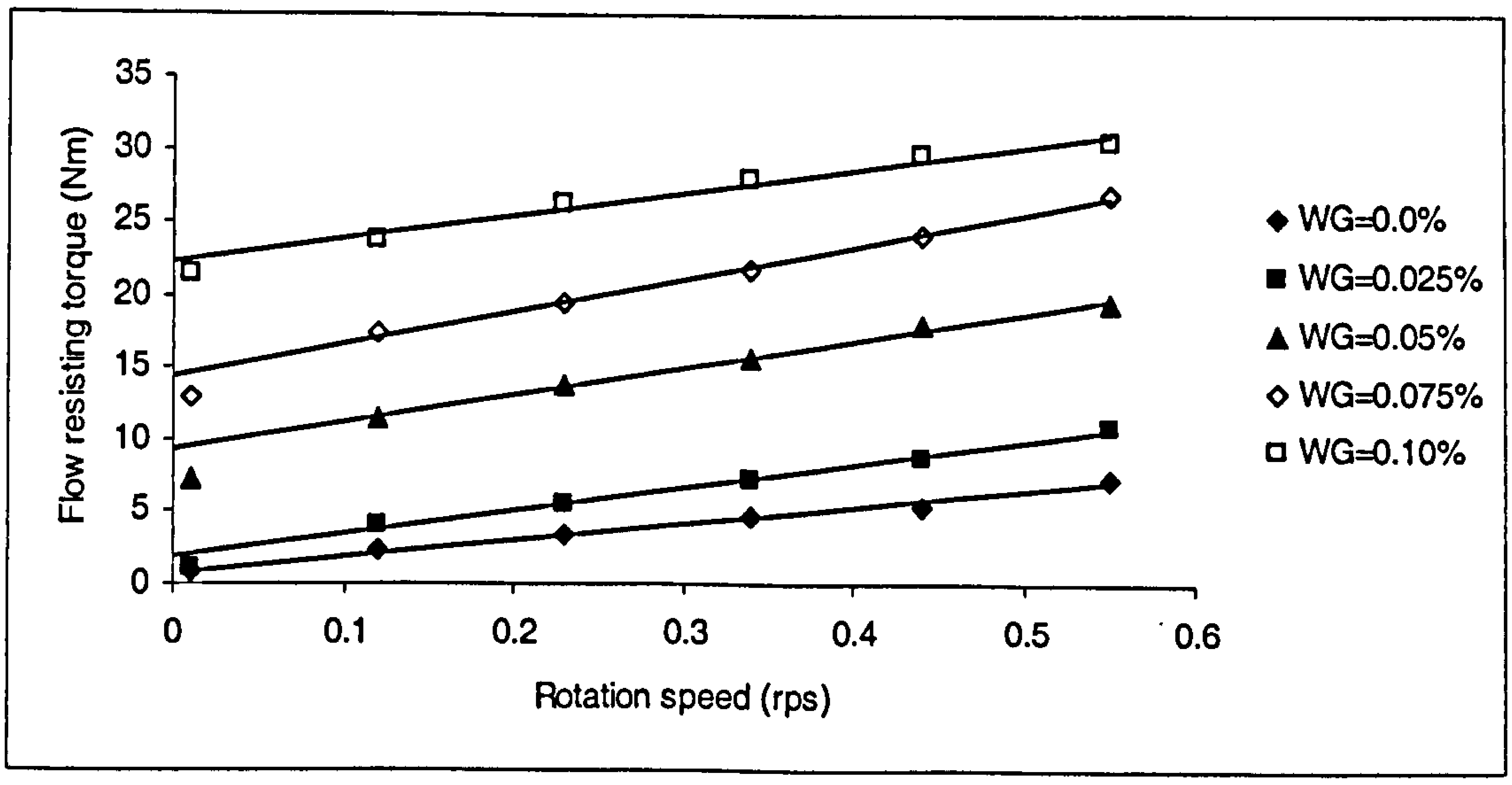


Figure 2-28 Effect of Welan gum on rheology of concrete mixes (w/c=0.5) (reproduced from [77]

Comments

There are many advantages of using Welan gum in SCC. Cement paste, mortar and concrete have much more stable fresh properties for variations in mix proportion, component materials and temperature. It has been found that the flow properties of fresh, highly fluidized concrete are extremely sensitive to changes in concrete temperature, quality of cement and grading of sand *etc.*, and the addition of the Welan gum viscosity agent can reduce the degree of sensitivity. This makes the production of high quality SCC easier. However, too high a dosage of Welan gum delays setting time and decreases the 28 days strength.

There is however little information about the rheological properties of SCC with Welan gum.

More research is needed on the compatibility between superplasticizer and Welan Gum. It has been reported that a cellulose-based water-soluble polymer has poor compatibility with a naphthalene sulfonate based superplasticizer. The interaction between the two becomes extremely weak because of the conversion of sodium naphthalene to calcium naphthalene sulfonate [8]. Similar problems could occur with Welan Gum and some superplasticizers.

2.4.1.5 Air entraining agent

The necessity of an air entraining agent for SCC is generally determined by the durability requirements. It is widely used in concrete in Japan because of the requirement for freeze-thaw resistance. Kreijger [78] proposes that air bubbles are able to form bridges between cement particles giving an increased yield stress; once flow occurs, the spherical bubbles move easily past each other and plastic viscosity decreases, but Banfill [79] found that yield stress also decreased. Other reported benefits of air entrainment in SCC are [80]: reduced bleeding, improved cohesion, grading rectification, reduced permeability, improved pumpability, increased workability retention and better surface finish. The paste volume content of SCC in Japan is typically about 40 l/m^3 less than some other countries; this may be because the entrained air works as a part of the paste.

The disadvantage of using air entrainment is that it is an additional factor to control and test, since excessive air can severely reduce strength and pumpability. Also fine particles in concrete, such as stone dust, can inhibit air entertainment. Fly ash with a high content of carbon also inhibits air entrainment. The selection of the blends of powder should be considered carefully if an air entraining agent is used.

2.4.1.6 Fine aggregate

Fine aggregate, i.e. sand, as medium size particles in concrete, has two roles in fresh SCC. It works in the same way as a coarse aggregate to obstruct flow, but on the other hand, together with the paste provides lubrication between the coarse aggregate particles. Many studies have been carried out on the effect of the characteristics of sand on the fresh properties of SCC; these are summarised below.

Types of sand and fineness modulus

The type of sand and fineness modulus have great effects on the properties of a concrete. Kim *et al* [81] have compared the effects of river sand, crushed sand, and sea sand, with fineness moduli of 2.64, 2.87 and 3.38 respectively on a range of mixes, as shown in **table 2-7**. The River sand had more rounded shape than the other two. The slump flow was controlled at 65 ± 5 cm.

Table 2-7 Mix proportions of the concrete with various types of sand (adapted from [81])

types of sand	w/p by wt.	V_w/V_p by volume	PFA by wt (%)	Target SF (cm)	s/a (%)	Mix proportion by wt (kg/m3)					
						water	PC	PFA	F.A.	C.A.	Sp (%)
River sand, crushed sand, sea sand	0.35	1.05	15	65±5	52	175	425	75	864	800	1.5
		1.00	30				350	150	849	784	1.5
		0.97	45				275	225	833	771	1.8
		0.93	60				200	300	820	756	2.0

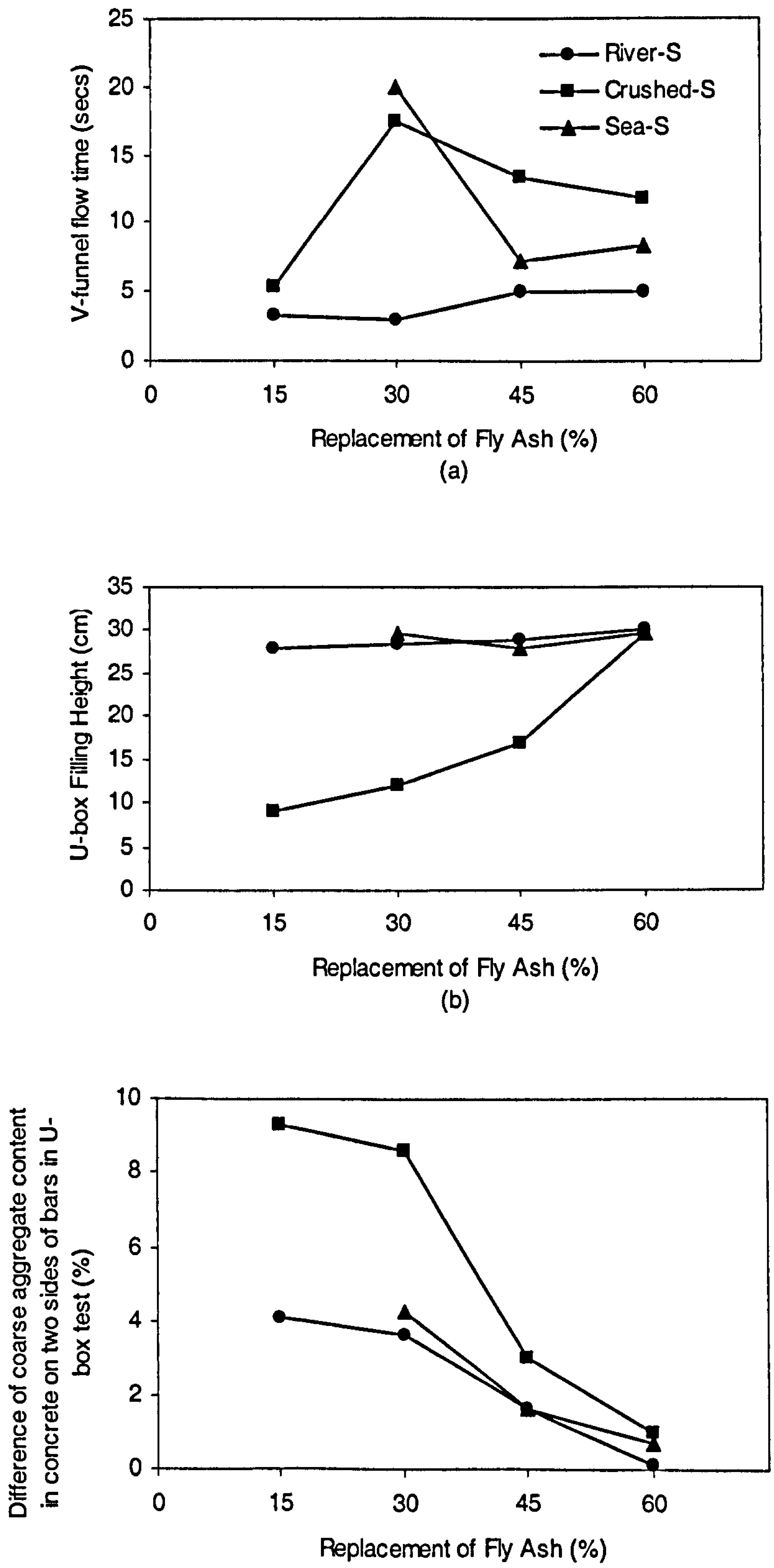
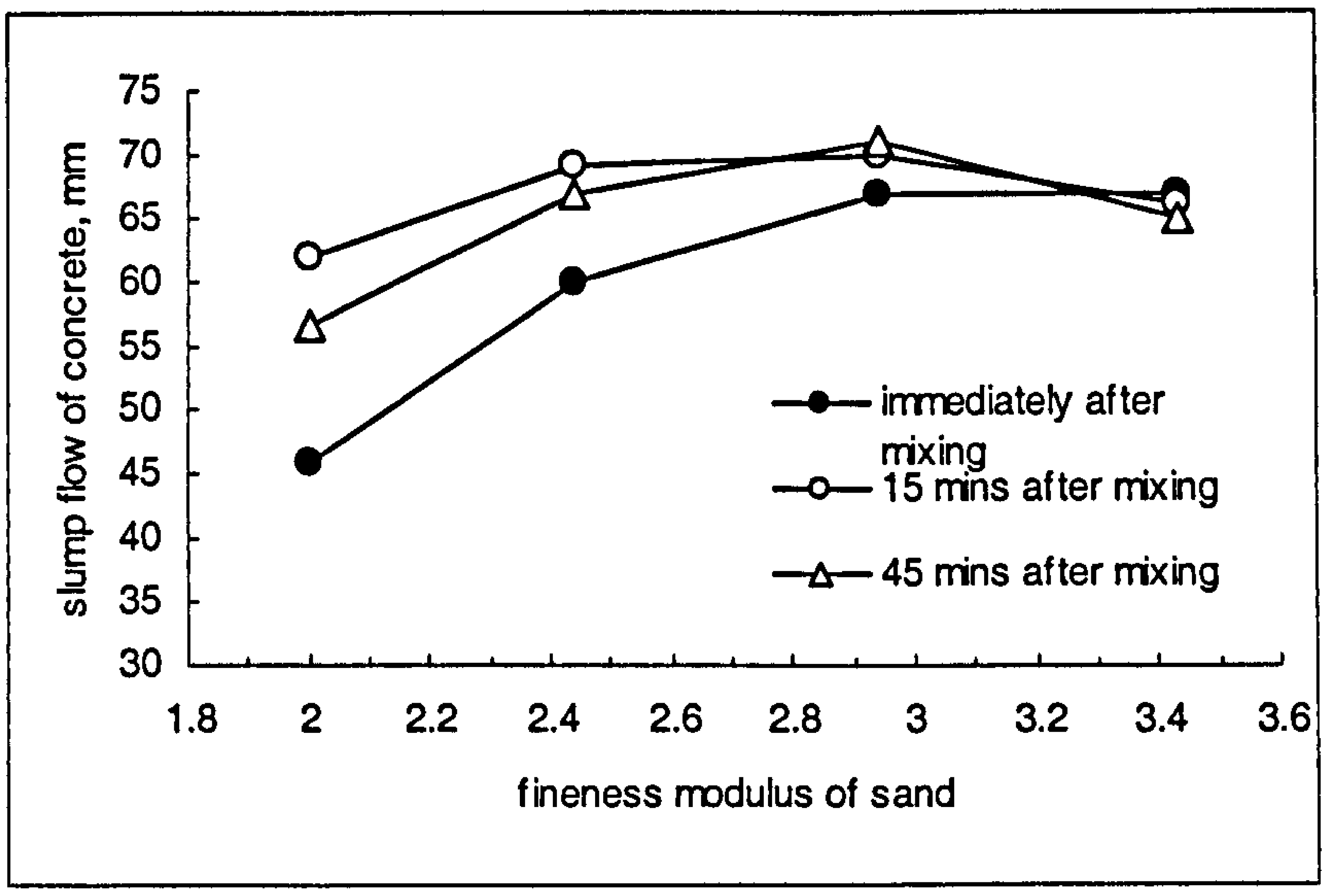


Figure 2-29 Comparison of concrete properties with different types and fineness modulus of sand (a) V-funnel flow time (b) Box filling height (c) Segregation (reproduced from [81])

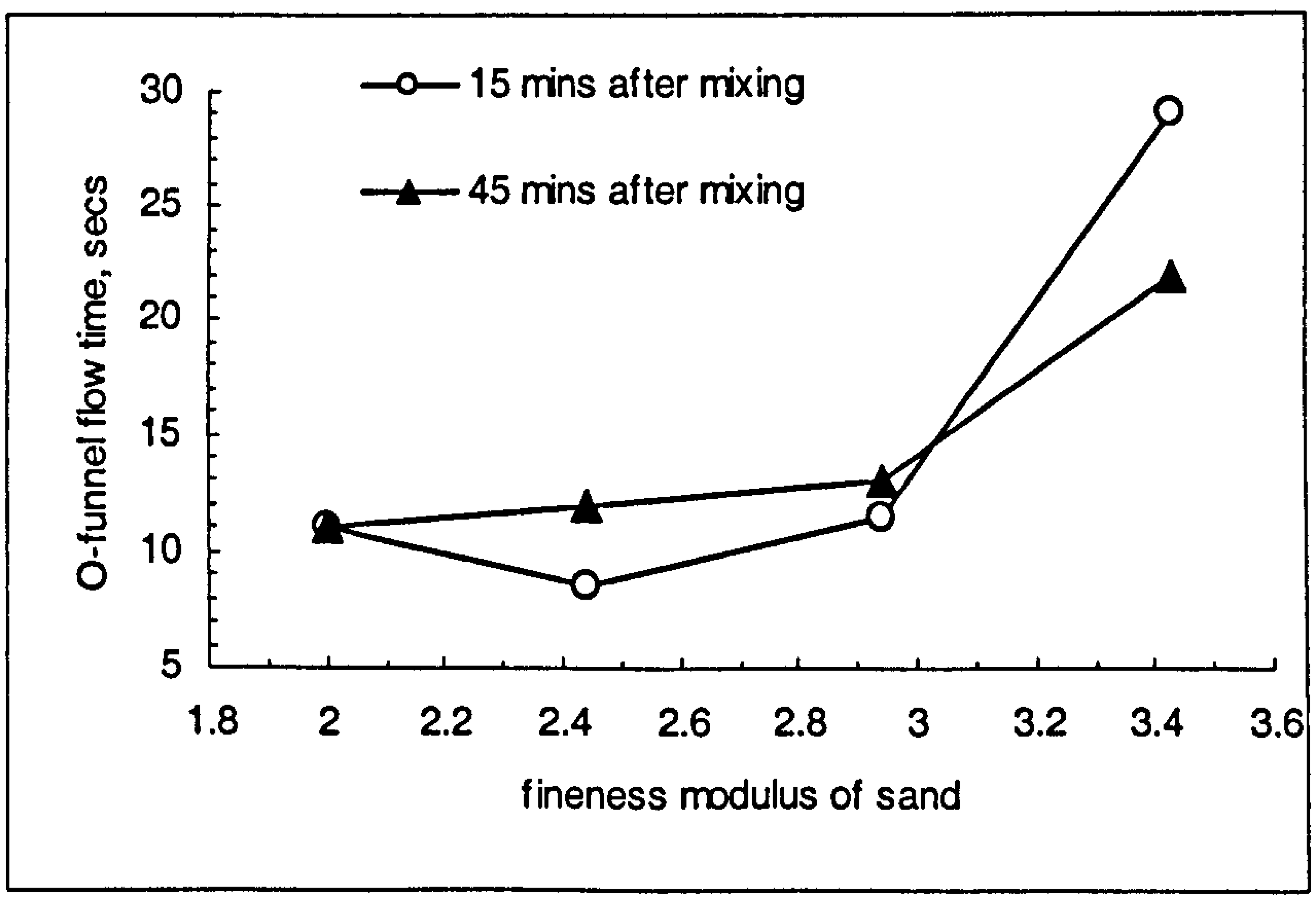
The test results are shown in **figure 2-29**. They found the V-funnel flow time was higher and varied in the mixes using crushed sand or sea sand. The U-box filling height for the mixes with crushed sand was much lower than that with river sand and sea sand. High segregation, which was assessed by the difference between the coarse aggregate contents in the concrete (in percentage) in the two compartments of U-box apparatus after the test, was also found in crushed sand mixes except the mix with 60% of PFA. In general, the crushed sand mixes performed less well than the sea sand and river sand mixes, which were largely similar. The performance of the crushed sand mixes was improved at high PFA content, suggesting advantage of using PFA in SCC with crushed sand.

Hirata *et al* [82] found that medium size sand, with a fineness modulus in the range 2.4-2.9, had the best performance in terms of slump flow among the mixes with sands with different fineness modulus; the O-funnel flow time rapidly increased when too coarse a sand was used (**figure 2-30**) due to blocking.

Sudo *et al* [83] compared the U-box filling height of mixes with different sizes of sand. A slump flow of 65 ± 5 cm and a flow time to 50 cm of 5 ± 2 seconds were targeted by adjusting the dosage of superplasticizer. All the mixes achieved the requirements except the mix with a water/powder ratio of 0.35 by weight and fineness modulus of the sand of 2.22, in which slump flow was 700 mm. The best filling height was obtained in the mixes with fine to medium sand; the filling height decreased when coarse sand was used, especially for the mixes with a high water/powder ratio (**figure 2-31**), suggesting blocking easily occurs for SCC with coarse sand.



(a)



(b)

Figure 2-30 Effect of fineness modulus of sand on the fresh properties of concrete
(reproduced from [82])

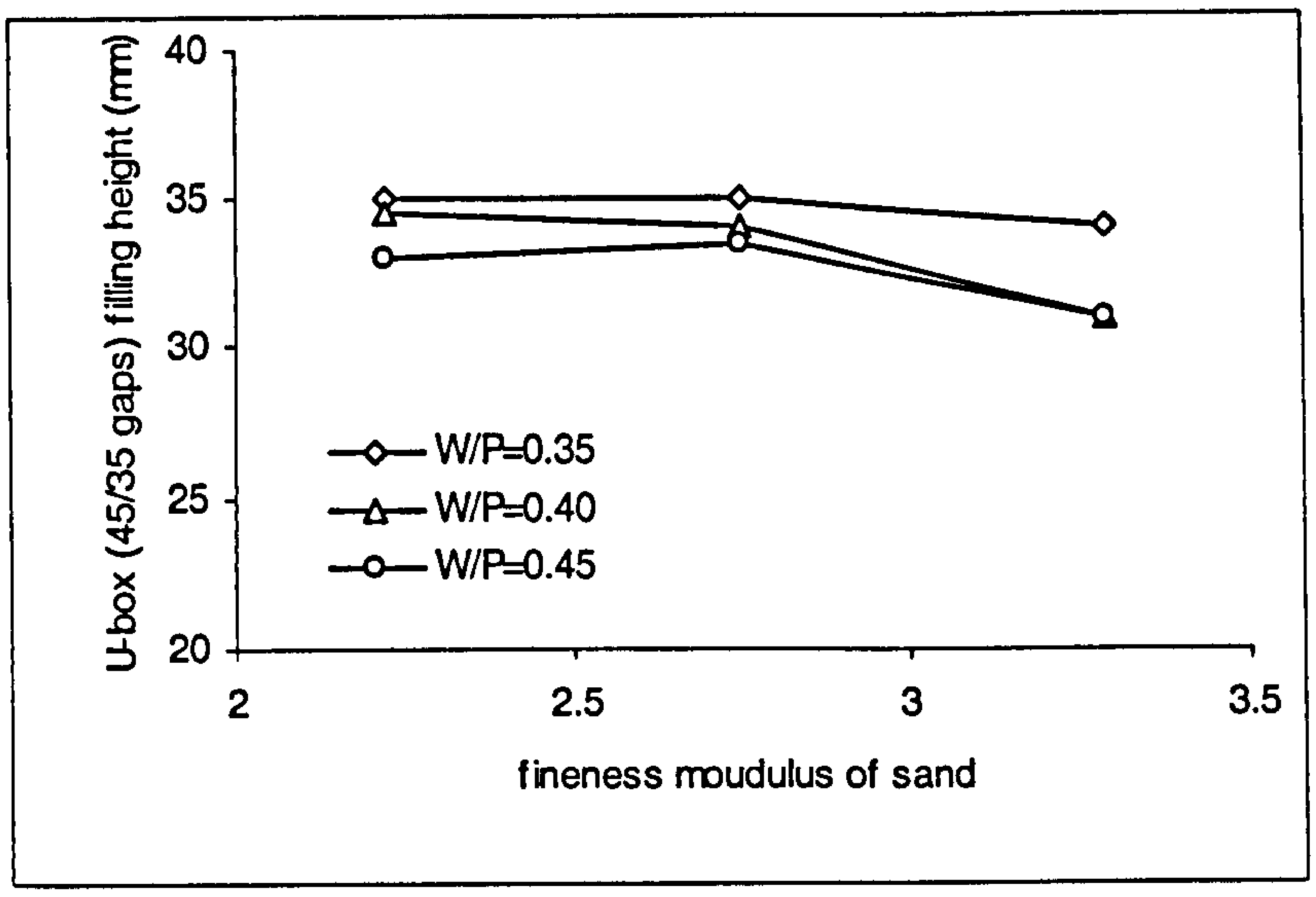


Figure 2-31 Effect of fineness modulus of sand on the U-box filling height (reproduced from [83])

Therefore, round sand with medium size (fineness modulus between 2.4 – 2.9) is recommended for SCC, and crushed and coarse sand with a fineness modulus higher than 3.0 may result in low quality SCC.

Sand content

The sand content is often expressed as a percentage by volume of the mortar phase of the concrete. There is a range of possible sand contents for successful SCC; outside this range the concrete will not satisfy self-compactability because of either segregation or insufficient flow.

Edamatsu *et al* [66] found that the maximum filling height from a U-box test reduced when the sand content was higher than about 50% of mortar by volume, when the coarse aggregate content was not more than 50% of its dry rodded bulk density (**figure 2-32**, see also **figure 2-11**).

Chai [29] suggested the sand content should be between 40% to 47% of mortar by volume.

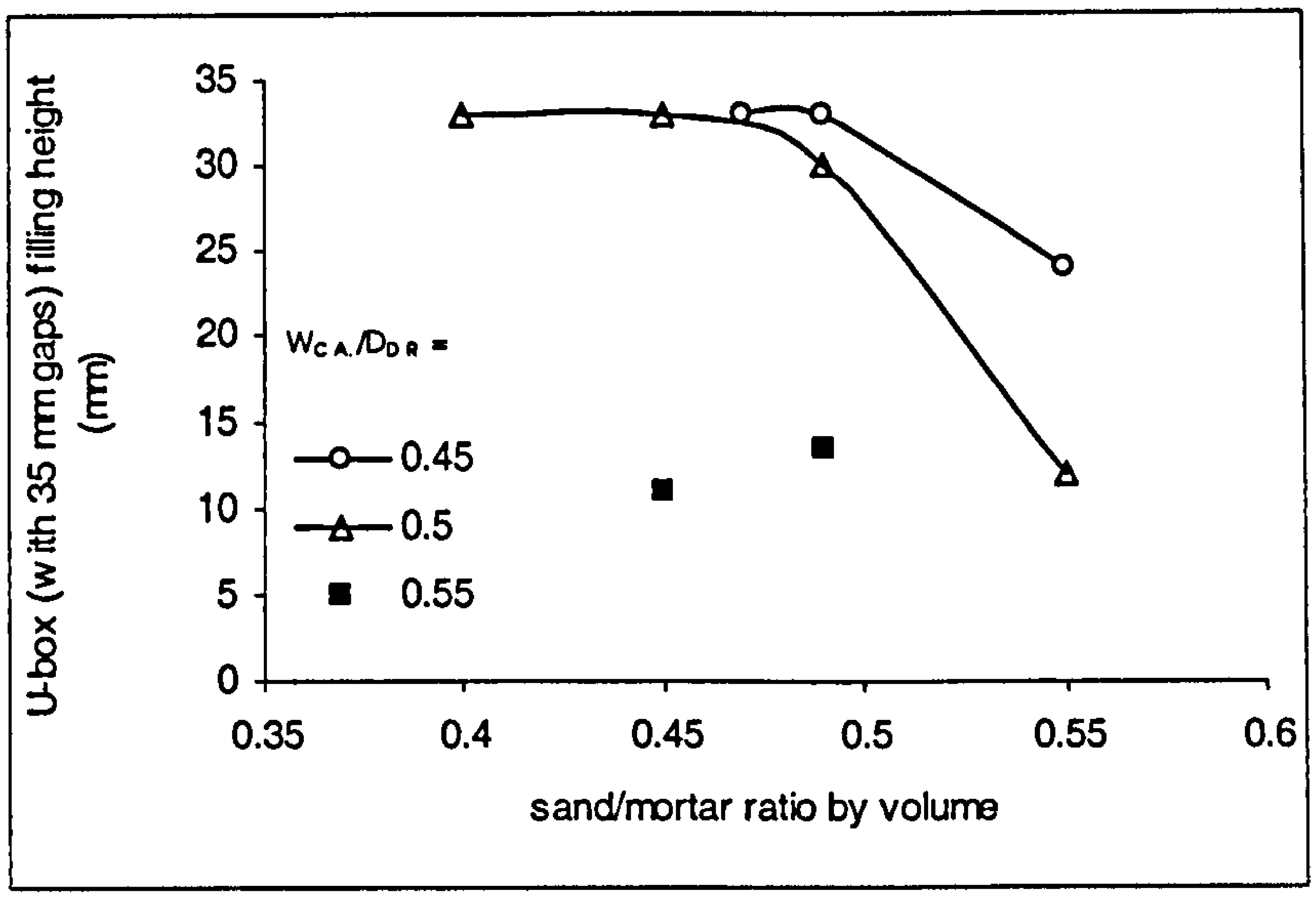
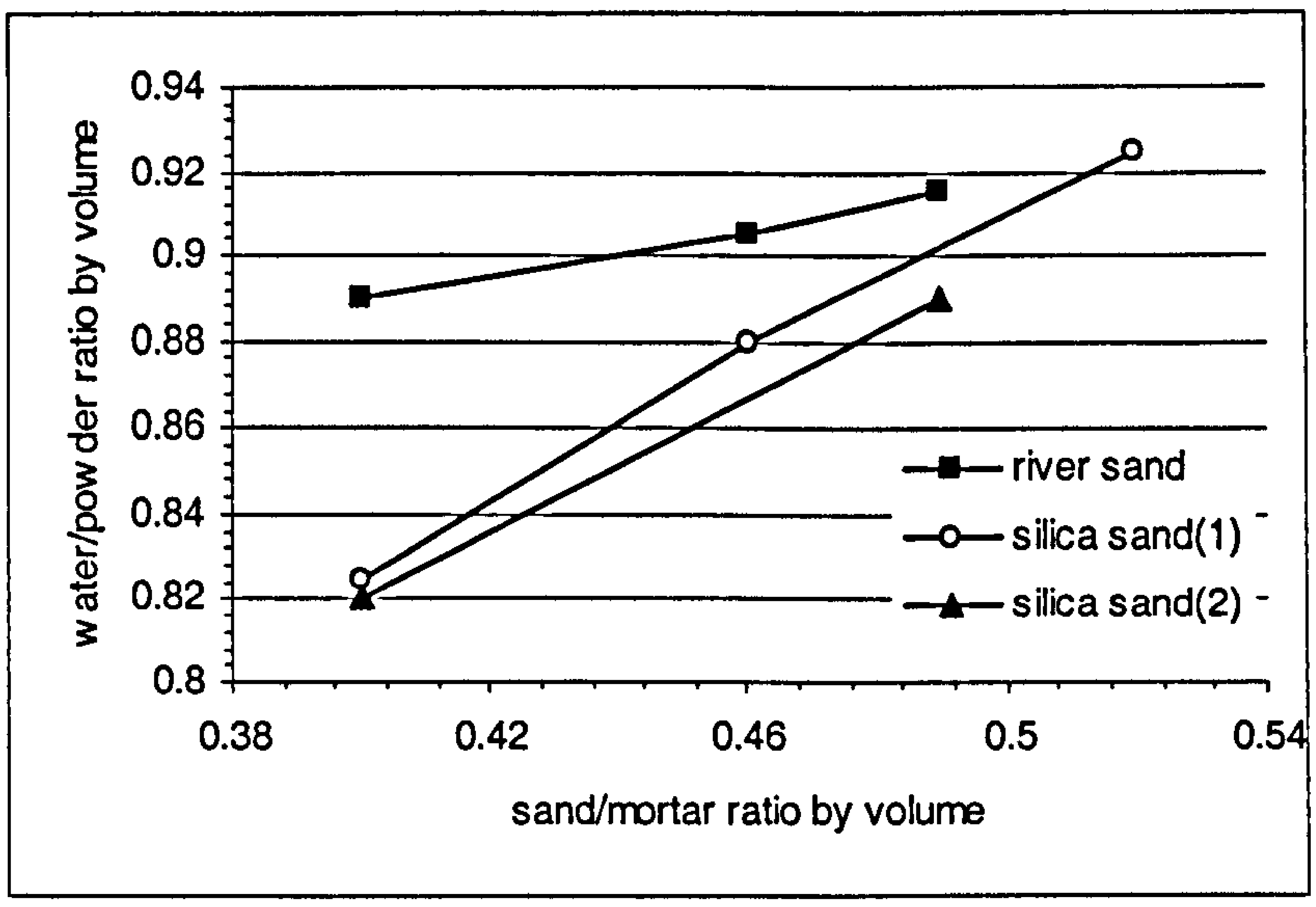
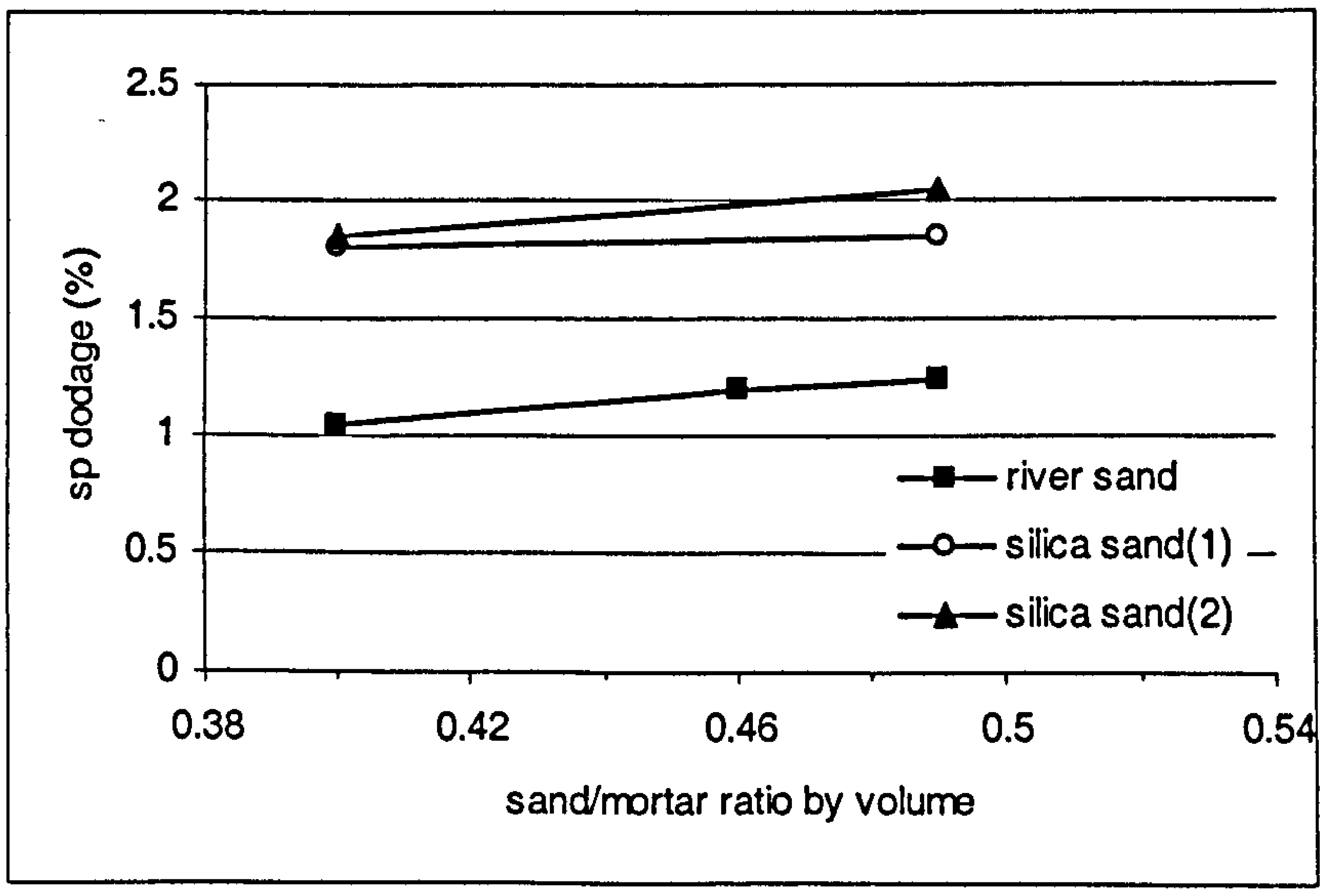


Figure 2-32 Effect of sand content on the maximum filling height by U-box test (reproduced from [66])

Naoki *et al* [84] studied the effect of sand content on the required water/powder ratio and superplasticizer dosage for a mortar to obtain controlled fresh properties. The spread was controlled to 245 mm and V-funnel flow time to 12.5 seconds by adjusting the water/powder ratio and the superplasticizer dosage for mixes with different sand contents. It was found that there was a significant increase in the required water/powder ratio and a small change in the required superplasticizer dosage with an increase of sand content (**figure 2-33**).



(a)



(b)

Figure 2-33 Effect of sand/mortar ratio on required (a) water/powder ratio (b) sp dosage for a mortar to achieve a controlled fresh properties (spread = 245 mm, V-funnel time = 12.5 seconds) (reproduced from [84])

They also studied the effect of sand content on the required mortar properties to achieve a specific concrete property, such as a slump flow of 650 mm. It was found that the required mortar spread was increased (**figure 2-34**) with an increase of sand content.

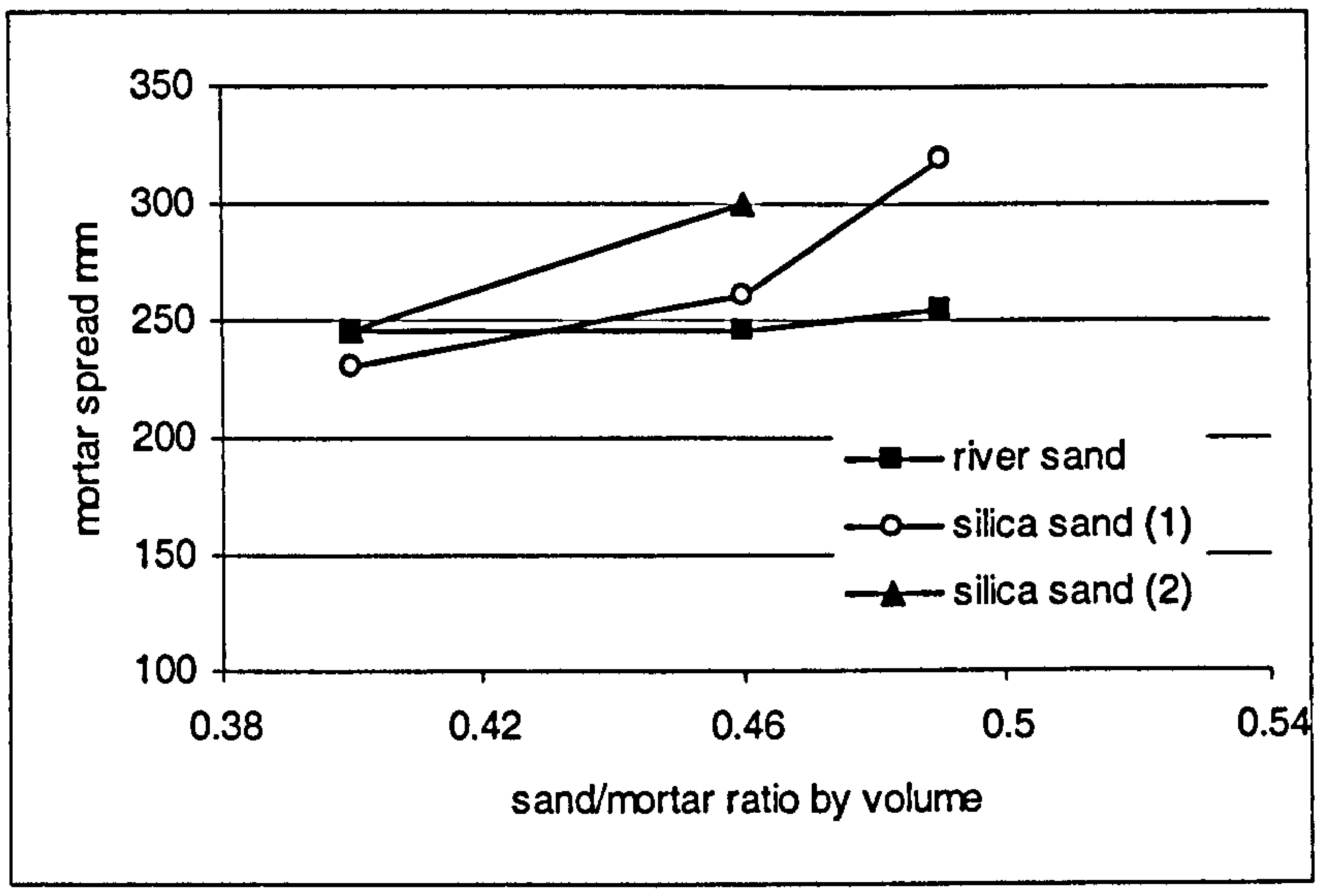


Figure 2-34 The effect of sand content on the required spread of mortar to achieve a specific fresh property of concrete (slump flow = 65 cm) (reproduced from [84])

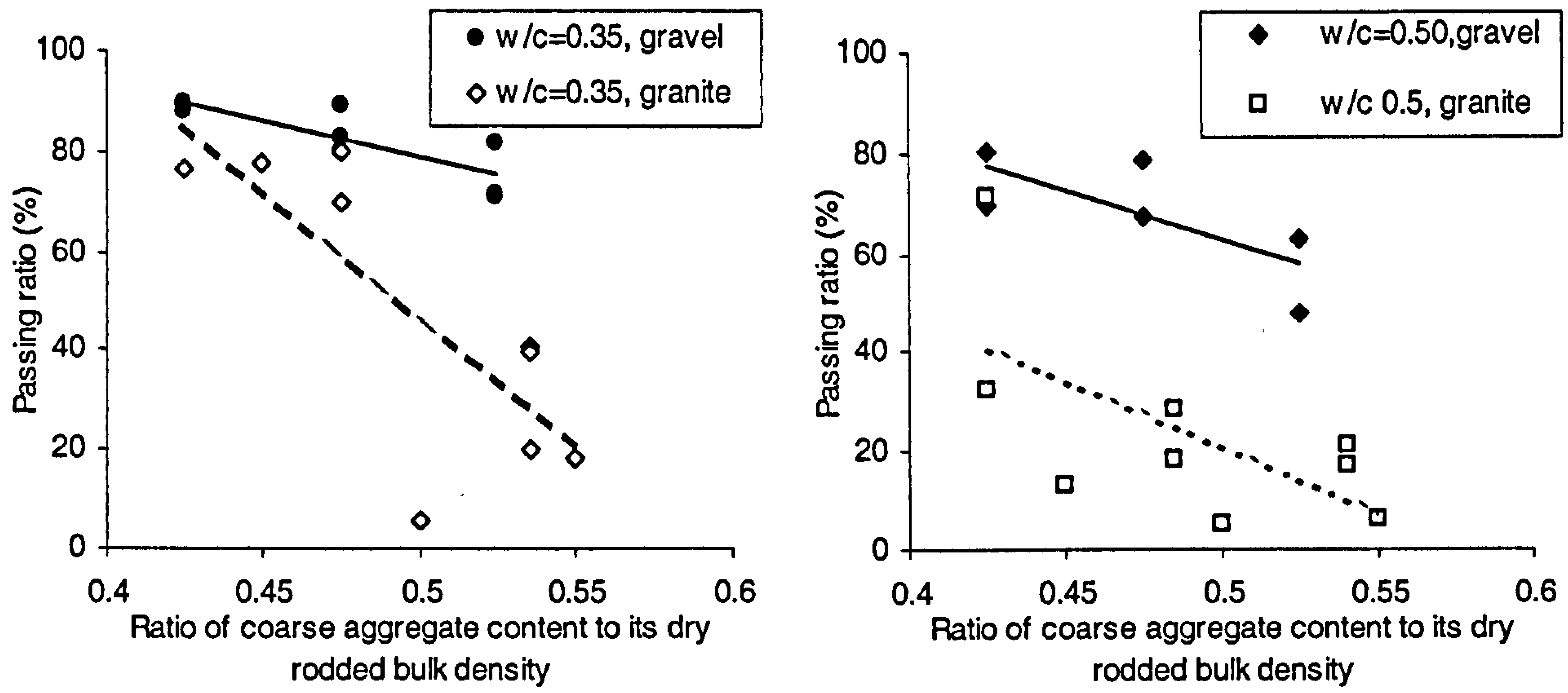
2.4.1.7 Coarse aggregate

The effect of types of coarse aggregate, the maximum size, the fineness modulus and the content are discussed in this section.

Types of aggregate

Two types of natural coarse aggregate are most commonly used in concrete, gravel and crushed rock, typically granite or limestone. The effect of these two types of aggregate has been found to be different.

Iwai *et al* [85] have compared the effects on passing ability by using a U-box similar to that described in section 2.2.2 without the downstream compartment. The passing ability was assessed by the amount of concrete that passed through bars which as a percentage of the whole concrete. The results, shown in **figure 2-35**, indicated that gravel has a higher passing percentage than granite for the same mix, and this difference is more significant at high water/powder ratios. This suggests that a low water/powder ratio is very necessary when granite is used, but less so with gravel.



(a) (b)

Figure 2-35 Effect of types of coarse aggregate on the passing ability of mixes with (a) w/c=0.35 (b) w/c=0.5 (reproduced from [85])

Maximum size of aggregate

The ratio of reinforcement spacing to the maximum size of coarse aggregate has a great effect on passing ability; this has been reported in several papers. For example, Fujiwara *et al* [28] calculated to find, using the geometry of aggregate and bars and considering aggregate as a sphere, that the maximum gap for stable arching is $(2 + \sqrt{3})$ times the aggregate radius for a one-dimensional mesh (1-D), and $(2 + 2\sqrt{2})$ times for a two-dimensional mesh (2-D) (**figure 2-36**). Above this, the risk of arching is greatly reduced. 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 meshes respectively, then the risk of arching is greatly reduced.

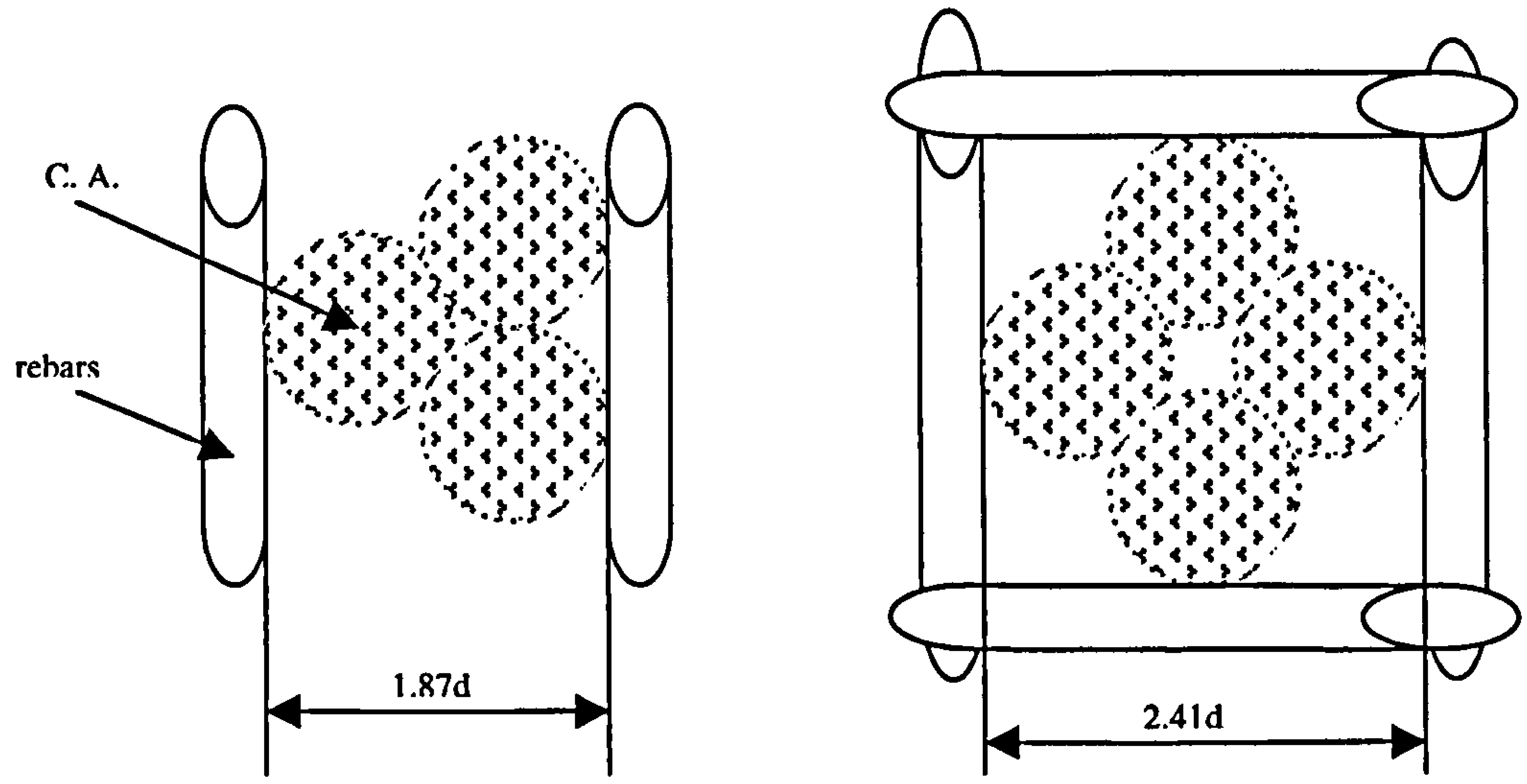


Figure 2-36 Maximum gaps for stable arching to occur with a 1-D and 2-D mesh (adapted from [28])

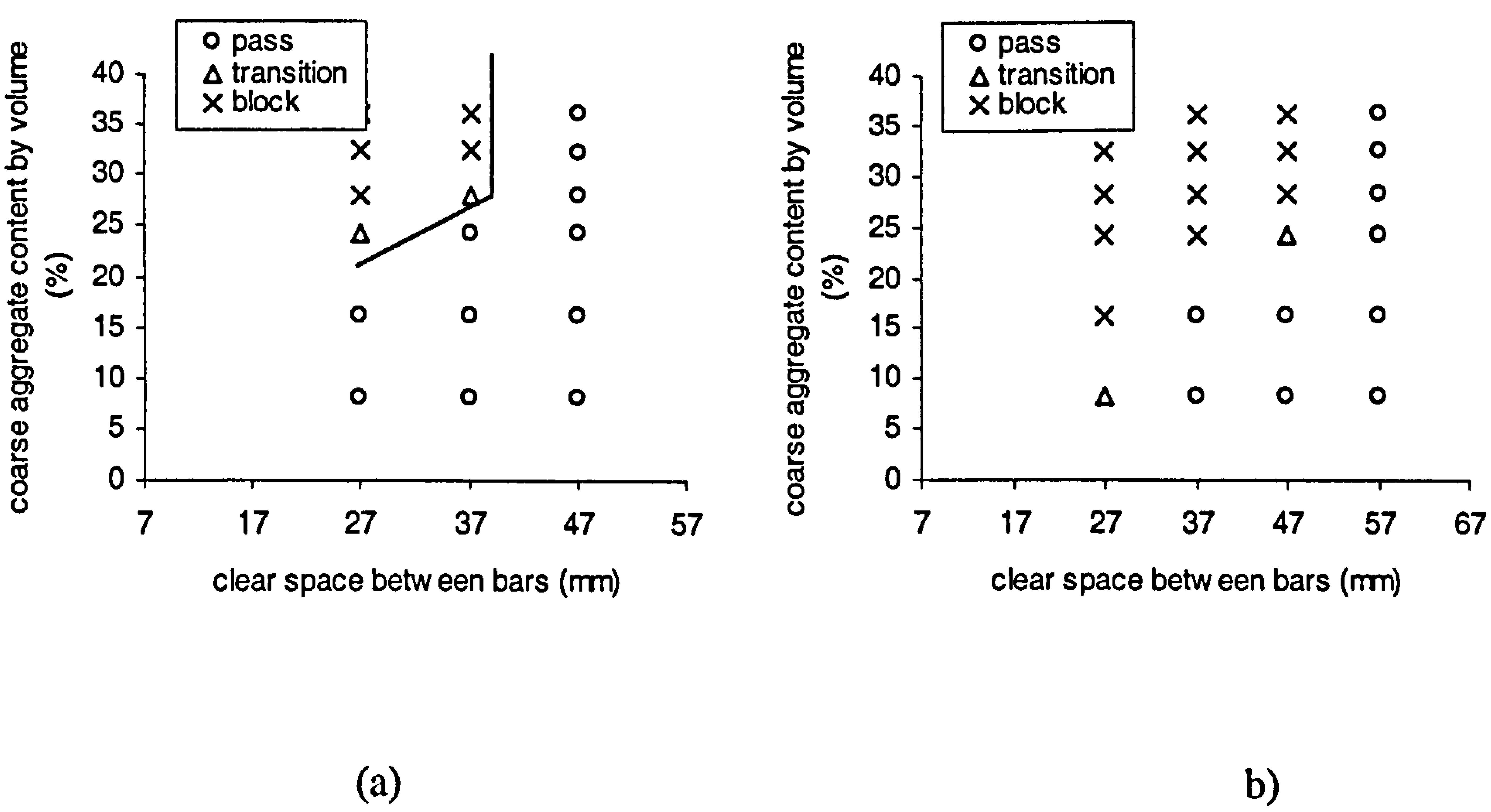


Figure 2-37 passing ability of SCC through bars with (a) 1-D mesh, (b) 2-D mesh (translated from [28])

They also carried out experiments to confirm their calculations. They used the U-box test, and the flowability of concrete was controlled by adjusting the mortar yield stress to 3-50 Pa and the plastic viscosity to 2-12 Pa.s. The results, shown in **figure 2-37,** were consistent with their calculation. The clear gaps of 37 mm and 47 mm are the critical values for concrete with 20 mm maximum size aggregate at 40% by weight to pass through a 1-D and 2-D mesh respectively, i.e. very close to the calculated values.

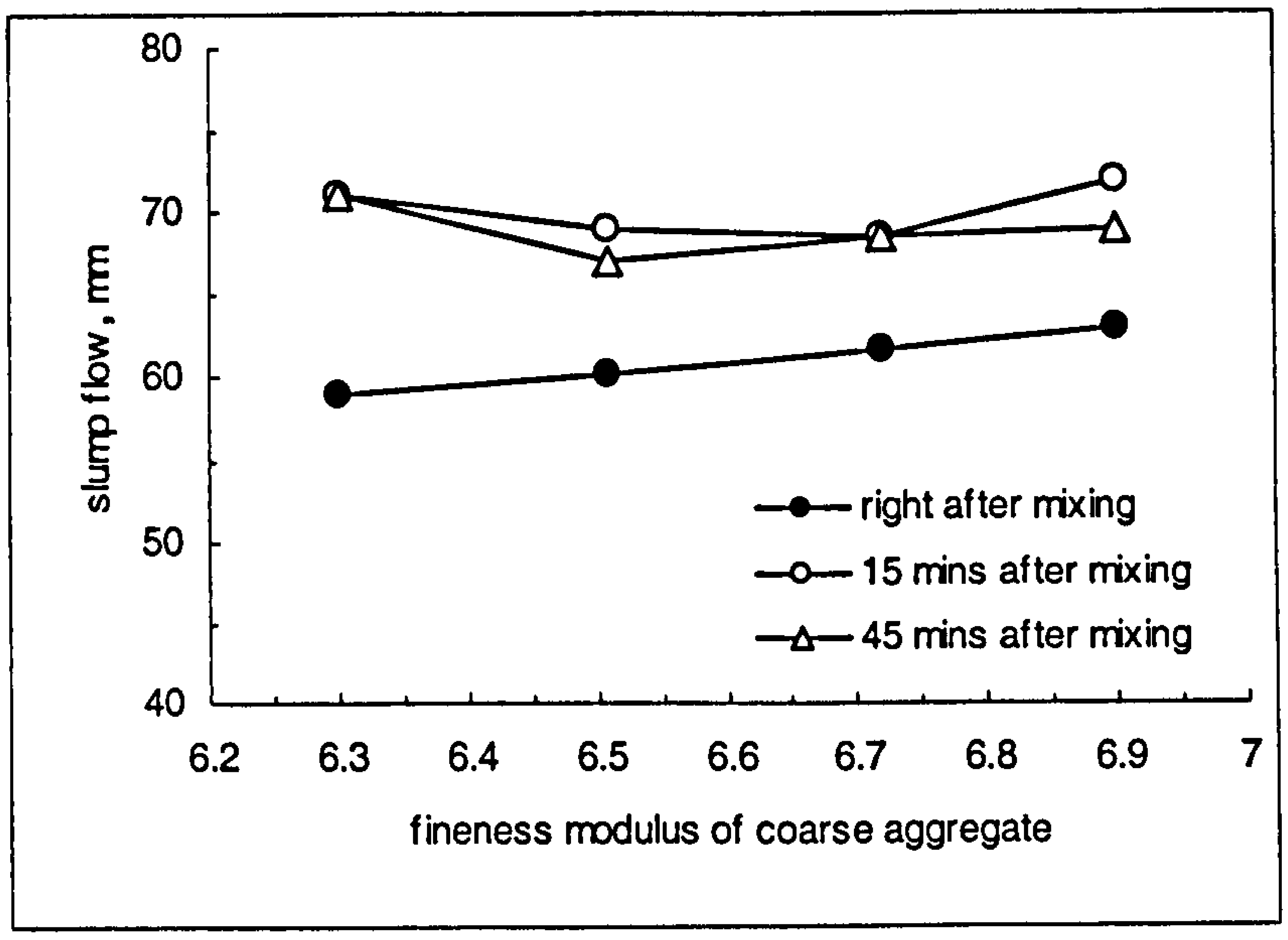
Nishibayashi *et al* [86] also investigated the effects of mix proportions and spacing of rebars on passing ability by using the L-box test. It was found that the concrete with 20 mm maximum size aggregate could flow freely without blocking when the clear spacing between rebars was 37 mm, however, it was blocked by the coarse aggregate regardless of the value of the plastic viscosity of mortar when the clear spacing between rebars was reduced to 30 mm and 27 mm.

Consequently, it may be difficult to obtain a satisfactory passing ability if the ratio of the clear spacing to maximum aggregate size is less than **2.0** and **2.5** for 1-D mesh and 2-D mesh respectively.

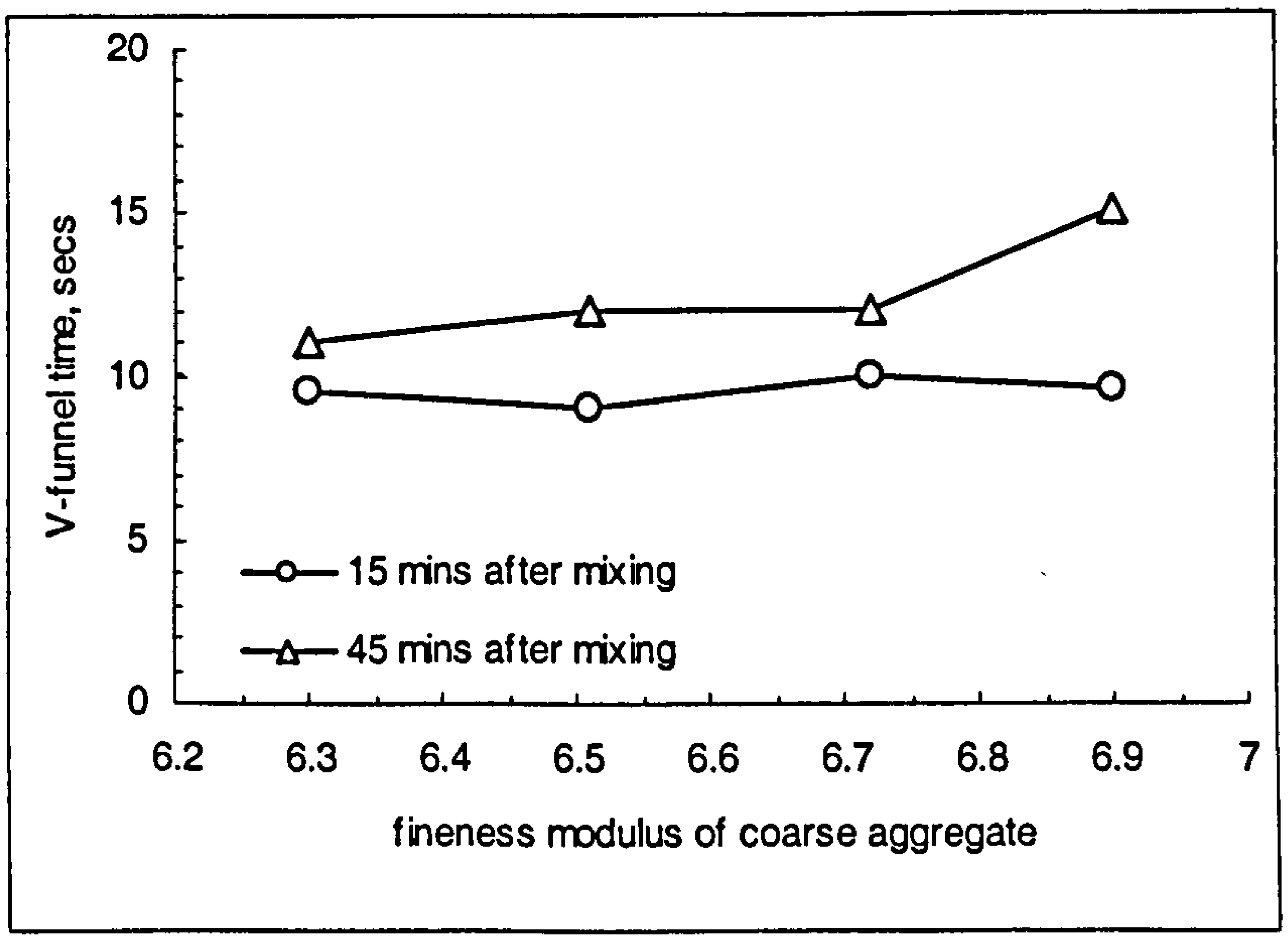
Fineness modulus of aggregate

There is an effect of fineness modulus of the coarse aggregate on the fresh properties, but it is not as significant as the maximum size of aggregate.

Hirata *et al* [82] compared four concrete mixes with same maximum size of coarse aggregate but different grading, these results are shown in **figure 2-39.** It can be seen that slump flow immediately after mixing increased with the increase of fineness modulus, but 15 minutes later the effect of fineness modulus is not very significant on entire slump flow or V-funnel flow time.



(a)



(b)

Figure 2-38 Effect of fineness modulus of coarse aggregate on (a) slump flow (b) V-funnel flow time of concrete (reproduced from [82])

Coarse aggregate content

The increase of coarse aggregate content leads to the decrease of mortar content, resulting in reduced slump flow and increased interference among coarse aggregate particles during flow, as shown in **figure 2-39**. Ozawa *et al* [88] also found that slump flow decreases and V-funnel flow time increases with an increase of coarse aggregate content, and a significant change is found when the coarse aggregate content is higher than 50% of its dry rodded bulk density (**figure 2-40**). Edamatsu *et* *al* [66] also reported that when the coarse aggregate content is higher than 50% of its dry rodded bulk density, the maximum filling height for a U-box test radically decreases with further increasing coarse aggregate content (**figure 2-41**).

Therefore there is a maximum limit of coarse aggregate content for successful SCC; a higher content will cause insufficient flow and passability. The JSCE recommends that the coarse aggregate content should be between 0.3 to 0.35 m^3/m^3 concrete, which is approximately 50 to 55% of dry rodded bulk density. The exact content is dependent on the of reinforcement details. As discussed earlier, selection of coarse aggregate content is a critical part of several mix design procedures.

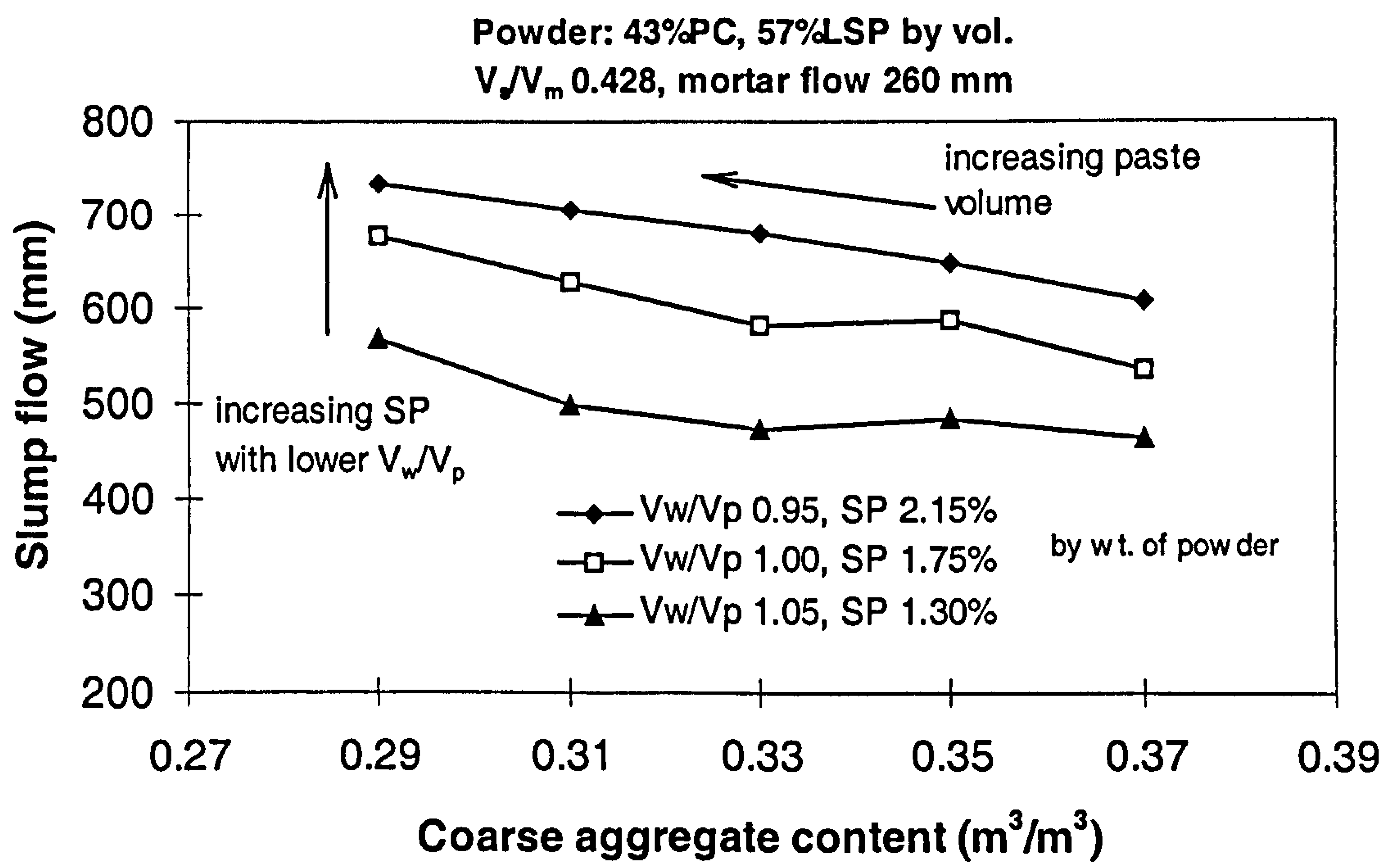


Figure 2-39 Relationship between concrete slump flow and coarse aggregate content for the same mortar flow (adapted from [87])

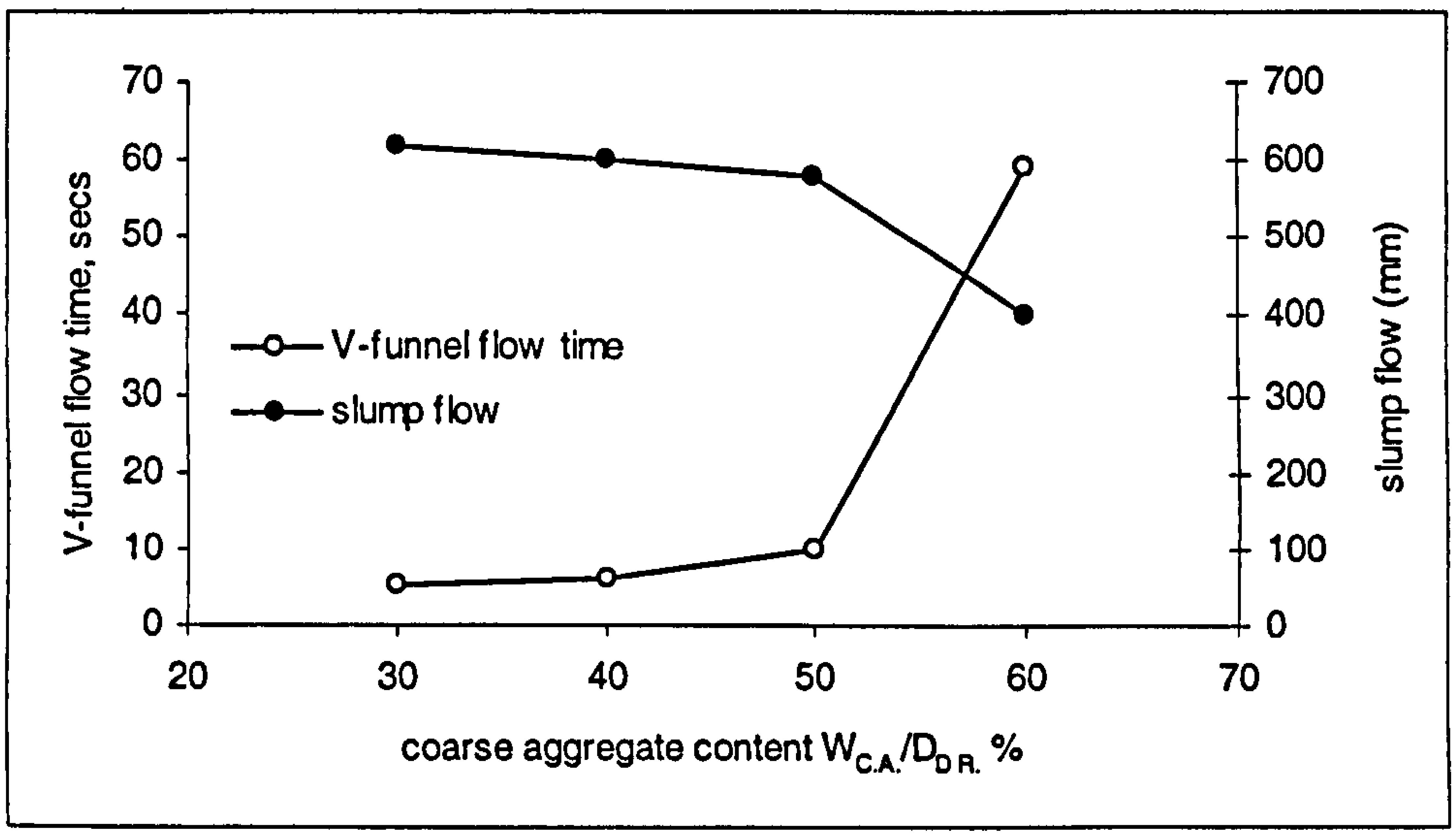


Figure 2-40 Effect of coarse aggregate content on slump flow and V-funnel flow time of concrete (reproduced from [88])

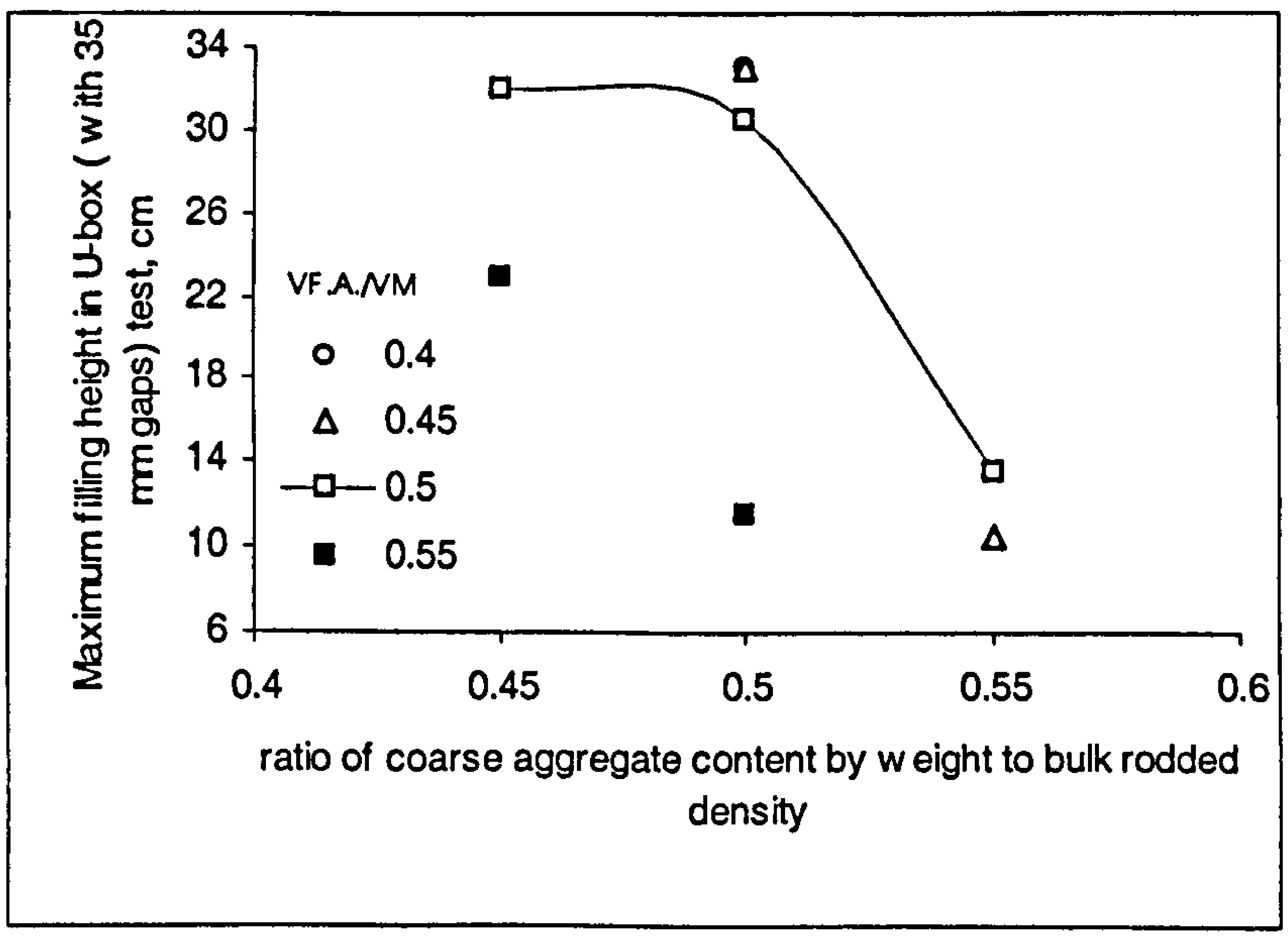


Figure 2-41 Effect of coarse aggregate content on the maximum filling height by U-box test (reproduced from [66])

2.4.2 Workability retention

For SCC, the problem arising from loss of self-compactability is more serious than in the case of normal concrete since it can not be 'rescued' by compaction with vibration during placement. Adequate workability retention is therefore imperative, but surprisingly, there seems to be little reported work in this area.

On site, like normal concrete, this is often controlled by using special types of superplasticizer. For example, in SCC for a prestressed concrete outer tank for LNG storage [89], the mixes had a very fast slump loss at high temperature as shown in **figure 2-42**. Therefore two types of poly-caboxlic acid superplasticizer were used to cope with this under different temperature conditions, e.g., one type for normal temperature and one for high temperature. The dosage was adjusted to maintain the required flowability for period of 60-90 minutes after mixing. Similarly, when building a large water purification tank using SCC, three types of poly-carboxylic superplasticizer were used in order to keep good workability retention under various temperatures [90]. In some cases, retarding admixtures were also used. As a result, the concrete may have a long setting time and a low initial strength, depending on the types of superplasticizer used.

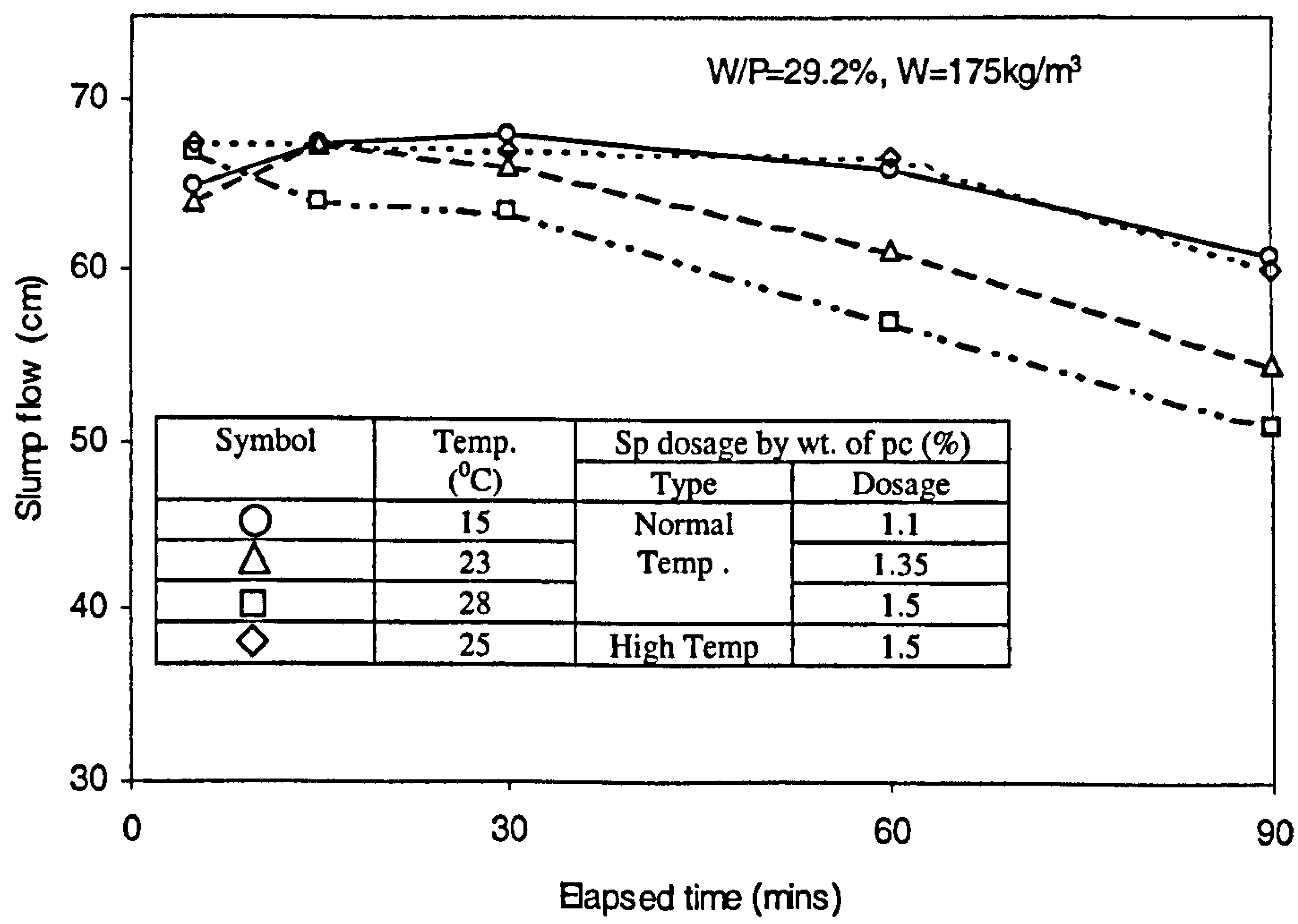


Figure 2-42 Effect of temperature and types and dosage of superplasticizer on slump flow loss (reproduced from [89])

It is interesting to notice that the slump flow of the mix at 15 ^{0}C in **figure 2-42** increased during the first 30 minutes after mixing. Similar performance was found in many other cases, such as these in **figure 2-30** and **figure 2-38**. Yamada *et al* [91] reported that this is because lower dispersibility at lower temperature due to high sulfate ion concentration in mixing water, flowability increased with time due to slower hydration and larger decreased of sulfate ion concentration. Further investigation will be useful.

Clearly the superplasticizers in SCC have a significant effect on the workability retention. This has also been shown by Pukki *et al* [92] with a sulfonated naphthalene formadehyde type superplasticizer when studying workability loss of high strength concrete. Three concrete mixes were tested with different water/cement ratio (0.39, 0.37, and 0.36). The superplasticizer dosages in each mix, adjusted to achieve the same initial slump, were 1.9%, 2.5%, and 3.1% respectively. The test results are shown in **figure 2-43**. The mix with the highest dose of superplasticizer had the lowest rate of workability loss in terms of slump or yield stress and the highest in terms of viscosity. They argued that this was due to the contribution of different dosages of superplasticizer, but the effect of water content should not be ignored.

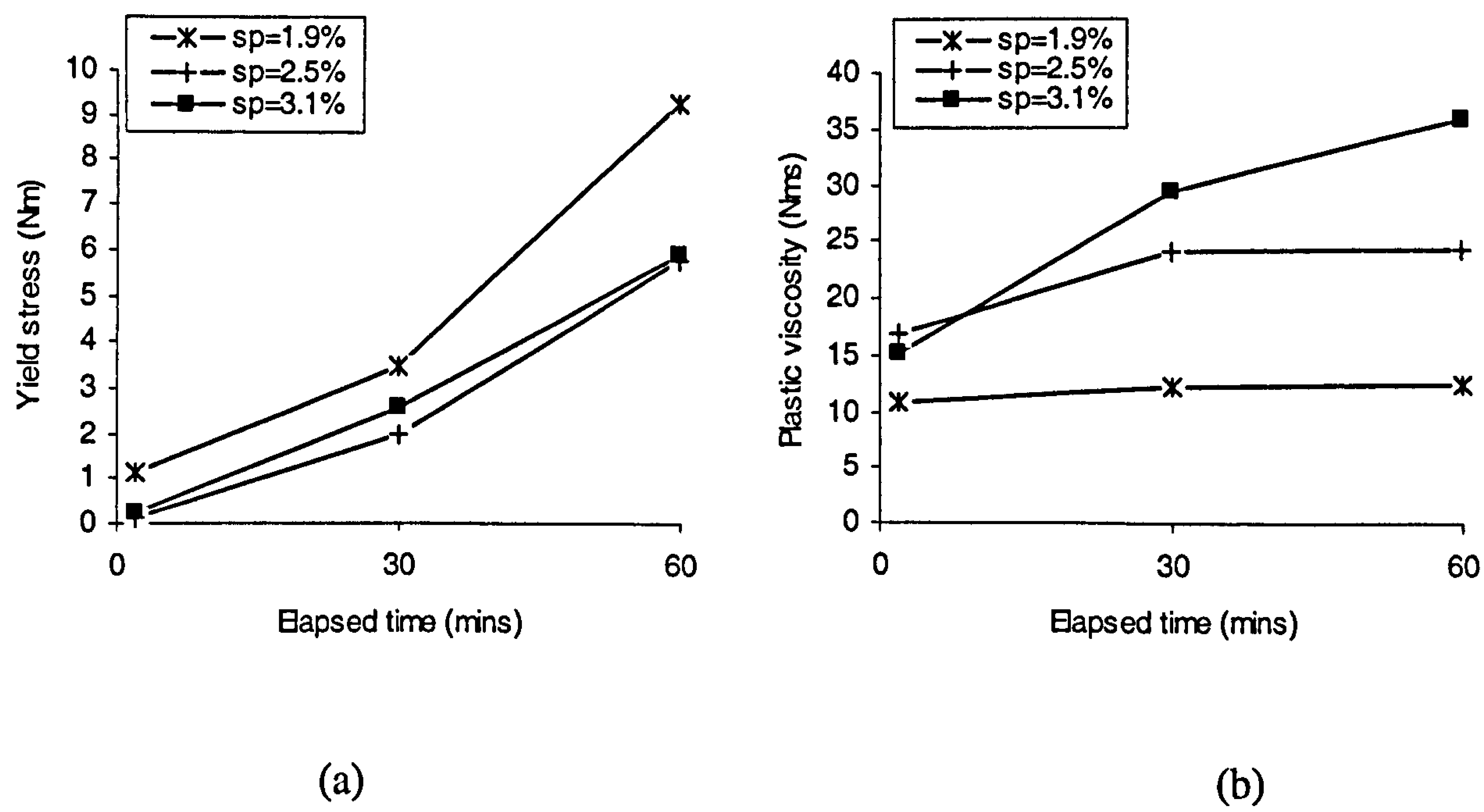


Figure 2-43 Effect of superplasticizer on workability retention in terms of (a) yield stress (b) plastic viscosity (reproduced from [92])

Bonen and Sarkar [93] studied the parameters of the pore solution of a cement paste that affect flow loss (this is similar to spread loss in a mortar test). They concluded that the flow loss increases with ionic strength, which is mainly governed by the presence of alkali sulfate or soluble calcium sulfate and alkali. They explained that a high strength pore solution will induce a greater polarization of the double surface layer formed around the particles and this in turn, would probably generate more electrostatic bonds, reducing fluidity. They found that the addition of a polynaphthalene sulfonate superplasticizer affected ionic strength of the solution by increasing the S and Na concentrations, and decreasing K and Ca. This implies that the flow loss of a superplasticized mix is dependent on the water content, the types of superplasticizer and its dosage.

Other admixtures such as air entraining agents, and viscosity agents may improve workability retention. For example in **figure 2-44** the spread loss was reduced with an increase in Welan gum dosage; however, this may be a combined effect of superplasticizer and Welan gum because the superplasticizer was also increased.

However, different results were obtained by others. Petersson *et al* [94] found the workability retention of SCC with Welan gum was not as good as that with a dolomite filler when Sika 10 as superplasticizer **(figure 2-45)**.

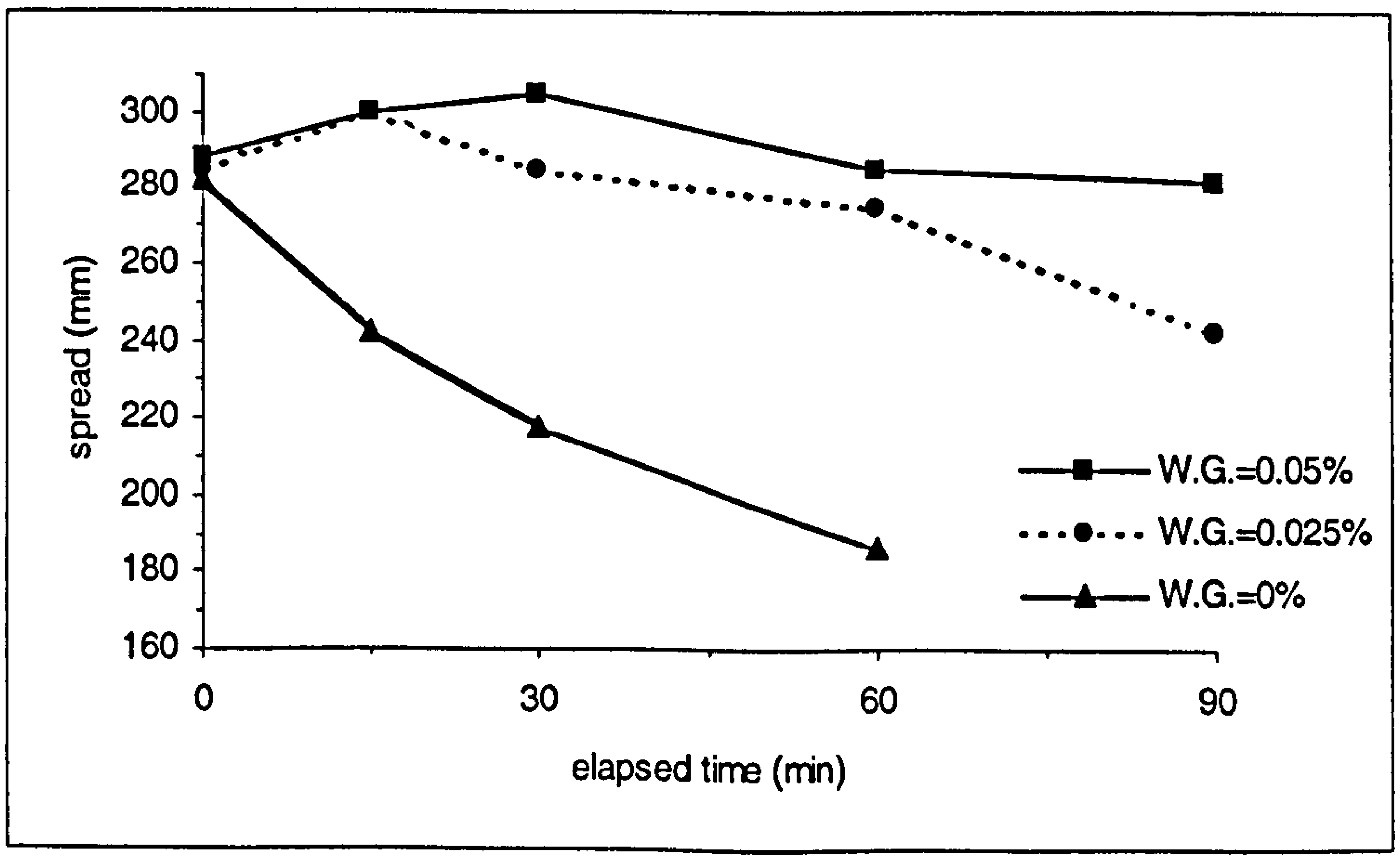


Figure 2-44 workability retention of mortar (reproduced from [76])

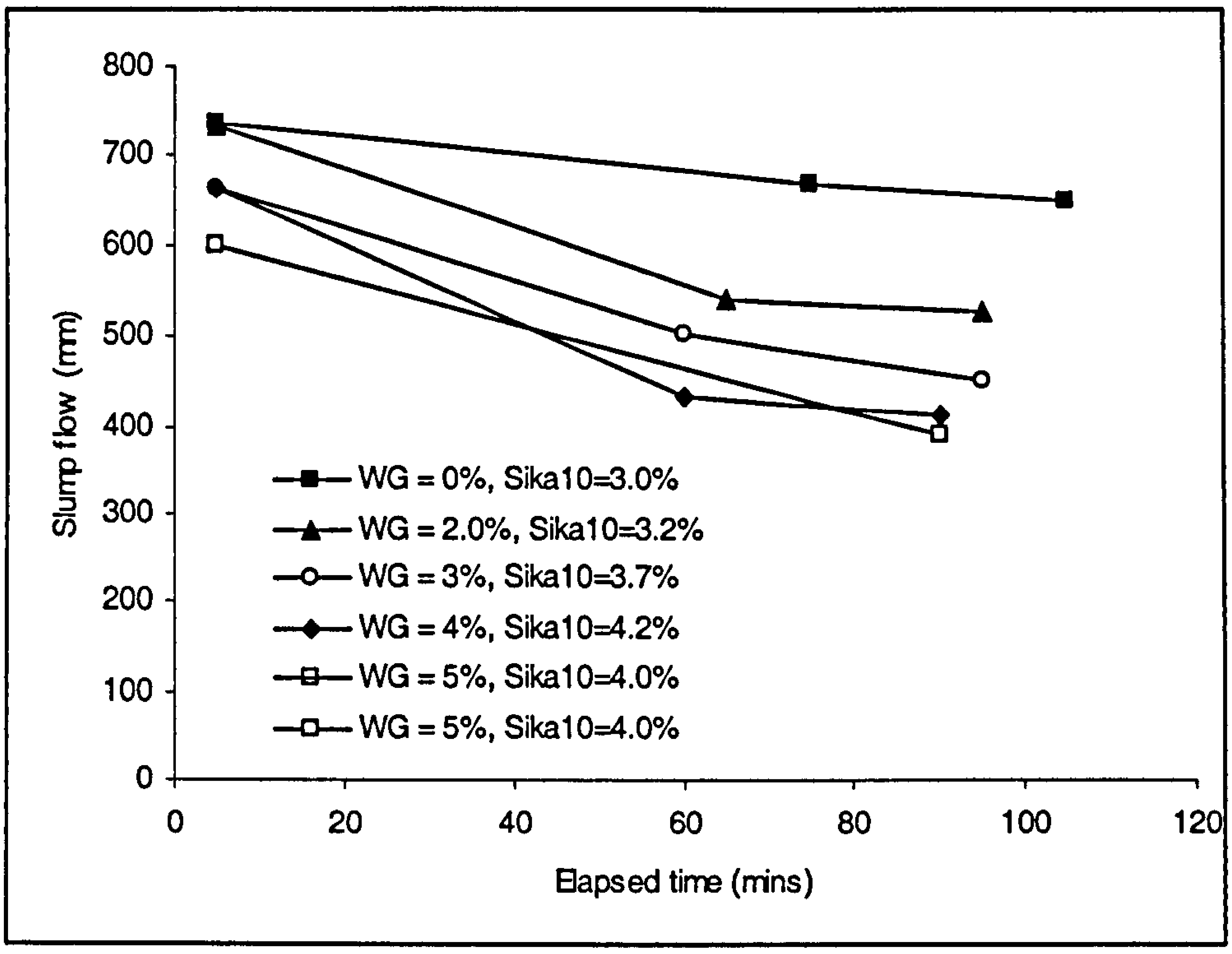


Figure 2-45 Effect of Welan gum and sika 10 on workability retention (reproduced from [94])

The effect of other constituents in SCC on workability retention seems to be more complicated because there is a combined effect of the components, particularly the powders and admixtures. However, there is limited information on this.

Figure 2-46 shows several Welan gum mixes with various types of powder [74]. The superplasticizer used was a naphthalene type and the dosage was adjusted to achieve same spread for each mix but the results were not mentioned. The 100% PC mix and all the binary powder mixes had water powder ratio of 0.948 and sand/powder ratio of 1.58 by volume while the ternary mix had value of 0.824 and 1.62 respectively. It is interesting to find out that LSP binary mix had the best workability retention among all. It is not clear how significant the effect of superplasticizer and further research will be useful.

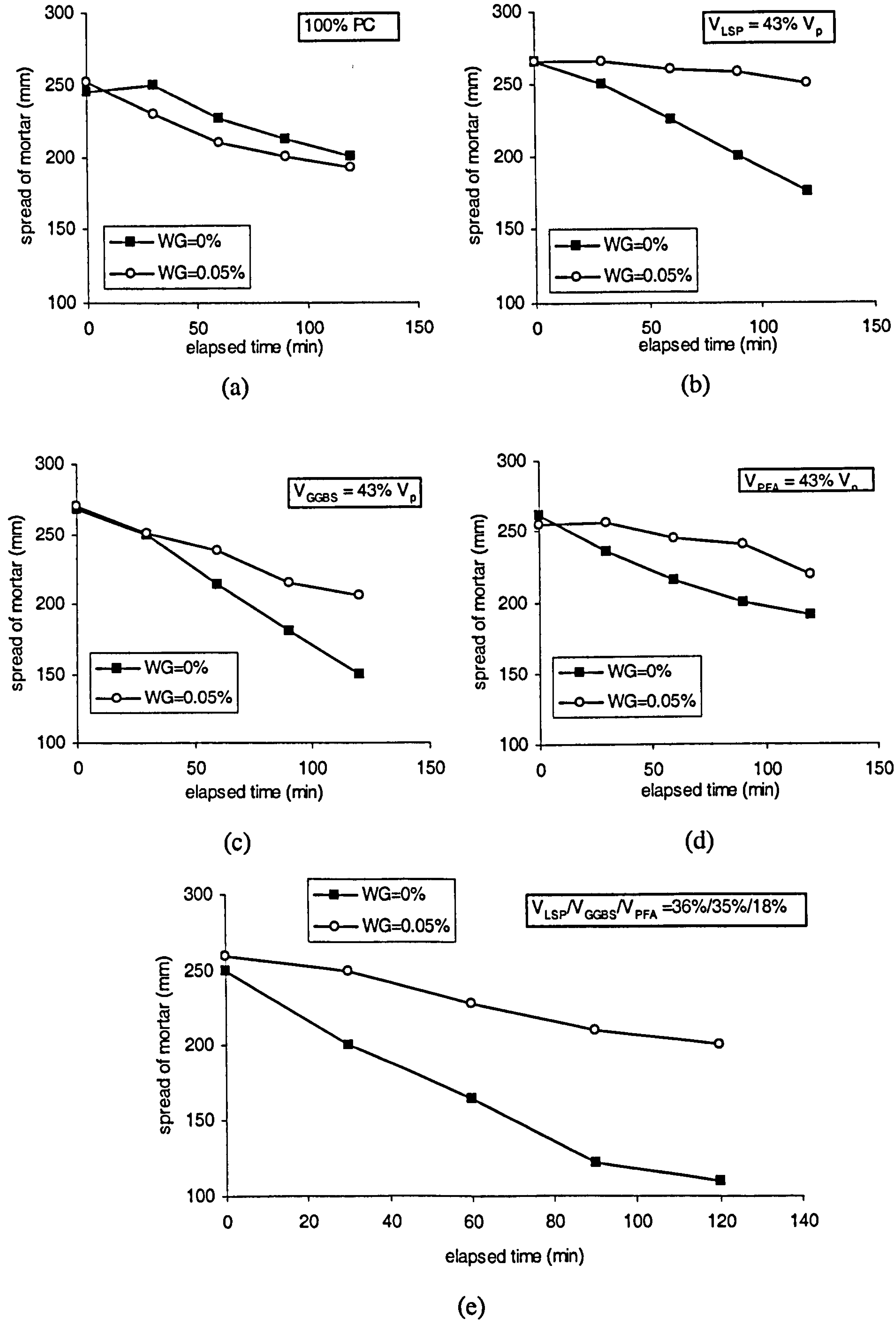


Figure 2-46 workability retention of Welan gum mixes (a) 100% PC (b) LSP binary powder (c) GGBS binary powder (d) PFA binary powder (e) LSP/GGBS/PFA ternary mixes (reproduced from [74])

The effect of silica fume on workability loss of high strength concrete has been studied by Punkki *et al* [92]. **Figure 2-48** shows their results. It was concluded that silica fume reduced the change in plastic viscosity and yield stress with time, which may be a useful effect in SCC.

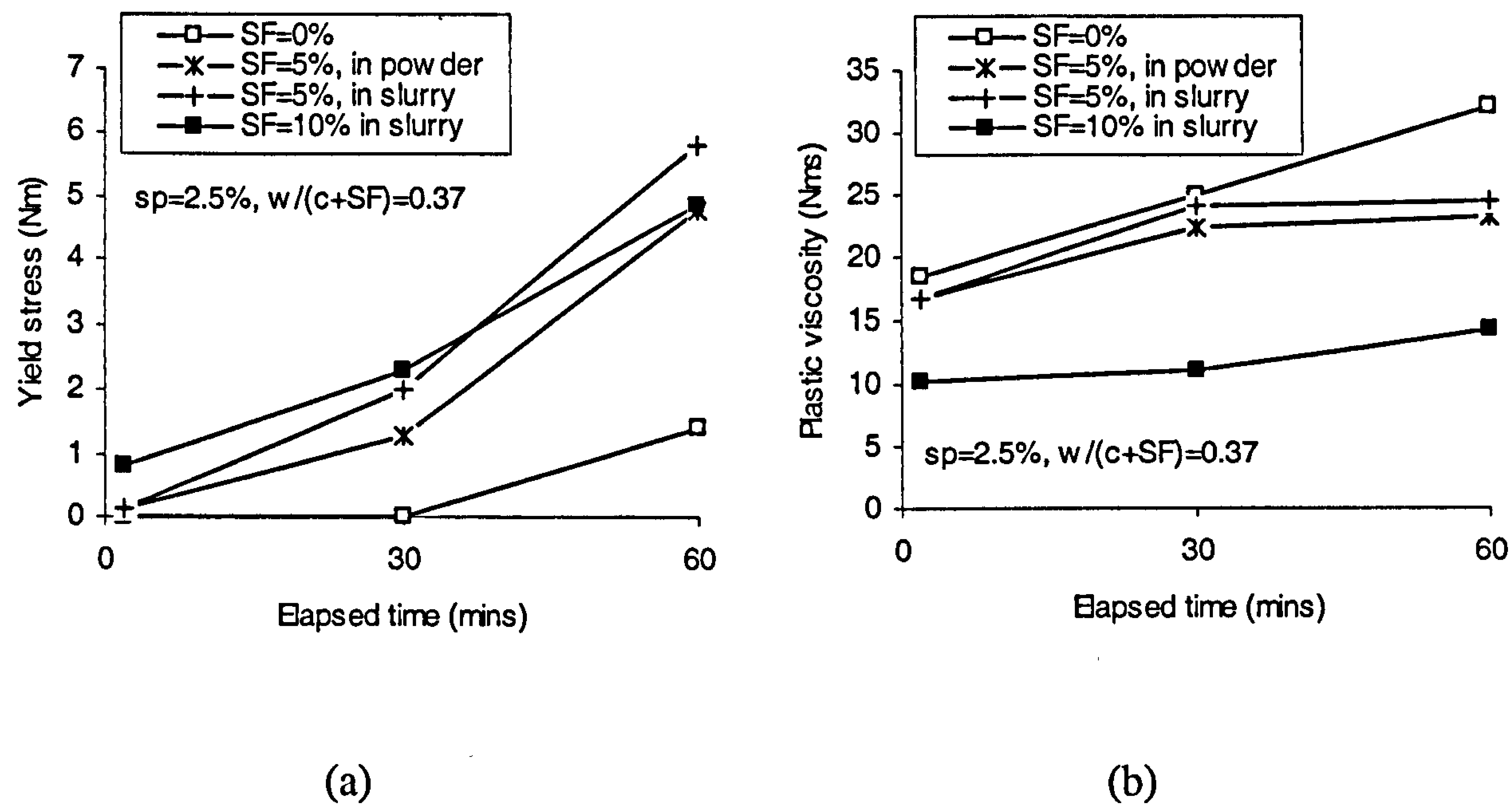
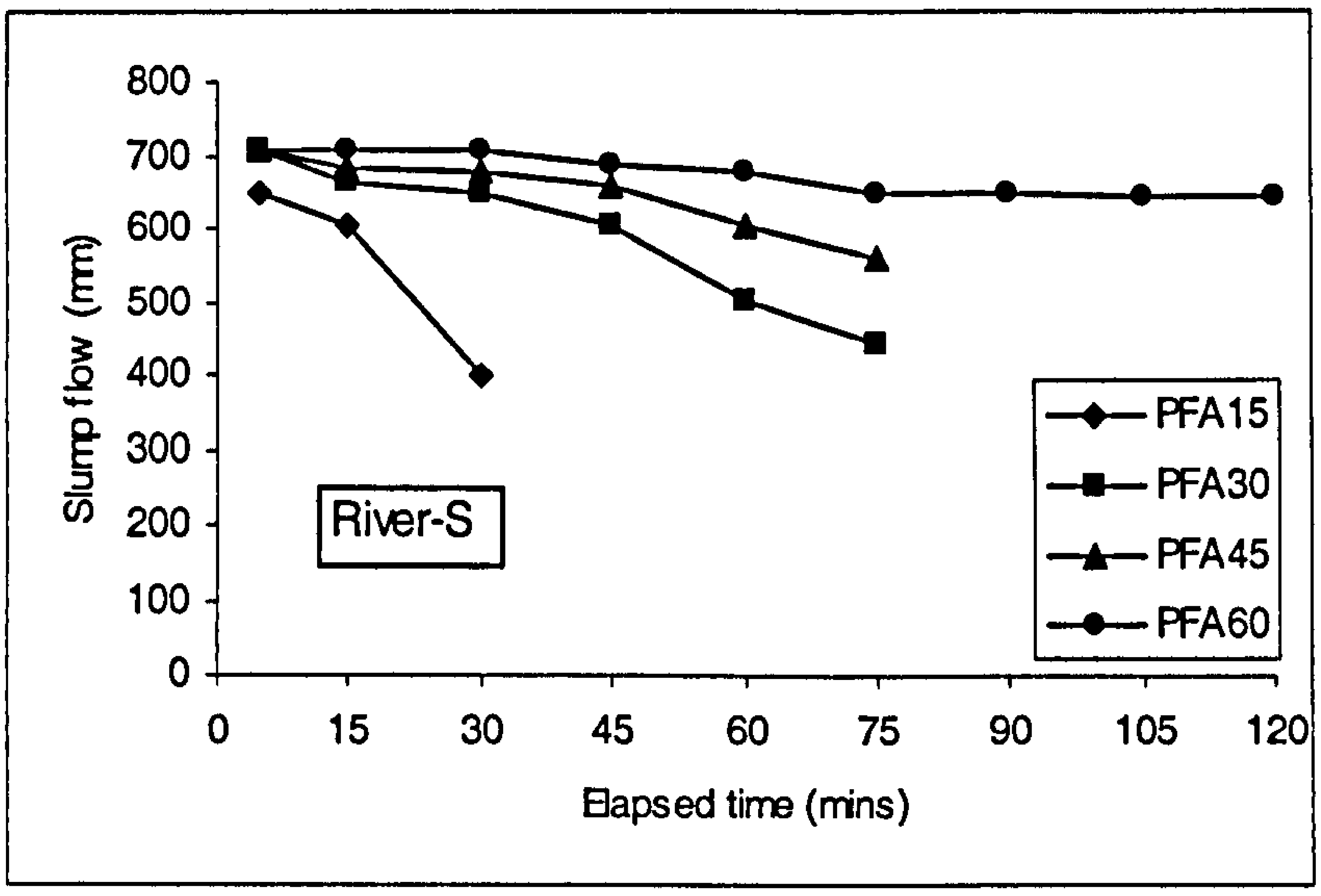


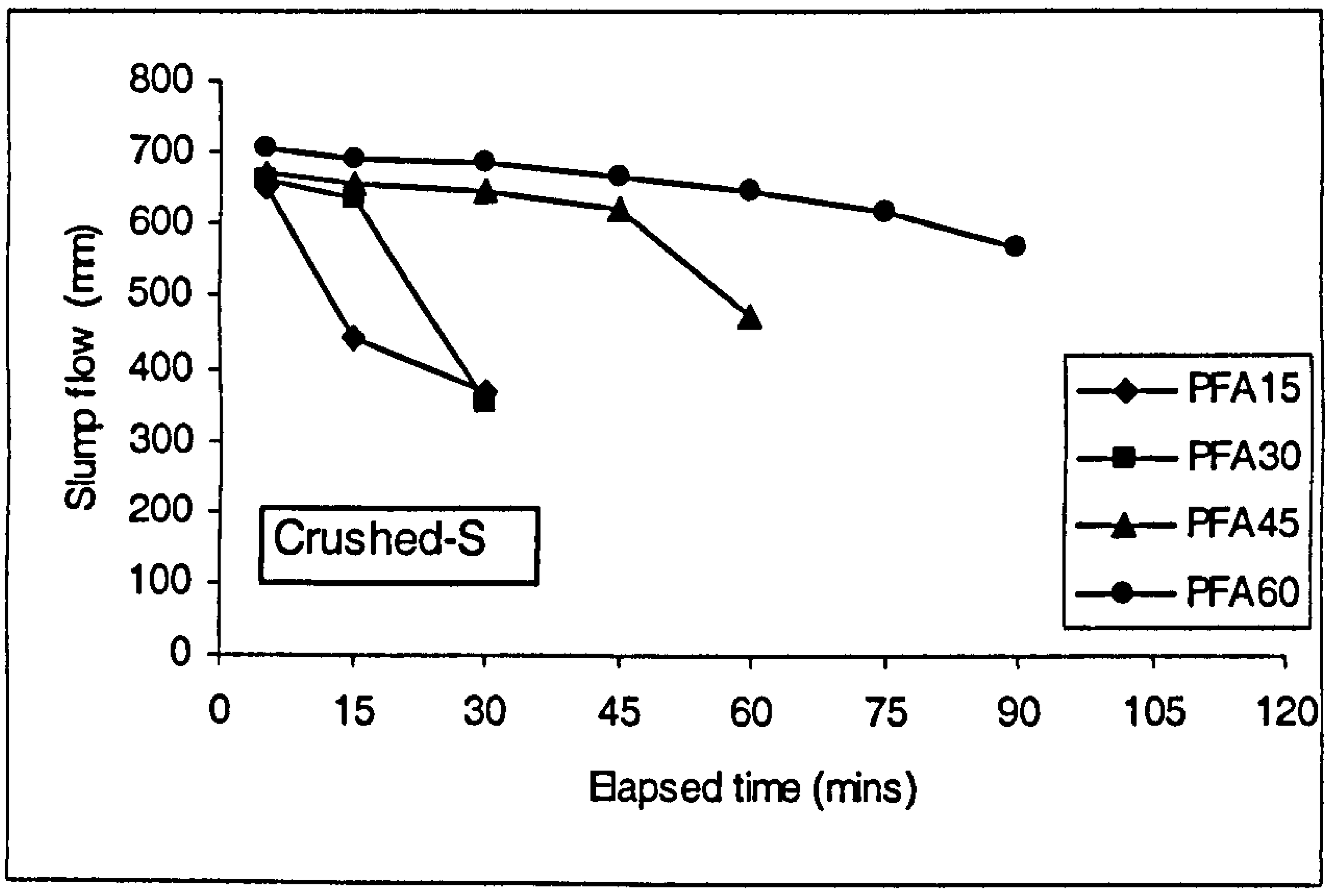
Figure 2-47 Effect of silica fume on workability retention in terms of (a) yield stress (b) plastic viscosity (reproduced from[92])

Bonen and Sarkar [93] have found, with sulfonated naphthalene formadehyde type superplastiser, that in mixes containing microsilica, the amount of superplasticizer adsorption increased, reducing the ionic strength, therefore the mini slump of the paste improved compared to 100% PC mix. This suggests that silica fume may improve flowing capacity by requiring more superplasticizer than other mixes, however, it is not clear how it affects development of flowing speed.

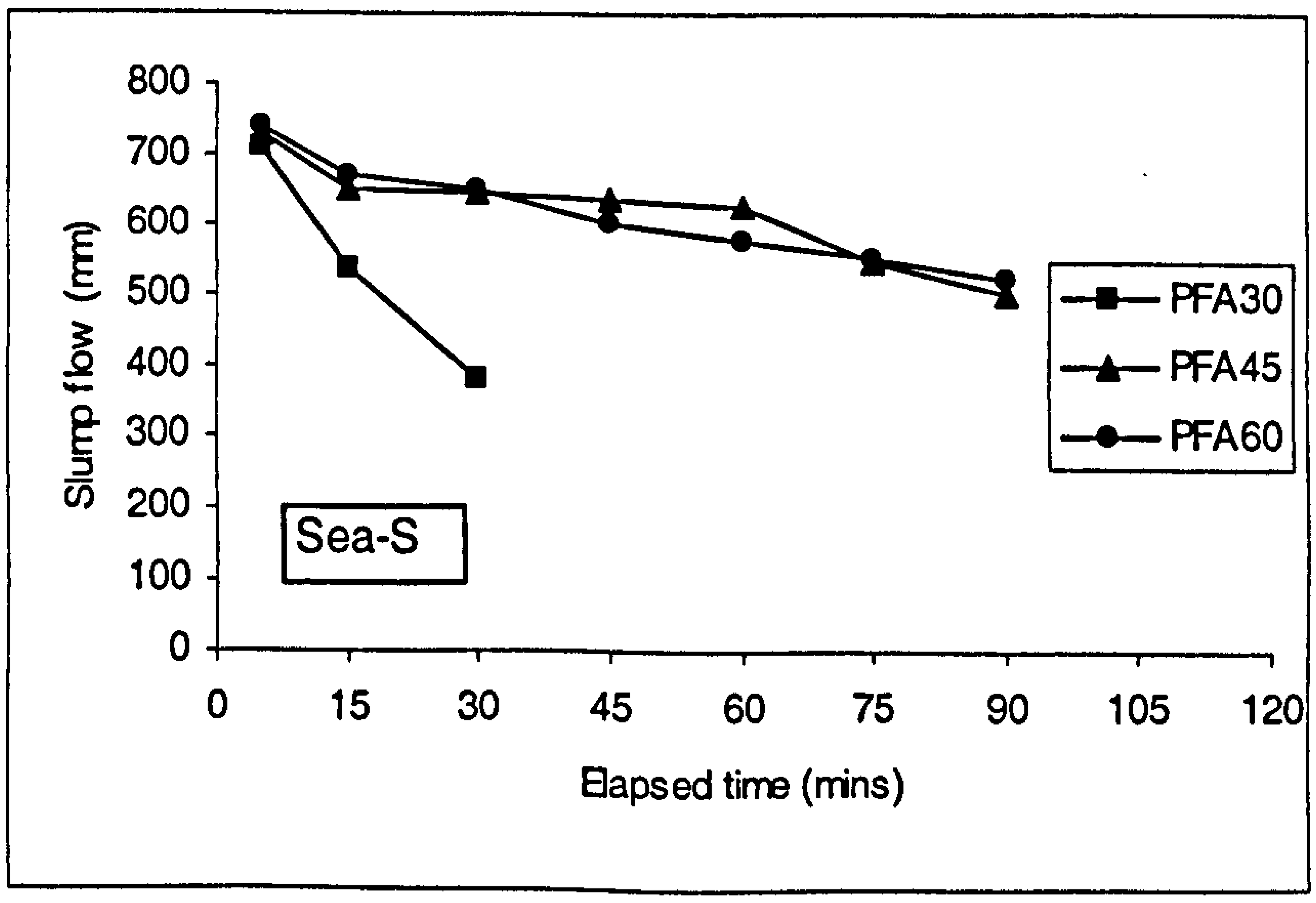
Mixing procedure, especially the time of addition of the superplasticizer, also has a great effect on the workability retention. This can be improved by delaying addition; this subject is reviewed in section 2.7.



(a)



(b)



(c)

Figure 2-48 Effect of types of sand on workability retention of SCC (a) river sand (b) crushed sand (c) sea sand (reproduced from [81])

There is little information about the effect aggregate on workability retention. Kim *et al* [81] compared the effects of river sand, crushed sand, and sea sand, using concrete with the proportion shown in **table 2-7.** It was found that the mixes with river sand produced the best workability retention, followed by crushed sand and sea sand **(figure 2-48)**, suggesting fine aggregate with round shape and medium fineness modulus can give better workability retention to the mix because of less fraction between sands. Workability retention was improved by replace part of cement with PFA by weight, but this may also be because of increased superplasticizer dosage with the increase of PFA content **(table 2-7)**.

2.4.3 Properties of mortar and their relationships with SCC

Three out of the five mix design methods reviewed earlier in this chapter use mortar test as an important part of process, especially to determine the dosage of superplasticizer. Also many investigations on SCC involved mortar tests [95-97]. This suggests an important role of the mortar properties in SCC. Several studies have been carried out to define these for successful SCC, as well as the relationships between properties of mortar and concrete.

Table 2-8 shows the criteria for mortar properties to achieve successful SCC proposed in several countries. It can be seen that there are some differences, the spread is lower and V-funnel flow time proposed by Ozawa and Edamatsu *et al*, both from Japan, is higher than that of Chai (UCL), although both use same size sand. Billberg in Sweden, whose fine mortar with the maximum size 0.25 mm was particularly studied for SCC mix design [96], therefore it is difficult to compare his figures with others. Nevertheless each criteria has been successfully used in its mix design method.

Clearly, the relationships between mortar and concrete are of great interest, but, surprisingly, only a few results have been reported.

Table 2-8 The criteria of mortar property to achieve successful SCC

reference	D_m(mm)	T_V(secs)	τ_0 (Pa)	μ (Pa.s)	comment
Ozawa [42]	245	10			Used as criteria in the simple mix design method
Edamatsu *et al* [97]	200-283	5-10			Used as criteria in the extended simple mix design method
Fujiwara [65]			5-20	6-12	Used as criteria to obtain minimum paste content for SCC
Chai [29]	≥300	2-10* or 4-10**			Used in UCL mix design method
Billerg [52]	No specified value, however, the fine mortar property is used in CBI mix design				Also used in CBI mix design method, but the maximum size of sand is 0.25 mm.

*: For SCC with 10 mm maximum size coarse aggregate,

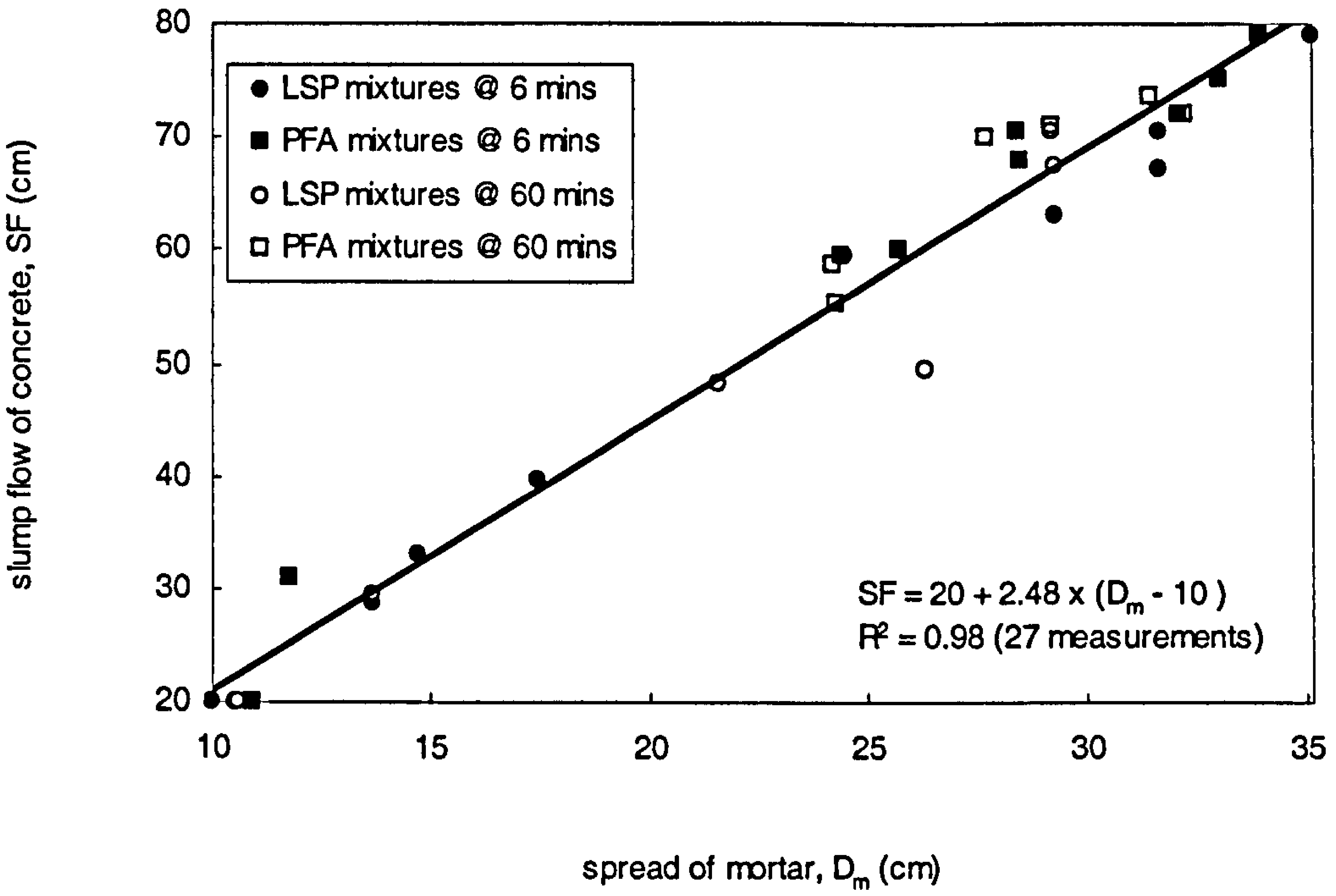
**: For SCC with 20 mm maximum size coarse aggregate.

The most important conclusion was made by Yahia *et al* who studied the effect of rheological parameters of the mortar component in the concrete containing 0.3 m^3 coarse aggregate on fresh properties of SCC [98]. The mortar was obtained directly from concrete mixer before the addition of coarse aggregate. **Table 2-9** and **figure 2-49** show their results. Very strong relationship between the spread of mortar and the slump flow was found **(figure 2-49 (a))**. The relationship between V-funnel flow time of mortar and concrete showed greater scatter **(figure 2-49 (c))**. The relationship between yield stress of mortar and slump flow of concrete, and plastic viscosity of mortar and V-funnel flow time of concrete **(figure 2-49 (b), (d))** were slightly weaker.

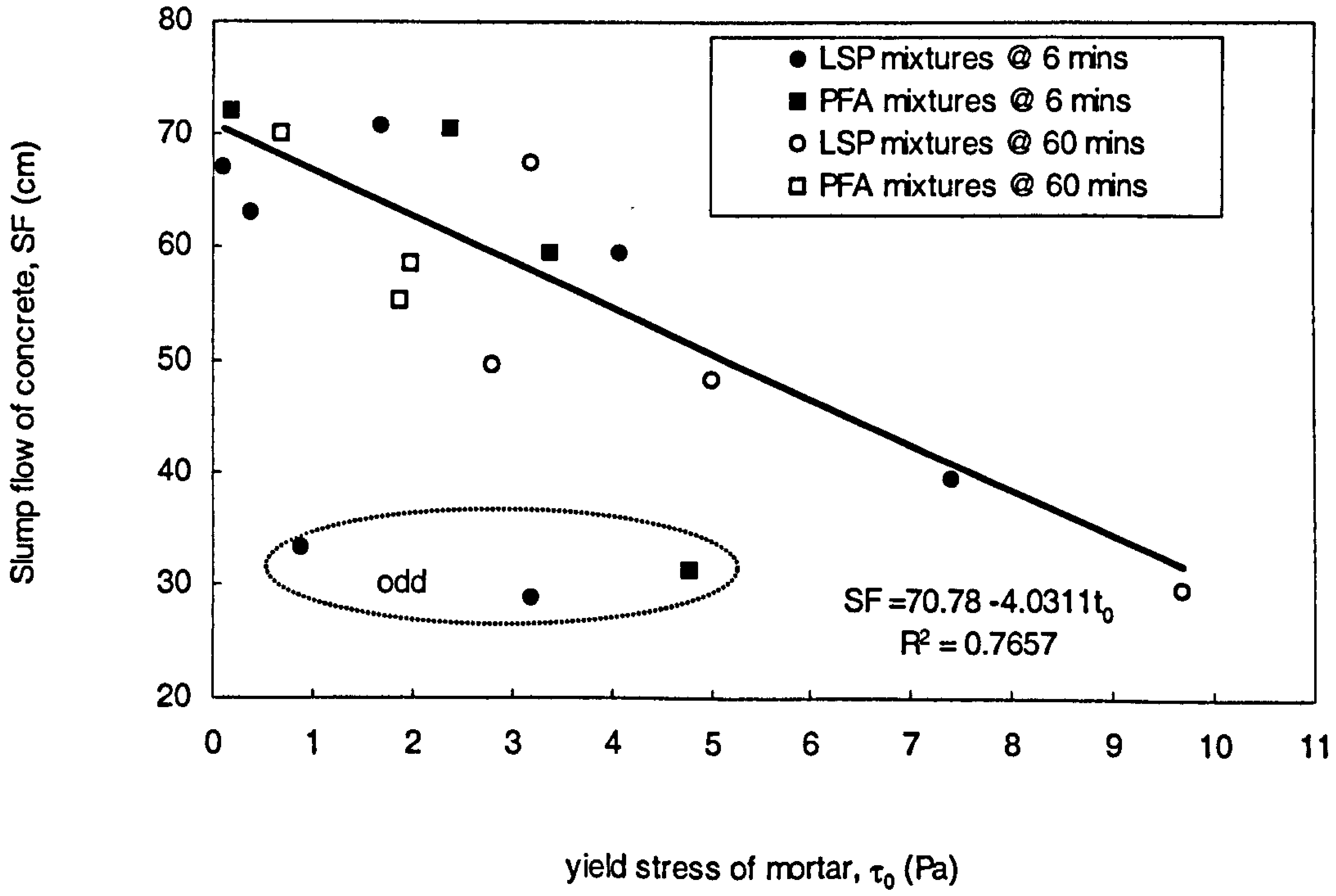
Table 2-9 Test results for fresh properties of concrete and mortar component* [98]

Mix	Mortar properties				Concrete properties		
	Spread, D_m (cm)	V-funnel flow time, T_V (secs)	Yield stress, τ_0 (Pa)	Plastic viscosity, μ_0 (Pa.s)	Slump flow, SF (mm)	V-funnel flow time, T_V (secs)	U-Box, U_H (cm)
LSP1	10.0 (--)	-- (--)	-- (--)	-- (--)	-- (--)	-- (--)	-- (--)
LSP2	13.7 (10.5)	21.2 (--)	3.2 (3.3)	11.0 (10.7)	28.7 (--)	-- (--)	-- (--)
LSP3	14.7 (10.6)	28.5 (--)	0.9 (15.4)	11.5 (11.2)	33.2 (--)	-- (--)	-- (--)
LSP4	31.6 (29.2)	8.7 (11.3)	1.7 (--)	3.8 (--)	70.6 (70.5)	17.5 (27)	35 (35.5)
LSP5	17.5 (13.7)	6.6 (9.3)	7.4 (9.7)	4.8 (6.2)	39.7 (29.5)	14.3 (--)	30.0 (24)
LSP6	29.3 (26.3)	3.3 (4.3)	0.4 (2.8)	2.5 (3.0)	63.0 (49.5)	9.1 (12.1)	35.0 (33.0)
LSP7	(31.6 (29.3)	4.3 (5.1)	0.1 (3.2)	2.6 (3.0)	67.0 (67.5)	7.0 (11.9)	35.5 (35.5)
LSP8	35.1 (--)	2.8 (3.3)	-- (--)	-- (--)	79.0 (--)	11.1 (--)	35.5 (--)
LSP9	24.5 (21.6)	6.1 (7.0)	4.1 (5.0)	3.5 (5.0)	59.5 (48.3)	9.5 (18.0)	34.5 (33.0)
PFA1	10.9 (--)	-- (--)	13.2 (--)	10.3 (--)	-- (--)	-- (--)	-- (--)
PFA2	24.4 (24.2)	7.6 (8.5)	3.4 (2.0)	4.7 (5.8)	59.5 (58.5)	11.7 (15.5)	35.0 (34.5)
PFA3	11.8 (11.0)	41.5 (49.7)	4.8 (1.8)	10.6 (13.9)	31.2 (--)	-- (--)	25.0 (21.5)
PFA4	28.4 (29.2)	7.9 (8.0)	-- (--)	-- (--)	70.5 (71.0)	8.7 (17.8)	35.5 (35.5)
PFA5	25.7 (24.3)	4.7 (6.2)	2.4 (1.9)	3.2 (4.4)	60.0 (55.2)	8.3 (12.6)	35.0 (35.0)
PFA6	33.0 (32.2)	3.1 (3.1)	-- (--)	-- (--)	75.0 (72.0)	4.5 (5.3)	35.5 (35.5)
PFA7	32.1 (31.4)	4.1 (4.3)	0.2 (--)	2.3 (--)	72.0 (73.5)	6.6 (10.9)	35.5 (35.5)
PFA8	33.9 (34.0)	2.6 (3.3)	-- (--)	-- (--)	79.0 (--)	5.0 (--)	35.5 (--)
PFA9	28.5 (27.7)	6.1 (6.8)	-- (0.7)	-- (4.6)	68.0 (70.0)	9.4 (12.9)	35.5 (35.5)

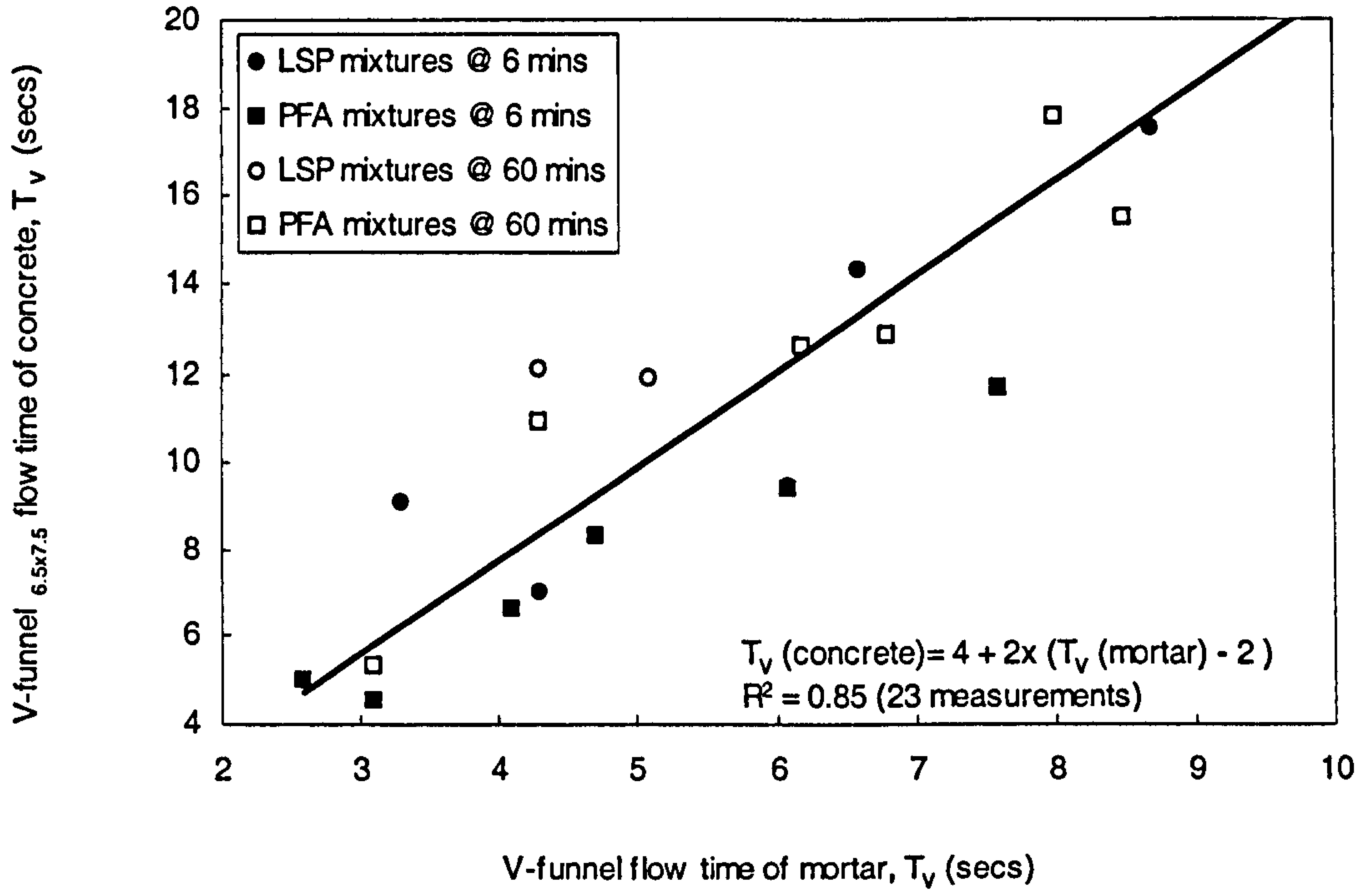
*: all mixes have sand volume ratio of 0.45, and coarse aggregate content 0.3m^3/m^3, ( ): Value obtained at 60 mins after mixing.


LSP mixtures @ 6 mins
PFA mixtures @ 6 mins
LSP mixtures @ 60 mins
PFA mixtures @ 60 mins
SF = 20 + 2.48 x (D_m - 10)
R² = 0.98 (27 measurements)
slump flow of concrete, SF (cm)
spread of mortar, D_m (cm)

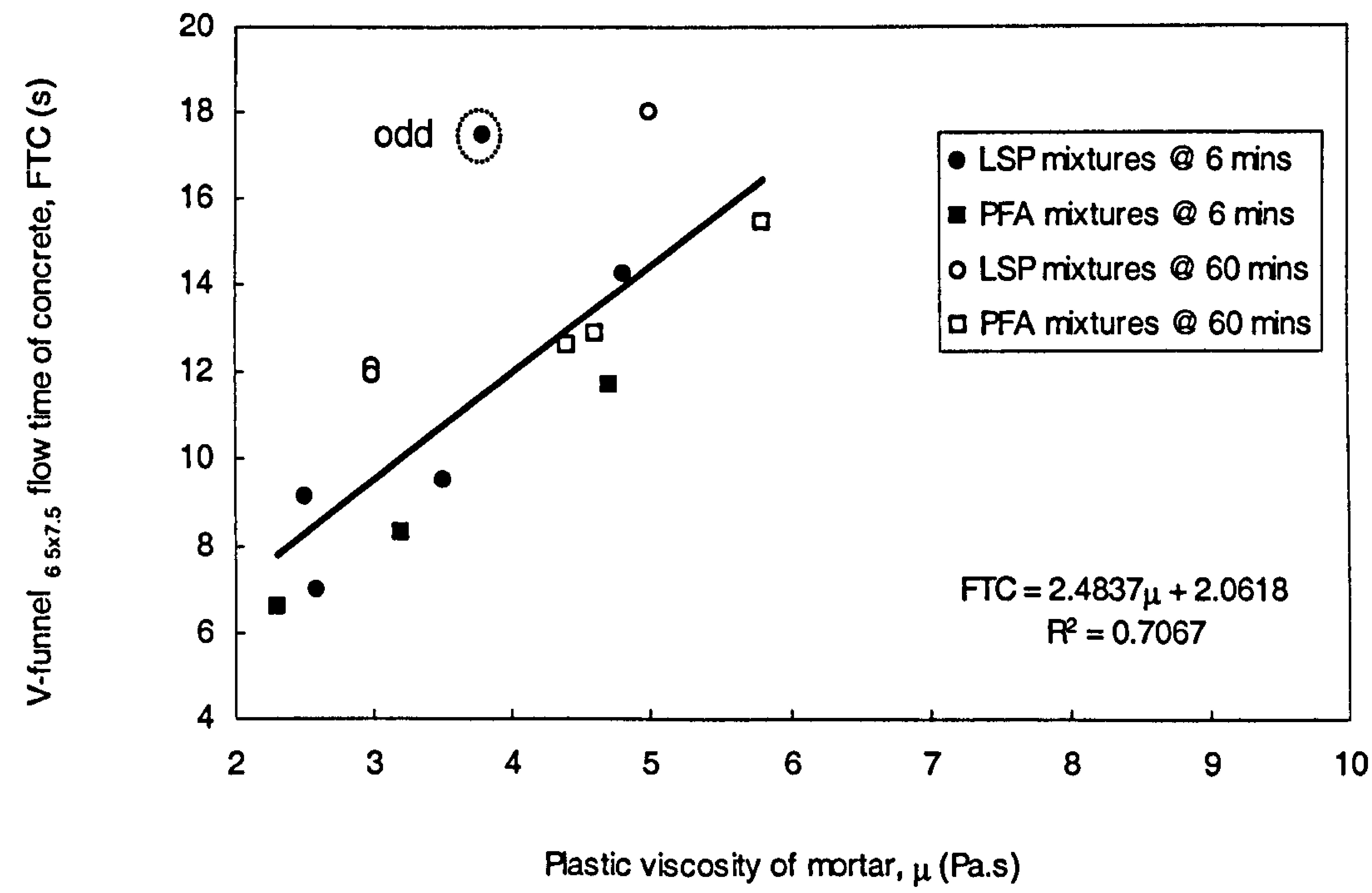
(a)


LSP mixtures @ 6 mins
PFA mixtures @ 6 mins
LSP mixtures @ 60 mins
PFA mixtures @ 60 mins
odd
SF =70.78 -4.0311t_0
R² = 0.7657
Slump flow of concrete, SF (cm)
yield stress of mortar, τ_0 (Pa)

(b)



(c)

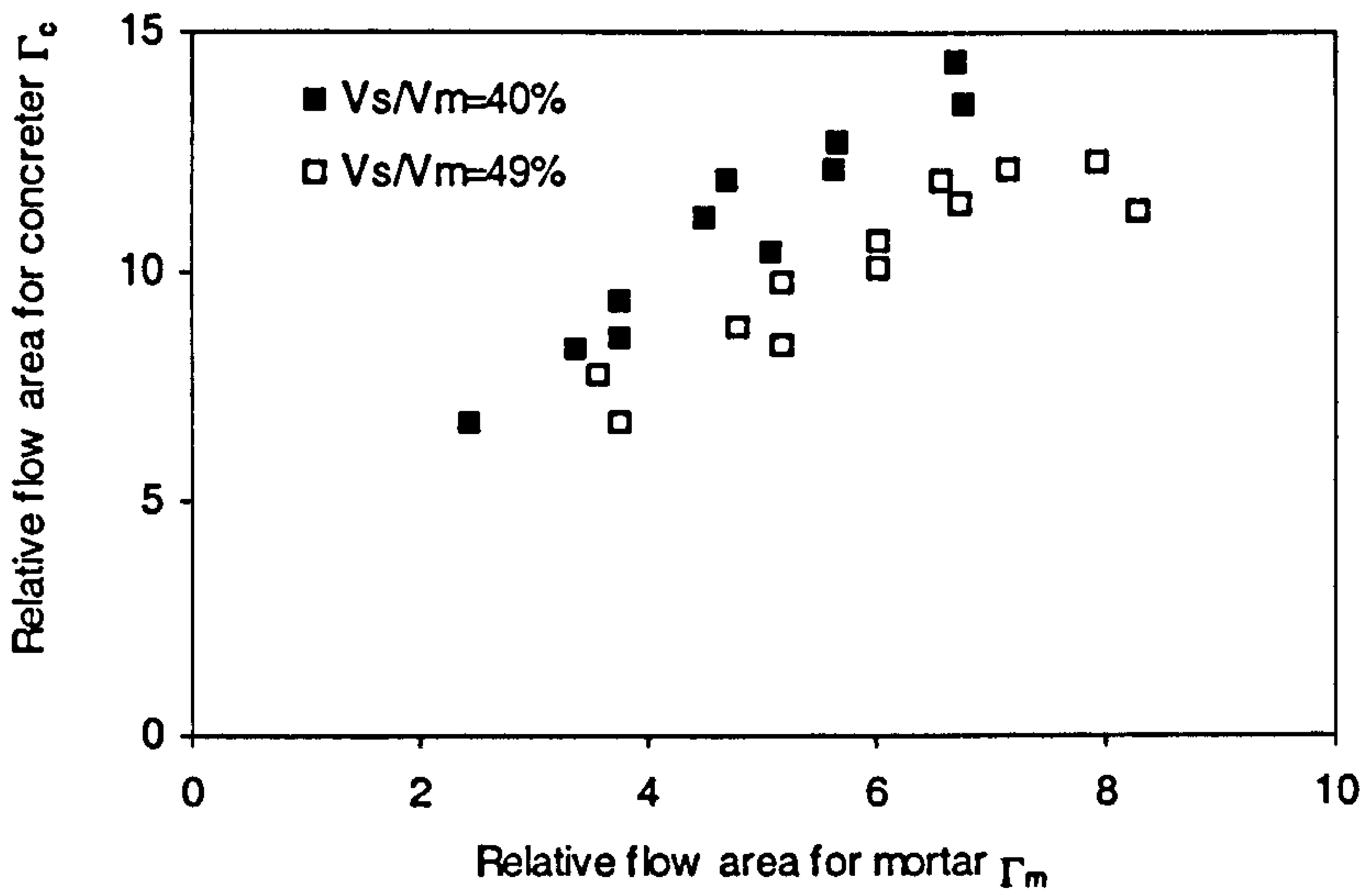


(d)

Figure 2-49 Relationships of fresh properties between concrete and mortar (a) SF - D_m, (b) SF-τ_o, (c) T_V(concrete)-T_V (mortar), (d) T_V- μ (reproduce from [98])

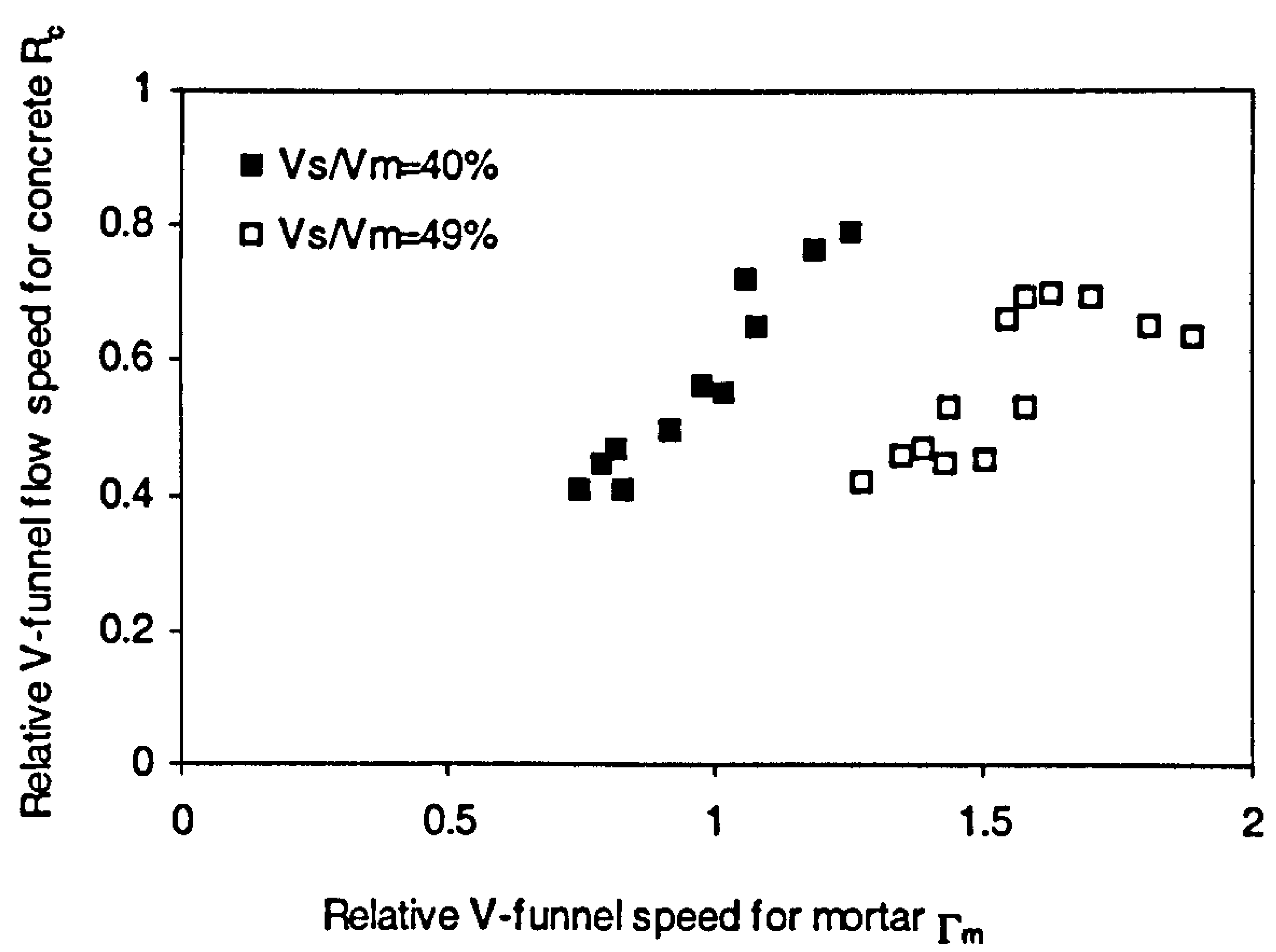
Nagamoto and Ozawa also found that there are good relationships between mortar spread and concrete slump flow, and the V-funnel flow time of mortar and concrete

[99]. These relationships are affected by sand content [99]; a higher spread and lower V-funnel flow time are required for mortar containing higher content of sand to achieve same properties of concrete (**figure 2-50**).



$$\Gamma_m = \left(\frac{Dm}{100}\right)^2 - 1 \text{ ; } \Gamma_c = ((\text{slump flow (cm)}^2\text{-}400)/400$$

(a)

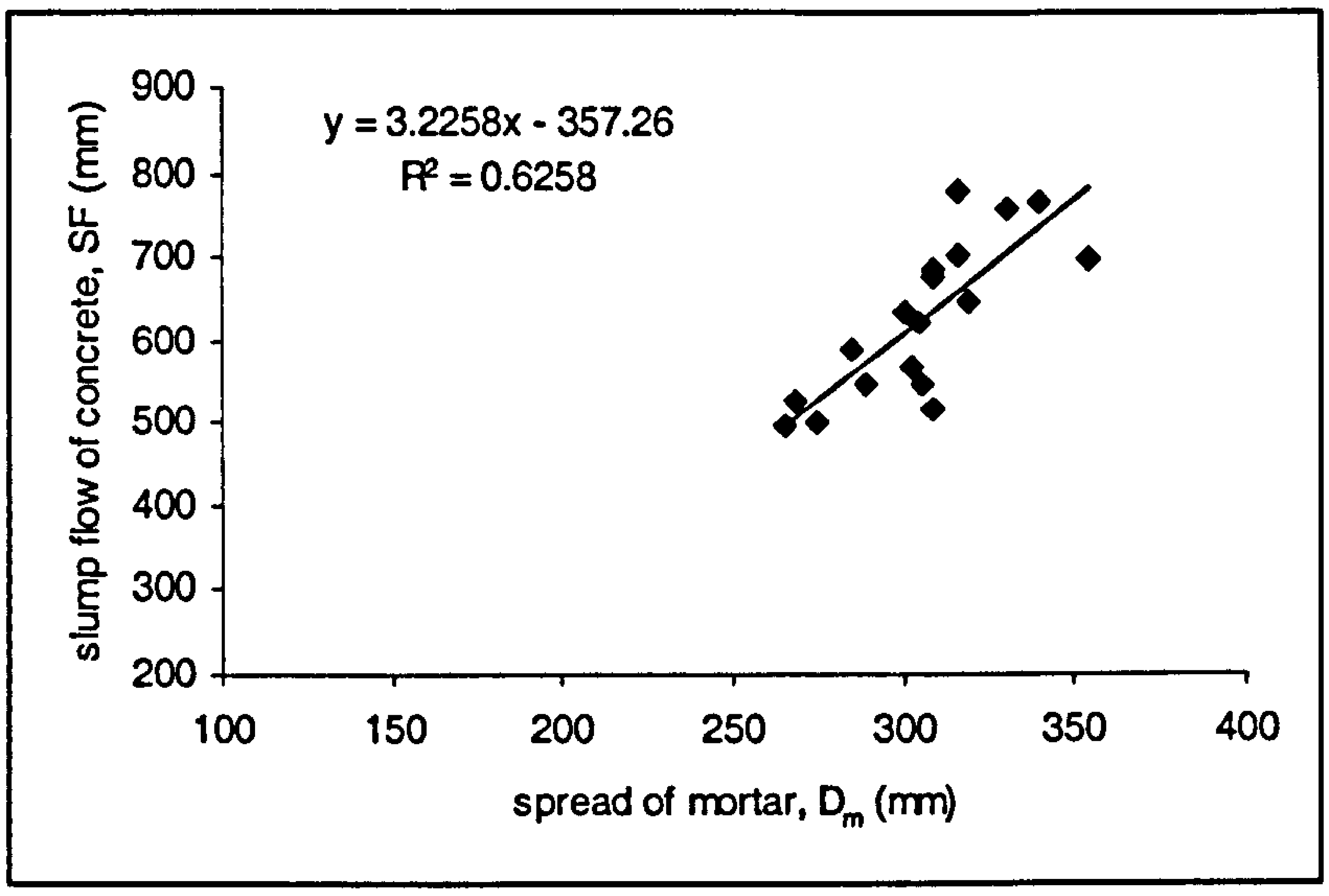


R_m = 10/t; R_c = 10/V-funnel flow time (sec)

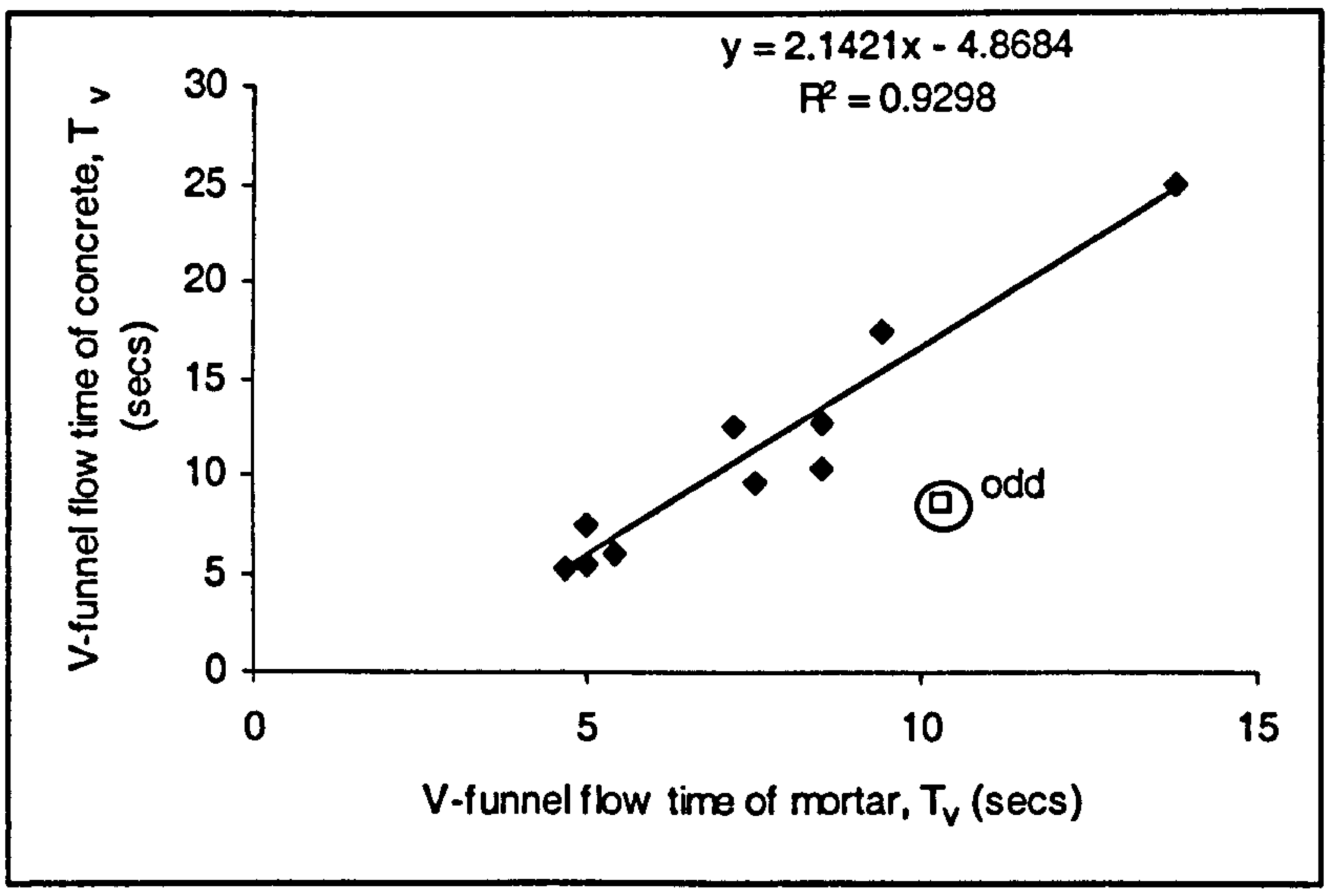
(b)

Figure 2-50 Relationships between fresh properties of concrete and mortar for (a) flow area (b) V-funnel flow time (reproduced from [99])

Chai [29] also briefly studied those relationships and the results are shown in **figure 2-51**. The concretes had 0.3-0.32 m^3/m^3 coarse aggregate and 0.4-0.47 sand volume ratio.



(a)



(b)

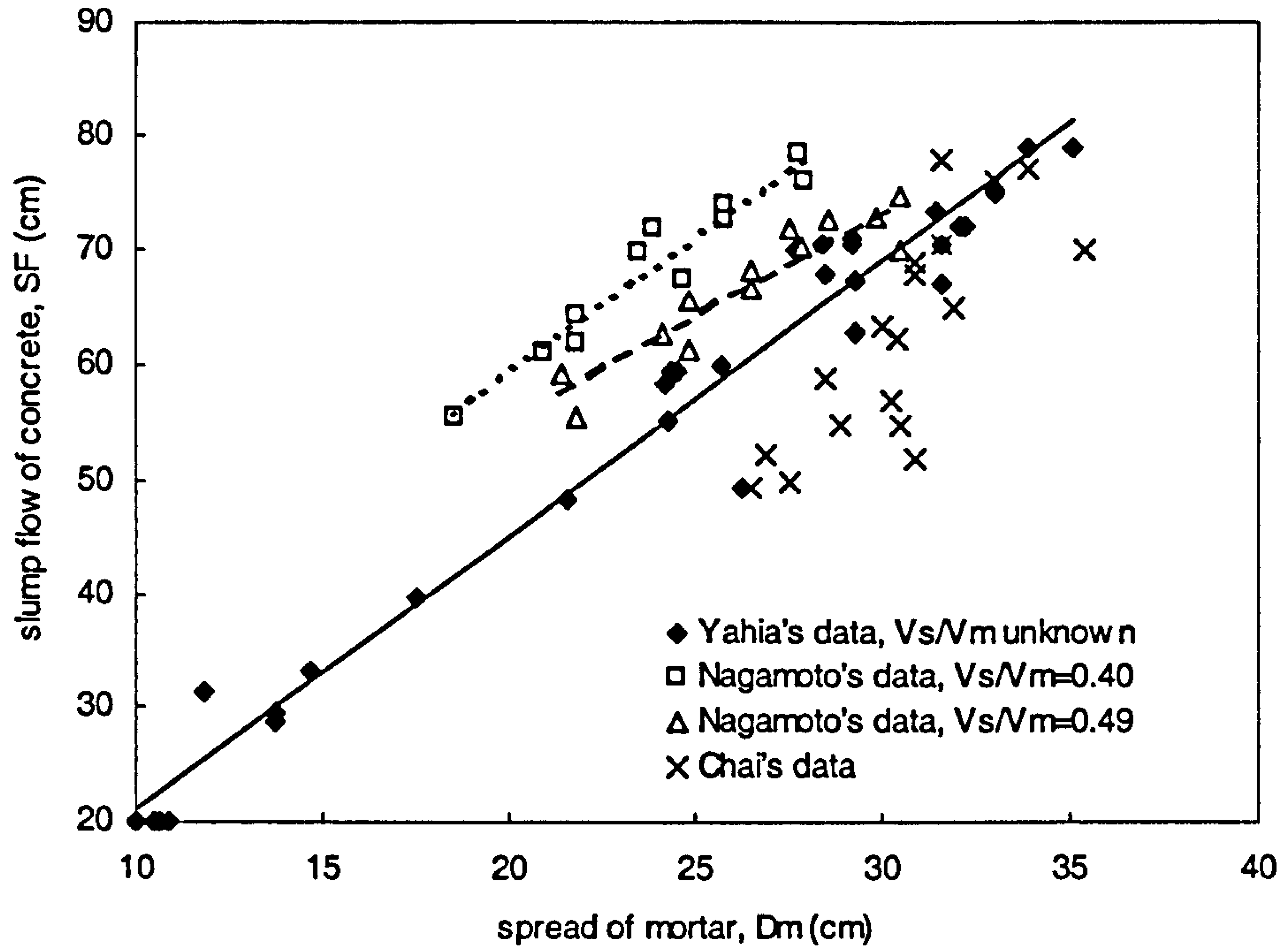
Figure 2-51 Relationships between fresh properties of concrete and mortar (a) SF - D_m, (b) T_V(concrete)-T_V (mortar), (reproduce from [29])

He suggested that for an SCC containing 20 mm maximum size coarse aggregate with slump flow higher 650 mm, the spread of its mortar component should be higher than 310 mm; this is consistent with the result in **figure 2-51 (a)**. He also proposed that the normal range of the V-funnel flow time for the mortar component should be between 4 and 10 seconds in order produce satisfying SCC with V-funnel flow time between 4 and 10 seconds. However, according to **figure 2-51 (b)**, the correspondent V-funnel flow time for concrete is between 4 and 17 seconds, larger than the range by his suggestion. He also suggested that the plastic viscosity of SCC should be kept as low as possible provided no segregation occurs, because excessive viscosity will impair the pumping and placing of the concrete. Therefore the correspondent range for the V-funnel flow time of mortar should be between 4 and 7 seconds.

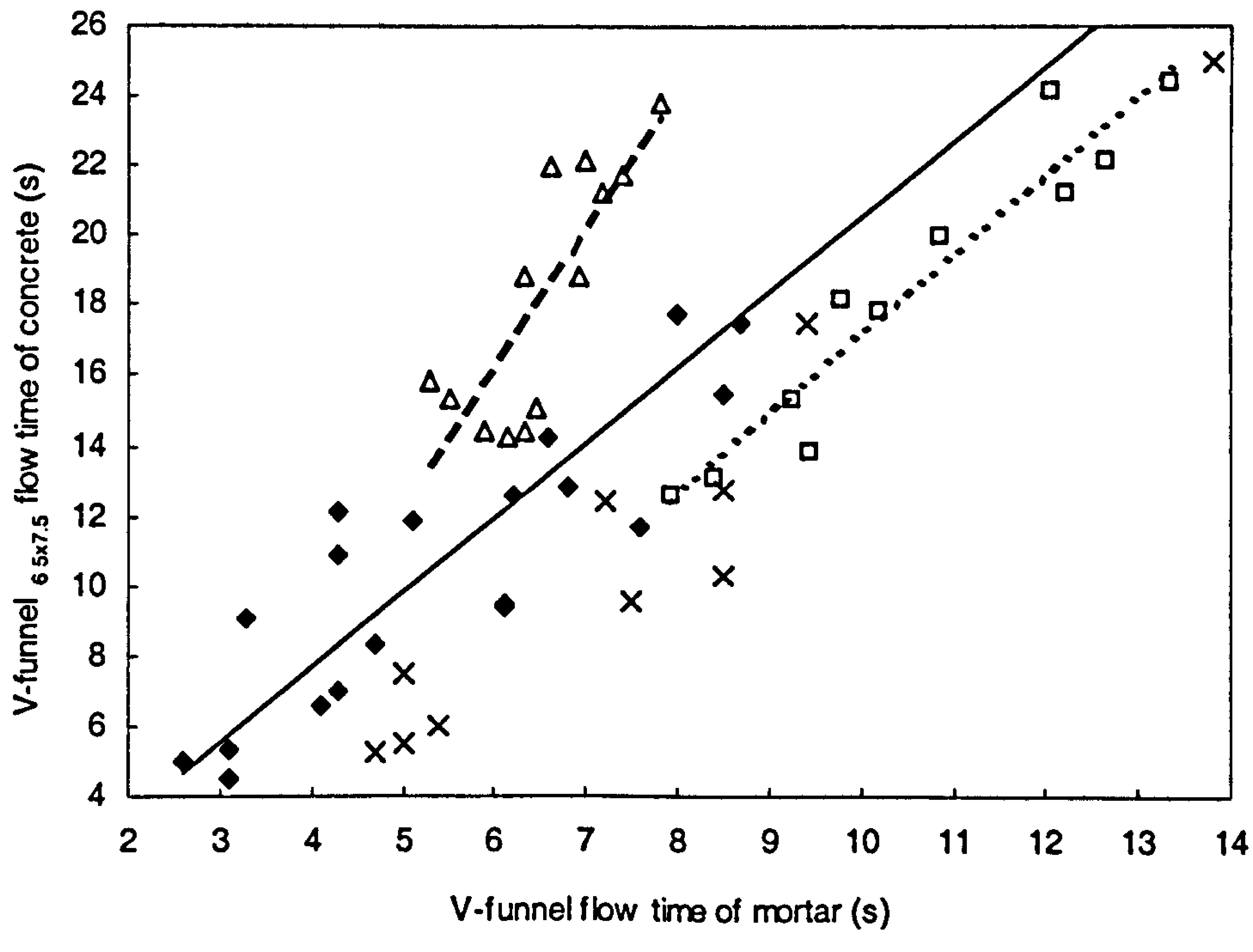
A comparison was made between the relationships obtained by Yahia, Nagamoto and Chai; the results are shown in **figure 2-52**. There is difference between them, and this may be caused by different types of materials used and mix proportions, especially coarse and fine aggregate types and contents.

Jacobs and Hunkeler also investigated the relationship between yield stress of mortar measured with a viscometer called "viskomat PC" and the slump flow of concrete as a first step in SCC mix design by using Swiss materials [101]. The maximum size of sand in the mortar was 1 mm. It was found the relationship could provide a good basis for mix design SCC, and was followed by tests on concrete (**figure 2-53**).

In summary there seems to be a good relationship between the properties of mortar and concrete in SCC. However, many factors may have influence on this, and the difference of definition of mortar makes the results difficult to compare. More study is clearly needed.



(a) Slump flow/spread



(b) V-funnel flow time

Figure 2-52 A comparison of the relationships between properties of concrete and mortar obtained by Yahia, Nagomoto and Chai

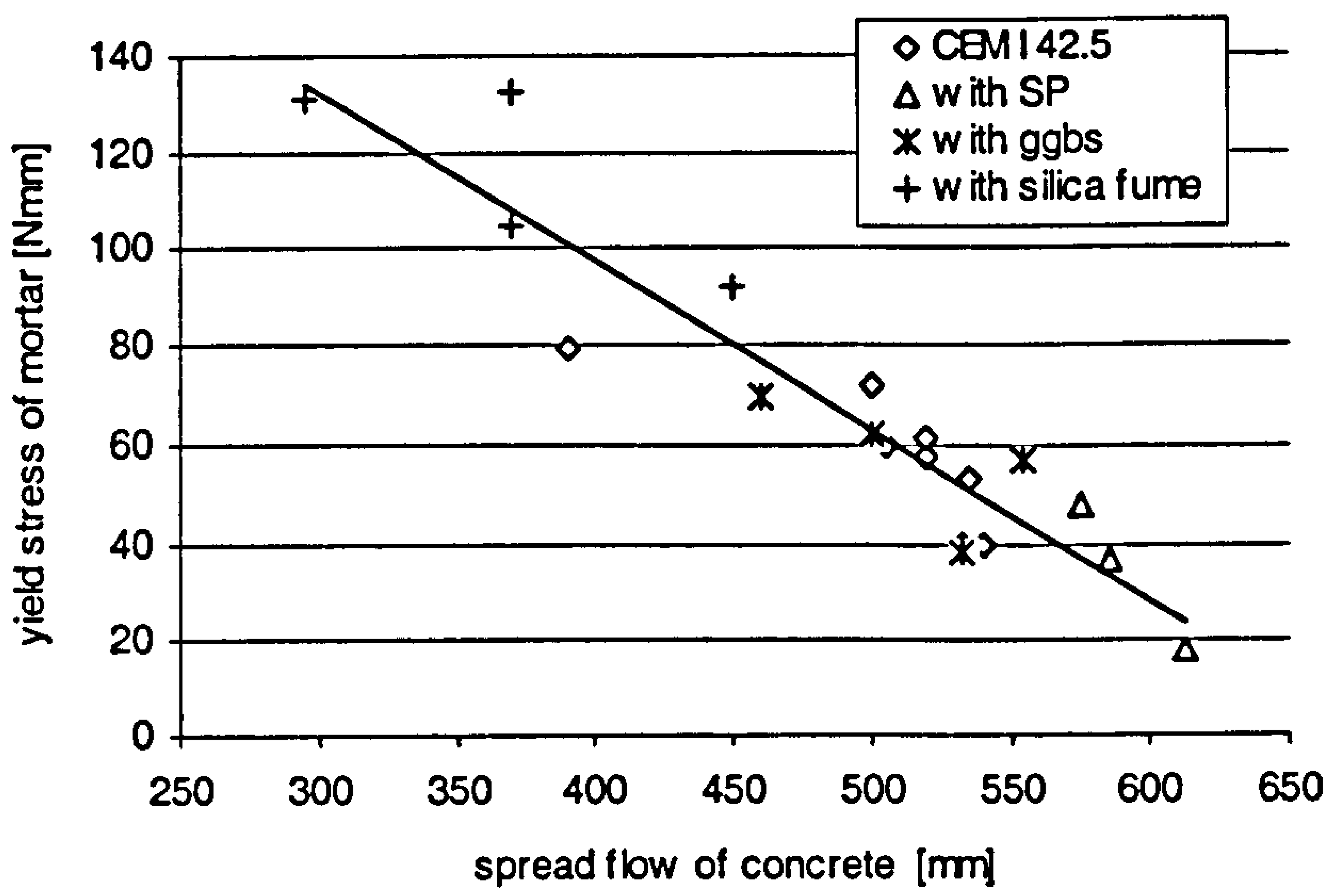


Figure 2-53 Relationship between spread flow of concrete and yield stress of mortar component (reproduced from [101])

2.4.4 Comments

The distinguishing feature of SCC is its fresh properties. Many studies have been carried out on these, and the picture of the effect of various factors can be summarized as follows:

- Coarse aggregate obstructs the flow, therefore a limited content and a maximum size is required. The maximum content is about 30-35 % of concrete volume, which is approximately 50 – 55 % of the aggregate dry rodded bulk density. The maximum size should be less than 0.5 and 0.4 of clearing spacing for 1 dimension and 2 dimension reinforcements respectively, a 20 mm or 25 mm maximum size is normally used. The grading has no significant effect, but a round shape and high packing density is preferable because these will reduce the flowing resistance and the required of paste content.

- Fine aggregate has two roles in SCC. On one hand it works in the same way as coarse aggregate to obstruct flow, but on the other hand it works with the paste to provide lubrication between the coarse aggregate particles. The contents within a range of 40%-50% of the mortar volume are required. Too high a content will cause insufficient flow and too low a content will reduce the mortar plastic viscosity and the required paste content will substantially increase. Medium size sand with round particle shape provides better fresh properties.

- Powder and admixture are the most important component. The paste fills the voids and provides the lubrication between aggregate particles to enable the concrete to flow, and preventing segregation. The following factors are important.
    1. The chemical composition of the powder affects the efficiency of the superplasticizer. Low C_3A content cement is recommended for SCC.
    2. The physical properties of the powder also affect the flowability. Good particle size distribution is very beneficial for making low powder content SCC.
    3. Superplasticizer can improve flowability by lowering yield stress without seriously decreasing the plastic viscosity comparing to water.
    4. There is a range of water/powder ratio for a mix to achieve a filling height more than 300 mm with U-box test, for example, for a 100% belite cement mix with sand/mortar ratio 0.45 and a coarse aggregate content 50% of its dry rodded bulk density, this range is 0.26-0.29 water/cement ratio by weight.
    5. There are many advantages and a few disadvantages of adding Welan gum in SCC. The details have explained earlier.

Not surprisingly each component of the powder has an effect on the fresh properties which is dependent on the characteristic of each component and the physical and chemical interaction between them.

There is, however, a lack of detailed information on these important effects, especially in the following areas.

1. The efficiency of different superplasticizer in SCC.
2. The fresh properties of different blends of powders, such as binary and ternary systems.
3. Superplasticizer and viscosity agent compatibility.
4. The effect of a viscosity agent when it is combined with different combinations of powder.

- Very good workability retention is required for SCC to ensure self-compactability at casting. The key factor is the types of admixtures and dosage, which also depend on other factors, such as types of powder and water/powder ratio. However, there is lack of information on the combination of these effects, and is worth investigating.

- There appear to be a good relationship between the properties of the mortar and the concrete, and the properties of SCC may be predicted by mortar test. In mix design, this can reduce the number of tests on concrete and shorten the whole procedure. However, many factors will influence in this relationship, and the different definitions of mortar make the results difficult to be compared. Investigation the relationship with a variety of UK materials will be beneficial.

2.5 Rheology

It is possible in principle to describe fresh properties of SCC in rheological terms, and to relate the rheological properties of the paste, mortar and concrete. If this is achieved, then the parameters will be well defined and scientifically measurable, comparable and transferable. One result will be that simple test methods (slump flow *etc.*) will be scientifically explained in rheological terms.

In this section the rheological models and equations for paste, mortar and concrete, and the relationships with respective simple test methods are briefly reviewed. The effect of the constituents on the rheological properties was reviewed in section 2.4 when discussing the fresh properties.

2.5.1 Rheological models and equations for paste, mortar and concrete

2.5.1.1 Rheology of Paste

Cement paste is a highly concentrated suspension, which the rheological relationship between shear stress and shear rate is far more complicated than a dilute suspension obeying the Newtonian equation. It is generally agreed that a paste can be described with the Bingham model, but it also shows shear thinning and sometimes shear thickening behaviour in some circumstances, such as with a high content of superplasticizer [102-104], and also it has time-dependent rheological properties. In some cases, it may also show Newtonian behaviour [104].

Many attempts have been made to establish rheological equations for the rheology of pastes, especially those for viscosity. **Table 2-10** shows some of these suggested. These equations were based on theoretical models containing of the variables of the characteristics of the suspension such as particle concentration, maximum packing density *etc*, and the coefficients are obtained by empirically.

Table 2-10 Equations for plastic viscosity of paste

Name	Equations*	comment
Struble & Sun [104]:	$\eta_{re} = (1 - \frac{\Phi}{\Phi_M})^{-[\eta]\Phi_M}$	Testing was carried out in a cylindrical viscometer using ASTM type I cement, white portland cement and type V cement, and the equation for apparent plastic viscosity of superplasticized paste was obtained based on the Krieger-Dougherty model.
Murata & Kikukawa [105]	$\eta_{re} = \left(1 - \frac{\Phi}{\Phi_M}\right)^{-(K_1\Phi + K_2)}$	It is said to be based on a modified Roscoe equation. It was defined from tests on four types of cement tested with a cylindrical viscometer. Superplasticizer was not used and the water/cement ratio was in the range of 0.4~1.0 by weight.
Kakuta [106]:	$\eta_{re} = 1 + \frac{3}{1/\Phi + 1/0.52}$	This is modified from the Mori-Ototake equation. Experimental results were obtained by using a Brookfield type viscometer and steel-ball-pull-up viscometer for a range of volume concentrations of cement particles.

*: The meaning of all the symbols are shown in the "List of Symbols"

Apparently several factors affect the viscosity, including the particle concentration, the degree of the particle flocculation and the maximum packing density by volume which is dependent on the characteristics of the particles such as particle shape, particle size and its distribution, *etc.* However further comparison of these equations is difficult because the experimental conditions to obtain the coefficients for each equation are different in each case.

2.5.1.2 Rheology of Mortar and Concrete

A few empirical and semi-empirical equations have been proposed for the rheology of mortar and concrete, mainly for plastic viscosity. These are based on following:

- Mortar and concrete can be considered as suspensions, assuming:
  1. These are continuous, homogenous and isotropic mixes.
  2. Concrete can be considered as a dispersion of coarse aggregate in a liquid medium of mortar, which in turn is considered as a dispersion of fine aggregate in a liquid medium of paste, which is a suspension of solid particles (cement) in a liquid medium (water). Alternatively, the concrete can also be considered as a multiphase material in which water is a continuous phase [107].

- The rheology of mortar and concrete is generally described by the Bingham model, which is characterized by yield stress and plastic viscosity. However, it has also been reported that for some concrete, such as self-compacting concrete, the Herschel-Bulkley model is more appropriate [108].

Table 2-11 lists some of the equations established for the plastic viscosity of mortar and concrete. Most of these give the relative plastic viscosity of mortar to paste or concrete to mortar which means the necessity of knowing plastic viscosity of paste, except for Hu's equation, which directly relates to the concrete compositions and the constituent characteristics. Again, comparison of these equations is difficult because of the different experimental conditions from which they are derived. This is clearly reflected in **figure 2-54** which shows the similarity between Murata and Kakuta equations but significant difference from the Nishibayashi equation for mortar. Nevertheless, it is clear that the relationship between the plastic viscosity of mortar and sand content is not a linear; greater increase with the increase of sand content is apparent. This implies that a small change in the plastic viscosity of paste will result in greater change of that for the mortar with a high sand content.

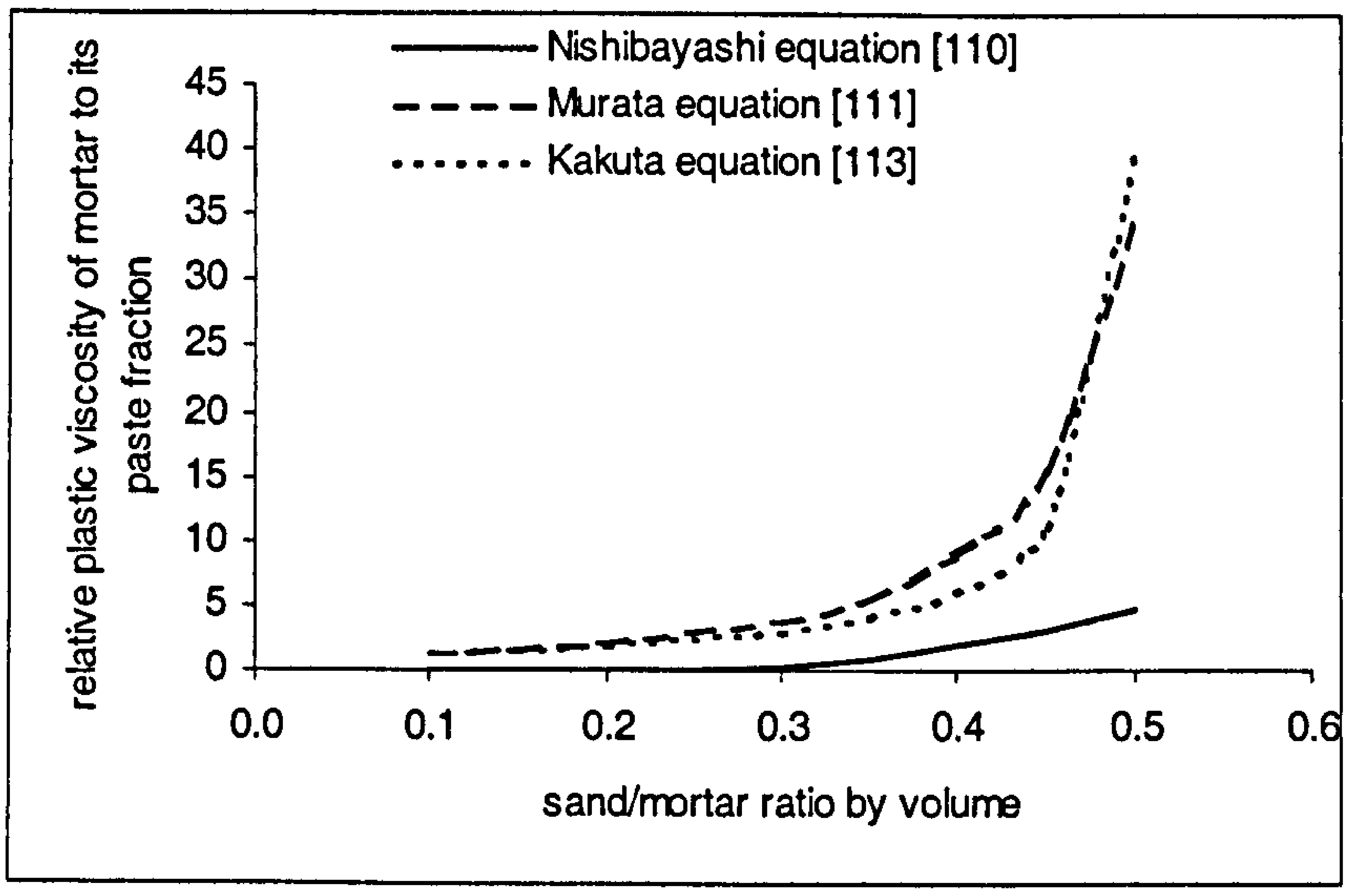


Figure 2-54 Comparison of three different equations for plastic viscosity of mortar

Table 2-11 Equations* for plastic viscosity of mortar and concrete

Name	Mortar	Concrete	comment	Note
Nishibayashi [109]:	$\log\eta_{re} = -2.37\times10^{-2}F_p + 1.06$ $F_p = \frac{(1-(V_s\times10^{-2}/C_s))\times10^4}{S_s\times V_s}$	$\log\eta_{re} = -0.29Fm + 1.59$ $F_m = \frac{(1-Vg\times10^{-2}/Cg)\times10}{Sg\times V_g}$	A pull up viscometer was used to test both mortar and concrete for SCC	F_p: thickness of paste covering the sand particles; V_s: sand volume ratio in mortar; C_s: maximum sand volume concentration; S_s : specific surface area (cm^2/cm^3) of sand F_m: thickness of paste covering the coarse aggregate particles; V_g: aggregate volume ratio in concrete; C_g: maximum aggregate volume; S_g: specific surface area (cm^2/cm^3)
Murata and Kikukawa [110,111]:	$\eta_e = \left(1-\frac{\Phi}{\Phi_M}\right)^{-(aFM_m+b)}$	$\eta_e = \left(1-\frac{\Phi}{\Phi_M}\right)^{-(aFM_c+b)}$	A series of tests were carried out for both mortar and concrete with a cylindrical viscometer. Superplasticizer was not used during the tests.	FM_m: fineness modulus of sand FM_c: fineness moudulus coarse aggregate A, b: coefficient
Kakuta [112,113]	$\eta_{re} = 1 + \frac{3}{1/\Phi + 1/\Phi_M}$		The experiments were carried out with mortar and concrete for SCC with a Brookfield type viscometer.	
Hu & Larrard [114]	$\mu = \mu_0(1+K_sP_s)\left(1-\frac{\phi_F}{\alpha_F}\right)^{-2.5\alpha_F}\left(1-\frac{\phi_C}{\alpha_C}\right)^{-K\alpha_F}\left(1-\frac{\phi_G}{\varepsilon_G}\right)^{-K\alpha_G}$ $\phi_F = \frac{V_F}{V_0+V_F};\phi_C = \frac{V_c}{V_0+V_F+V_C};\phi_G = \frac{V_G}{V_0+V_F+V_C+V_G}$ $\alpha_X = 1-0.45\left(\frac{d_X}{D_X}\right)^{0.19};X = F,C,G.respectively$		An equation was established for SCC by experiments based on a suspension model in which multiphase particles from cement to coarse aggregate were suspended in water. The BTRHEOM apparatus was used for rheology measurement.	μ_0: viscosity of water (0.001 Pa.s at 20 ^{0}C); P_s:proportion of superplasticizer as fraction of its saturation dosage; Φ_F, Φ_C, Φ_G:volume concentration of silica fume, cement, and aggregate, respectively; V_0,V_F,V_C,V_G :partial volumes of water, silica fume, cement, and aggregate, respectively; α_F, α_C, α_G:maximum packing density of silica fume, cement and aggregate, respectively; d_x, D_x, :sieve sizes corresponding to 10% and 90%, respectively of the material concerned passing the sieve (I.e. silica fume, cement and aggregate).

*: The meaning of the symbols are shown in the "List of symbols"Relationships between the rheological properties and simple test results

Rheology of concrete can be defined by two Bingham constants, i.e. yield stress and plastic viscosity, suggesting there is relationship between these two properties and values obtained by simple test methods, such as slump flow or V-funnel time. Several attempts have been made to find relationships, and most studies have been on concrete.

Mortar

The only information found for mortar was that given in **table 2-9**, plotted in **figure 2-54**. It can be seen that except for a few odd data points there is a good relationship between spread (obtained at low shear rate) and yield stress, and V-funnel flow time (obtained at high shear rate) and plastic viscosity. Unfortunately, there is no confirmation from others.

Concrete

Ferraris *et al* [115] have predicted the following relationship between slump (S) and yield stress (τ_0),

$$\tau_0 = \frac{\rho}{347}(300 - S) + 212 \qquad (2\text{-}5)$$

where

ρ: density of concrete,kg/m^3,

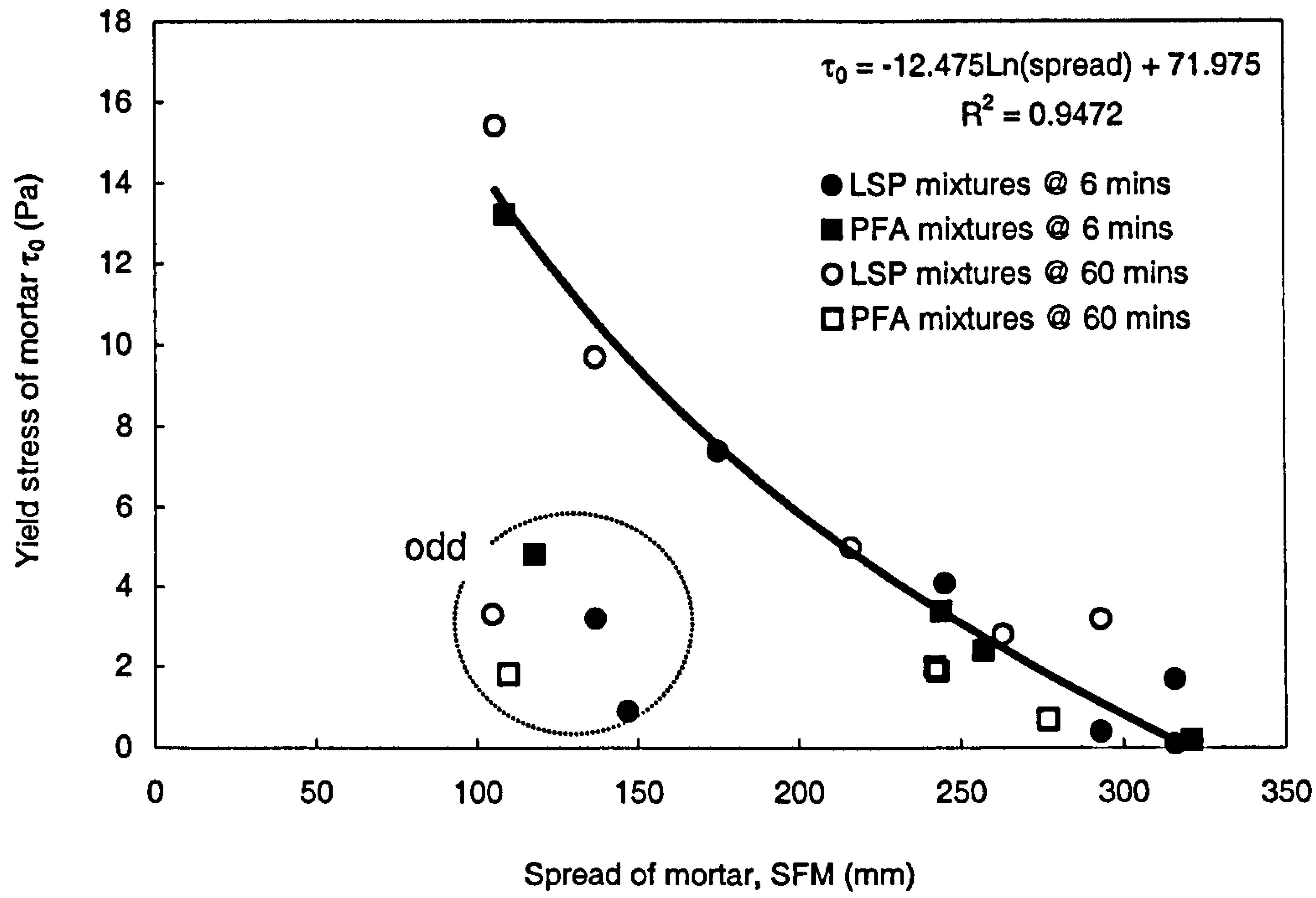
S: slump of concrete, mm.

and also have related the plastic viscosity to the time for concrete to fall a distance of 100 mm (T) in slump test :

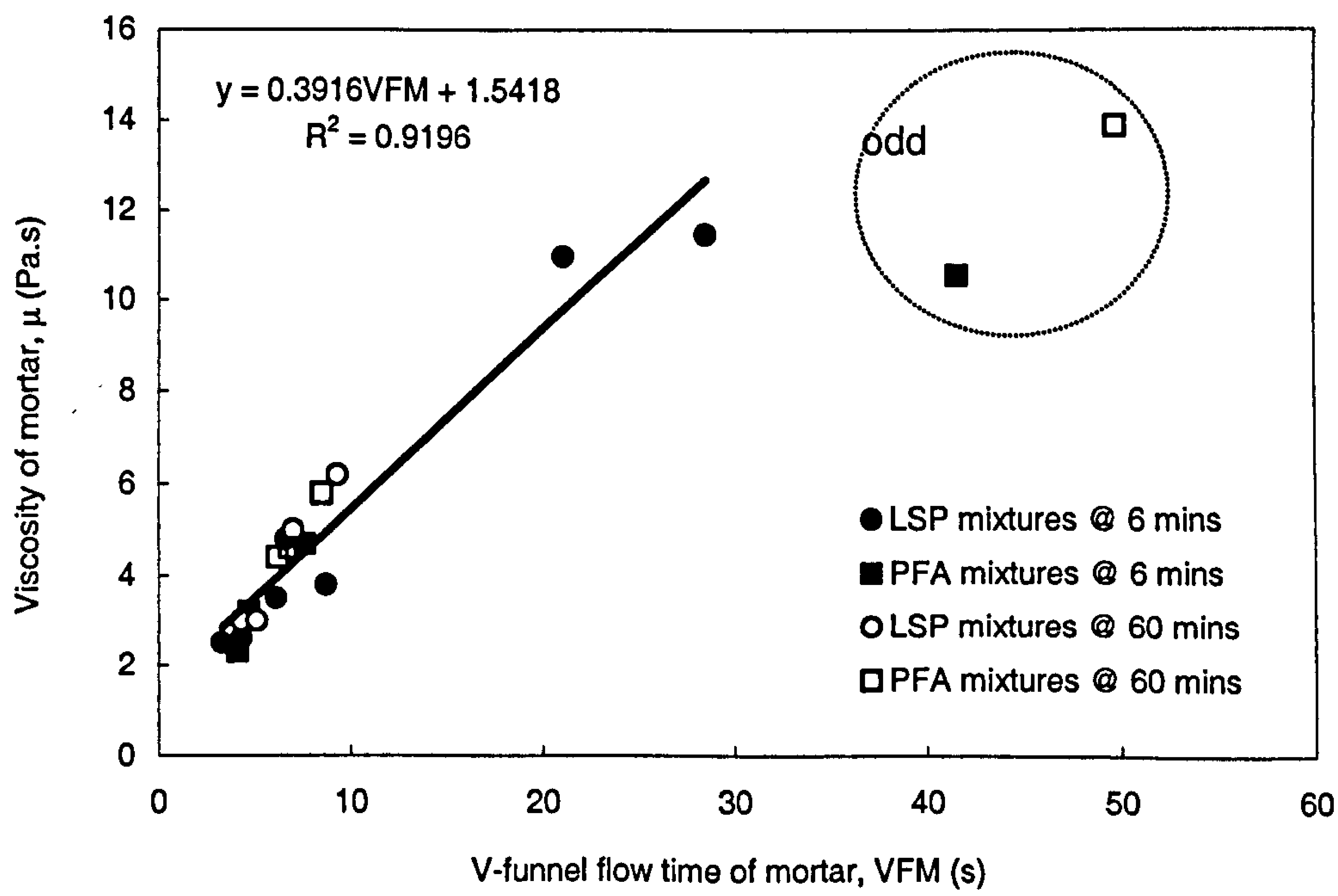
$$\mu = \rho T \cdot 1.08 \cdot 10^{-3} \cdot (S - 175) \qquad \text{for } 200 < S < 260 \text{ mm} \qquad (2\text{-}6)$$

$$\mu = 25 \cdot 10^{-3} \rho T \qquad \text{for } S < 200 \text{ mm} \qquad (2\text{-}7)$$

There have been several investigations on the relationship between rheological properties and the values obtained from slump flow test for high flowing and self compacting concrete.



(a)



(b)

Figure 2-55 Relationships between (a) spread and yield stress of mortar (b) V-funnel flow time and plastic viscosity of mortar (reproduced using data in table 2-9)

Kurokawa *et al* [32] reported that yield stress and plastic viscosity can be predicted from slump flow and the time to 500 mm slump flow with the following equations:

$$\tau_0(SF) = \frac{\rho g_0 Vol.}{25\sqrt{3}\pi SF.^2}\times 10^8 \tag{2-8}$$

$$\mu(SF, T_{500}) = 125.3\left(1-\frac{4\times 10^4}{SF.^2}\right)\left(1-\frac{25\times 10^4}{SF.^2}\right)T_{500} \tag{2-9}$$

where,

g_0	:acceleration due to gravity (= 9.8067m/s^2);
H	:initial height of material (=30 cm);
Vol.	:volume of slump cone (m^3) =8.6*10^{-3} m^3
SF	:slump flow (mm);
D	:bottom radius of slump cone (= 200 mm);
T_{500}	:the time to achieve 500 mm slump flow.

Sedran [116] has also confirmed that, for SCC, the yield stress and plastic viscosity could be roughly estimated with standard slump cone, using:

$$\tau_0(SF) = (808 - SF)\frac{\rho g_0}{11740} \text{ (mean error 95 Pa)} \tag{2-10}$$

$$\mu(SF) = \frac{\rho g_0}{11740}(0.0261SF - 2.39)T_{500} \text{ (mean error 35 Pa.s)} \tag{2-11}$$

All those equations suggested that those relationships between rhological properties and simple test results are affected by the density of concrete and acceleration.

Comparing Kurokawa's and Sedran's equation by plotting them on same figure, significant differences are found in **figure 2-56**. The reasons may be that these two equations were obtained from different mixes, the first is from normal to high flowing concrete, the second is from SCC only, and different rheology equipment were used. Clearly further study in this area is needed.

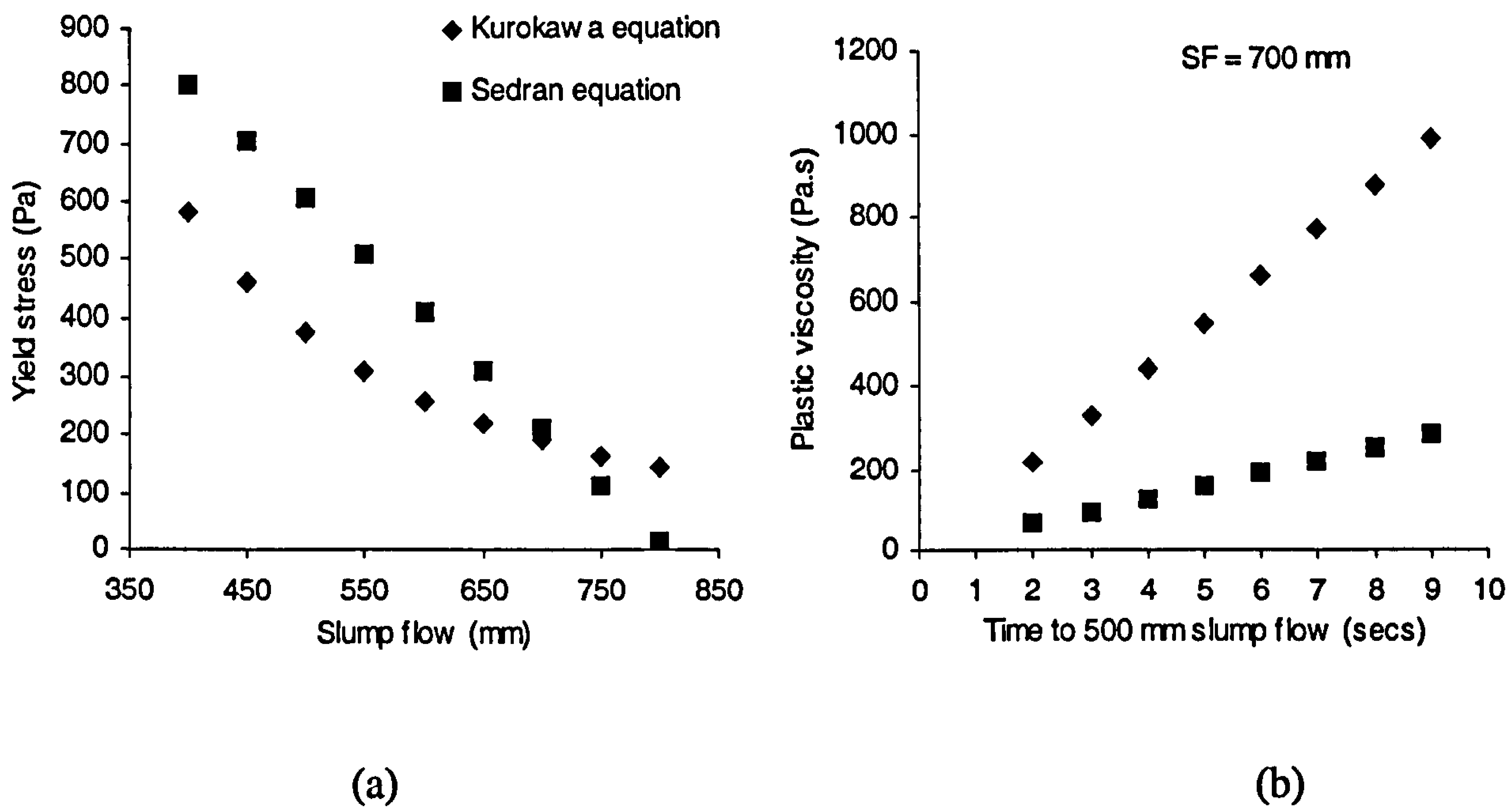
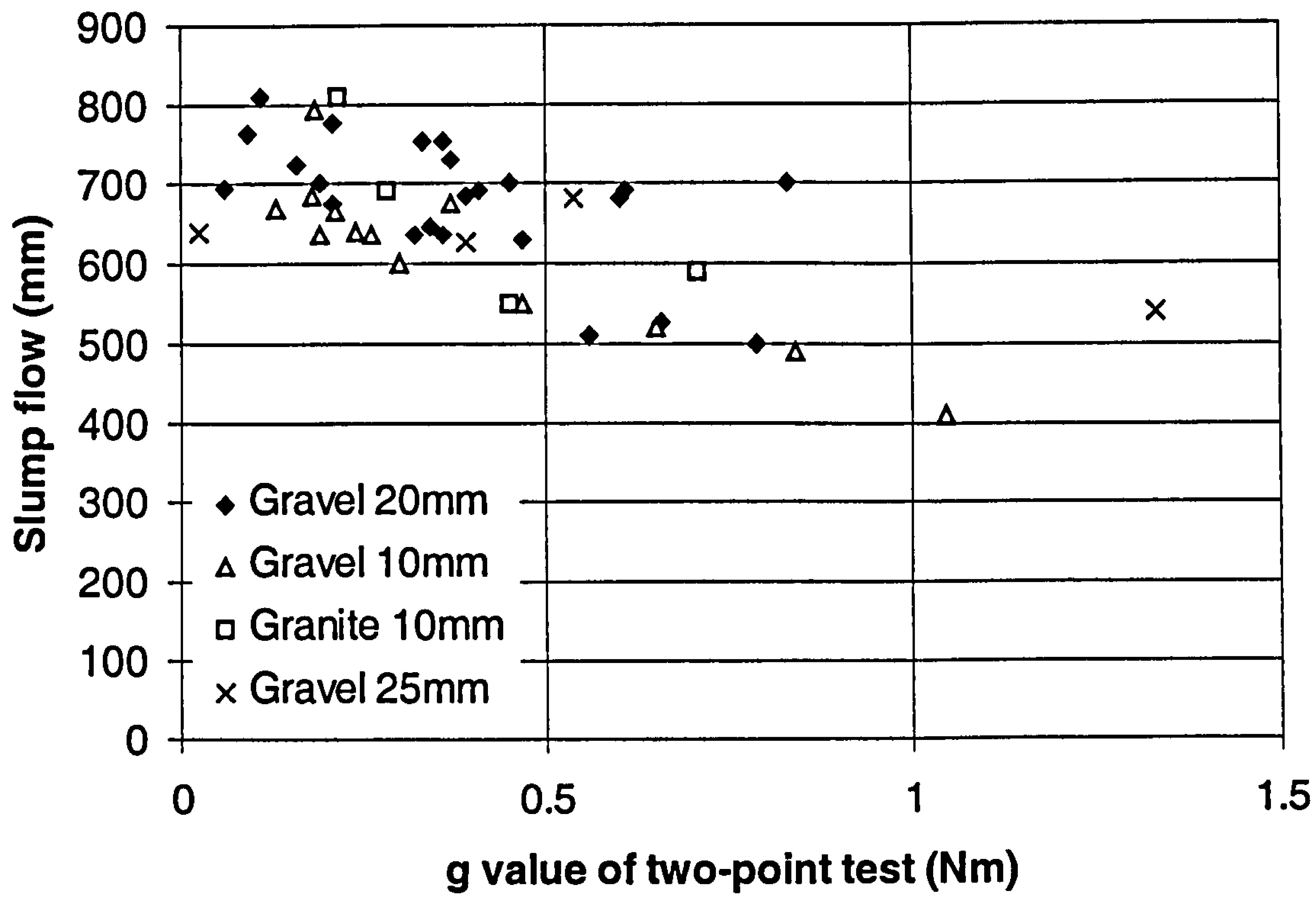


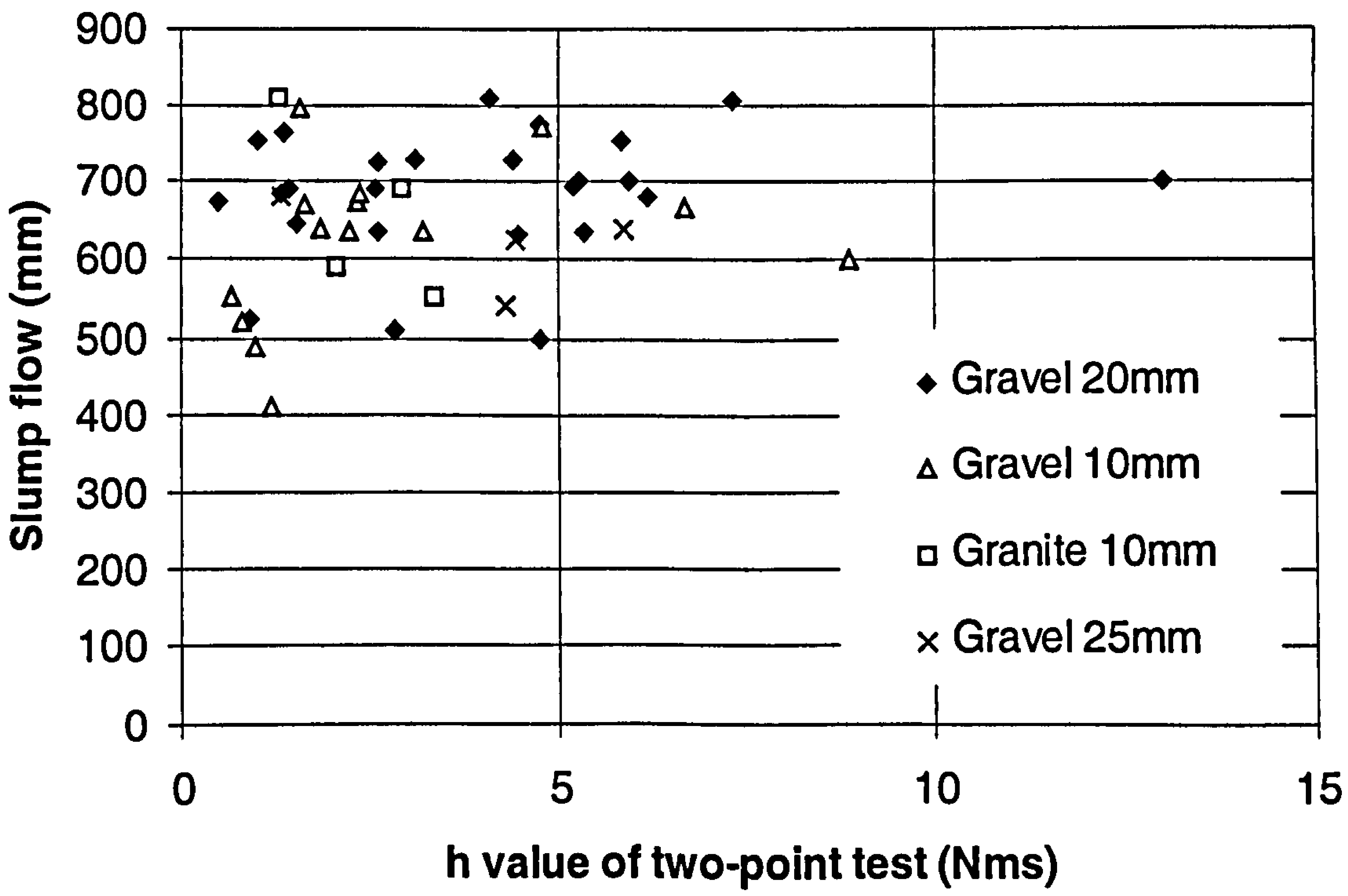
Figure 2-56 Comparison of Kurokawa and Sedran equations for (a) slump flow and yield stress (b) time to 500 mm slump flow and plastic viscosity

Chai has obtained the relationships between the Bingham constants of g and h measured with the two points and slump flow and V-funnel time results on SCC [29] **(Figure 2-57)**. He concluded that there is a broad correlation between g and slump flow while the h values have a close relation with V-funnel flow time.

However, Emborg [118] concluded, by studying the correlation between the target rheological properties measured by the BML test and the corresponding data of slump flow and the time to 500 mm slump flow, and that the correlation between the results is very weak **(figure 2-58)**, suggesting many factors may affect those relationship.

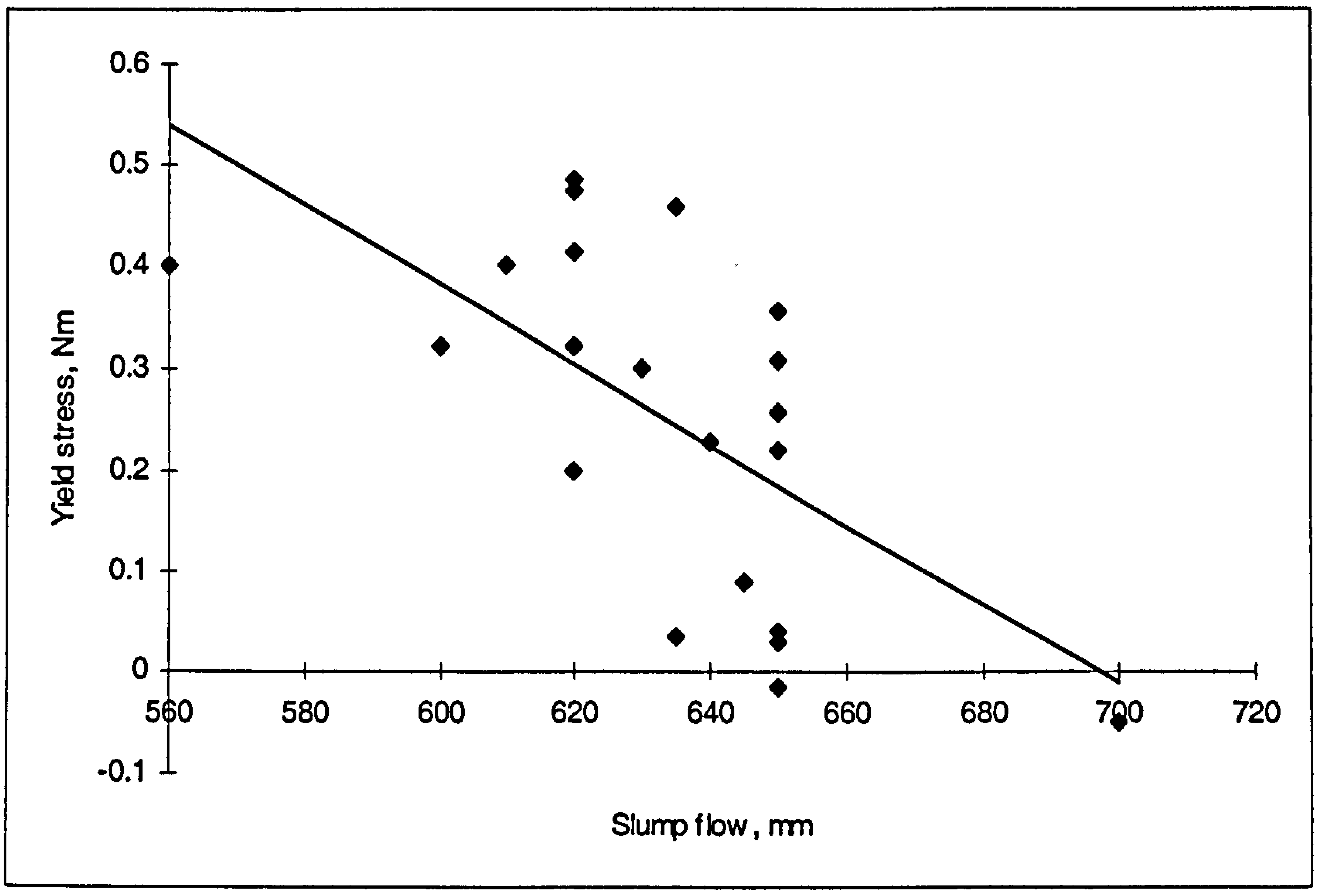


(a)

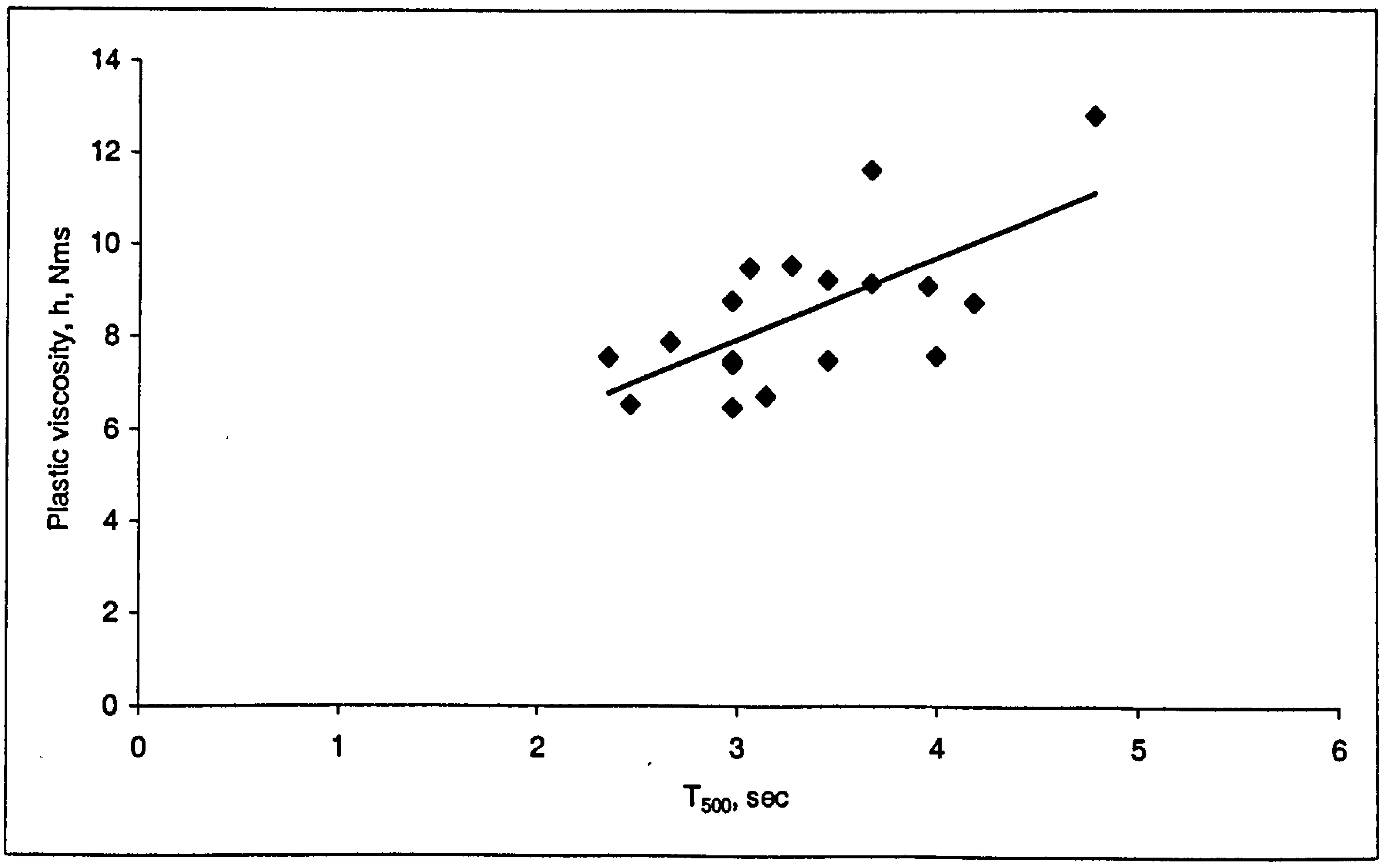


(b)

Figure 2-57 Relationships between (a) slump flow and yield stress (b) V-funnel (7.5*7.5 mm) time and plastic viscosity for SCC (reproduced from [[29])



(a)



(b)

Figure 2-58 Relationship between (a) slump flow and yield stress (b) T_{500} and plastic viscosity (reproduced from [118])

2.5.2 Comment

Establishment of the rheological equations for paste, mortar, concrete and their relationships to simple test results is important to help understand their flow behaviour, but the analysis could be very complex. The number of different equations and testing methods indicates the degree of difficulty in establishing of widely accepted equations and test methods. This may be for the following reasons.

1) Concrete is a complex suspension with the particle sizes ranging from a 1 μm powder to 20 mm coarse aggregate or even larger. The hydration of the cement makes the rheology even more complicated.
2) Some of the parameters used in the equations are difficult to be obtained in a normal laboratory, such as the specific surface area of powder, sand and coarse aggregate. Consequently, it is difficult to apply these equations in practice.
3) Various types of apparatus are used in the experimental work, and there is no consistency of the values measured with different rheometer.

Certainly, more work is needed before widely accepted rheological property equations and their relationships with practical and relatively simple test methods are developed.

2.6 Hardened properties and durability

The hardened properties, including durability, of SCC have been of great concern since it was first developed. Broad investigations have been carried out, which are summarised here, but the details are not included because this is outside the scope of the project.

Chai [29] reported that the strength of SCC containing various powder type can be predicted by Feret's rule as modified by de Larrard [56],

$$f_c = \frac{K_g \bullet R_c}{\left(1+3.1\dfrac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} \tag{2-12}$$

where

- f_c :compressive strength,
- K_g :an aggregate coefficient;
- R_c :the cement strength;
- W :free water content;
- A :entrapped air volume;
- K_1 :a pozzolanic activity coefficient = 0.4PFA/C + 3CSF/C ($K_1 \leq 0.5$)
- K_2 :a limestone activity coefficient = 0.2 LSP/C ($K_2 \leq 0.07$)
- C, PFA, CSF, LP and GGBS :content of cement, fly ash, microsilica, limestone powder and blast furnace slag.

The main difference of mix proportion between SCC and normal concrete is that SCC has higher powder content and lower content of coarse aggregate. This may be result in the difference in some properties such as shrinkage, elasticity and creep between normal concrete and SCC, but there are some differences of opinion [119,120]. However, in general it is accepted that the hardened properties are equivalent to those of the equivalent strength conventional concrete [121].

It is said that the durability of SCC, e.g., air and water impermeability, freeze-thaw resistance *etc*, is generally better than normal concrete of equivalent strength because the blends of powder (reactive or non-reactive) decreases the voidage in the interfacial transition zone and paste [52].

2.7 Mixing procedures

SCC mixing, i.e. the types of mixer, feeding sequence, mixing time *etc*, is more important than normal concrete mixing because it greatly affect the fresh properties, but only few investigations were carried out. A common experience from production of SCC is the need of more frequent control of moisture content in the aggregate (sand) and the need for prolonged mixing time [2]. It has been concluded that a gravity mixer is not suitable to produce SCC because it takes quite a long time to disperse the powder particles sufficiently in concrete [2], and a forced mixer is generally used in the laboratory in Japan, but gravity drum mixer has also been used in Sweden for full scale project, and no comparison has been made with forced mixer.

One of the most important factors in the manufacture of SCC is the mixing method of superplasticizer and viscosity agent, which significantly affects their efficiency. This is reviewed in this section.

2.7.1 Mixing methods for the superplasticizer

The effect of superplasticizer mixing methods on workability and workability retention has been investigated since they became popular in the 1970s [122-132]. However, only a few well-documented papers have been found [125-132].

In 1985, Chiocchio *et al* [125] tested mixes with sulfonated naphthalene or melamine-formaldehyde condensate superplasticizer, and found the maximum initial slump and the best slump retention can be obtained when superplasticizer is added at the beginning of the dormant period of the cement hydration without an admixture, i.e. two minutes after initial mixing.

They explained that the dispersing effect of the superplasticizers is limited by two phenomena, both related to the hydration of the cement:

- The coating of the polymer by the early hydrated products;
- The aggregation of the cement particles.

When a superplasticizer is added at the beginning of the dormant period, the adsorbed polymer is not incorporated within the hydrated products and, therefore, it remains almost completely active in dispersing the cement particles. Considering that the aggregation of particles increases with increasing mixing time, whereas the coating of the polymer becomes negligible during the dormant period, they concluded there is an optimum time for the addition of superplasticizers, which is the beginning of the dormant period. This time will depend on the composition of the cement, the temperature and mixing procedure.

Hsu *et al* [126] studied the effect of addition time a naphthalene-based superplasticizer on the adsorption behaviour on type I Portland cement slurries and on concrete workability. They concluded that the adsorption behaviour follows a Langmuir isothermal adsorption model; the saturated adsorption amount of SNF decreases sharply with the initial increase of delayed addition time, and then more slowly.

Tsuji *et al* [127] also found that generally, a delayed addition of superplasticizer increases the slump flow and decreases the slump flow loss. The sand/cement ratio also affects the efficiency of delayed addition and the optimum addition time. For example, for a naphthalene superplasticizer the effect of delayed addition decreased with the increase of sand/cement ratio. The 28 days compressive strength of superplasticized mortar was not affected by a delayed addition.

Hanehara *et al* [128] concluded by testing four types of superplasticizer that any types of admixture is adsorbed less by delayed addition than by simultaneous addition with the mix water. However, the effect of the addition time depends on the types of the admixture: the effect of the naphthalene sulfonic and amino sulfonic acid-based admixture is larger, while that with the lignin sulfonic and polycarboxylic acid-based admixtures is smaller.

However, Collepardi [129] found that unlike the traditional sulfonated polymer-based admixtures, the efficiency of new types of superplasticizer, such as copolymers of carboxylic acrylic acids, is not dependent on mixing procedure.

Certainly the efficiency of superplasticizer can be improved by delayed addition, but the most effective delay time and the benefit is much dependent on the type of superplasticizer. Self compacting concrete usually contains a high dosage of superplasticizer, at or near its saturation dosage (SSD). Therefore, it is very interesting to know how mixing procedures affect the SSD as well as workability and workability retention. An optimum mixing procedure can then be established.

2.7.2 Optimization of the use of Welan Gum during mixing

As with a superplasticizer, the efficiency of Welan Gum is also affected by the mixing procedure; and to obtain optimal performance, consideration needs to be given to this. It has been found that the order of addition, the product form, the mixing conditions, and the relationship between Welan Gum and the superplasticizer all affect the performance, such as the plastic viscosity, bleeding, fluid loss *etc.* The optimal use of Welan Gum is achieved by adding it as a solution after the superplasticizer, or at the same time as, or after, the superplasticizer if that is in solid form. High fluidity with controlled bleed and fluid loss is then obtained [133].

2.7.3 Comments

The mixing procedure is clearly very important in achieving maximum and consistent fresh properties of concrete. The maximum efficiency of a superplasticizer and a viscosity agent may be obtained by using an optimum mixing procedure, and this may also result in the best workability retention. It is possible that the optimum mixing procedure may be different for different superplasticizers and viscosity agents. Studies are required to obtain the optimum mixing procedure for each individual superplasticizer.

2.8 Conclusions

This chapter has reviewed the published literature on the following aspects of SCC:

- Materials
- Test methods
- Mix design methods
- Fresh properties
- Rheology

- Hardened properties and durability
- Mixing procedures

The main conclusions that can be drawn from this are,

- Almost any material that is suitable for normal concrete can be used for SCC. There are some advantages of using low heat or high Belite cement; a superplasticizer is essential.

- The standard tests for normal concrete are not adequate for SCC; many different testing methods have been proposed, and some are still under the development. The fresh properties of a SCC mix must be evaluated by a combination of several test methods, including those measuring flowability, passing ability, segregation and filling ability. Many different combinations of test methods have been used in different countries. Comparison of these is difficult, and further investigations are needed to establish some consensus.

- Several mix design methods have been proposed and used by different groups. Each has its distinguishing features and advantages. The choice of method should depend on the mix purpose and the extent of understanding and experience of the mix design method.

- There are three key fresh properties that distinguish SCC from other concrete: high deformability, good segregation resistance and a non-blocking property (or passing ability). Systematic studies have been carried out on the effect of aggregate type and properties on these properties. The properties and the compositions of paste have a great effect but more systematic investigations are needed, especially on different combination of powders.

- Good workability retention is essential in SCC, and more studies are needed to understand the factors that affect this.

- Properties of mortar have an important role in SCC, and a good relationship between the properties of mortar and the SCC seems to exist, but more studies are needed on this.

- Several relationships between the rheology of paste and mortar, and mortar and concrete have been established. These have been very useful in the mix design and assessment of a mix. However, more work is needed for these to be accepted fully. There seem to be relationships between rheological properties and the values obtained by simple test methods, however, further confirmation is needed.

- In general SCC has the same level of hardened properties and better durability compared to normal concrete of the same strength. However, there are unresolved arguments when considering some hardened properties such as shrinkage, creep and elastic modulus.

- The mixing procedure is very important for SCC, since in particular it affects the superplasticizer efficiency. Studies are required to obtain the optimum mixing procedure for each individual superplasticizer.

It is clear that much work has been carried out on SCC, but more work is still needed in most aspects before SCC fulfils its full potential and becomes as widely used as normal concrete. The aspects of these chosen for this project are described in the next chapter.

Chapter 3

Aims and scope of research

3.1 Aims and scope of research

It was concluded from the literature review that three very important aspects of SCC that need further investigation are,

- testing methods,
- the relationships between the rheology of paste, mortar and concrete, and their compositions, and the relationships with single point test methods,
- the fresh properties, especially the effect of each of the constituents of the paste and their combination on workability and workability retention.

Each area is a full project in itself; the third one was chosen for my project for following reasons.

1. As mentioned in the literature review, it is necessary for the continuing use of SCC to establish a series of standard testing methods for the fresh properties. However, this needs the cooperation of many research groups to examine prospective methods simultaneously. This subject is therefore not suited to a single PhD project, mainly because the availability of all the test apparatus is beyond the capability of a single university (It is in fact being investigated in an EU funded project involving twelve partners).

2. The application of established rheological relationships between paste, mortar and concrete will be very helpful to the mix design and quality control of SCC. However, it is difficult to compare the established rheology equations because the test conditions and test methods to measure the rheological properties to establish these are different in different countries. Therefore this also needs the cooperation of many research groups. For example, in October 2000, a

programme of comparative tests on concrete rheometers including five groups was carried out in France [43].

3. Fresh properties of SCC are very important because the degree of the compaction is fully dependent on these. There has been, however, a lack of systematic research. For example, as has been made clear in chapter 2, to achieve the required properties, SCC often uses a combination of a greater number of constituent materials than normal concrete, e.g. the paste can contain one or more cement replacement materials, inert fine fillers, superplasticizers, and a viscosity agent. However, there is general lack of detailed information of the effects of these different components and their combinations on the fresh properties. Both workability and workability retention are of importance, and studies have shown that these are not only influenced by the properties of each individual constituent but also the physical and chemical interaction between them. More studies are therefore needed in both these areas.

Furthermore, tests on mortar, as well as being convenient, form an important part of several mix design procedures, but these uses have not been systematically examined.

The objective chosen for this research project is therefore to investigate the effect of types and amount of powder materials, admixtures, sand content and water content on the properties of SCC by using tests on mortar, and to establish relationships between the mortar and concrete properties.

As well as providing an understanding of the behaviour, this will help to show the value of the mortar test as part of the general process of mix design. Since the rheological properties of mortar and concrete were measured, the results are helpful in understanding some different rheological models of SCC as well as establishing the relationship between rheology parameters and single point test results for these although this was not a prime objective of the research.

A number of factors that have been identified as important in SCC, but which have not been previously systematically examined, were evaluated in the test programme.

1. The optimisation of mixing procedures for several typical types of superplasticizers – in particular the time of addition of the superplasticizer during the mixing process. One superplasticizer was then chosen for the research on mixes without a viscosity agent.
2. Fresh properties of mixes with a single powder type. The effects of sand content, water/cement ratio and types of cement were studied.
3. Fresh properties of mixes with binary blends of powder. The blending materials include PFA, GGBS, CSF and LSPs.
4. Fresh properties of mixes with ternary blends of powder. Mainly mixes with CSF as one component were investigated.
5. Fresh and hardened properties of the mixes containing Welan gum, a viscosity agent. This included preliminary research on Welan gum properties, Welan gum and superplasticizer compatibility, and Welan gum mix properties with single and binary blends of powder.
6. The relationship between mortar and concrete properties to predict the fresh properties of concrete from related mortar properties.
7. An analysis of the rheological behaviour of some mixes and their implication for fresh properties, the relationships between fresh properties for mortar and concrete.

The fresh properties were studied initially by mortar tests, and then some important results were confirmed by concrete tests.

3.2 Why mortar tests?

Mortars were tested for the following reasons:

- In SCC, the mortar phase provides lubrication between the coarse aggregate particles and overall stability of the concrete. Its required properties are similar to those of the concrete itself, i.e., a low yield stress to ensure flow under self-weight and a plastic viscosity sufficient to ensure that the concrete does not segregate during flow, but not so high that the flow is too slow for practical concerns.
- It contains all of the materials except coarse aggregate and the effect of the test variables will be similar to those in the concrete. SCC has a coarse aggregate

content substantially less than that of normal concrete (typically 31-35% by volume), and therefore this similarity is likely to be greater than with normal concrete.

- There is a general consensus on the properties of the mortar required for successful self-compactability of the concrete as discussed in the literature review.
- Assessing the properties of the mortar is an integral part of many SCC mix design processes, and therefore knowledge of the mortar properties is itself useful.
- Batching and testing concrete involves significant effort, particularly in a research laboratory, and with mortar a greater number of combinations of variables can be investigated in a given time.
- The variables can be easily controlled, the test methods are similar to that for concrete, and the properties can be easily measured and are repeatable. Also the test equipment gives more precise results than those for concrete.

3.3 Scope of test programme

The method of investigating the fresh properties of SCC is very different from that of normal concrete because of the particular criteria for fresh properties. These requirements make it impossible to study a single factor independently without considering the effect of other factors. For example, if the water/cement ratio increases, the dosage of superplasticizer and/or the composition of powder have to change for the mortar to satisfy the required spread value and V-funnel flow time. Therefore instead of studying an individual factor, combined effects were mainly investigated.

Table 3-1 presents the stages and scope of the experimental test programme, including the objectives, factors investigated and the range of variables in each stage; the thesis chapter in which each is discussed is also shown.

Stage 1 is the establishment of a two-point test for mortar, which comprised two steps. First, the effect of cup size was investigated, and two cups, which had significantly different effect, were chosen for further study. After calibration so that the results could be expressed in fundamental units, comparison of the results for three SCC mortars with these two cups was made enable a cup to be chosen for subsequent tests.

In stage 2, the spread and V-funnel tests were used throughout. The optimization of the addition time for each type of superplasticizer was carried out in three steps:

1) The effect of addition time on saturation dosage (SSD) for Conplast430 superplasticizer was examined, and an optimum addition time chosen.
2) The SSD was determined by using this addition time for the remaining superplasticizers.
3) A dosage was then chosen which was slightly less than the SSD in each case, and the superplasticizer efficiency at different addition times obtained. The optimum addition time for each type of superplasticizer was selected.

The most efficient superplasticizer was then chosen by comparing the initial properties and workability retention for mortar with the SSD and the optimum addition time for each.

In stages 3, 4 and 5, the properties of mixes with single types of powder, binary blends and ternary blends respectively were studied. The range of variables in each case is shown in **table 3-1**. In each stage, the full range of variables was tested with mortar, while a selected range tested on concrete.

Stage 6 was a study of the properties of a viscosity agent based SCC. Welan gum was chosen as the viscosity agent. Spread, V-funnel and two-point test, setting time and compression strength tests were carried out. The substages were

1) to examine Welan gum solution properties and select a mixing procedure to optimise the use of Welan gum;
2) to determine the Welan gum/superplasticizer compatibility with a preliminary study, followed by a full comparison of properties (workability, workability retention, setting time and compressive strength development) of the mixes with different types of superplasticizers;
3) a suitable superplasticizer was then chosen, and mixes with single or binary powders were then studied as a aim fully on mortar then on concrete.

Following the completion of the experimental programme, further analysis of the results (included in chapter 10) was carried out to assess:

1. Rheological models. In particular, the applicability of the Herschel-Bulkley model for some types of mortar was considered.
2. The relationships between the test results for
   - mortar properties,
   - concrete properties,
   - mortar and respective concrete properties.
3. Feret's rule for the prediction of compressive strength

More detail of the test programme is included at the beginning of each chapter.

Table 3-1 Scope of test programme

Stage	chapter	objective	Factors investigated	The range of variables
1	4	• Establishment of a two-point workability test for mortar	• Cup size;	• Cup size diameter between 55-130 mm
			• Calibration coefficient	• The Newtonian liquid was glycerol at various dilutions. The pseudoplastic liquid was 1%, 1.5% and 2% Welan gum solution.
2	5	• Optimization of addition time for several types of superplasticizer • Selection of superplasticizer for remaining studies.	• Effect of addition time of Conplast430 on its saturation dosage	• Direct addition, 2 and 4 minutes delayed addition.
			• Determination of SSD* for each type of superplasticizer	• Superplasticizers included Conplast430, Darcem2001, Sika10, Glenium51 and Viscocrete
			• Optimization of addition time for each type of superplasticizer	• Direct addition, 1, 2, 3, 4, 6 minutes delayed addition
			• Selection of most effective superplasticizer for SCC without viscosity agent	• Superplasticizers included Conplast430, Darcem2001, Sika10, Glenium51 and Viscocrete
3	6	• Workability and workability retention of mixes with a single type of powder	• Water/cement ratio.	• w/c was 0.275, 0.30, 0.325, 0.35, 0.375 by weight
			• Sand/mortar ratio by volume;	• V_s/V_m 0.40, 0.425, 0.45 and 0.475 by volume
			• Types of cement.	• PC and SRC,
4	7	• Workability and workability retention of mixes with binary blends of powder	• Types of blends;	• PC/PFA, PC/GGBS, PC/LSP100, PC/CSF, SRC/PFA
			• Particle size of lime stone powder;	• PC/LSP15, PC/LSP50, PC/LSP100
			• Content of blends	• PC/CSF binary blends of powder at replacement of 5, 10 and 15% level, and PC/LSP100 at 20, 40 and 60%. level
5	8	• Workability and workability retention of mixes with ternary blends of powder	• Types of CSF ternary mixes	• PC/LSP15/CSF, PC/GGBS/CSF at 10% CSF replacement compared with PC/PFA/LSP15, PC/CSF and 100% PC mixes
			• Effect of CSF content	• PC/GGBS/CSF powder at CSF replacement of 10, 15%
6	9	• Properties of Welan gum solution • Effect of mixing procedure on the efficiency of Welan gum • Viscosity superplasticizer compatibility, • Properties of welan gum with single powder mix; • Properties of Welan gum with binary types of powder mix	• Welan gum solution properties compared with cellulose viscosity agent	• Welan gum and cellulose in deionized water and filtered cement solution
			• Effect of mixing procedure on the efficiency of Welan gum	• High and low mixing speed with 3, 4, 6, 8, 10 minutes mixing time
			• Welan gum and superplasticizer compatibility	• Superplasticizers Conplast430, ConplastM1, Darcem2001, Sika10, Glenium51
			• Workability, workability retention, setting time and strength development of welan gum mixes	• 100% PC mix with Welan gum dosage of 0, 0.025, 0.05, 0.075, 0.1% by weight of water. SRC mix with 0.05% of Welan gum also tested.
				• Welan gum dosage 0.05% by the weight of water, blends of powders PC/GGBS, PC/PFA, PC/LSP100 and PC/CSF

Note: In stage 2-6, the effect of all variables was assessed on mortar, with confirmary tests on a smaller number of concrete mixes
* superplasticizer saturation dosage

Chapter 4

Materials and Test Methods

This chapter presents the details of the materials and experimental methods used in the research. The materials are reported in section 4.1, the test methods are described in section 4.2, the mixing and testing procedures are detailed in section 4.3, and the repeatability and reproducibility of the results for both mortar and concrete are discussed in section 4.4.

4.1 Materials

All the materials used in this study were readily available in the UK.

4.1.1 Cements

Table 4-1 shows the composition and physical properties.

Table 4-1 Composition of Portland cement and sulfate resisting cement

No	Types of cement	Date (mm/yy)	C_3S (%)	C_2S (%)	C_3A (%)	C_4AF (%)	Alkalis (%) $Na_2O_{(eq)}$	SSA (m^2/kg)
PC1	PC	05/98	57	14	10.1	8.6	0.62	330
PC2	PC	01/99	56	13	8.2	9.2	0.66	360
PC3	PC	07/99	56	13	7.6	9.6	0.61	355
PC4	PC	02/00	48	21	10.0	8.8	0.69	370
SRC1	SRC	03/99	61.7	14.0	1.6	14.4	0.52	319
SRC2	SRC	04/00	69.9	5.6	2.5	15.3	0.52	392

Portland cement (PC, class 42.5N), complying with BS 12:1996, was used. There were four batches collected at different times from same source at Rugby Cement and these were therefore nominally similar. PC1 was used for preliminary tests in the mixes without a viscosity agent; PC2 and PC3 were used in all the other mortar mixes; and PC4 for the concrete tests and the mortar tests for predetermination of superplasticizer dosage in concrete. Two batches of sulphate-resisting cement (SRC) from Rugby Cement and Blue Circle Cement were also used in both mortar and concrete tests.

4.1.2 Other powder types

Several other types of powder were used:

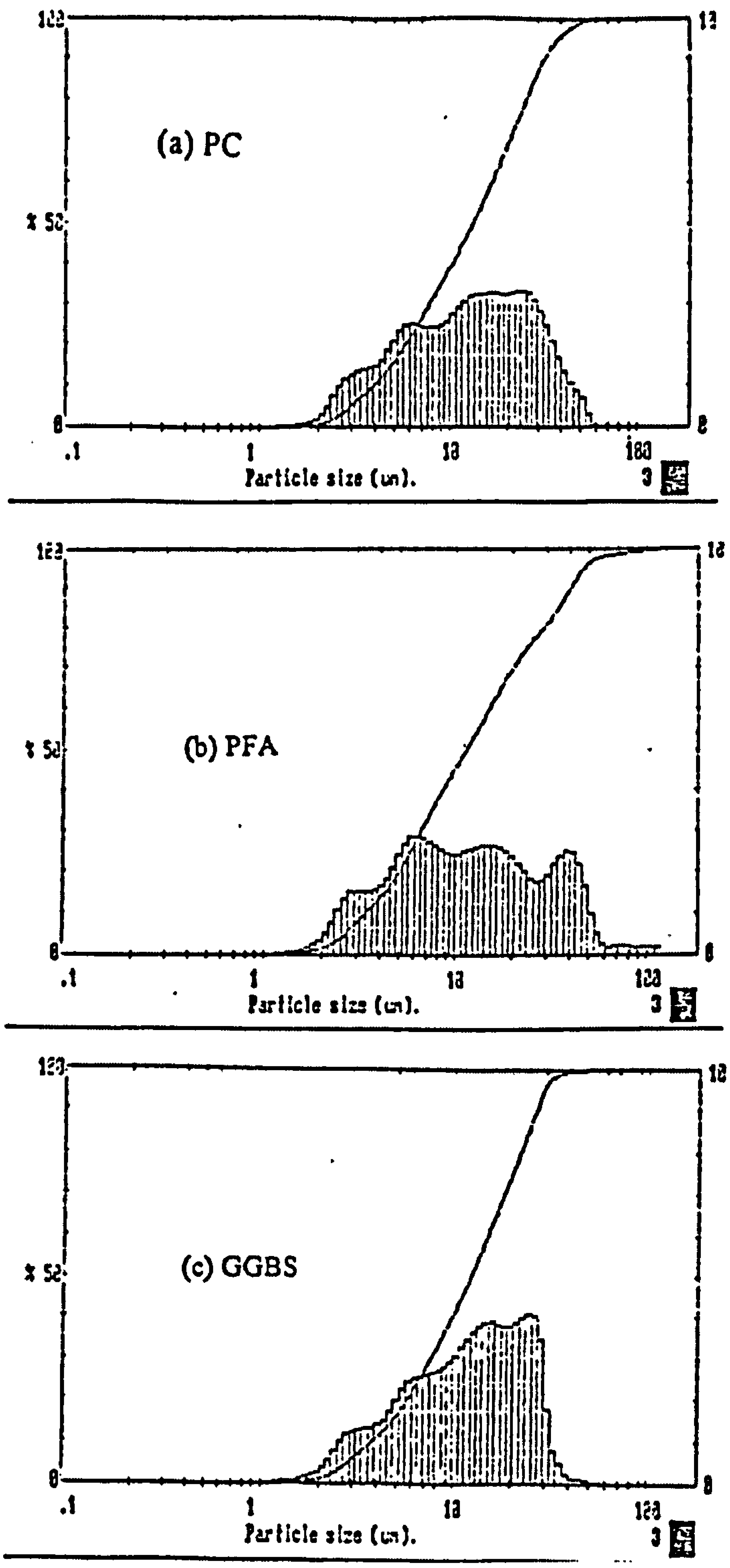
- Pulverised fuel ash (PFA), complying with BS 3892-3 1997, supplied by Ash Resources Ltd.
- Ground granulated blast furnace slag (GGBS), complying with BS 6699:1992, supplied by Civil and Marine Ltd.
- Condensed silica fume (CSF), in slurry form (50% water), supplied by Elkem Chemicals.
- Limestone powder (LSP) including LSP100, LSP50 and LSP15, supplied by Longcliffe Quarries Ltd.

Table 4-2 shows the composition and physical properties. The particle size distributions of all the powders except the CSF as measured by a laser diffraction instrument are shown in **figure 4-1.** The range for PFA, GGBS and LSP100 was similar to that of PC, but with the LSP50 and LSP15 being somewhat finer.

Table 4-2 Composition and physical properties of powder

powders	Passing ratio or SSA(m^2/kg)	S.G.	*SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O (eq)	SO_3	S^{2-}	LOI
PFA	(87.5% < 45μm)	2.4	51.4	25.0	9.4	1.4	1.4	0.15			5.6
GGBS	400-440	2.9	35	11	0.8	42	8.5	0.48	0.2	0.9	0.6
CSF	15000-20000	2.2	92	1.0	1.0	0.3	0.6				
LSP100	96.7% ≤ 75 μm	2.68		0.06	0.024	55.46	0.24				43.60
LSP50	92.9% ≤ 25 μm	2.68		0.06	0.024	55.46	0.24				43.60
LSP15	95.4% ≤ 10 μm	2.68		0.06	0.024	55.46	0.24				43.60

*percentage by weight, LOI: loss on ignition, SSA: specific surface area, S.G.: specific gravity


(a) PC
(b) PFA
(c) GGBS

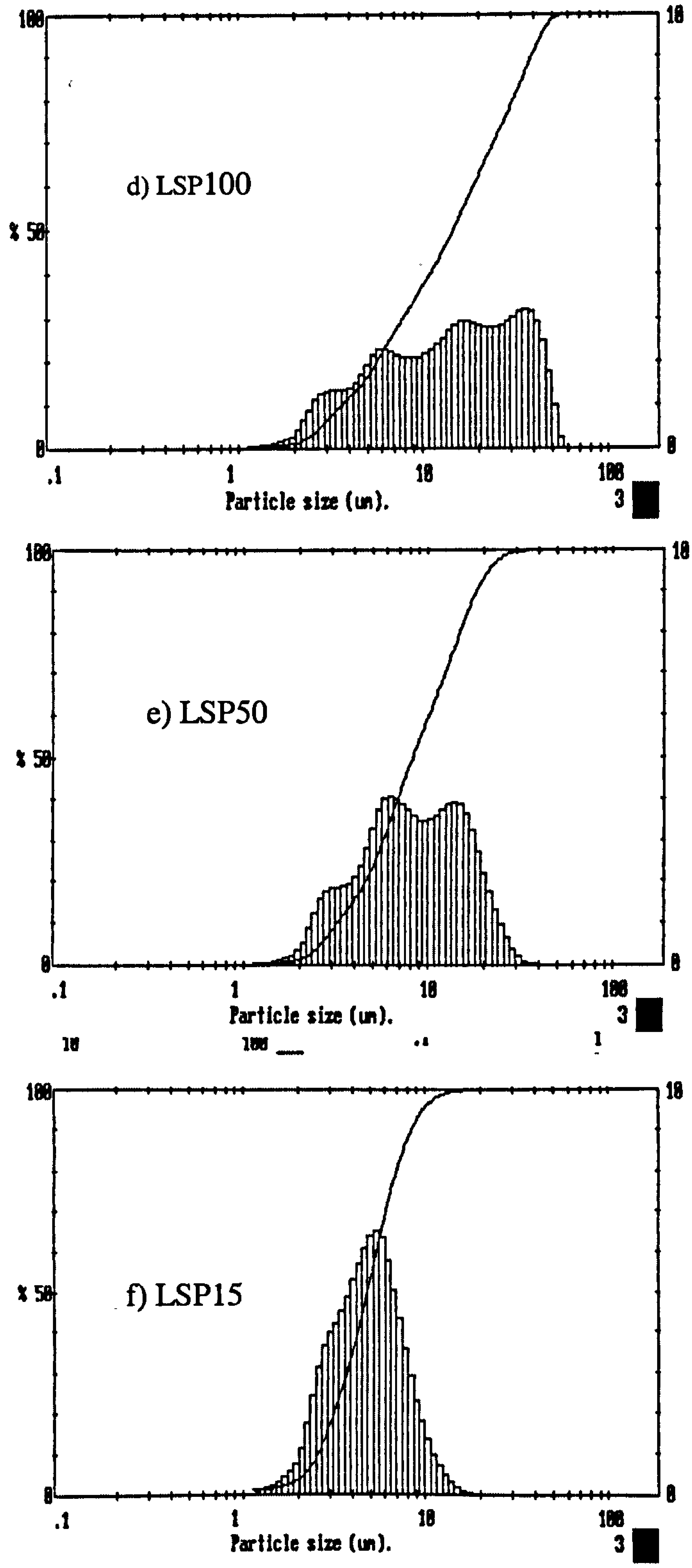


Figure 4-1 Particle size distributions of powders

4.1.3 Admixtures

Five different types of superplasticizer were used, listed in **table 4-3.** They are typical of those used in many reported SCC applications. Sika10 and Glenium51 are called 'new generation' materials by their suppliers, both have actions of a combination of electrostatic dispersion and steric hindrance. It is claimed that this will be the main type of superplasticizer in the 21st century. Sika Viscocrete is produced especially for SCC; however, it was obtained during the later stages of the project and was used in only a few studies.

Table 4-3 Details of admixtures

	Name	Description	Solids content (% by wt)	Na_2O_{eq} (%)	Recommended solid dosage (%)
Superplasticizer	Conplast430	Sulfonated naphthalene polymer	40	<6	0.34-0.96
	ConplastM1	Sulfonated melamine polymer	40	<3.6	0.44-1.76
	Darcem2001	Acrylate-methacrylate co-polymer	35	5.2	0.16-0.41
	Sika10	Vinyl copolymer	20	3	0.16-0.3
	Glenium51	Modified polycarboxylic ether	20	0.45	0.11-0.22
	Sika viscocrete	Superplasticizer blended with property enhancing polymers	20	2.3	0.2-0.4
Viscosity agent	Welan gum	Linear polysaccharide	In powder form		
	Cellulose	Carboxymethyl cellulose sodium salt	In powder form		

All the superplasticizers except ConplastM1 were studied in the mixes without a viscosity agent, and all except Sika Viscocrete in the mixes with a viscosity agent.

Two different types of viscosity agent were used. Welan gum, high molecular weight, linear polysaccharide, was mainly used, with a cellulose viscosity agent as a comparison.

The dosage rates for all five superplasticizers are expressed in terms of the percentage of admixture solids by the weight of powder material in the mix; this enabled comparison of their effectiveness to be made. The dose of the viscosity agents is expressed by weight of water in the mix, since they dissolve in water to increase the viscosity.

4.1.4 Water

Tap water was used in all the mixes. Its temperature was controlled between 18°C~22°C. The room temperature was maintained between 17~24°C throughout the whole year.

4.1.5 Aggregate

A single batch of Thames Valley gravel and two batches of Thames Valley sand were used in the mixes. **Table 4-4** shows the properties.

Table 4-4 Properties of sand and coarse aggregate

	Percent passing			
Sieve size	$Sand_1$	$Sand_2$	Gravel (5-10 mm)	$Gravel_1$ (10-20 mm)
25.4 mm	100	100	100	100
19.1 mm	100	100	100	94
10.0 mm	100	100	92	16
5.00 mm	98	99	16	2
2.36 mm	87	78	3	1
1.18 mm	75	64	1	0
600 μm	55	53	1	0
300 μm	19	27	1	0
150 μm	4	8	0	0
Fineness modulus	2.6	2.7	5.9	6.9
Specific gravity	2.64	2.64	2.60	2.60
Absorption	1.2%	1.2%	1.1%	1.0%
*$D_{D.R.}$ (kg/m^3)	1756	1789	1592	1566

* Dry rodded bulk density

The coarse aggregate was used as a mixture of 10-20 and 5-10 mm gravel at ratio of 2:1 by weight. All aggregates were stored and used moist, and allowance was made for free water content of sand and gravel, and the water content of superplasticizer, when calculating the batch weights for mixing.

4.2 Test methods

As discussed in the literature survey, workability tests for normal concrete are not suitable for the assessment of SCC, and many test methods have been proposed. Those used in this programme are listed in **Table 4-5**. All were available at UCL at the start of the research, with the exception of the two-point test for mortar, which was developed during the programme.

Table 4-5 List of tests for mortar and concrete

	Tests	Measured value	Property assessed
Mortar	Spread test	Spread (mm)	Flowing capacity
		Flow time (secs)	Flowing speed
	V-funnel test	Flow time (secs)	Flowing speed
	Two-point test	Yield stress (Pa), plastic viscosity (Pa.s)	Yield stress, plastic viscosity
		Shear stress/shear rate curve	Rheological model
	Setting time test	Setting time (hours)	Initial and final setting time
	Compression test	Compressive strength (MPa)	Compressive strength
Concrete	Slump flow test	Spread (mm)	Flowing capacity
		Flow time (secs)	Flowing speed
	V-funnel test	Flow time (secs)	Passing ability
	Box-test	Filling height (mm)	Passing ability
	Two-point test	Yield stress (Pa), plastic viscosity (Pa.s)	Yield stress, plastic viscosity
	Setting time test	Setting time (hours)	Initial and final setting time
	Compression test	Compressive strength (MPa)	Compressive strength

4.2.1 Tests on mortar

In this section, the spread and V-funnel tests are described. The two-point test which uses a helical impeller rheometer, is described in section **4.2.3.** The setting time test and the compressive strength test were carried out according to BS EN 480-2: 1997 and BS EN 1015-11:1999, except no compaction was used.

4.2.1.1 Spread test

This test method is adapted from Japanese standard JIS R5201, in which it is used as a cement physical property test. **Figure 2-2** illustrates the apparatus. The cone is dampened and placed at the centre of a clean glass plate, which is marked in concentric circles with diameters of 100 mm, 200 mm, 250 mm, and 300 mm. The cone is filled with the mortar without compaction then lifted immediately. After the mortar stops flowing, the diameters of the spread in two perpendicular directions are measured and the average of these two determined. The time for the mortar to flow to a diameter of 250 mm was also recorded in this project.

4.2.1.2 V-funnel flow test

This test, suggested by Okamura and Ozawa [46], is used as a measure of the flowing speed of mortar. The dimensions of the figure are shown in **figure 2-3**. The capacity of the funnel is 1.1 litres. The funnel is dampened, and after filling with mortar the flow time is measured as the time from opening the orifice to the first daylight appearing when looking vertically down through the funnel.

4.2.2 Tests on concrete

In this section, the slump flow, the V-funnel, the U-box and the two-point tests are described. Compression test was also carried out in accordance with BS1881: part 116:1983, except that the mix was not compacted.

4.2.2.1 Slump flow test

The slump flow test for concrete uses a standard concrete slump cone, and in other respective is similar to the spread test for mortar, i.e., no tamping is applied, it is as shown in **figure 2-2**. Concentric circles are marked on a smooth surface board at diameters of 200 mm and 500 mm. The slump flow is the mean diameter of spread of the concrete after the test and the flow time (in seconds) is that for the concrete spread to reach 500 mm diameter in average. Some difficulty was found in measuring the slump flow time because not all of the concrete reached the 500 mm spread at the same time, consequently the average diameter was estimated. A systematic error may occur, and good experience is needed to reduce this. At the end of the test the distribution of coarse aggregate is checked and recorded in case there is any segregation, particularly at the edge. No other specific segregation resistance test was carried out although, as discussed later, the V-funnel test gives an indication of this as well as other properties. The test is also described in RILEM TC-SCC report [2].

4.2.2.2 V-funnel test

The dimensions of the V-funnel used for concrete are shown in **figure 2-3**. The opening had a cross section of 75×75 mm. The funnel has a capacity of 10 litres, and the test procedure is the same as for the V-funnel test for mortar. The test is also described in RILEM TC-SCC report [2].

4.2.2.3 U-box test

A number of passing ability tests have been used by different research groups, including the U-type box test, the L-type test and the J-ring test, all described in chapter 2. The U-type box test (**figure 4-2**) was chosen for this programme for the following reasons:

- it has been recognised as a standard by Japan Society of Civil Engineers [31];
- the concrete property can be simply quantified by the filling height, a minimum of 300 mm is normally required;
- the flowing speed can also be measured by recording the flow time to a chosen height;
- the flowing behaviour can be observed through the transparent sliding door;
- it can be easily cleaned after opening the transparent door;
- it has been previously successfully used for SCC testing at UCL.

The effect of the ratio of clear spacing between rebars to the maximum aggregate size on the passing ability has been reported in several papers which were reviewed in chapter 2. In this project the obstacle made with D13 mm bars with equal clear distance between them of 40.25 mm was used for concrete with 20 mm maximum size aggregate; the ratio of clear spacing between rebars to the maximum aggregate size was therefore 2.0. Concrete passing through this obstacle represents the majority of SCC for general reinforced concrete structures [134].

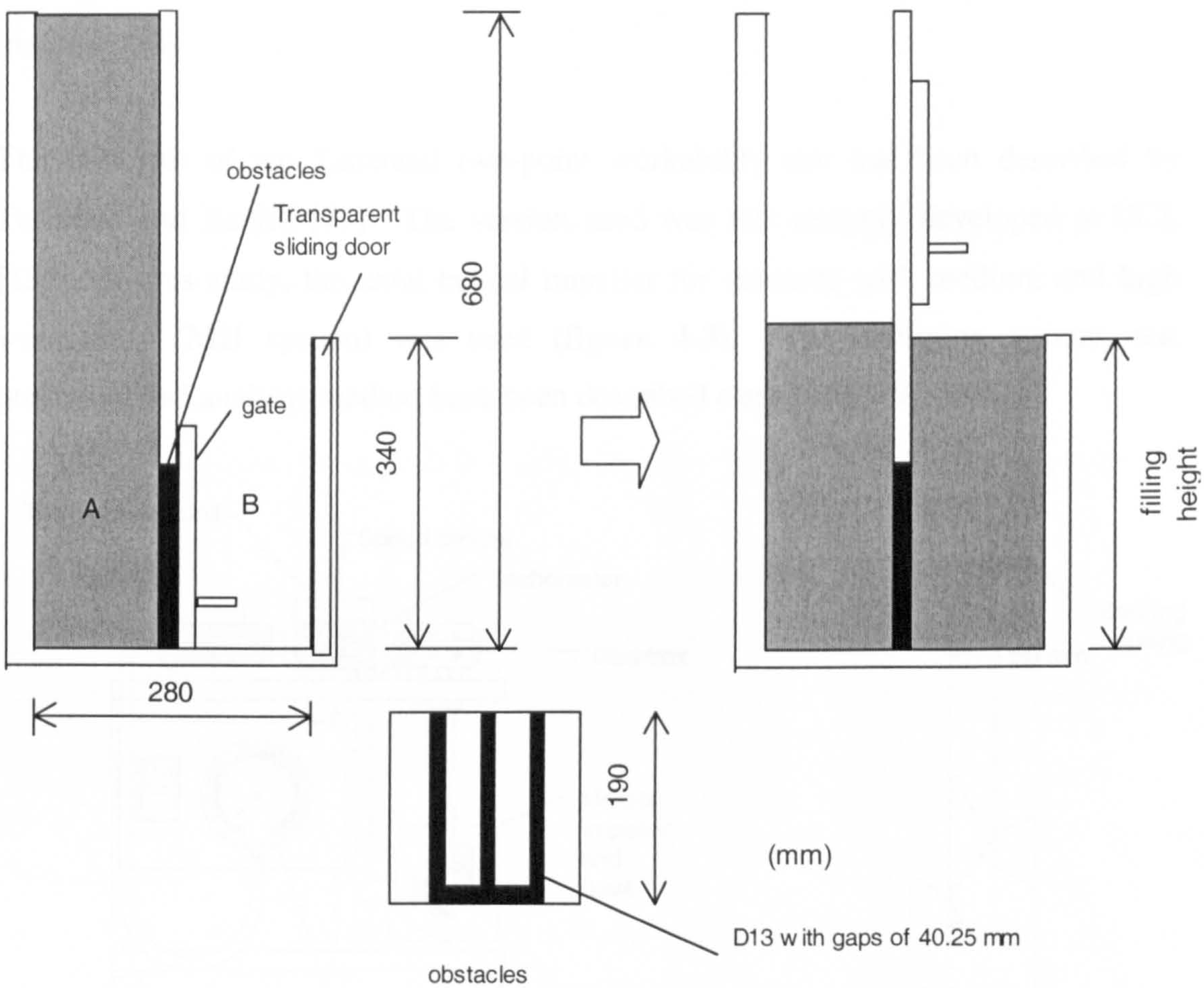


Figure 4-2 U-box test for concrete

When testing, 18 litres of concrete is poured into compartment A, and allowed to stand for one minute. The gate is then raised, and the concrete flows through the obstacles into compartment B. The filling height of concrete is then measured. These test details are as described in RILEM TC-SCC report [2], which also requires a measure of the time from the opening of the gate until the completion of the flowing. However, in this programme the time for the concrete to flow to a height of 250 mm was measured instead because this was thought to be more accurate and reliable. In some cases, the concrete flow was very slow beyond the 250 mm height, and it was very difficult to assess when the concrete stopped flowing.

4.2.2.4 Two-point workability test

In this research all mortar and concrete were considered as a Bingham material and two-point tests were used to obtain values of the yield stress and plastic viscosity. Non-Bingham model behaviour for some mortar mixes was also found and discussed in chapter 10.

The principle of the Tattersall two-point workability test has been described by Tattersall and Banfill [79]. The version used was that recently developed at UCL [135]. In this study, the axial helical impeller for concrete with medium and high workability (MH system) was used (**figure 4-3**). The operating system, test procedure and analysis method have been described elsewhere [79,135,136].

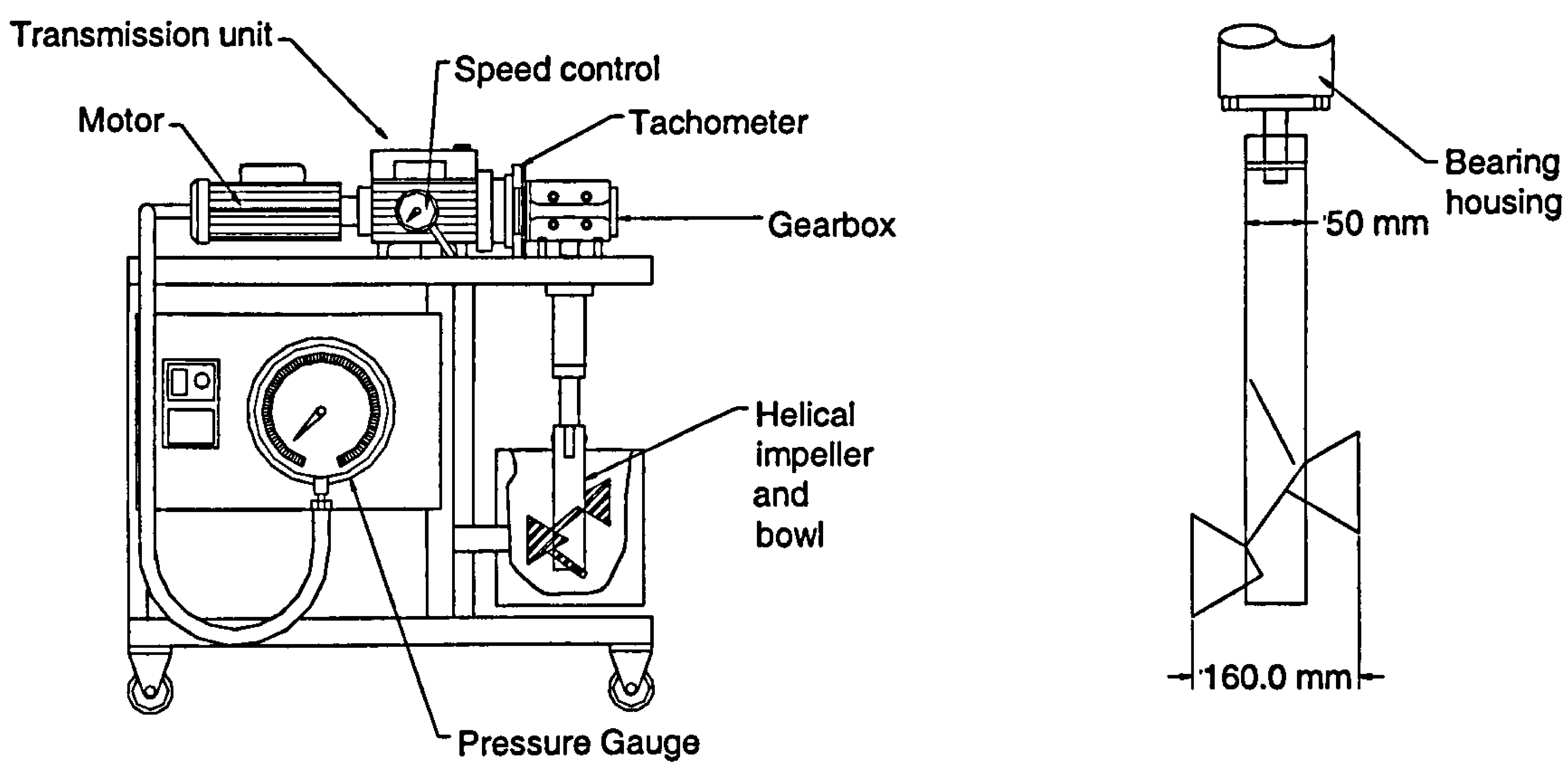


Figure 4-3 Two-point workability apparatus

The impeller is driven via a variable-speed hydraulic drive unit motor, and the torque measured indirectly via oil pressure. The speed is controlled manually. The output from a pressure transducer and an optical interference tachometer is recorded by computer installed with Instacal^{TM} programme.

The machine is ready for test after warming up for an hour at speed setting 4. The operation procedure included:

- Recording the idling pressure:
  1. switch on the computer, open the recording programme;
  2. raise the bowl into position and the set the speed control at 1;
  3. increase the impeller speed to setting 4;
  4. while recording reduce the speed continuously from setting 4 to 0 in 30 seconds manually;
  5. save recorded data as a file.

- Measuring concrete properties:

This procedure is the same as that for recording the idling pressure except concrete is loaded into the bowl to about 75 mm from the top of the bowl after step 2.

- Repeat recording of idling pressure

After removing the bowl and the concrete, the idling pressure measurement is repeated.

It was found the relationship between idling pressure voltage and fly wheel voltage became non-linear when the machine had been running for more than 3 hours, hence it was switched off for about 30 minutes when not testing.

Data analysis:

The test gives three spreadsheets of speed and pressure data, two for idling and one for concrete. There was a strong linear relationship between these in each case. Linear regression was carried out on each to obtain,

$V_P = a_1+b_1\ V_S$, for concrete (4-1)

$V_P = a_{01}+b_{01}\ V_S$, for idling before concrete test (4-2)

$V_P = a_{02}+b_{02}\ V_S$, for idling after concrete test (4-3)

where,

V_P : pressure obtained during the test (volts);

V_S : impeller rotating speed (volts);

a_1, b_1, a_{01}, b_{01}, a_{02}, b_{02}: constants.

Then the net pressure for the concrete (ΔVp) alone was obtained, using

$$\Delta Vp = (a_1 - (a_{01} + a_{02})/2) + (b_1 - (b_{01} + b_{02})/2)\ V_S \quad (4\text{-}4)$$

Previously the following torque/pressure and speed volt/speed calibrations had been obtained [136] as follows:

$T = 0.053\Delta P = 0.053 \times 725 \times \Delta Vp$ (4-5)

$N = 0.208 \times Vs$ (4-6)

where,

T: torque (Nm),

ΔP: pressure (psi),

N: speed (revolution per second),

0.053: a torque/pressure calibration constant obtained with a lever arm and a spring balance system as described by Tattersall and Banfill [79],

725: constant obtained by measuring the pressure with the pressure gauge and the pressure voltage,

0.208: constant related to the tachometer and gearing.

Substituting equations (4-4), (4-6), (4-7) into Bingham model equation T= g + hN gives,

$0.053 \times 725 \times ((a_1 - (a_{01} + a_{02})/2) + (b_1 - (b_{01} + b_{02})/2)\ V_s)$

$\equiv g + h \times\ 0.208 \times Vs$; (4-7)

Therefore,

$g = 0.053 \times 725 \times (\ a_1 - (a_{01} + a_{02})/2)$

$= 38.4 \times (a_1 - (a_{01} + a_{02})/2)$ (4-8)

$h = 0.053 \times 725 \times (b_1 - (b_{01} + b_{02})/2) / 0.208$

$= 184.7 \times (b_1 - (b_{01} + b_{02})/2)$ (4-9)

For the helical impeller, calibration by Banfill using a silicone fluid and carboxyl cellulose (using the method as described below for two-point mortar test) has given,

$\tau_0 = 122g$

$\mu = 17.24h$

where

τ_0 : yield stress (Pa),

μ : plastic viscosity (Pa.s),

g: in Nm,

h: in Nm.s.

Therefore yield stress and plastic viscosity of concrete can be obtained in fundamental units. A typical output of the programme is shown in **Appendix 2.**

4.2.3 Development of helical impeller rheometer for mortar and the calibration

The study of the rheological properties of high slump concrete using the two-point test with a helical impeller as described above is a proven and well-established method. A smaller version was used to test mortar. **Figure 4-4** illustrates the impeller, which is about ¼ of the size of the one used for concrete, and was already available at UCL at the start of the programme.

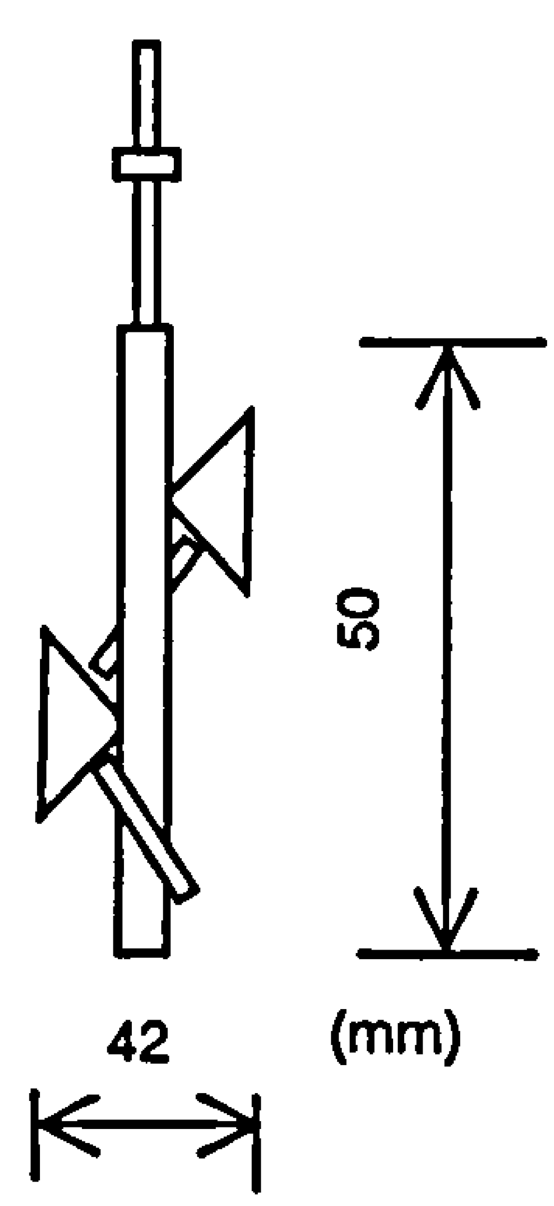


Figure 4-4 Helical impeller rheometer for mortar

This was used with a Rheomat 115 viscometer with a Rheoscan 115 control Unit, which was originally used as a concentric cylinder viscometer for testing liquids, as shown in **figure 4-5**. The rotating speed was varied from 0 to 112 revolutions per minutes (rpm). Initially, the data was recorded by an integrated chart recorder. This became defective during the programme, and so the data was recorded manually from the screen, and later by a computer installed with a Instacal^{TM} logging programme. It was found that the manually recorded data were slightly and consistently different from those by chart recorder and computer, which were consistent between themselves, and therefore were not included in the analysis in chapter 10. They were used in figures for experimental results in chapter 6 and 7. This will be specified at the end of each table in the appendices. Before testing the mortar was first sheared at a highest speed (780 rpm) for one minute to ensure full structural break down therefore providing a reproducible starting condition. In the test the speed was increased from 0 to 112 rpm in 1 minute (up curve), then decreased to zero in another 1 minute (down curve). The down curve was used for analysis.

In following sections, the assessment and calibration of the apparatus are described including the selection of cup size and the method of the expressing the test results in fundamental quantities of yield stress and plastic viscosity.

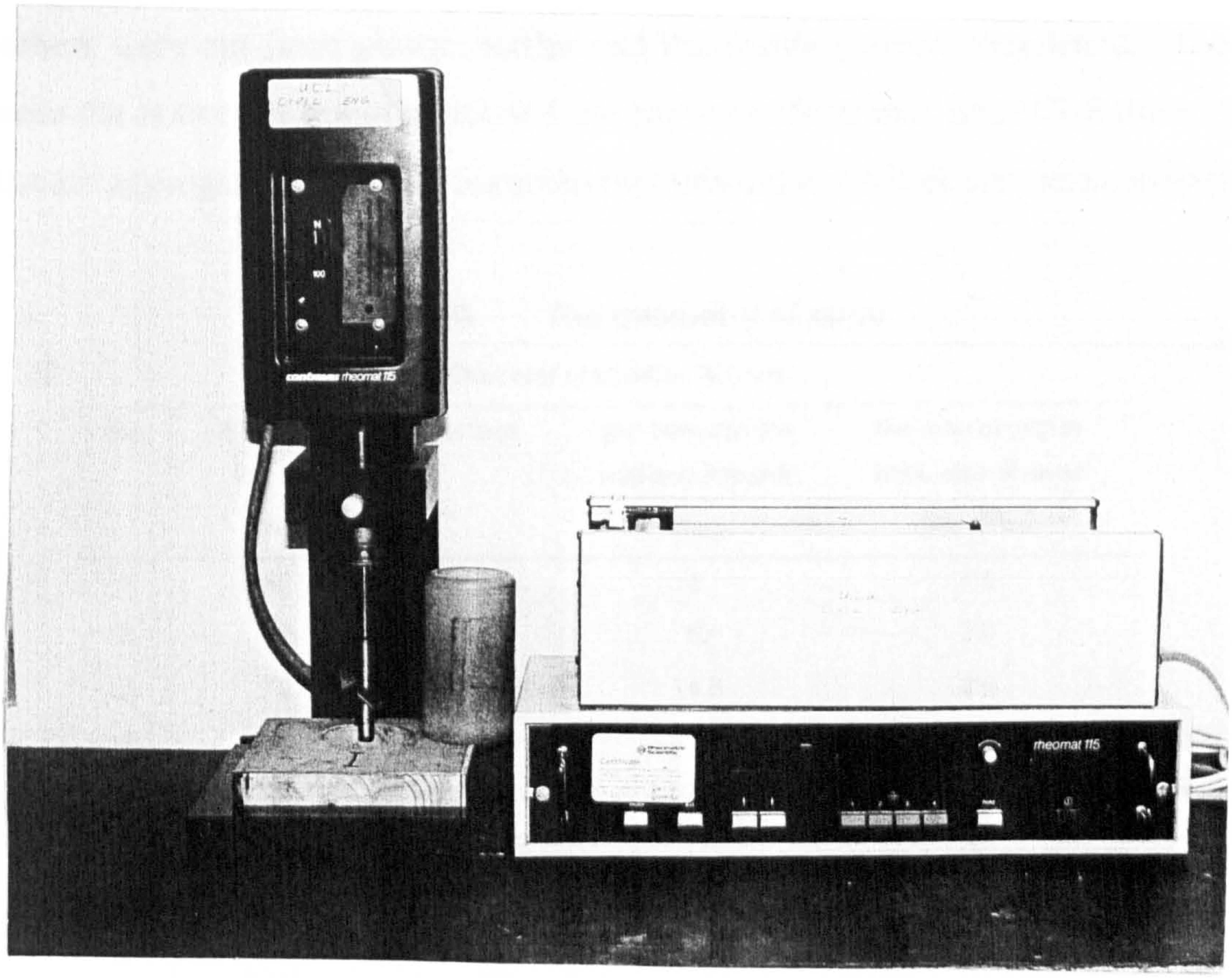


Figure 4-5 Rheomat 115 viscometer with a Rheoscan 115 control Unit and chart recorder

4.2.3.1 Effect of cup size

In general there is no specific geometric requirement of a container for a particular impeller as long as the gap between the wall of the container and the edge of an impeller is big enough to avoid trapping of the coarse aggregate for a concrete. However, there may be slippage between concrete and the wall of cup, which can occur when the wall is too smooth and/or there is lubricating layer of cement paste between the material and the wall. This wall-effect might also be significant when the volume of locally more flowable concrete near the wall is a high percentage of the whole sheared concrete, the consequent effect is similar to slippage. The same phenomena may happen when testing mortar, but may be avoided by selection of proper size of cup with sufficient surface roughness or with ribs on the inside of the wall. Therefore, a series of experiments was carried out to examine the significance of these effects and to choose an acceptable cup size for the mortar.

Table 4-6 shows the geometry of the cups tested. All the cups had smooth walls except No. 6, which had internal ribs (the clear distance between the ribs was 10 mm and the height of each of rib was 5 mm). The cups No. 1 & 4 were glass beakers and the others were cut from plastic bottles and the inside surface roughened. The gap between the bottom of the impeller and the cup was 35-40 mm, about 7-8 times of the maximum aggregate size; it was assumed that this did not affect the measurement.

Table 4-6 The geometry of cups

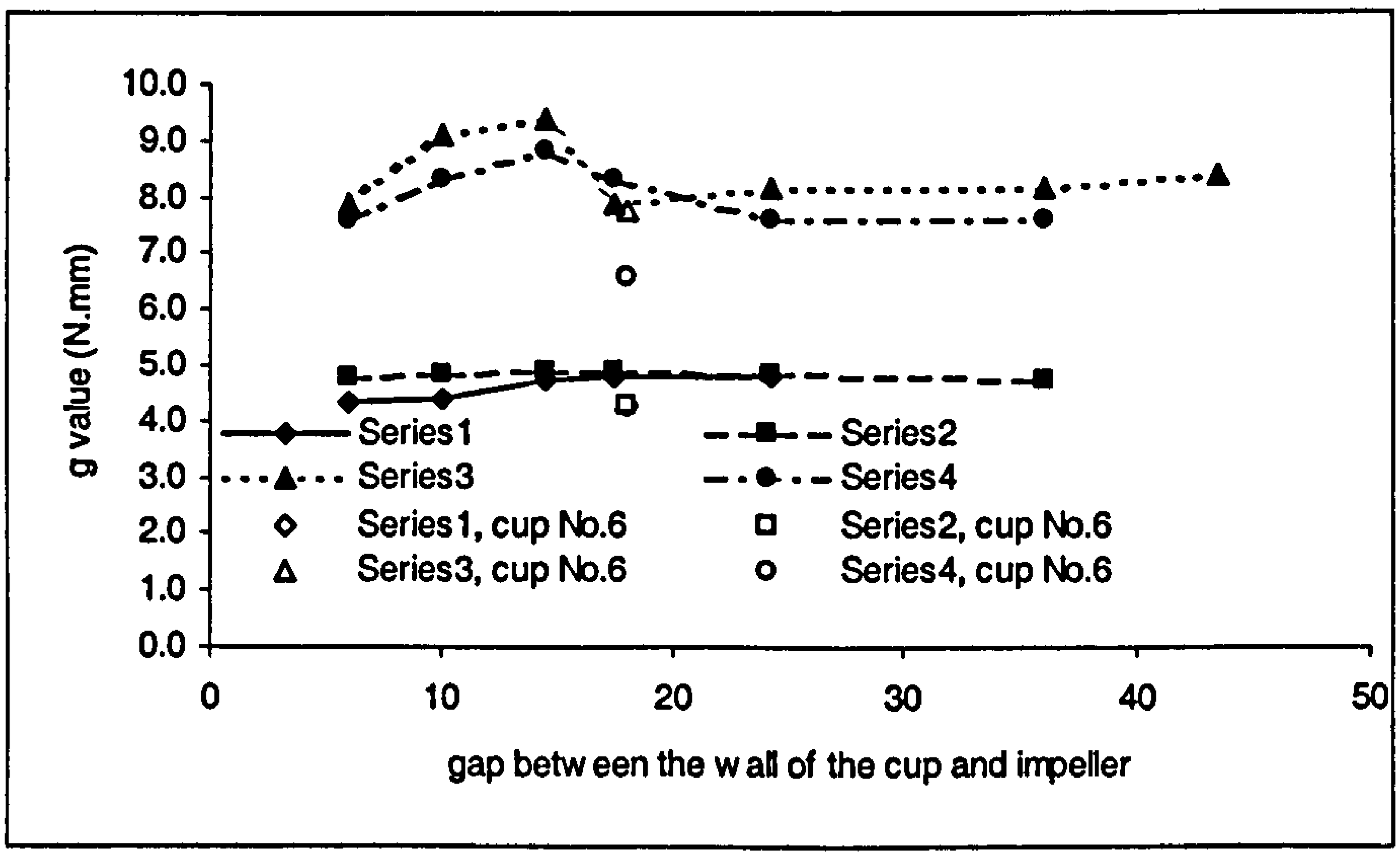
Diameter of impeller: 43 mm.

No.	diameter of the cup (mm)	surface	gap between the wall and impeller (mm)	the ratio of gap to max. size of sand ($D_{gap}/D_{f.a.}$)
1	55	smooth	6	1.2
2	63	rough	10	2.0
3	72	rough	14.5	2.9
4	78	smooth	17.5	3.5
5	92	rough	24	4.8
6	78	rib	17	3.6
7	115	rough	36.0	7.2
8	130	rough	43.5	8.7

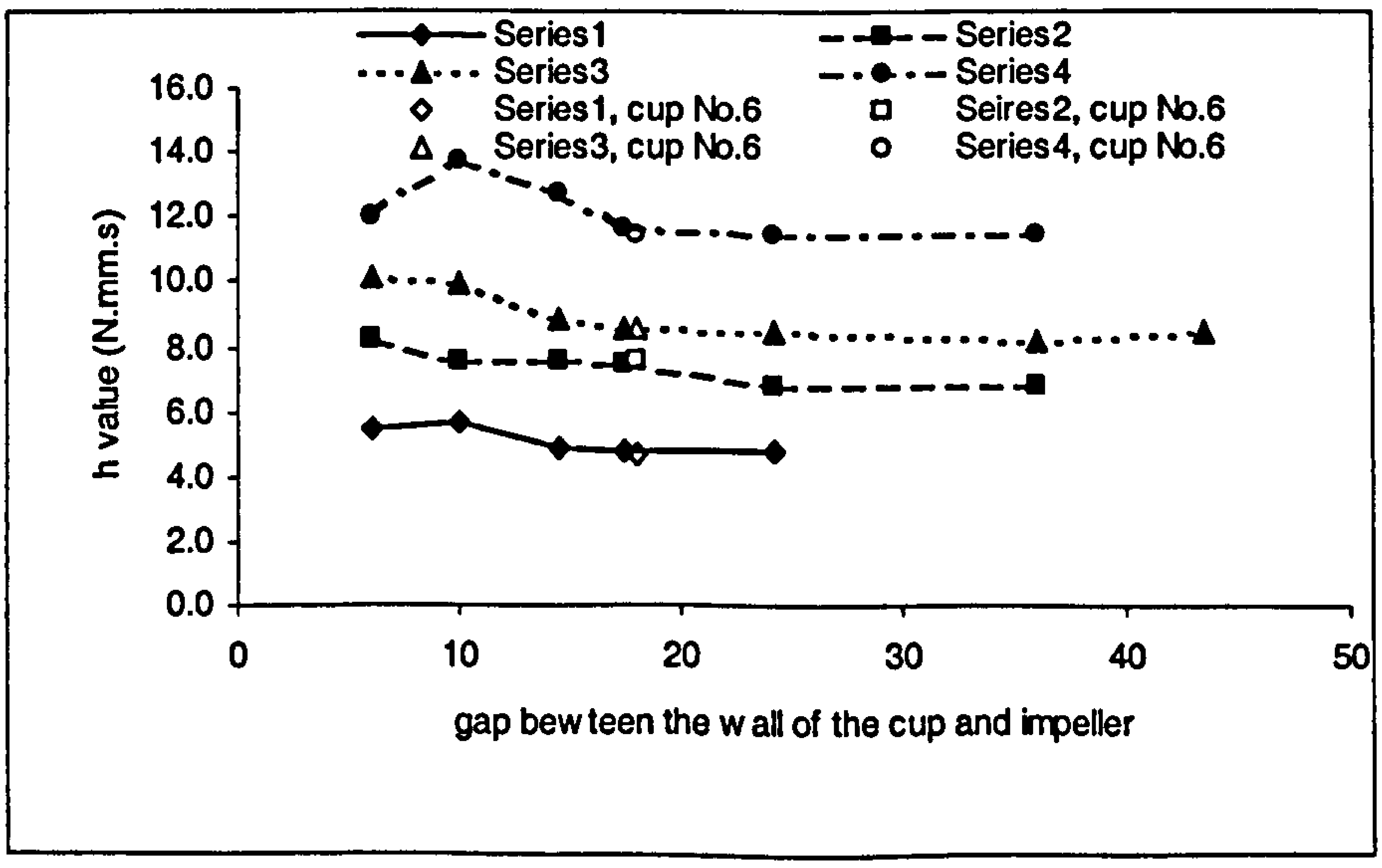
Four mixes with medium flowability were tested, with mix proportions giving spreads between 230 and 260 mm and V-funnel flow times 2 and 5 seconds. The water/powder ratio by volume was in the range of 0.72-0.945, the sand/mortar ratio by volume was 0.45. The powder was 100% PFA to keep the mixes with long and stable workability retention during the tests, however, the workability still decreased, and therefore Conplast R retarding admixture was also added. Even with this, the rheological property of the mix still changed slightly during the test, therefore, it was checked with a reference cup (cup No. 5) each time before starting the next test with a different cup.

Visual observation showed that all the mortar was fully sheared in each cup during the test, but it is difficult to observe slippage. The values of the two constants, g and h in the relationship were obtained from the torque/speed flow curve.

As shown in **figure 4-6,** both g and h values were slightly affected by the cup size. Moreover, the significance of the effect was dependent on the cup size and flowability of mortar. When the mortar had a high flowability, i.e. low g and h values, the effects were small enough to be negligible; however, with a mortar with low flowability, the effects of cup size became significant. In general differences occurred when the gap was less than about 20 mm. However, it is very difficult to distinguish between the effect of slipping, trapping and the wall-effect.



(a)



(b)

Figure 4-6 Effect of cup size on the two-point test measurement (a) g value (b) h value

The measured g and h values with cup No. 6 (with ribs) were slightly lower than or the same as those measured by the cups of No.5, No.7 and No. 8, with the exception of the g value in series 4. Again this proves that the effect of slippage and the wall-effect decreased with the increase of cup size in the test range.

A further study was carried out to compare results using cup No.3 and No.5, because both were used in two-point test before, using real mortar for SCC. The test results were determined in fundamental units, so calibration was first carried out for these two cups.

4.2.3.2 Calibration

As explained in section 4.2.2.4, the purpose of the calibration of the two-point test is to enable the fundamental Bingham constants (yield stress τ_0 and plastic viscosity μ) to be obtained from the torque/speed (T/N) flow curves. The calibration requires the use of a Newtonian and a pseudoplastic material.

- Theory and governing equations

The calibration theory is described in detail by Tattersall and Banfill [79]. This is based on mixer theory proposed by Metzner and Otto. The average shear rate in the mixer might be regarded as being simply proportional to the speed of impeller

$$\dot{\gamma} = KN. \tag{4-10}$$

where K is a constant.

The two constants from two-point test can be expressed in terms of τ_0 and μ using

$$\tau_0 = (K/G)g \tag{4-11}$$

$$\mu = (1/G)h \tag{4-12}$$

where

K and G: apparatus constants.

The constants, K and G, can be obtained as follows.

(1) For a Newtonian material in the two-point apparatus, there is the relationship

$$T/N = G\eta \qquad (4\text{-}13)$$

therefore,

$$G = 1/\eta \times T/N, \qquad (4\text{-}14)$$

where

η:viscosity of Newtonian material (measured or known);

T:an impeller torque;

N:impeller speed.

(2) For a pseudoplastic material of the type that obeys a power law,

$$\tau = r\dot{\gamma}^{s} \qquad (4\text{-}15)$$

where,

r, s:constants for a pseudoplastic materials, measured using a concentrical rheometer.

Therefore, the apparent viscosity is given by

$$\eta_{app} = \frac{\tau}{\dot{\gamma}} = r\dot{\gamma}^{s-1} \qquad (4\text{-}16)$$

In the two-point apparatus, the material gives a flow curve of the form

$$T = pN^{q} \qquad (4\text{-}17)$$

where

p,q: constants.

Therefore,

$$\eta_{app} = \frac{T/N}{G} = \frac{pN^{q-1}}{G} \qquad (4\text{-}18)$$

Hence, by equating the values of η_{app} from equations 4-17 and 4-19,

$$\dot{\gamma} = \left(\frac{p}{rG}\right)^{1/(s-1)} N^{(q-1)/(s-1)} \qquad (4\text{-}19)$$

If **q=s**, as is to be expected, and the range of shear rates are similar in the two-point apparatus and in viscometer, by equating the values of $\dot{\gamma}$ from equations 4-11 and 4-19,

$$K = \left(\frac{p}{rG}\right)^{1/(s-1)} \qquad (4\text{-}20)$$

- Experimental details and test results

The calibration was carried out for cups No. 3 and No. 5. The Newtonian liquid used was glycerol at various dilutions. The pseudoplastic liquid was approximately 0.5%, 1%, 1.5% and 2% Welan Gum solution. During the test the temperature was controlled by using water circular system through the rheometer. The temperature varied within ± 0.2 ^{0}C.

- Determination of G

With the series of Newtonian fluids,

a) η was measured in a concentric cylinder system with cylinder D145;
b) the slope of the T/N flow curve was measured in the helical impeller system;
c) values of G were then calculated from (4-15);
d) the mean G was then obtained.

Table 4-7 shows the test results. The mean G value was 1.10 × 10^{-3} m^3 for cup No.3 with a variation of ± 0.03 m^3, and 0.98 × 10^{-3} m^3 with variation ± 0.03 m^3 for cup No 5. These constants are close, and the difference may be experimental error because the G value should be related to the impeller only, and be independent of cup size.

Table 4-7 Test results for calibration

Test No	G for cup No. 3 (m^3)	G for cup No. 5 (m^3)
1	1.12E-3	1.01E-3
2	1.09E-3	1.00E-3
3	1.13E-3	0.97E-3
4	1.06E-3	0.96E-3
5	1.12E-3	0.97E-3
Average	**1.10E-3**	**0.98E-3**

- Determination of K

With the series of power law fluids, i.e., Welan Gum solutions,

a) the fluid was tested with the concentric cylinder rheometer, and values of r and s were determined by using power law regression ($\tau = r\dot{\gamma}^s$);

b) the fluid was tested in the two-point test with the helical impeller, and values of p and q were determined by using the power law regression ($T = pN^q$);

c) s and q were compared, and if these close to each other, K was determined from equation 4-21.

The chosen range for equivalent shear rate in the helical impeller system is in the range covered by the range of shear rates in the concentric cylinder system which was between 0.1-1.9 revolution/sec.

Table 4-8 test results for calibration

	Welan gum concentration	DIN 145		Helical impeller		s/q	K	Average of K
		r	s	p	q			
Cup No. 3	0.5 %	4.70	0.176	8E-04	0.181	0.973	9.83	9.98
	1.0 %	19.26	0.127	0.0028	0.121	1.050	10.11	
	1.5 %	43.54	0.096	0.006	0.097	0.990	9.98	
	2.0 %	69.81	0.081	0.0092	0.086	0.942	9.98	
Cup No. 5	1.0 %	23.71	0.086	0.00284	0.083	1.04	9.96	9.41
	1.5 %	40.27	0.081	0.00502	0.077	1.052	9.44	
	2.0 %	57.607	0.087	0.00774	0.083	1.05	8.82	

Detailed data are given in **Appendix 4**, and **table 4-8** shows the results. The values of s/q are very close to 1, and therefore are satisfactory. The values of K show only a small difference with the mean value being 9.98 for cup No. 3 and 9.41 for cup No. 5.

4.2.3.3 Effect of cup size, further study

The measurements of yield stress and plastic viscosity by using cup No. 3 and No. 5 were compared. Three different but typical mortars for SCC were used, with the mix proportions shown in **table 4-9**. All the mixes had initial spreads between 300-310 mm by adjusting the dosage of superplasticizer. Mix 4-1 had a very high initial plastic viscosity, mix 4-2 had a low plastic viscosity and mix 4-3 included a viscosity agent.

Each mix was tested in both cups, and the time of mixing and testing were strictly controlled because the mortar properties were very time dependent. Each mix was tested twice, and the testing order of the cups was changed. All the mixes were remixed by hand just before filling the cup.

Table 4-9 Mix proportions for cup size effect study

Mix No.	V_w/V_p	Sp type	Sp (%)	WG (%)	V_s/V_m	Composition of powder
Mix 4-1	0.945	Glenium51	0.014	0	0.45	100 % PC
Mix 4-2	0.945	Glenium51	0.07	0	0.45	PC/LSP = 60/40
Mix 4-3	1.103	Conplast430	0.01	0.075	0.45	100 % PC

Figure 4-7 shows the test results for Mix 4-1. Both tests showed the same trend of property change with time (t) but with slightly different ranges of value. Trend lines can be obtained; for example, for each test with different cups:

For cup No. 3,

test1: $\tau_{03} = 0.0172t^2 - 0.8871t + 9.967$; (4-21)

test2: $\tau_{03} = 0.0176t^2 - 1.1581t + 18.732$. (4-22)

For cup No. 5,

test1: $\tau_{05} = 0.0142t^2 - 0.4292t + 1.7994$ (4-23)

test2: $\tau_{05} = 0.0145t^2 - 0.5768t + 4.2164$. (4-24)

The average yield values are,

For cup No.3,

$$\tau_{03} = 0.0174t^2 - 1.0225t + 14.3495 \quad (4\text{-}25)$$

For cup No.5,

$$\tau_{05} = 0.01435t^2 - 0.503t + 3.0089 \quad (4\text{-}26)$$

Hence the values of τ_{03} and τ_{05} can be obtained from equations (4-26) & (4-27) at any given time. A similar analysis was carried out for yield stress and plastic viscosity for mixes 4-2 and 4-3. **Figure 4-8** shows the plot of yield stress and plastic viscosity for each cup size. It can be seen that the yield stress measured with cup No. 3 is slightly lower than that from cup No. 5, with a maximum difference of 10 Pa, and the plastic viscosities were very close. The difference of yield stress can be ignored because it is within the reproducibility error of mortar (see section 4.4).

In general, it can be concluded that there may be slippage, wall-effect and trapping effects if a cup size is too small and surface of wall is very smooth, but it can be easily avoided by using slightly bigger size cup while the wall surface is rough enough to prevent slippage. In this programme, the cup size No. 3 or bigger could be used, and the normal surface of the cup was sufficiently rough, and no vertical ribs were required. Therefore cup No.5 which had a gap about 5 times of the maximum size of sand (5 mm) was used in the most of studies. The cup No.3, with gap about 3 times of the maximum size of sand, was also used in some tests carried out before September 1999.

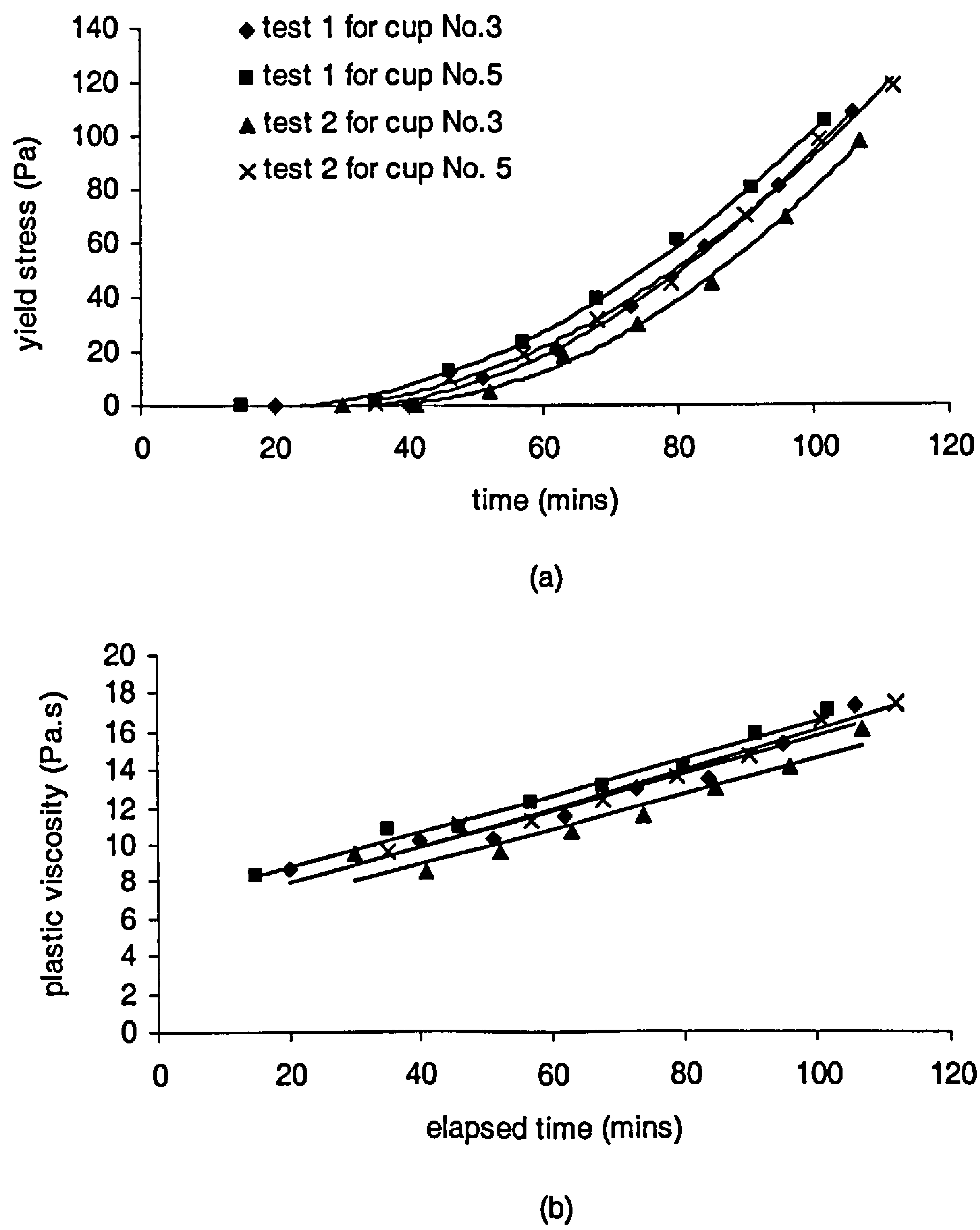
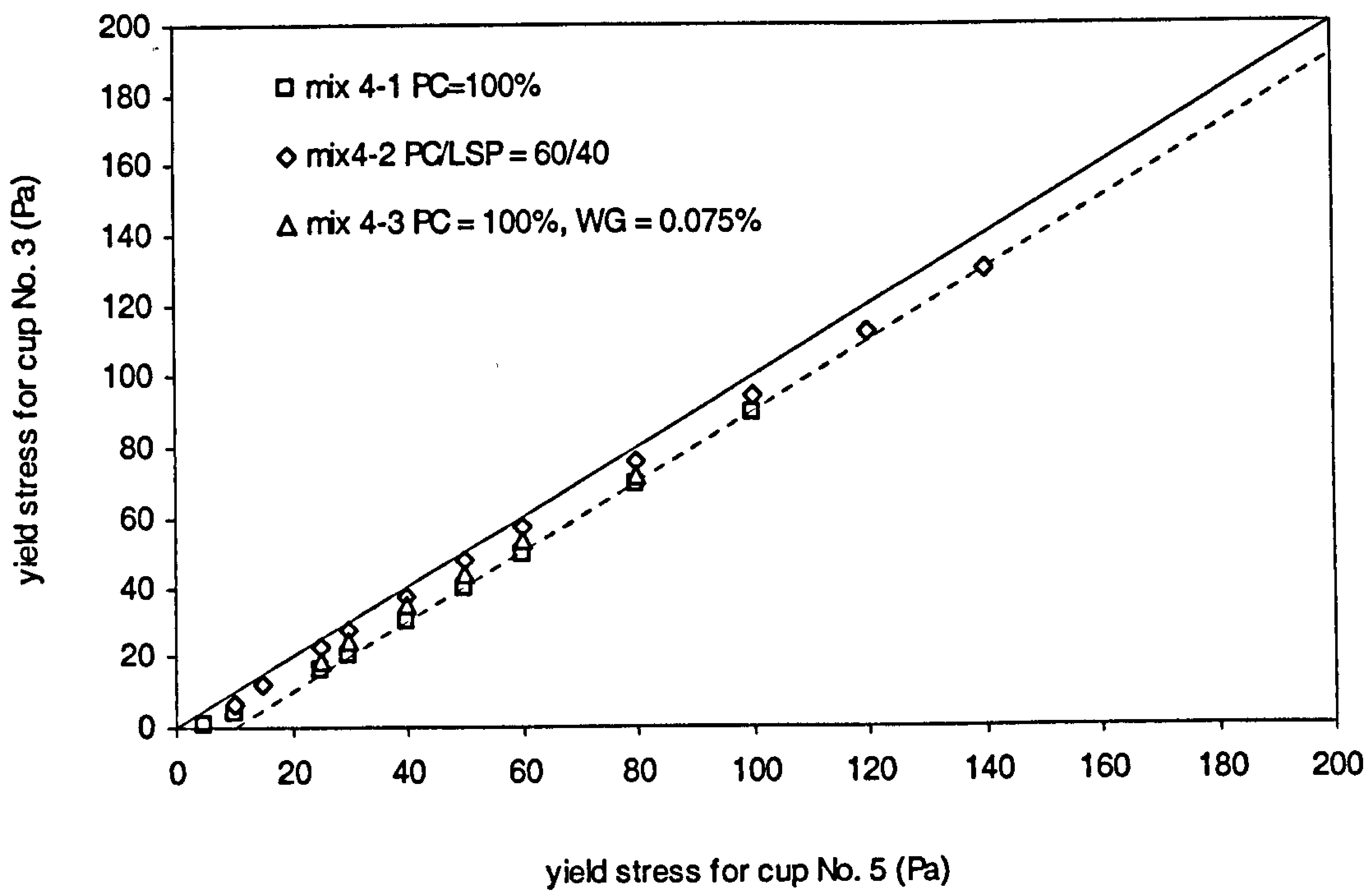
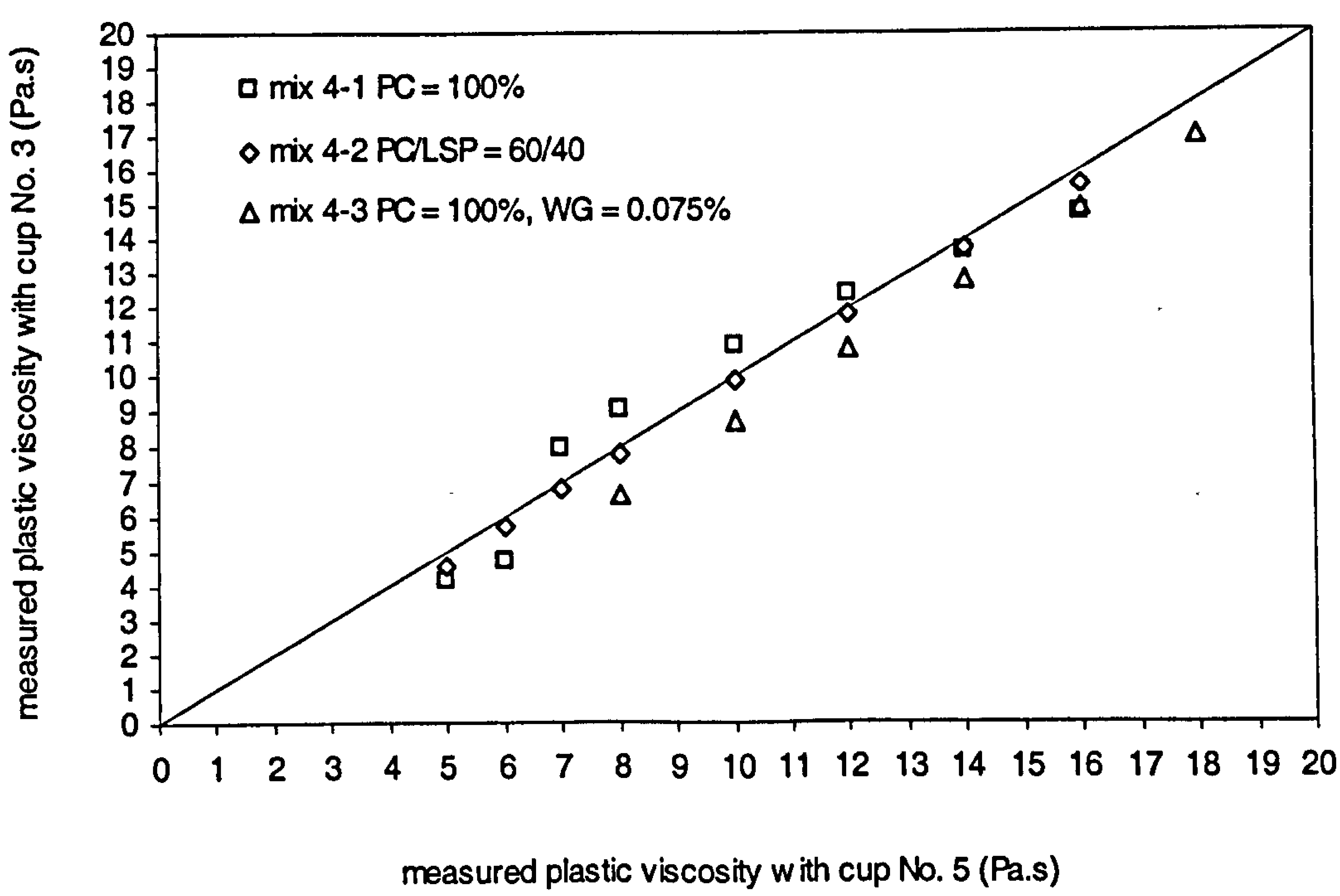


Figure 4-7 Test results for Mix 4-1 obtained with cup No. 3 & and No. 5 (a) yield stress (b) plastic viscosity



(a)



(b)

Figure 4-8 Comparison of (a) yield stress (b) plastic viscosity obtained by cup No. 3 and No. 5

4.2.3.4 Discussion

It was thought important to confirm the validity of the helical impeller rheometer by comparison of results from this with those from alternative devices such as the ViscoCorder and a coaxial cylinder viscometer (as described in chapter 2). Unfortunately, these two devices were not available in the lab at UCL, and therefore a comparison was made using information obtained from literature. **Table 4-10** shows rheological properties of mortars measured by the Viscocorder, a cylinder viscometer and the helical impeller rheometer. Mix 1 and 2 are from [145], mix 3 and mix 4 were obtained during rheology lab demonstrations for undergraduate students at UCL.

Table 4-10 Results of test in mortar in a ViscoCorder, cylinder viscometer and the Rheometer with helical impeller: Cross comparison

Test devices	Mix No.	Test No.	type of cement	type of sand	w/c	sand/cement by wt.	yield stress (Pa)	mean	Plastic viscosity (Pa.s)	mean
	Mix 1	1	fairly coarsely				173		5.0	
		2	ground Portland	maximum			160		4.8	
ViscoCorder		3	cement with	size of 2 mm	0.453	1.51	182	171	4.3	4.6
		4	~ 3% filler	(sand A)			171		4.6	
		5	SSA=3140cm²/g				169		4.5	
	Mix2	1	same type as				320		2.2	
coaxial		2	above, but demands	maximum	0.453	1.51	255	267	2.3	2.7
cylinder		3	more water	size of 2 mm			226		3.7	
viscometer			SSA=2895cm²/g	(sand B)						
	Mix 3	1					140		4.1	
		2					150		4.1	
		3			0.4	1.33	145	147	3.8	4.0
		4	Ordinary Portland				144		3.9	
helical		5	cement from	maximum			154		3.9	
impeller	Mix 4	1	Rugby, UK	size of 5 mm			60		1.9	
rheometer		2	SSA=3550cm²/g		0.45	1.33	60	59	1.7	1.9
		3					57		1.9	
		4					59		2.0	

Clearly, different test results were obtained with the different rheometers. Banfill [145] has suggested that a possible reason is the difference in the two cements. The cement in mix 2 is coarser that that in mix 1 but has a greater water requirement for standard consistency, increasing the yield stress of the mortars. He also confirmed that there is general agreement between the ViscoCorder and the cylinder viscometer results by another series of mortar tests [143], as reviewed in chapter 2. The different results of mix 3 & 4 and mix 1 are largely due to different types of sand and mix proportions. The use of a lower content of coarser sand decreases both yield stress and plastic viscosity. Nevertheless, all the results are of the same order of magnitude, suggesting validity of the established rheometer after calibration.

Also, Shindoh *et al* [142] have studied the effect of mix compositions on the rheological properties of SCC using a coaxial cylinder viscometer, and showed that the yield stress of the mortar component was between 5 and 40 Pa, and the plastic viscosity between 4 and 10 Pa.s. Fujiwara *et al* [65] concluded that the rheology of mortar for SCC, obtained with a rotating cylinder viscometer, should be a yield stress of 20~50 Pa, a plastic viscosity of 6 ~ 12 Pa.s. In this project, with the helical impeller rheometer, the yield stress of the mortar of SCC was found to be lower than 20 Pa, and the plastic viscosity between 6 ~ 14 Pa.s (see also chapter 10). Clearly there is general agreement in values of the rheology of SCC mortar measured with different rheometers.

4.3 Mixing and testing procedures

In order to obtain consistent and reliable test results, a controlled and well organised mixing and testing procedure was needed for both mortar and concrete.

4.3.1 Mortar

Usually 1.7 litres of mortar were mixed using a Hobart mixer, with the mixing procedure being varied as part of the study, as described in chapter 5. When assessing workability retention, a series of tests were carried out at 10 mins, 30 mins, 60 mins, 90 mins, and 120 mins after the start of mixing. Each series of tests took 5 minutes, and was in the order of V-funnel, spread, and two-point test. The mortar was remixed for 1 min before each series.

4.3.2 Concrete

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 of 18 rpm. Normally 40 litres of concrete were mixed. The mixing method was normally consistent with that of the mortar unless specified otherwise. More details are given in chapter 5.

With concrete, two operators carried out the tests in order to shorten the testing time and minimise errors. The procedure after completing of the concrete mixing was:

1. The two-point test bucket was filled with concrete. One operator then carried out the two- point test, the other filled the V-funnel with concrete.
2. The V-funnel test was carried out while the second operator took a sample for the slump flow test.
3. The slump flow test was carried out.
4. All the concrete was put back into the mixer and remixed for 30 seconds, before carrying out the U box test.

All the tests were finished within about 12 minutes.

A complete set of tests was carried out at 60 and 120 minutes after mixing, however, the V-funnel and the slump flow test were also carried out at 30 and 90 minutes after mixing; this took 5 minutes. All testing was stopped when slump flow was lower than 400 mm, and nine cubes were then cast for the compressive strength test.

4.4 Repeatability and reproducibility of mixing and test methods

Due to the large number of tests carried out within two hours, each test was only performed once to obtain the result. Repeatability and reproducibility of test results was examined in order to evaluate them correctly.

According to BS 5497: part 1: 1987, the repeatability value r, is defined as 'The value below which the absolute difference between two single test results obtained with the same method on **identical test material** under the **same conditions** (same operator, same apparatus, same laboratory, and a short interval of time) may be expected to lie with a probability of 95%. The reproducibility value, R, is defined in a similar way except that it refers to different test conditions, that is, to results obtained by different operators with different pieces of apparatus, in different laboratories or at different times. As far as reproducibility was concerned in this research it refers to different room temperature otherwise test conditions were unchanged.

In mortar and concrete tests, the error for repeatability generally occurred during sampling of materials, weighing, mixing, and testing, while the error for reproducibility included all the above and also testing conditions such as temperature, moisture, the change of testing equipments and operator *etc.*

When testing the fresh properties of mortar and concrete, obtaining identical mixes for a reproducibility test is very difficult, and the properties change with time during the repeatability test. Therefore the repeatability and reproducibility of the test results for mortar and concrete obtained in this section did not strictly satisfy the above definitions; however, these can still be useful when evaluating the test results.

All repeatability and reproducibility analyses were carried out according to BS 5497: Part 1: 1987; the details are shown in **appendix 6**.

4.4.1 Mortar

The reproducibility of mortar workability properties was estimated from the results for a 100% PC mix with a water/cement ratio of 0.3 by weight, a sand/volume ratio of 0.45 by volume and Glenium51 at 0.09% of PC by weight. The mix was batched three times, and was tested once each time. **Table 4-11** shows the test results and the calculated reproducibility of spread, V-funnel flow time, yield stress and plastic viscosity on 95% probability level.

Table 4-11 Mortar test results for reproducibility assessment

Test No	Spread (mm)	V-funnel (secs)	Yield stress (Pa)	Plastic viscosity (Pa.s)
1	226	7.23	45.4	15.2
2	229	6.9	43.4	15.0
3	220	7.29	50.9	16.0
average	**225.0**	**7.1**	**46.6**	**15.4**
Standard Deviation	**4.6**	**0.2**	**3.9**	**0.5**
Reproducibility (R)*	**12.8**	**0.6**	**10.9**	**1.5**

* at 95% probability level: R=2.8 x Standard Deviation

As summarised in **table 2-12**, Fujiwara *et al* found that the yield stress of mortar for SCC is in a range 5-20 Pa and the plastic viscosity 6-12 Pa.s, while Chai concluded that the spread is higher than 300 mm and the V-funnel flow time between 2-10 seconds for the mortar component of SCC. Therefore it can be concluded that all the reproducibility errors are low enough for the properties of mortar to be evaluated.

4.4.2 Concrete

Slump flow and V-funnel

The repeatability and reproducibility of slump flow and V-funnel test results of a concrete mix was examined with a sulphate-resisting cement mix. The water/cement ratio was 0.3 by weight, the ratio of sand to the mortar was 0.45 by volume, and the coarse aggregate content was 50% of dry rodded bulk density. The time to flow to 500 mm slump was also measured during the slump flow test. Two-point testing was not carried out in this test series because of the difficulty in carrying out a sufficient number of tests in short time, but an estimate will be made based on other results and discussed later.

Two nominally identical batches were tested, namely Mix1 and Mix2. In Mix1 the slump flow and V-funnel test were carried out immediately after mixing and repeated twice (i.e., three times in total) in about 15 minutes. Then the concrete was remixed for 1 minute and tested again. **Figure 4-9** shows the test results. It was found that the slump flow increased for 30-50 minutes after mixing, then decreased. Moreover, mixing affected the properties; the V-funnel flow time and time to 500 mm slump flow increased for a time right after mixing. It was therefore decided to remix the concrete each time before each series of test for Mix2 to keep same testing condition.

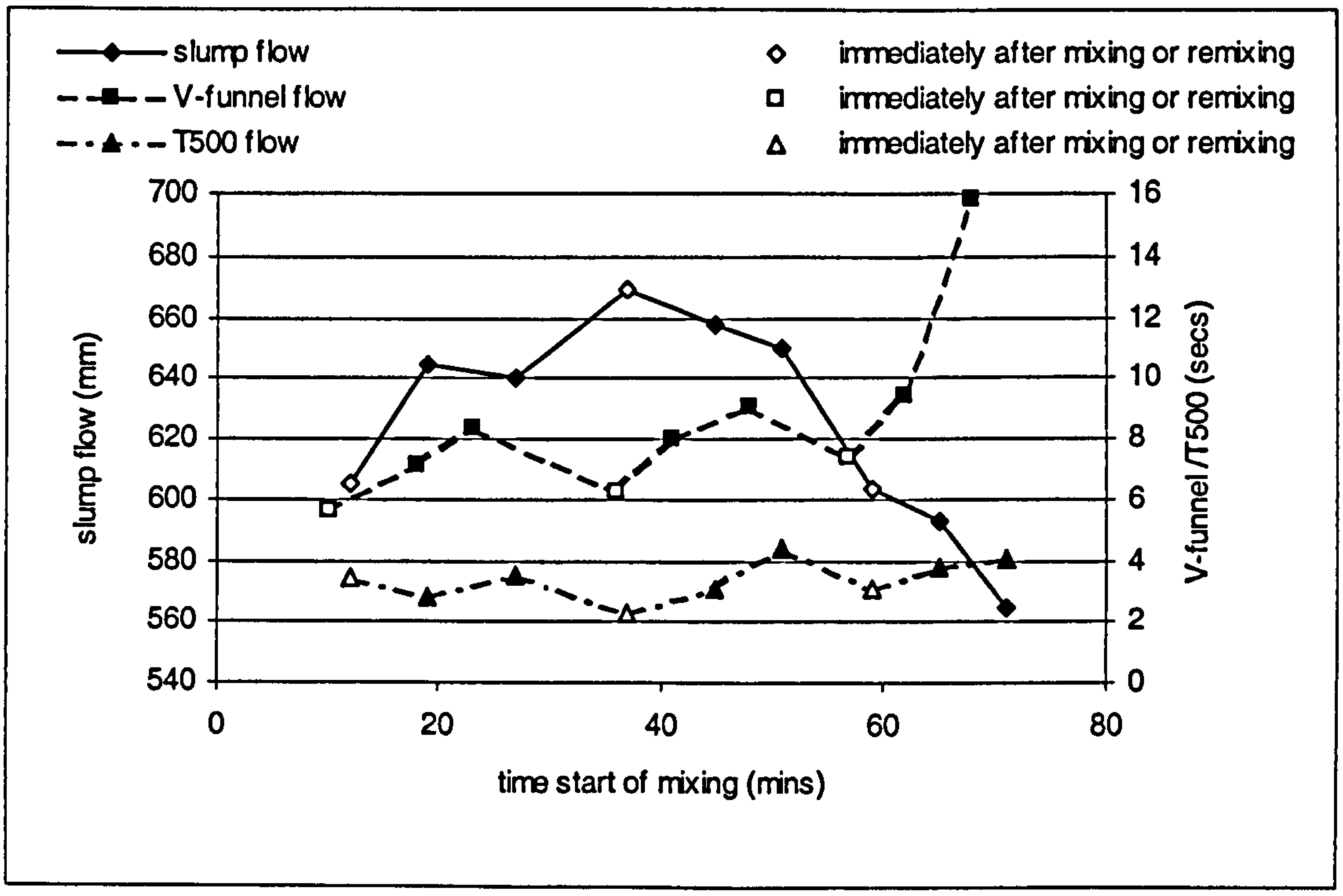


Figure 4-9 SRC concrete properties of mix1

The properties of Mix1 and Mix2 obtained between 30 minutes and 90 minutes after mixing are shown in **figure 4-10** & **4-11.** To keep mixing conditions consistent for Mix 1 and Mix 2 the results obtained immediately after remixing were only used in the figure; therefore only two points were obtained for Mix1 which is not enough for repeatability analysis. Data from Mix 2 shows that the slump flow decreased linearly with time, and each point was on or very near to the regression line, as with the V-funnel test results shown in **figure 4-11.**

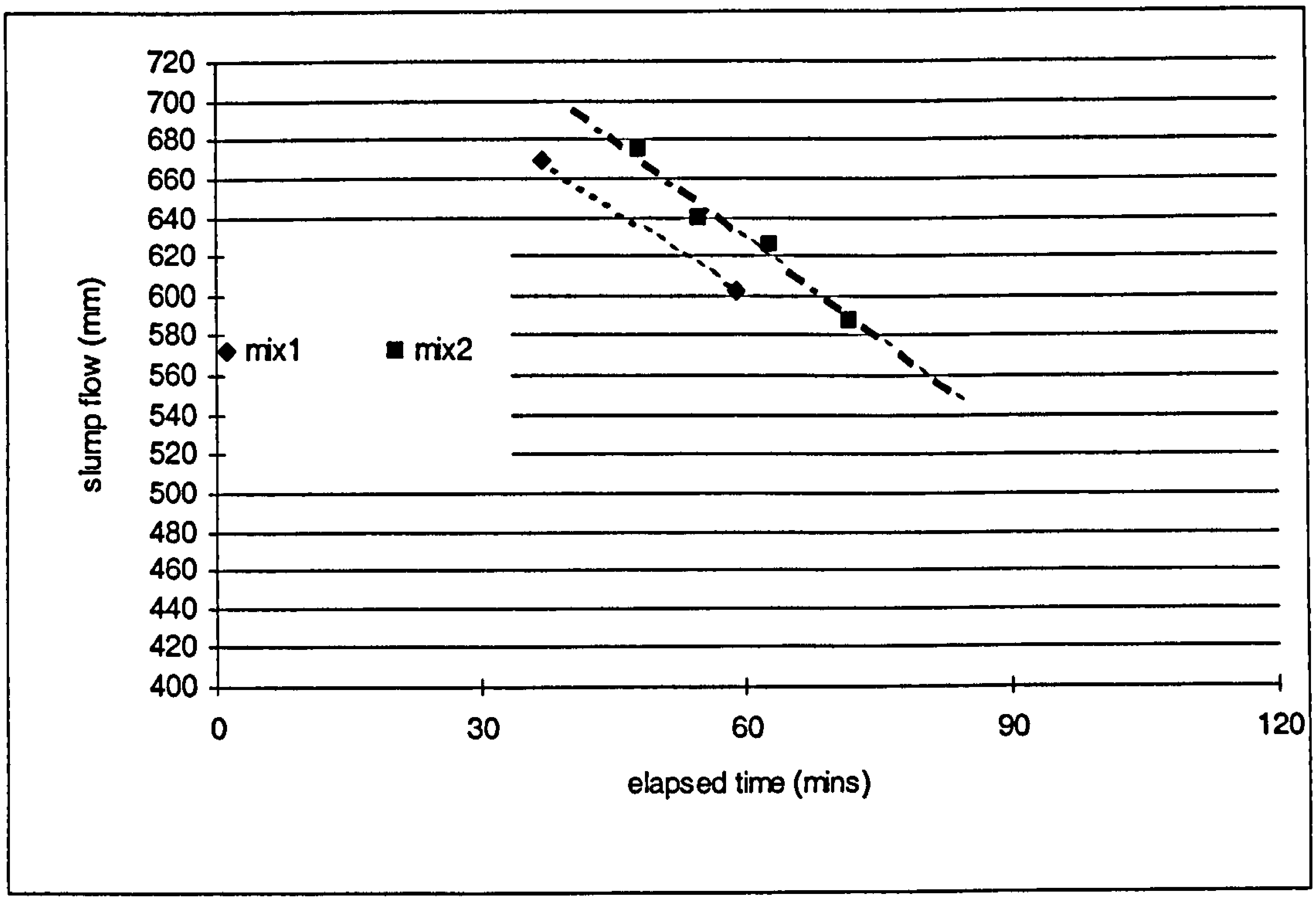


Figure 4-10 Reproducibility of slump flow

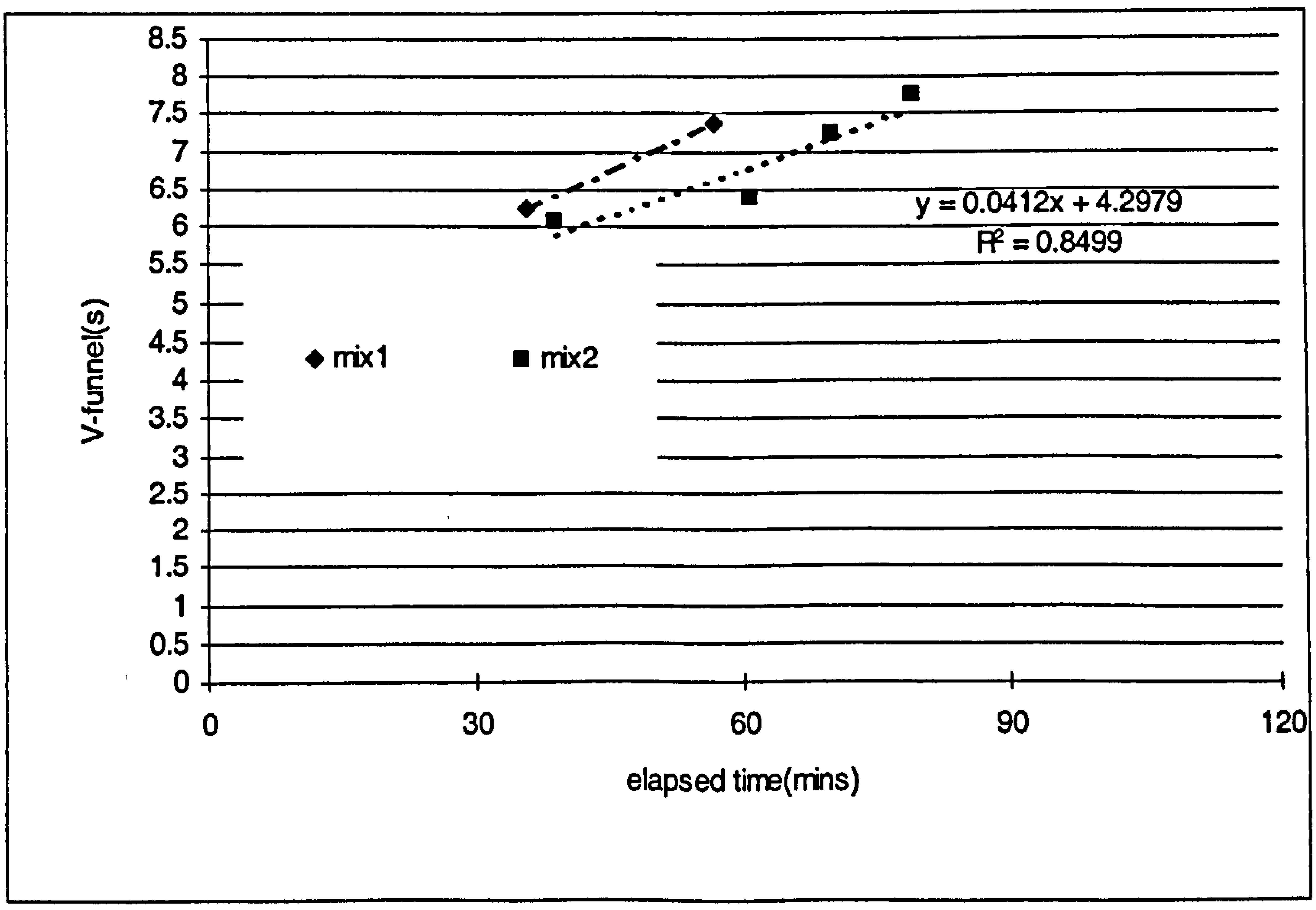


Figure 4-11 Reproducibility of V-funnel flow time

Table 4-12 Repeatability and reproducibility analyses for slump flow and V-funnel of concrete

Time after start of mixing (mins)	slump flow (mm) Original data	Data on the trend line	error (e_i)	Time after start of mixing (mins)	V-funnel (secs) Original data	Data on the trend line	error (e_i)
48	**675**	671.60	3.396	**54**	**5.50**	5.9047	0.1853
55	**640**	647.51	-7.51	**61**	**6.38**	6.8111	-0.4311
63	**625**	619.97	5.026	**70**	**7.22**	7.1819	0.0381
72	**588**	589.0	-0.996	**79**	**7.76**	7.5527	0.2073
Repeatability variance, var(e)= $\frac{1}{n-1}\sum_{i=1}^{n} e_i^2$, (n=4)			*31.4*	Repeatability variance, var(e)= $\frac{1}{n-1}\sum_{i=1}^{n} e_i^2$, (n=4)			*0.09*
Repeatability standard deviation = $S_r = \sqrt{\text{var}(e)}$			*5.60*	Repeatability standard deviation = $S_r = \sqrt{\text{var}(e)}$			*0.30*
Repeatability at 95% probability level $r = 2.8 \times S_r$			*16*	Repeatability at 95% probability level $r = 2.8 \times S_r$			***0.84***
variance between Mix1 and Mix2 (obtained from average difference between two trend lines) var (B)= $S_L^2 = 33.5^2$			*1122.3*	variance between Mix1 and Mix2 (obtained from average difference between two trend lines) var (B)= $S_L^2 = 33.5^2$			*0.36*
Reproducibility standard deviation = $\sqrt{S_r^2 + S_L^2}$			*34*	Reproducibility standard deviation = $\sqrt{S_r^2 + S_L^2}$			*0.7*
Reproducibility at 95% probability level = $2.8\sqrt{S_r^2 + S_L^2}$			*95*	Reproducibility at 95% probability level = $2.8\sqrt{S_r^2 + S_L^2}$			***2.0***

Table 4-12 shows the test results and calculations for repeatability and reproducibility. The repeatability standard deviation of slump flow was calculated using the error of each result from the regression line, which was 5.6 mm. The reproducibility standard deviation was obtained from the sum of repeatability variance in Mix 2 and average difference between Mix 1 and Mix 2 (about 33.5 mm), and this was 34 mm. Therefore the repeatability of slump flow at 95% confidence was 16 mm, and reproducibility 95 mm. Similarly the repeatability of V-funnel flow time at 95% confidence was obtained to be 0.8 seconds, and reproducibility 2 seconds. The calculation is fully presented in **table A6.3 in appendix 6**. Because only two mixes were tested and only two data obtained in Mix 1, the results was not very reliable, but still the information is useful for evaluating the test results.

The test results for T_{500} is shown in **figure 4-12.** The data was insufficient for analysis, therefore no calculation was carried out.

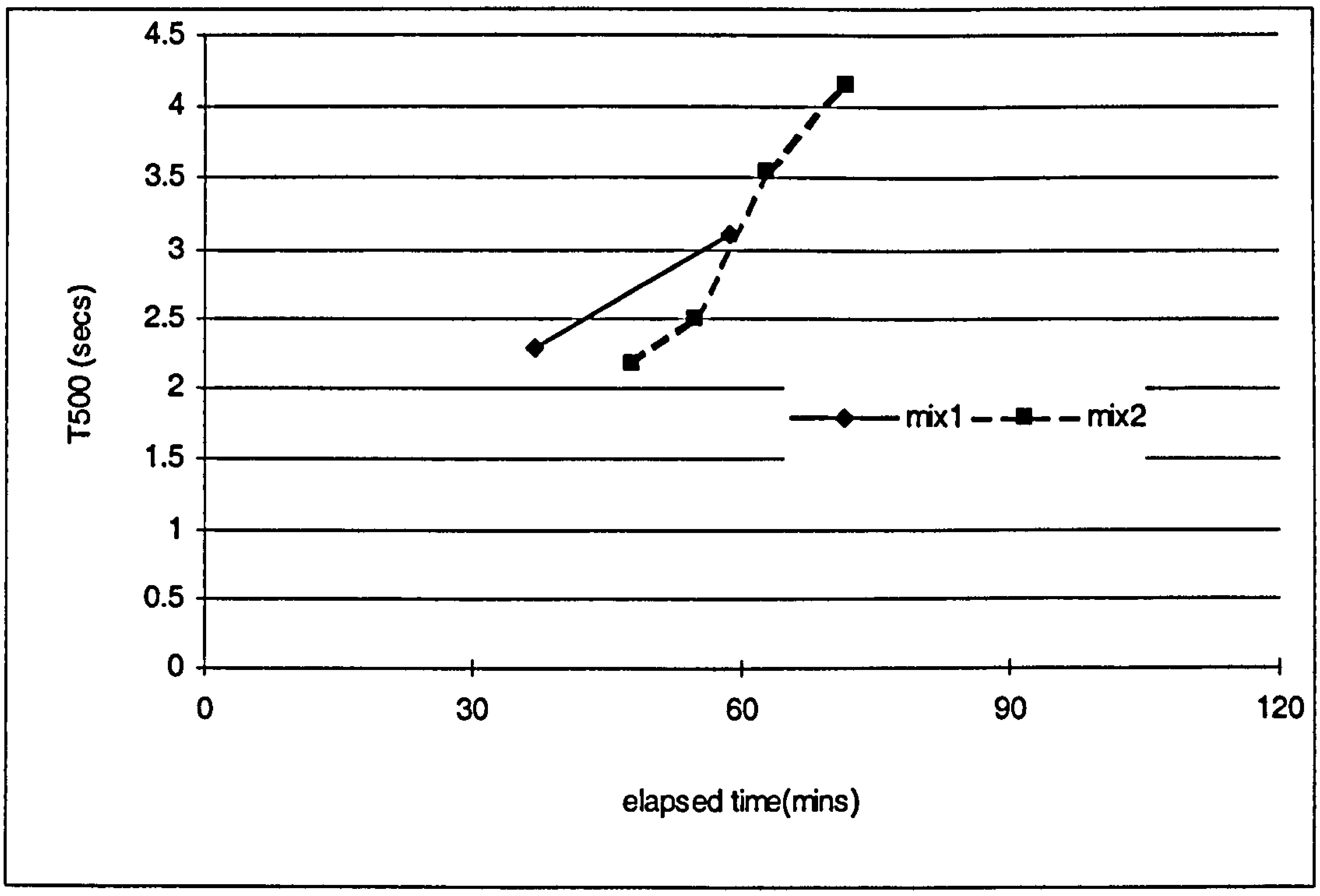


Figure 4-12 Reproducibility of T_{500}

Two-point test results

The repeatability of yield stress and plastic viscosity results for concrete was analysed by using the two-point test results for mixes in LCPC, France, during the comparison of different rheology tests in which UCL participated [43]. Two-point tests were repeated in five mixes with high slump, and detailed test results are shown in **table 4-13.** The repeatability at 95% probability level of yield stress and plastic viscosity is 47 Pa and 14 Pa.s respectively.

Table 4-13 Repeatability of two-point test results for concrete.

Mix No.	Slump (mm)	Yield stress(Pa)			Plastic viscosity (Pa.s)		
		τ_0 (Pa)	Standard deviation (Pa), S_r,	Repeatability at 95% probability level $r = 2.8\times S_r$	μ (Pa.s)	Standard deviation (Pa), S_r,	Repeatability at 95% probability level $r = 2.8\times S_r$
Mix1	220	83	3.5	10.0	13	2.12	6.0
		88			10		
Mix2	185	405	27.6	77.2	61	1.4	4.0
		366			59		
Mix3	230	103	17.0	47.5	39	8.48	24
		79			51		
Mix4	230	161	7.1	19.8	22	2.83	7.9
		171			18		
Mix5	222	252	29.0	81.2	23	10.6	29.7
		211			38		
		Average of repeatability at 95% probability (r)		47	Average of repeatability at 95% probability (r)		14

For a successful SCC, Kawai and Hashida [41], using a two-point test, proposed a yield stress about 50 Pa and the plastic viscosity 20-80 Pa.s, and Wallevil and Nielsson, using BML viscometer, proposed 50-70 Pa and 20-30 Pa.s respectively [2]. It seems that the current two-point machine may be not sensitive enough to distinguish the yield stress of different SCCs.

4.5 Conclusions

1. A small version of the two-point test for concrete with a helical impeller (with diameter of 42 mm) for measuring the Bingham constants of mortar was developed. The possibility of trapping of aggregates, slippage between mortar and the wall, and the influence of wall-effect were avoided by selection of cup size. The cup with 92 mm in diameter and a gap of 24 mm and rough surface was chosen.

2. Repeatability and reproducibility of test results was examined, shown in **table 4-14.** The high errors in the current two-point test machine suggest that it may be not sensitive enough to quantify the yield stress and plastic viscosity for SCC.

Table 4-14 Repeatability and reproducibility of mortar tests and concrete tests

Repeatability (r) or reproducibility (R) at 95% probability level	Mortar tests				Concrete tests			
	D_m, (mm)	T_V, (secs)	τ_0, (Pa)	μ, (Pa.s)	SF, (mm)	T_V, (secs)	τ_0, (Pa)	μ, (Pa.s)
r							47	14
R	12.8	0.6	10.9	1.5	95	2.0		

Chapter 5

Mixing procedure and selection of superplasticizer

In SCC, the superplasticizer is a key component to obtain sufficient flow, and therefore the type and mixing method to produce the greatest efficiency and effectiveness are desirable. This is an important factor in all stages of the current investigation, and was therefore studied first.

The objective of the work presented in this chapter is as follows:

- optimisation of the mixing methods, specifically the addition time, for several typical types of superplasticizers,
- selection of most effective superplasticizer for the remainder of the programme.

The superplasticizers tested included Conplast430, Darcem2001, Sika10, Glenium51 Viscocrete; their properties have been listed in **table 4-3**.

Mortar tests were first carried out, and then some important findings were confirmed by concrete tests. The test methods included,

- spread (D_m) and V-funnel flow time (T_V) for mortar;
- slump flow (SF) and the time to 500 mm slump flow (T_{500}), V-funnel flow time (T_V), U-box filling height and the time flow to 250 mm height ($T_{U\text{-}box}$) for concrete.

Concrete cubes were also cast for compressive strength tests after the workability test; these results are reported in chapter 10.

5.1 Optimisation of superplasticizer addition time

Before the effect of the addition time could be studied, a dosage for each of the superplasticizers had to be selected. In each case, it was thought that a dosage just less than the saturation dosage (SSD) would be appropriate, i.e., high but not sufficient to cause segregation and bleeding. The SSD may itself be influenced by the addition time, and if so the selected dosage should be less than the minimum value to avoid segregation. To avoid an unnecessarily extensive number of tests, the following procedure was adopted.

For one superplasticizer (chosen arbitrarily to be Conplast430) the SSD was determined for addition at the start of mixing (zero delay), and 2 and 4 minutes after the start of mixing (i.e., 2 and 4 minutes delay)

The 2 minutes delayed time gave the 'best' performance, i.e. the lowest SSD, and may therefore be the 'best' for all other types of superplasticizers, was used in obtaining the SSD's for the remaining four superplasticizers.

The effect of delay times of 0-4 minutes was measured for each of the superplasticizers at a dosage level slightly lower than their SSD's. A delayed time of 6 minutes was also tested for the Darcem2001.

A single mix composition with a 100% PC, water/cement ratio of 0.3 by weight, and sand/mortar ratio of 0.45 by volume was used throughout.

5.1.1 Effect of addition time on saturation dosage for Conplast430

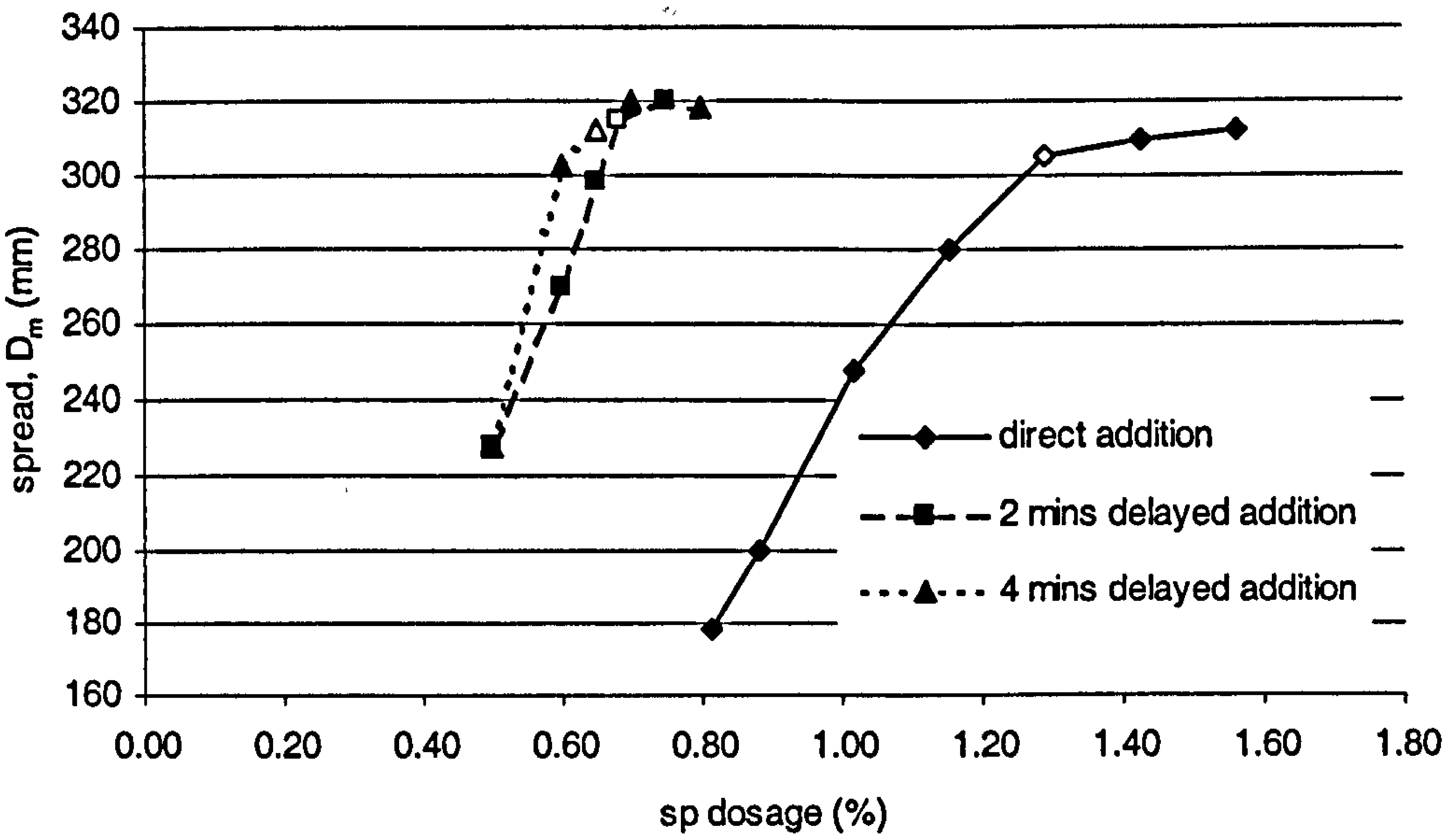
Three different addition times were compared, direct addition (no delay), 2 and 4 minutes delayed additions. For the direct addition, the water and superplasticizer were first poured into the bowl then the cement was added whilst starting mixing, immediately followed by the wet sand. This ensured that the cement was first contacted by superplasticizer and water simultaneously. For the delayed additions 80% of the mix water was added at the start of the mixing, and the remaining 20%

added with the superplasticizer. The mixing was continued for 5 minutes after adding the superplasticizer, then stopped, then continued for another 1 minute before testing. All the mixes were tested at 10 minutes after the start of mixing.

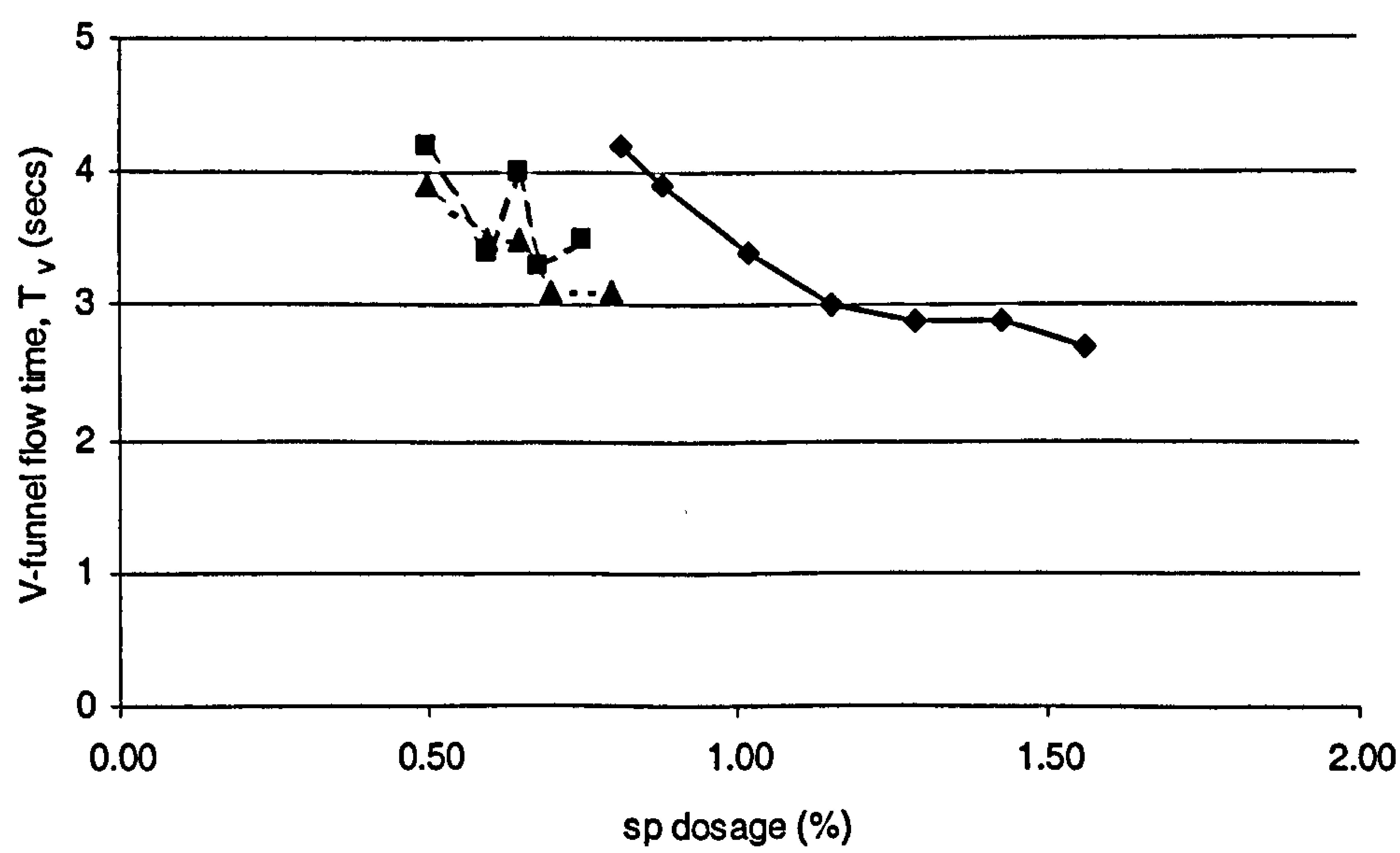
The change of spread and V-funnel flow time with superplasticizer dosage is shown in **figure 5-1.** With increasing the dosage, the spread results increased rapidly towards a maximum and then remained approximately constant or slightly increased by 5-10 mm. There was bleeding if more superplasticizer was added to the mortar with the maximum spread. The V-funnel flow-time decreased towards a minimum value, but the results tended to be more erratic than the spread results. This might be because of the segregation during the test when the mortar flowability is high. The spread test took less time and the quantity of material used is less than the V-funnel test, and therefore, segregation might be avoided.

The saturation dosage was selected to be the maximum spread just before bleeding became visible, in this case, 1.3% for direct addition, 0.65% and 0.68%, for 2 and 4 minutes delayed addition respectively.

Clearly different addition times resulted in significant differences in saturation dosage. The most efficient dispersing action occurred with delayed addition, the SSD being about half of that for direct addition. The spread ceiling (i.e. the maximum spread value) and V-funnel flow time were also slightly higher with delayed additions, but not sufficiently so to be considered as a useful improvement.



(a) spread



(b) V-funnel

Figure 5-1 Effect of Conplast430 dosage on the properties of mortar with the superplasticizer added at various delayed time

5.1.2 Determination of SSD for each type of superplasticizer with 2 minutes delayed addition method

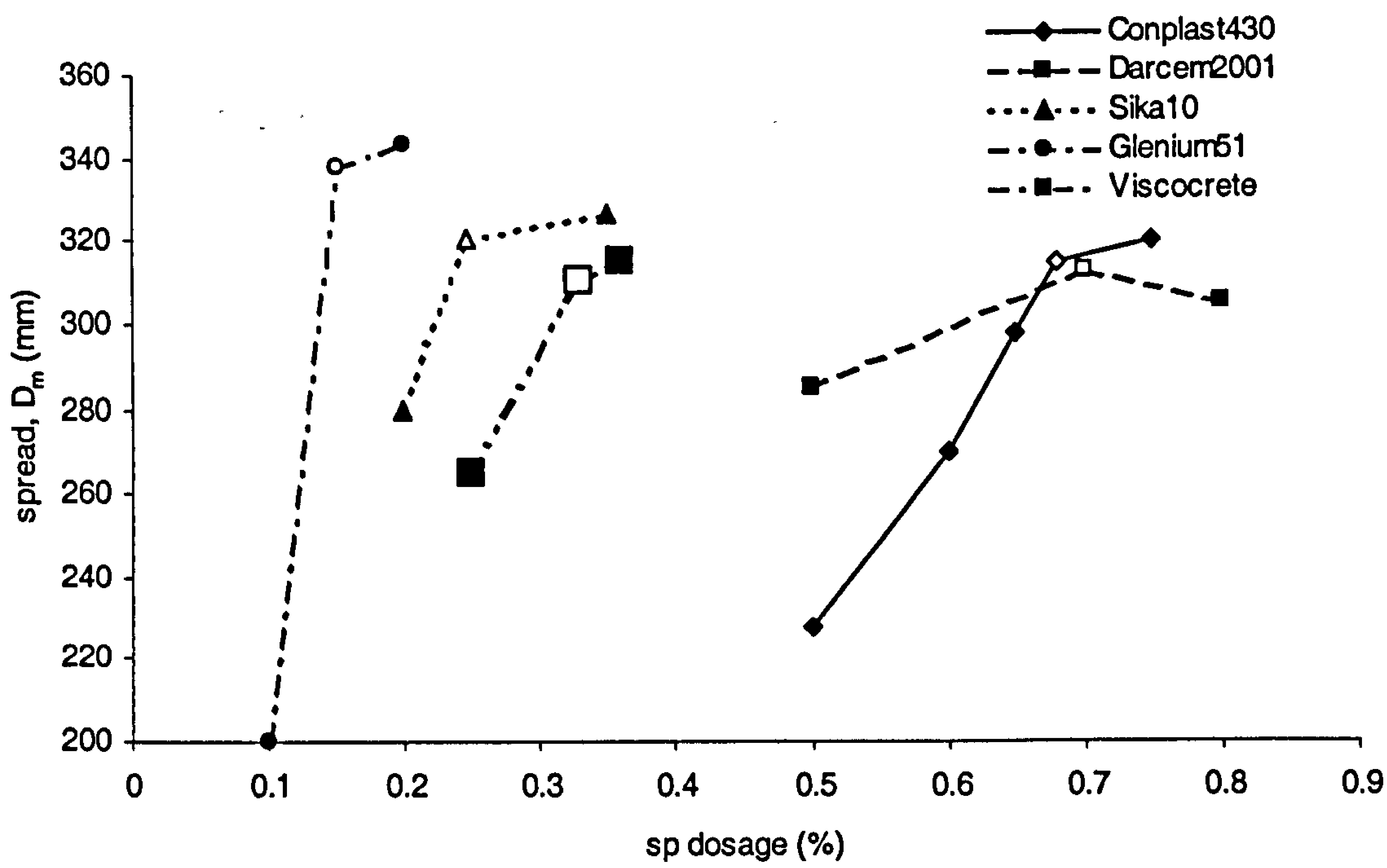
The above results showed that two minutes delayed addition was likely to result in the greatest efficiency of action. This was therefore used to determine the saturation dosage for the other types of superplasticizer, Darcem2001, Sika10, and Glenium51 and Viscocrete (their composition have been given in table 4-3).

Figure 5-2 shows the change of spread and V-funnel flow time for each superplasticizer. It can be seen that the spread increased significantly with increased dosage while there were relatively small reductions in the V-funnel flow times. In fact the V-funnel flow times for Conplast430, Darcem2001 and Viscocrete were nearly constant with the dosage of superplasticizer.

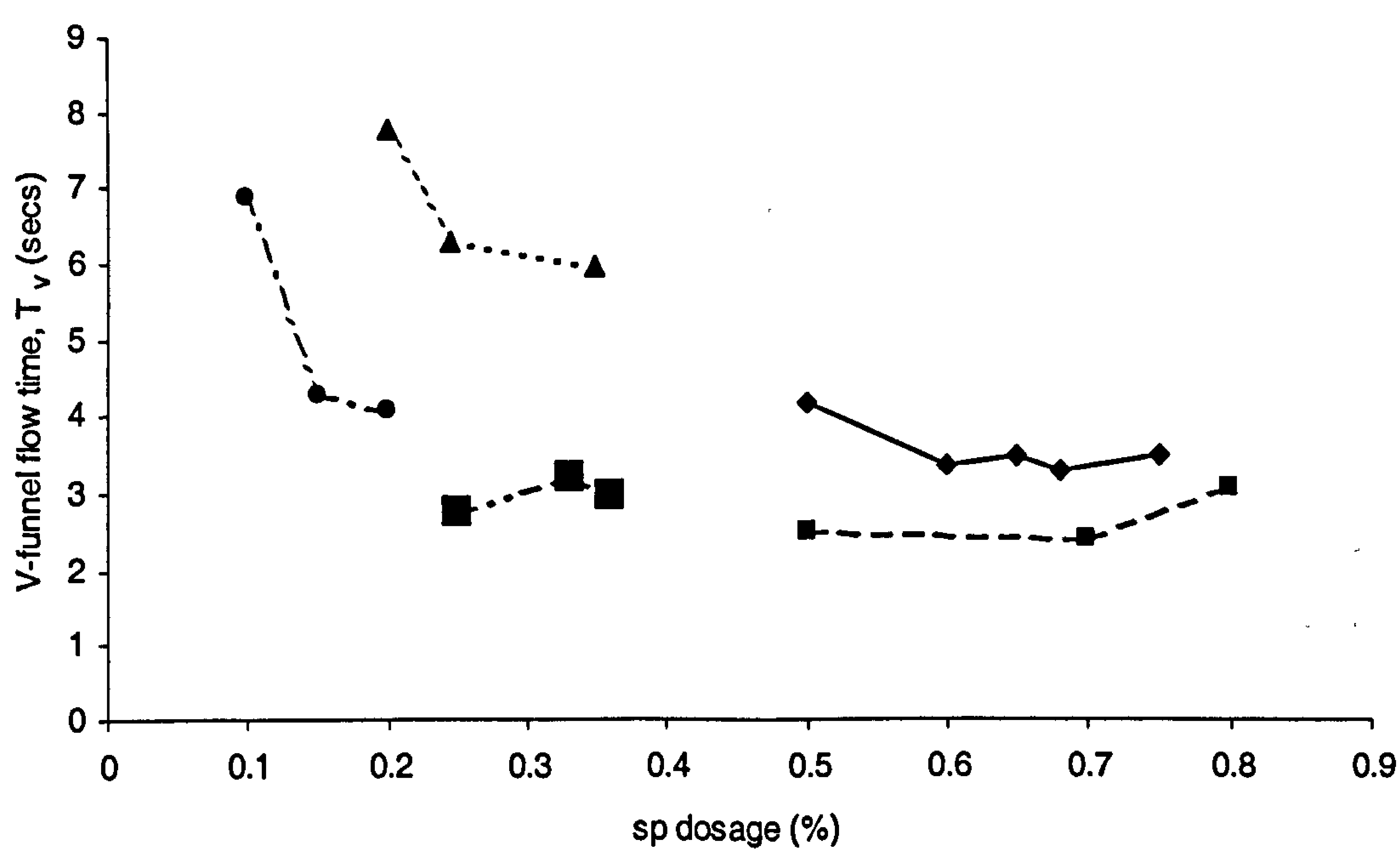
The saturation dosage therefore was more clearly defined by the spread test than by the V-funnel test. When the spread of a mortar increased, the V-funnel flow-time decreased towards a minimum value, but more erratically than the spread results.

The saturation dosages determined by the spread test were found to be:
Conplastp430: 0.65%, Darcem2001: 0.6%, Sika10: 0.3%, Glenium51: 0.15%, Viscocrete: 0.33%.

Much less dosage was required for new generation superplasticizers than the conventional type, especially for Glenium51 for which the SSD was only a quarter amount of that for Conplast430, clearly showing higher efficiency of the new generation.



(a)



(b)

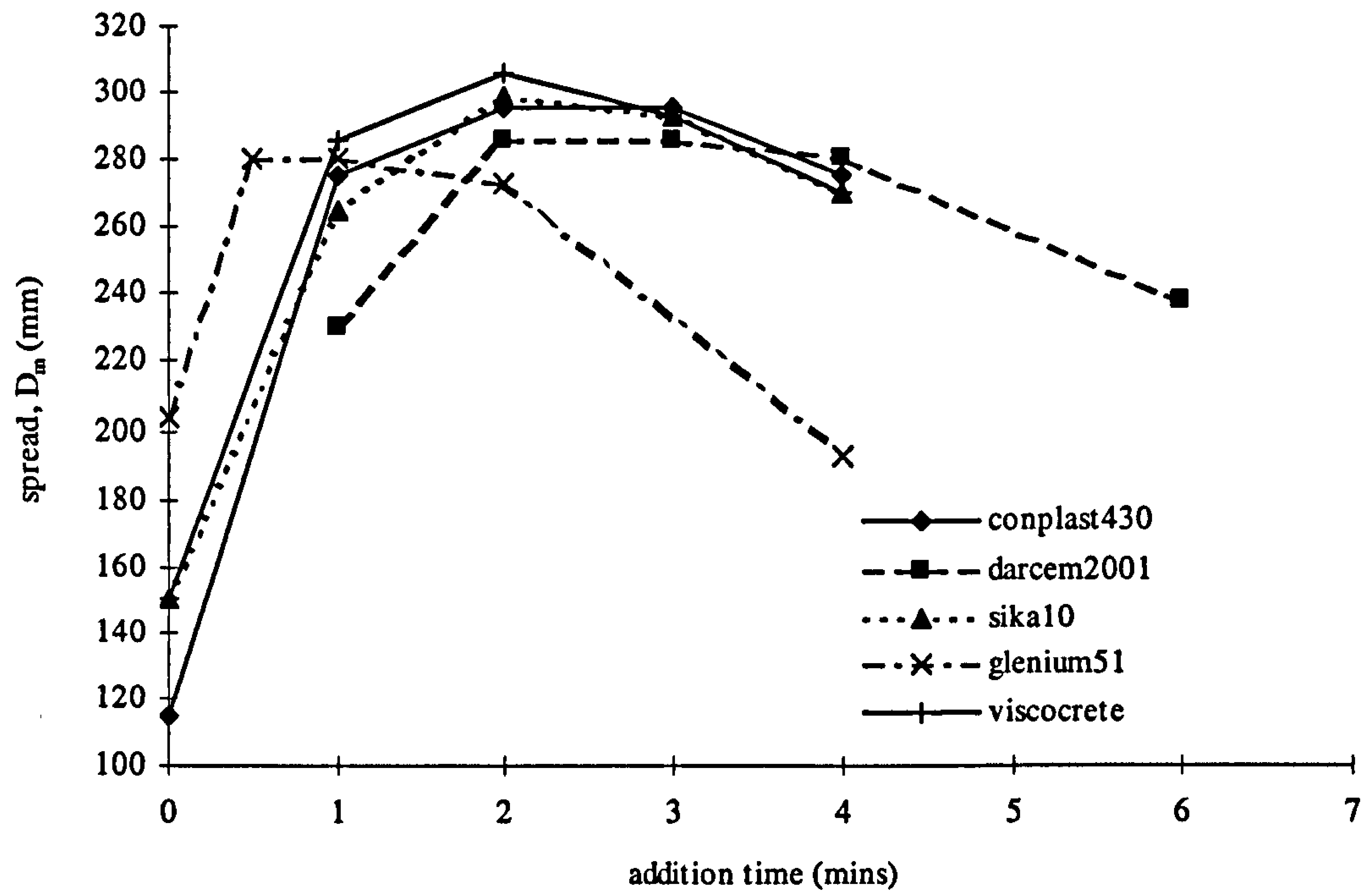
Figure 5-2 Saturation dosage of superplasticizers determined by (a) the spread test (b) the V-funnel test

5.1.3 Optimisation of addition time for each type of superplasticizer

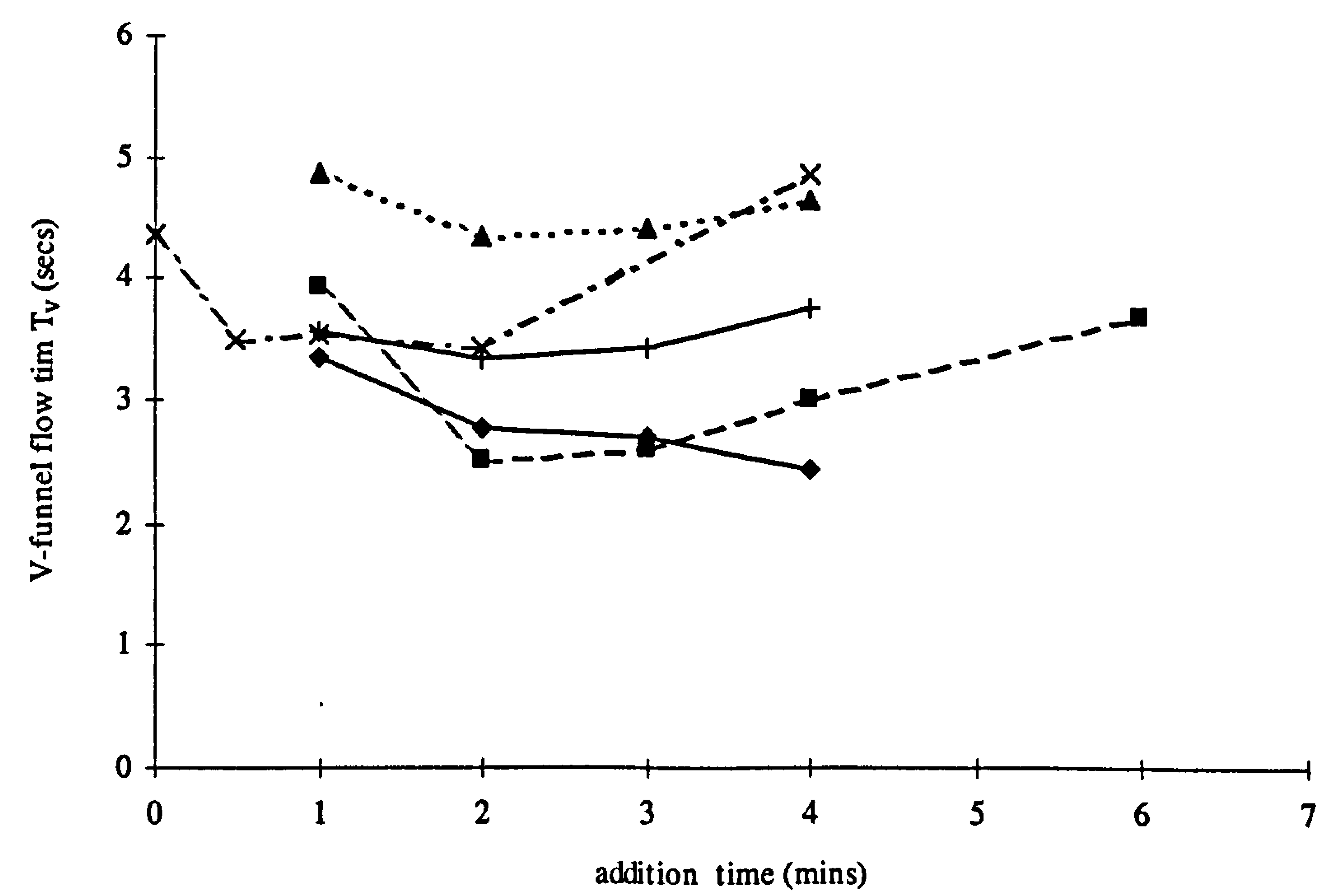
The effect of delay times of up to 6 minutes were examined for each superplasticizer at dosages slightly less than the SSD obtained in the section 5.1.2, i.e. Conplast430: 0.6%, Darcem2001: 0.5%, Sika10: 0.25%, Glenium51: 0.125%, Viscocrete: 0.3%.

As before, all the mixes were tested at 10 minutes after the start of mixing, except for the mix with a delayed addition of 6 minutes, which was tested at 11 minutes.

The effect of the different addition times on the spread and V-funnel flow time for each superplasticizer is shown in **figure 5-3**. Delayed addition increased the effectiveness of all the admixtures significantly. Moreover, there is an addition time 'window' for each admixture where maximum efficiency is obtained, i.e. the spread is the highest and the V-funnel flow time the lowest (except for the Conplast430 in which the V-funnel flow time continuously decreased with delayed addition time). For Conplast430, Sika10 and Viscocrete this window is between 2 and 3 minutes; for Darcem2001 between 2 and 4 minutes; and for Glenium51 between 0.5 and 2 minutes. This general effect of delayed addition is well known and has been reported for naphthalene and melamine based admixtures [125-127] but at the time of testing it had not previously been reported for admixtures of the types Sika10, Glenium51 and Viscocrete.



(a)



(b)

Figure 5-3 Effect of delayed addition time of superplasticizer on (a) spread (b) V-funnel flow time for mortar

This is consistant with Chiocchio and Paolini [125] result that there is an optimum time for a superplasticizer to be the most efficient. Hsu *et al* concluded that the adorption of a naphthalene-based superplasticizer on cement particles decreases sharply with the increase of addition time at the beginning and then more slowly. Their results were however obtained on cement pastes. It has been reported that sand/cement ratio influences the effect of delayed addition, e.g., the effect of delayed addition decreased with increased sand content for naphthalene type superplasticizer [127], but the reason is not clear. Further study on this will be useful.

For Glenium51, a new generation superplasticizer, the window started at a half minute delayed addition, which is much earlier than conventional superplasticizer. It may be because its action of a combination of electrostatic dispersion and steric hindrance from the side chains linked to the polymer backbone is less affected by the coating of the polymer by the early hydrated products. Hanehara and Yamada [128] concluded that the effectiveness of the addition method depends on the type of the admixture, with the effect of delayed addition of naphthalene sulfonic and amino sulfonic acid-based admixtures being greater than lignin sulfonic and polycarboxylic acid-based admixtures. This is consistent with the results in the current programme (**figure 5-3**), for example, with Conplast430, the spread by delayed addition increased by about 180 mm compared to that of direct addition, whereas for Glenium51 the increase was 80 mm.

The advantage of delayed addition is not only that the superplasticizer is more efficient but also that the fresh properties of the mix do not vary provided the addition time of superplasticizer is within the window. Clearly this general effect has implications for both control of laboratory experiments and batching practice. All of the tests reported in the remainder of this project were carried out with a delayed addition time of 2 minutes for Conplast430, Darcem2001and Sika10, and 1 minute for Glenium51.

5.2 Selection of superplasticizer

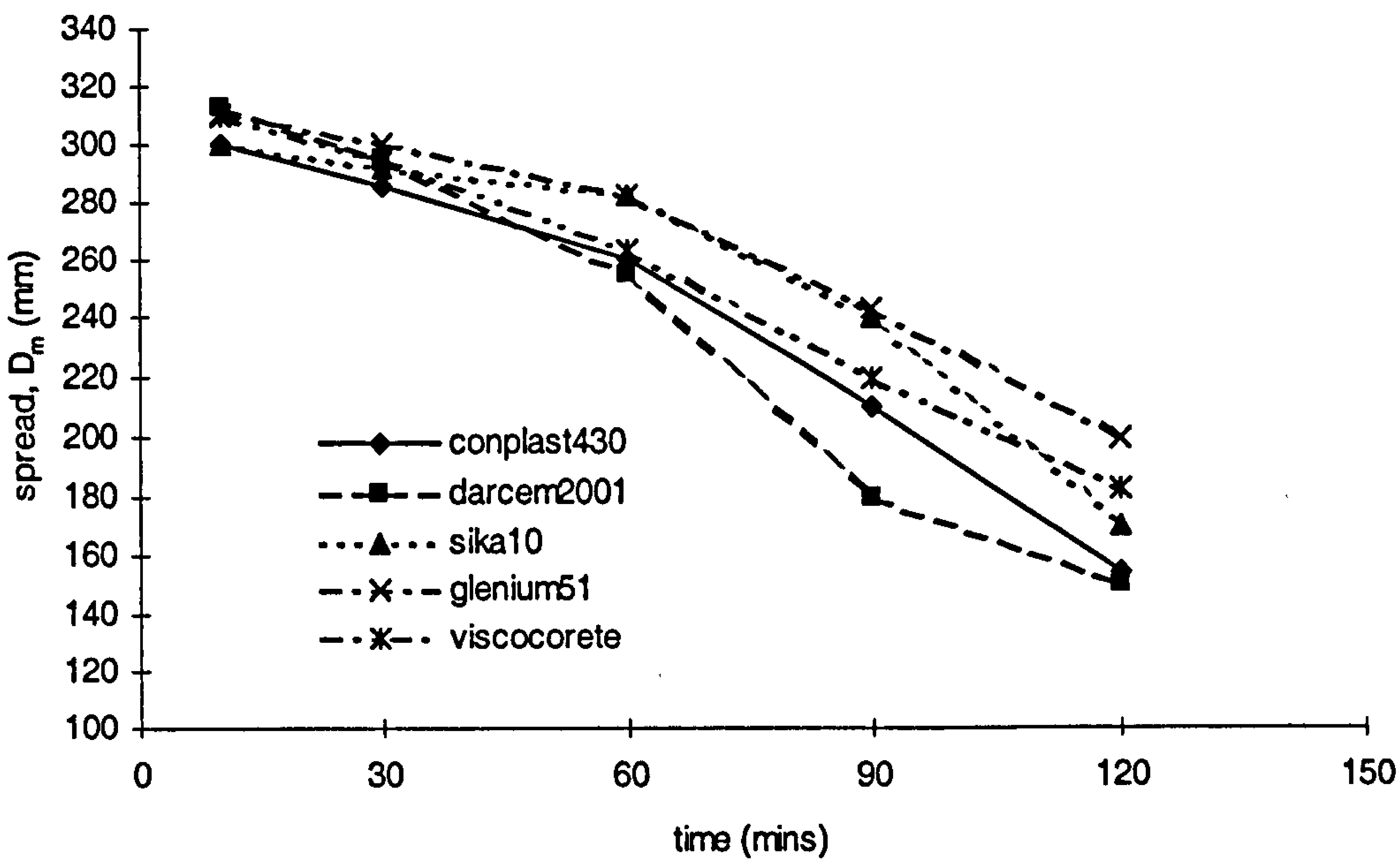
The selection of the superplasticizer for the remainder of the project was based on the following considerations:

- to obtain the best combination of a low yield stress and high plastic viscosity, assessed in this part of the programme by a high spread and a high V-funnel flow time;
- to obtain the longest workability retention.

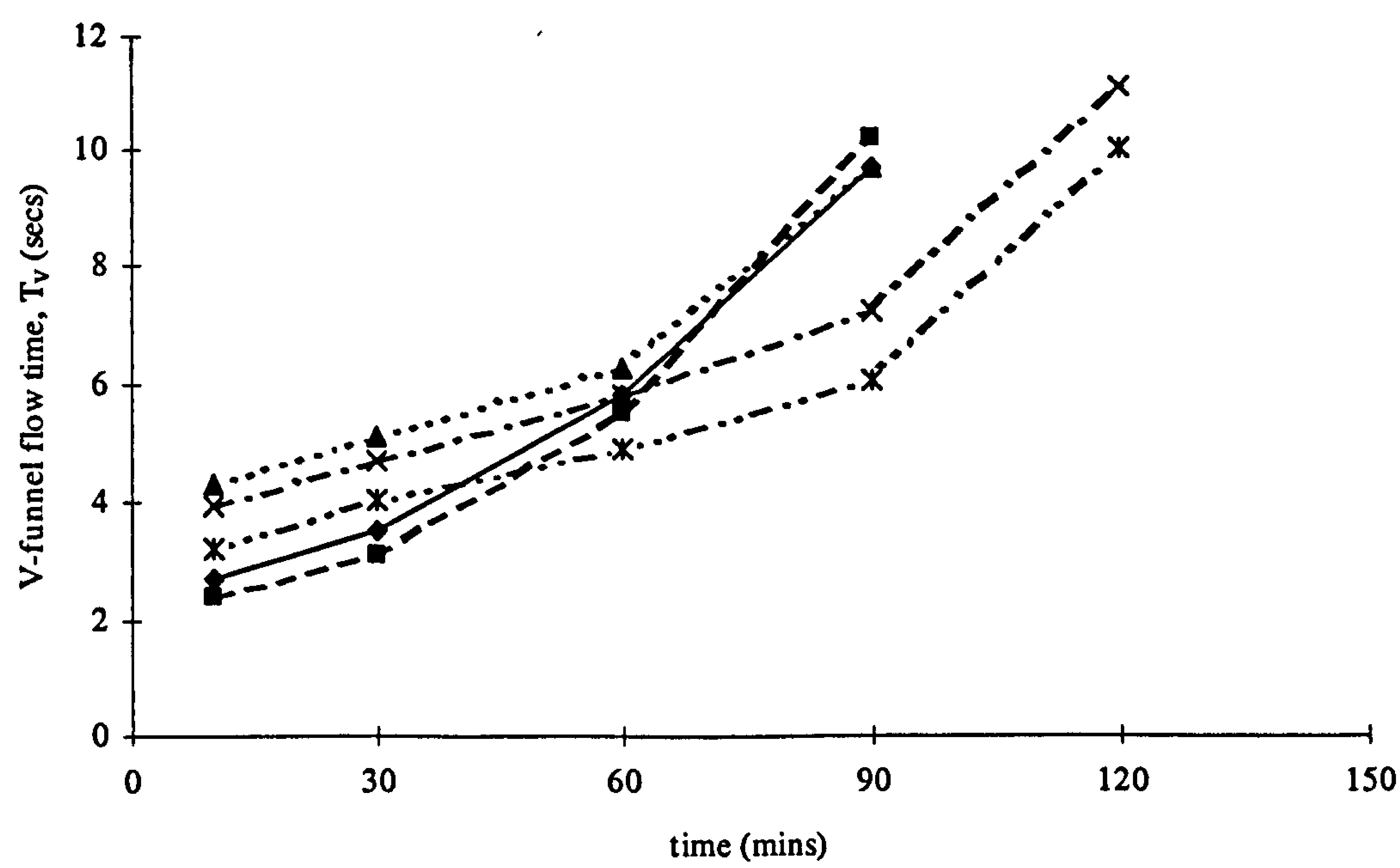
Each superplasticizer was added at its saturation dosage, obtained at 2 minutes delayed addition, as descibed in **section 5.1.2.** It was assumed that the SSD for Glenium51 at 1 minute delayed addition is same as that at 2 minutes delayed because both were within the 'window'.

The results for initial workability and workability retention are shown in **figure 5-4.** The initial spread values are similar for all five admixtures, but the V-funnel times for Sika10 and Glenium51 are distinctly higher than that for Conplast430, and Darcem2001 and Viscocrete. This confirms that the tests are measuring two different properties. As mentioned earlier Viscocrete is a superplasticizer especially produced for SCC, with the aim of reducing the segregation and increasing stability, but it did not provide as high viscosity (as assessed with V-funnel) as that with Glenium51. The effect of Viscocrete in SCC is however, apparent with other properties, will be discussed in chapter 10.

The rate of workability loss also varied. Glenium51 had the lowest loss in terms of spread, which was about 55 mm less than the conventional superplasticizer (Conplast430) at 120 minutes after the start of mixing; this was followed by Viscocrete and Sika10 while the spread loss of Darcem2001 was similar to that of Conplast430. The development of the V-funnel flow time for Glenium51 and Viscocrete were similar but both were slower than Sika10 than that for Darcem2001 and Conplast430. This again therefore proved Glenium51 to be the most effective superplasticizer, and it was used for the remainder of the test programme for the mixes without viscosity agent.



(a)



(b)

Figure 5-4 Comparison of superplasticizer performance in terms of (a) spread (b) V-funnel flow time

5.3 Test on concrete

Concrete tests were carried out to examine the effect of mixing procedures and the efficiency of the Glenium51 and Conplast430.

Three mixes were tested, C5-1, C5-2 and C5-3, all with a powder of 100% PC4, sand content of 0.45 by volume of mortar, and a coarse aggregate volume of 0.317 m^3 of concrete, which was 50% of its dry rodded bulk density (this mix was a reference mix used in the remainder of the project). The dosage of superplasticizer was the saturation dosage determined by tests on the mortar fraction of the concrete but repeated due to different batch of cement being used. The mixing procedures are shown in **table5-1.**

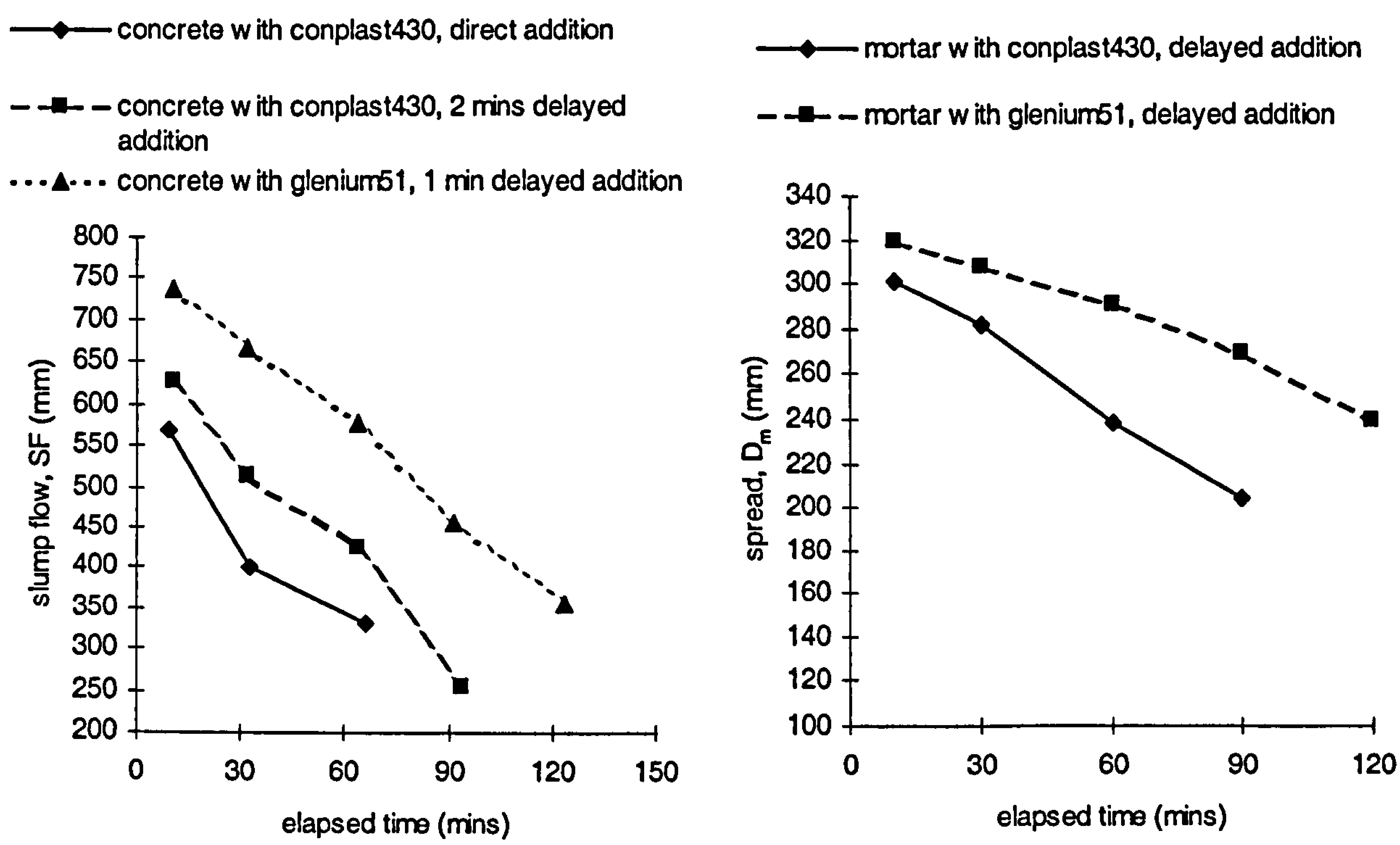
Table 5-2 shows the superplasticizer dosages and initial properties of mortar and concrete. Glenium51 produced higher spread and slump flow values than Conplast430, but similar V-funnel flow times, in mixes C5-1 and C5-2, unlike the mortar test results with the PC1 cement. The mixing procedure has a significant effect on both the initial slump flow and V-funnel flow time. About 60 mm of slump flow was lost with direct addition in mix C5-3 compared to mix C5-2.

Table 5-1 Mix proportion and mixing procedure of concrete

Mix No	Types of superplasticizer	Mixing procedure
C5-1	Glenium51	1 min. delayed addition, 6 minutes mixing time.
C5-2	Conplast430	2 mins delayed addition, 7 minutes mixing time.
C5-3	Conplast430	Direct addition, 5 minutes mixing time.

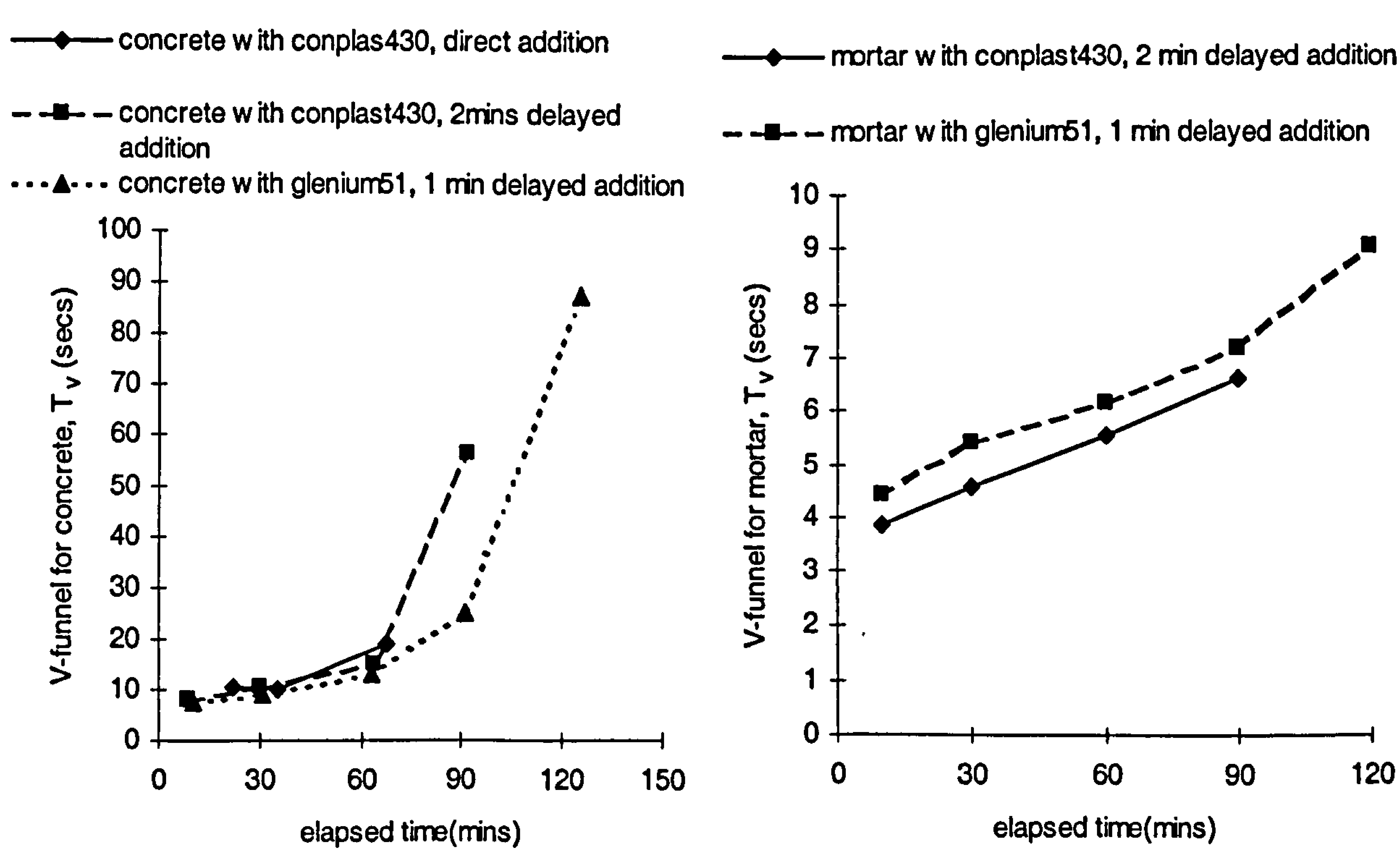
Table 5-2 Mix proportion of the concrete as a reference mix

mix no	Types of cement	Types of superplasticizer	sp dosage (% by wt. of cement)	Properties of mortar		Properties of concrete		
				Spread (mm)	V-funnel (secs)	Slump flow (mm)	V-funnel (secs)	Box filling height (mm)
C5-1		Glenium51	0.13	320	4.4	735	7.53	340
C5-2	PC4	Conplast430	0.75	301	3.8	625	8.0	325
C5-3		Conplast430	0.75			568	10.6	320



(a) concrete (b) mortar

Figure 5-5 Change of slump flow and spread for concrete and mortar mixes



(a) concrete (b) mortar

Figure 5-6 Change of V-funnel flow time for concrete and mortar mixes

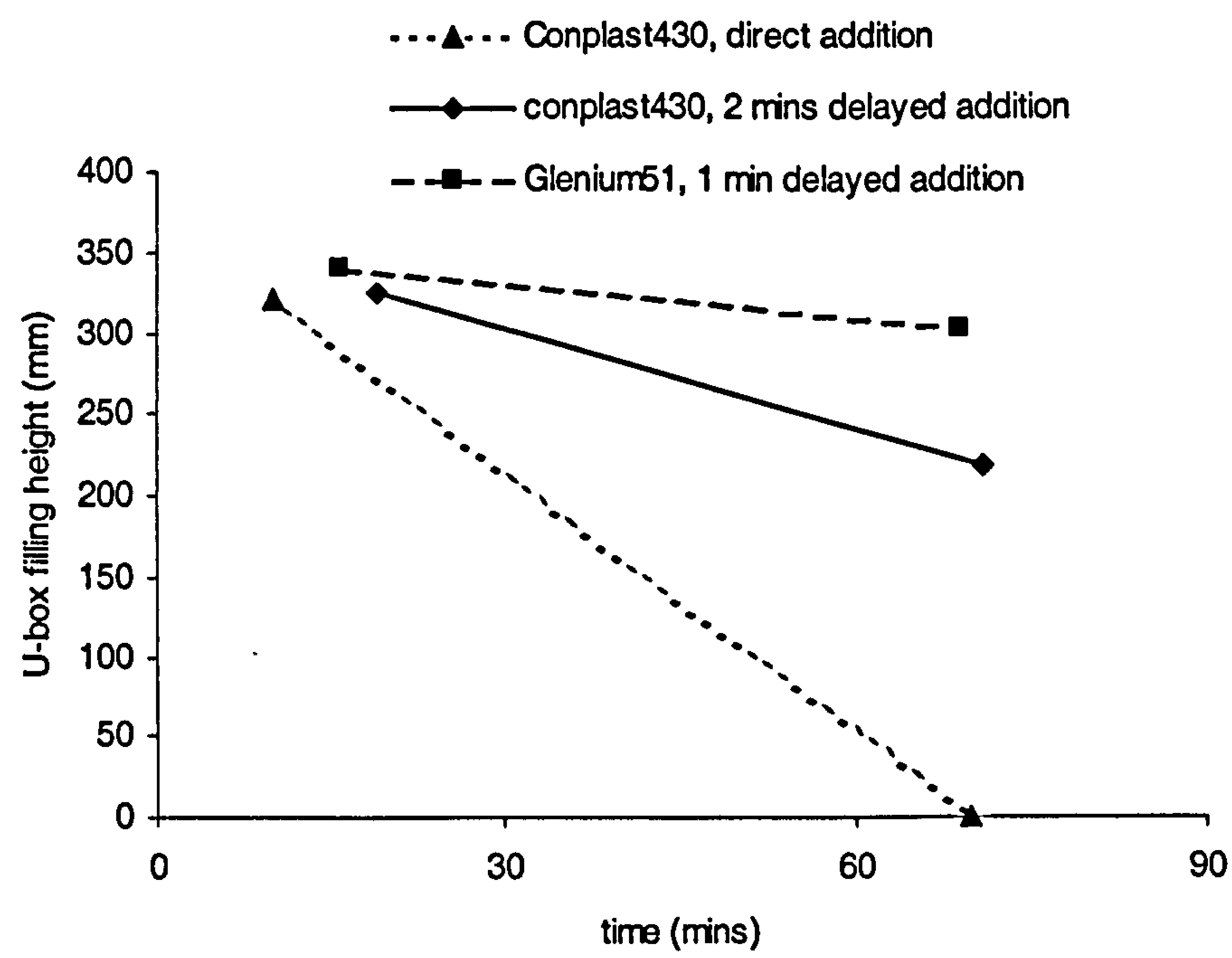


Figure 5-7 Change of U-box filling height for concrete mixes with time

Figure 5-5, 5-6 & 5-7 shows the change in workability of the mixes. The Glenium51 mix showed the best performance in terms of slump flow, providing the concrete with slump flow 250 and 150 mm higher than Conplast430 with direct and delayed addition respectively at 60 minutes after the start of mixing. Moreover the U-box filling height remained in excess of 300 mm for one hour after mixing, compared to a faster drop for the Conplast430 mix with either direct addition or with 2 minutes delay. The workability retention in terms of the V-funnel flow time was very similar for both mixes with delayed addition. This performance does not necessarily indicate that every SCC mix with Glenium51 can always achieve better workability than those with Conplast430, but it does suggest a wider choice for making SCC with Glenium51. This confirmed the results of the mortar tests that Glenium51 was the most suitable for SCC among these superplasticizers.

The effect of mixing procedure on the workability and workability retention of the Conplast430 mixes, is also shown in the figures; for the same dosage of superplasticizer, the slump flow with direction addition was lower and the rate of slump flow loss slightly higher than those with delayed addition. The V-funnel results of the mixes are similar. All the mixes had good passing ability (U-box filling height was more than 300 mm) immediately after mixing but a faster drop for the direct addition was apparent.

There seems to be good correlation between the measured properties of the mortar and concrete. This confirms that the dosage of superplasticizer can be determined by related mortar test as long as both concrete and mortar use the same superplasticizer addition time. Clearly, this is very important when using mortar tests as part of a mix design process. This will be discussed in more detail in chapter 10.

5.4 Conclusion

The effect of several superplasticizers and their addition times on the properties of the mortar for SCC was examined. The conclusions are as follows,

- The addition time affected the saturation dosage of a superplasticizer (SSD), for delayed addition the SSD is about half of that for direct addition for Conplast430, but the spread ceiling and the V-funnel flow time has no significant change.

- There was an addition time 'window' for each superplasticizer where maximum efficiency was obtained. Only as little as 0.5 minute delayed addition is needed for Glenium51 to obtain the greatest efficiency. It was confirmed by concrete tests that delayed addition gave a higher slump flow and better workability retention than direct addition.

- The initial workability and the rate of workability loss also varied for different superplasticizers, with Glenium51 having the highest slump flow and the lowest loss, and therefore proving to be the most effective superplasticizer. It was used for the remainder of test programme. The same conclusion was made from the limited number of tests on concrete.

- The dosage of superplasticizer for SCC can be determined by mortar tests as long as the addition time of the superplasticizer for mortar is same as that for concrete.

Chapter 6

Fresh properties of mixes with a single type of powder

This chapter presents the results of the tests on the fresh properties of mixes with single types of powder. The factors assessed included,

- water/cement ratio, varied between 0.275-0.375 by weight,
- sand/mortar ratio, varied between 0.40-0.475 by volume,
- types of cement, Portland cement, sulphate resisting cement.

As in other parts of the programme, the complete set of variables were examined in tests on mortar, and then some important findings were confirmed by tests on concrete. The fresh properties measured during two hours after the start of mixing included,

- spread (D_m) and the time to 250 mm spread (T_{250}), V-funnel flow time (T_V), yield stress (τ_0) and plastic viscosity (μ) for mortar;
- slump flow (SF) and the time to 500 mm slump flow (T_{500}), V-funnel flow time (T_V), yield stress (τ_0), plastic viscosity (μ), U-box filling height (U_H) and the time to 250 mm height ($T_{U\text{-}box}$) for concrete.

Concrete cubes were also cast for compressive strength test after the workability tests; these are reported in chapter 10.

6.1 Effect of water/cement ratio

6.1.1 Tests on mortar

Table 6-1 shows the mortar mix proportions and the properties immediately after mixing. 100% PC2 was used, the water/cement ratio varied from 0.275 to 0.375, which is in the range for SCC without a viscosity agent, as reviewed in **section 2.3.4**. The sand/mortar ratio was kept at 0.45 by volume in all mixes. Glenium51 was used, and the dosage was such that with one minute delayed addition a spread of 310-320 mm was obtained; this is higher than the minimum requirement of the spread for SCC according to the UCL mix design method, and the same as or lower than the spread ceiling at the saturation dosage for each mix. A higher dosage was required with reducing water/cement ratio. The T_V and T_{250} decreased with increasing water/cement ratio, as did the plastic viscosity (μ), and the changes are higher than their reproducibility (it is 0.6 seconds V-funnel flow time and 1.5 Pa.s for plastic viscosity). The yield stresses were in a range of 3.6-10.8 Pa, which is smaller than its reproducibility, i.e. 10.9 Pa, (see chapter 4), and were therefore considered as similar.

Table 6-1 Mix proportions and initial properties of the mortar with various water/cement ratios*

Mix No.	w/c	% sp**	D_m (mm)	T_{250} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)
M6-1	0.275	0.18	311	5.59	5.22	3.6	11.4
M6-2	0.3	0.145	315	3.5	3.26	4.5	6.9
M6-3	0.325	0.125	310	3.03	2.38	9.9	4.9
M6-4	0.35	0.11	310	2.2	1.75	10.8	3.2
M6-5	0.375	0.105	310	1.5	1.47	10.8	2.3

*All mixes with 100% PC2 as powder, ** By weight of powder

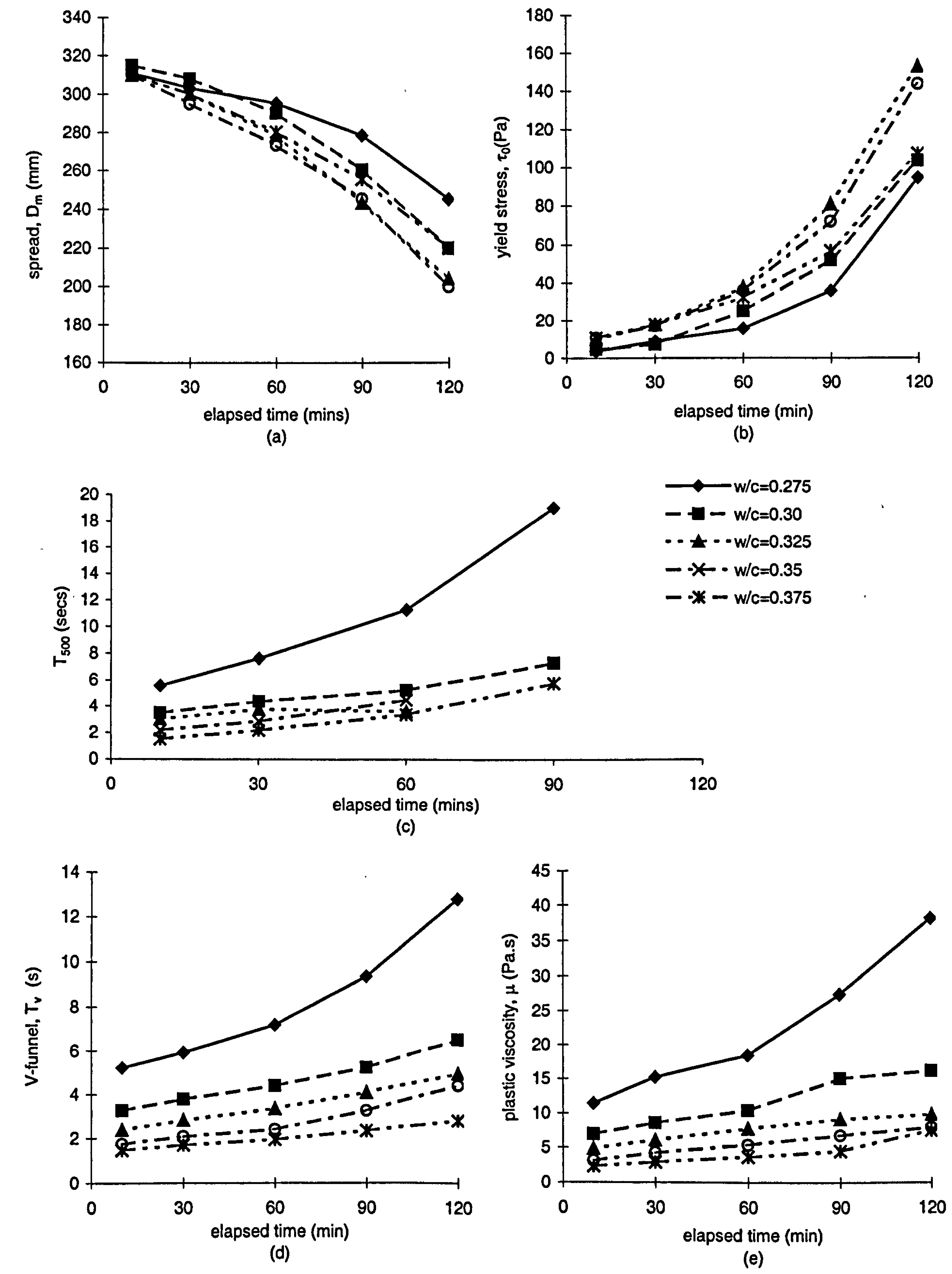


Figure 6-1 Development of the properties of the mixes with various w/c for 2 hours after mixing: (a) spread (b) yield stress (c) V-funnel flow time (d) plastic viscosity (e) the time to 250 mm spread

Figure 6-1 shows the changes in properties retention for the two hours after mixing. Workability decreased with time for all the mixes, but the trend of workability loss was found to be dependent on the properties measured. The D_m and τ_0 results showed similar pattern of behaviour, as did T_{250}, T_v and μ. The relationship between these properties will be discussed further in chapter 10.

The change of yield stress and plastic viscosity with water/cement ratio at various times is shown in **figure 6-2.**

The slowest yield stress development was obtained with the mix M6-1 that had the lowest water/cement ratio (0.275) and the highest superplasticizer dosage (**figure 6-2(a)**), which increased about 90 Pa for 120 minutes after mixing. The degree of yield stress development increased with the increase of water/cement ratio until it reached 0.325, which had 140 Pa of increase for the same period, then decreased beyond this. The mix M6-5 (w/c=0.375) had the same degree of workability loss as mix M6-2 (w/c=0.3). This suggests that the yield stress retention of these mixes is affected by the combination of superplasticizer dosage and water/cement ratio, and both an increase of superplasticizer dosage and water content improves this.

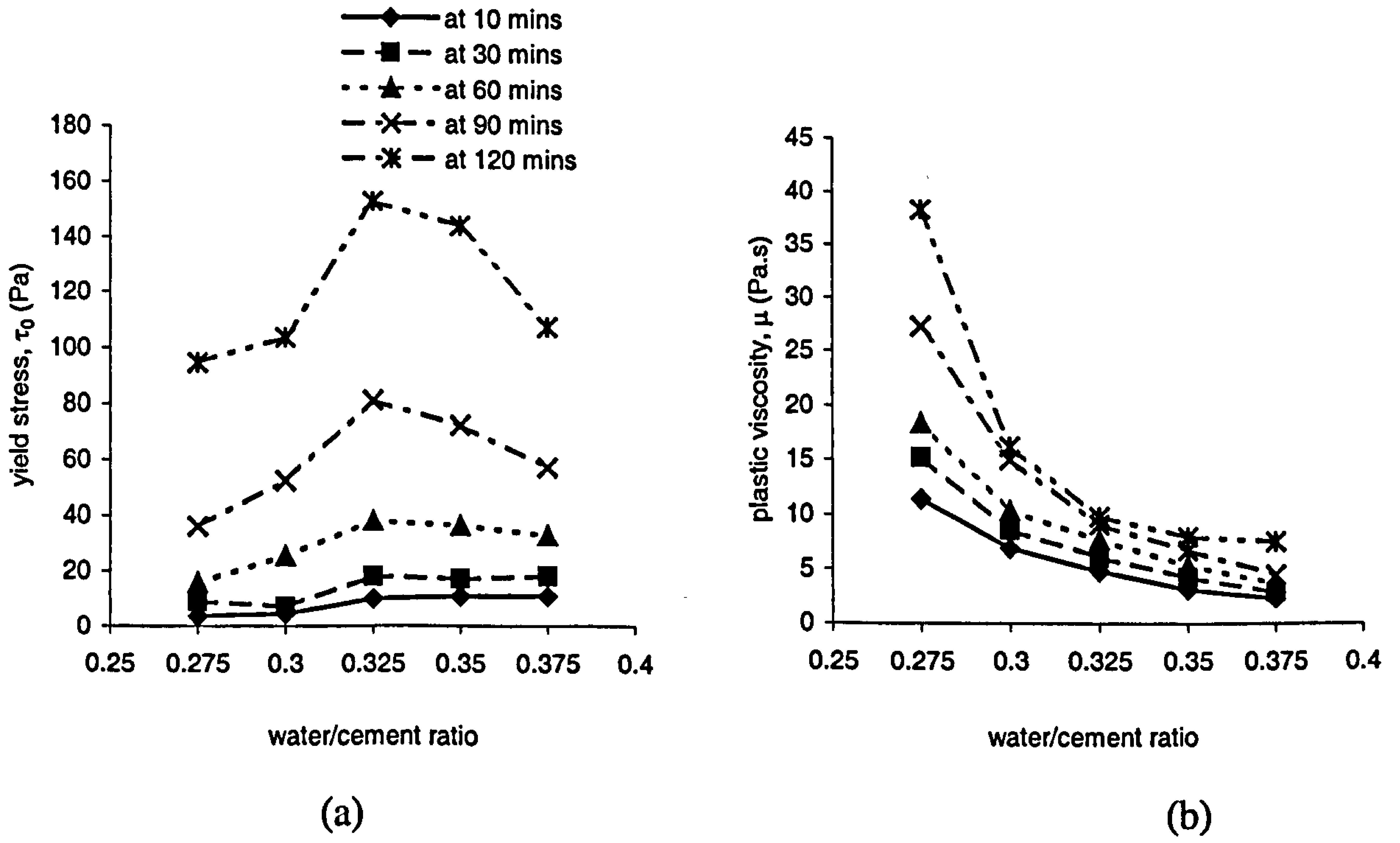


Figure 6-2 Comparison of the workability loss of the mixes with different w/c in terms of (a) yield stress (b) plastic viscosity

However, workability retention in terms of plastic viscosity showed a very different performance (**figure 6-2 (b)**). The best workability retention was obtained in the mix M6-5 with the highest water/cement ratio of 0.375 and the lowest initial plastic viscosity with the value only increasing by 5 Pa.s at 120 minutes after mixing. The workability loss increased with the decrease of water/cement ratio, indicating that it is closely related to the water content, which controls the volume concentration of particles, and therefore the distance between particles, and hence the initial plastic viscosity.

The mix with water/cement ratio of 0.275 showed much higher plastic viscosity increase of about 5 times that for M6-5 (w/c=0.375) at 120 minutes after mixing; this is different to its workability performance in terms of yield stress, confirming that these are two different properties. The dosage of superplasticizer seemed to have no significant contribution to improved workability retention in terms of plastic viscosity.

In order to understand the effect of **dosage** of superplasticizer on workability retention a series of tests were carried out with the mixes and initial properties as shown in **table 6-2**. The control, plain mix, had a higher water/cement ratio and lower sand/mortar ratio than the previous mixes so that the spread was measurable; these were 0.45 by weight and 0.35 by volume respectively. Two types of superplasticizer were tested, Conplast430 and Glenium51, each at two dosage levels. It can be seen that the initial properties of these mixes are very different because of the different dosage of superplasticizers. Both yield stress and plastic viscosity decreased with the increase of superplasticizer dosage but the amount of relative reduction of yield stress was much higher than that of plastic viscosity.

Table 6-2 Mix proportions and the initial properties of mortar with w/c=0.45*

Mix NO.	Types of sp	% sp**	D_m, (mm)	T_V, (secs)	τ_0, (Pa)	μ, (Pa.s)
M6-6		0	178	1.67	84.9	1.8
M6-7	Conplast430	0.1	194	1.36	63.2	1.3
M6-8	Conplast430	0.3	300	0.97	8.3	0.7
M6-9	Glenium51	0.015	217	1.21	46.6	1.2
M6-10	Glenium51	0.03	275	1.17	20.0	0.9

* 100 % PC4 was used. ** by weight of cement

The changes in properties of the mixes at various times up to 90 minutes after mixing were measured by spread, yield stress and plastic viscosity; the results are shown in **figure 6-3** & **6-4**. The spread loss from 10 to 90 minutes after mixing increased with the increase of superplasticizer dosage for both types of mixes, but the change of yield stress reduced (**figure 6-3**). The different performance between the spread and yield stress, which had same pattern of behaviour in **figure 6-1**, implies that the relationship between the two is not simply linear.

The workability loss of different mixes has normally been compared by their flowing capacity loss, even though they may have different initial values. However, the result in **figure 6-3** indicates that the mixes with same spread loss but different initial values have different workability loss in terms of yield stress. Therefore it is important to carry out both tests when examining workability retention and/or to have a full understanding of the relationship between flowing capacity and yield stress.

In general superplasticizer dose affect workability retention in terms of spread and yield stress, and the significance of the effect depends on the type and dosage. The workability retention of Glenium51 mix in terms of yield stress can be improved with the increase of superplasticizer dosage.

The V-funnel test was not completed because the fluidity was not sufficient for the flow to be continuous in some mixes, and therefore these results are not discussed here. **Figure 6-4** shows the change of plastic viscosity of all the mixes with time after mixing. Insignificant effect of superplasticizer was found in Conplast430 mixes, and slightly improvement with the increase of superplasticizer dosage was found in Glenium51 mixes. In general, the losses of plastic viscosity for all mixes were close although they had different initial value. This confirms that workability retention in terms of plastic viscosity is closely related to the water content, which was constant in those mixes, while the effect of superplasticizer is very weak.

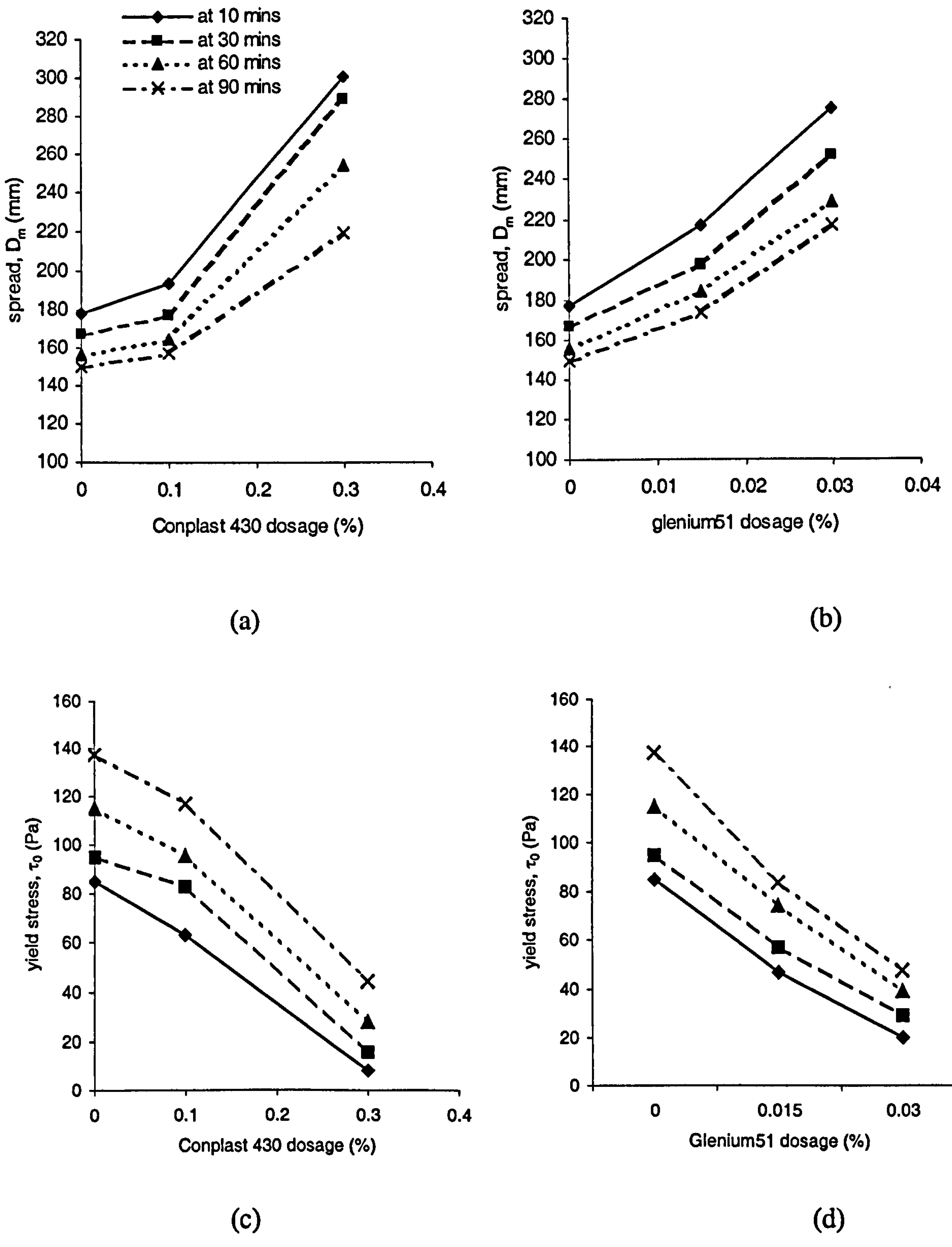


Figure 6-3 The effect of sp dosage on the change of properties in terms of spread for (a) Conplast430 mixes (b) Glenium51 mixes, and yield stress for (c) Conplast430 mixes (d) Glenium51 mixes

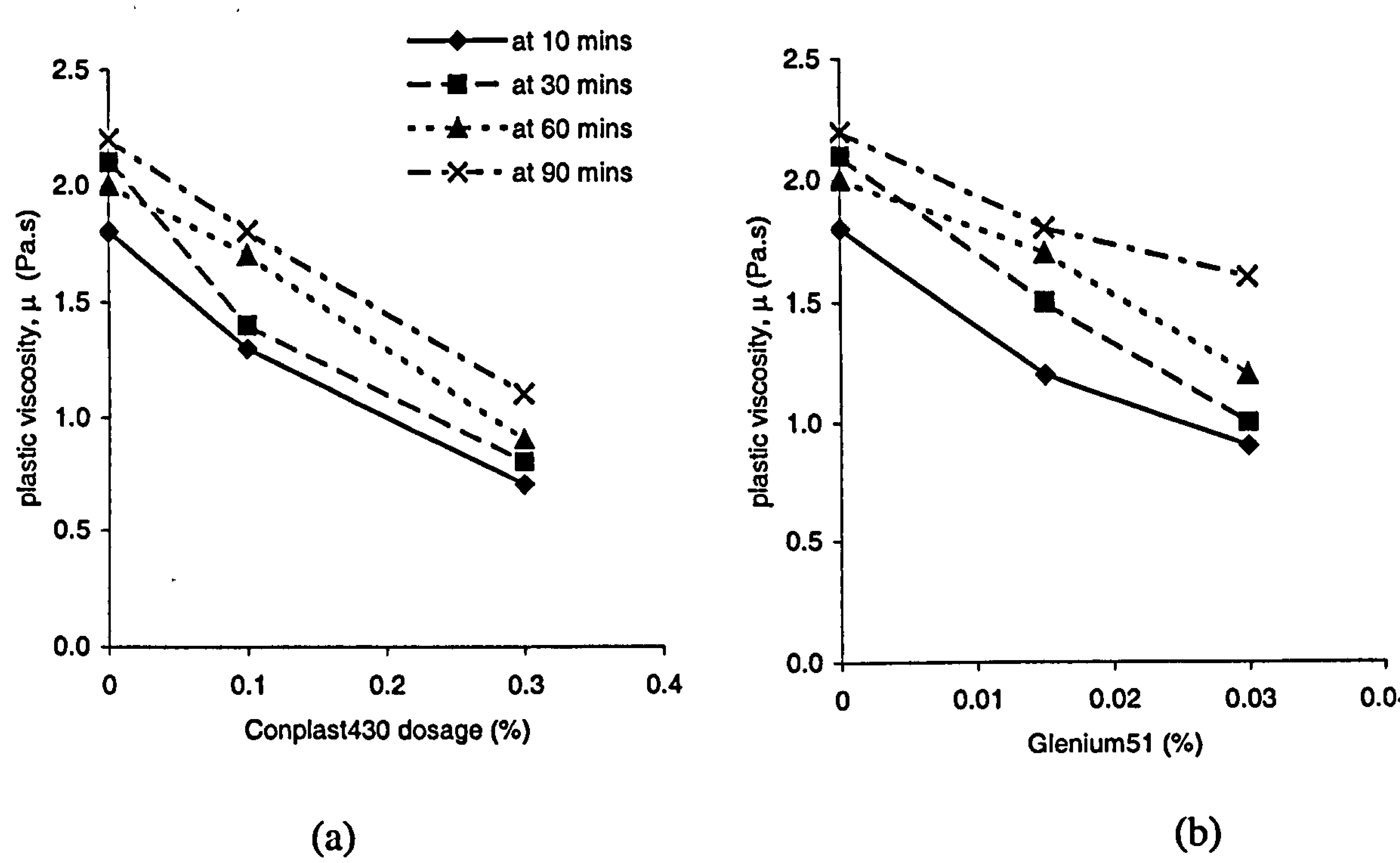


Figure 6-4 The effect of sp dosage on the development of plastic viscosity for (a) Conplast430 mixes (b) Glenium51 mixes

Pukki *et al* [92] obtained similar results with a sulfonated naphthalene formadehyde type superplastizer. The mix with the highest dose of superplasticizer had the lowest rate of workability loss in terms of slump or yield stress and the highest in terms of plastic viscosity because it had the lowest water/cement ratio (similar to the properties for mix M6-1). They argued that this is the contribution of different dosage of superplasticizer, however, the effect of water content on workability retention in terms of plastic viscosity should not be ignored.

In general the slump loss of concrete is affected by the reactivity of cement constituents, particularly the C_3A, C_4AF, and SO_3 contents and the cement fineness, which may change the hydration rate. However, in the dominant period, **coagulation** of particles plays a more important role in the flow loss than chemical bonding through hydration, which may be the main force to built up yield stress. Bonen and Sarkar [93] concluded that the mini slump loss of a paste increases with ionic strength in the pore solution which generates electrostatic bonds, which is mainly governed by the presence of alkali sulfate or soluble Ca sulfate and alkali, the higher the ionic strength the lower workability retention. This implies that the mini slump loss of a superplasticized mix is dependent on the water content, the types and dosàge of superplasticizer and cement that supply ions to the solution. The increase of water content reduces the concentration of these ions, hence reduces the ionic strength and improves workability retention. Moreover, for a mix with a polycarboxylic acid-based admixture, e.g. Glenium51, the side chains of polyethylene oxide (EO) extend from the surface of cement particles in the form of a brush or comb to prevent cement particles from coagulation; this is known to play a more important role in the slump loss than the chemical bonding during hydration in the dormant stage. Therefore Glenium51 improves the workability retention of a mixture, especially at high dosage level, but dose not work as a retarder.

The fundamental reason for the effect of water/cement ratio on the development of plastic viscosity may be that it changes the powder concentration, and therefore the distance between the particles. The higher water/cement ratio is, the less the powder concentration, the higher distance and the less friction force between the particles, resulting in a lower initial plastic viscosity and slower development.

In SCC, the dosage of superplasticizer and the water/cement ratio (or water/powder ratio) have together to produce both the required slump flow and plastic viscosity; therefore, they normally change simultaneously. Both have effects on workability retention in terms of yield stress or spread, and one may be more significant than the other in different situations. However, the development of V-funnel flow time and plastic viscosity seemed to be mainly affected by the water/cement ratio.

6.1.2 Tests on concrete

Concrete tests were carried out on the four mixes shown in **table 6-3**, which also shows their initial properties. All the mixes used a powder of 100% PC4, a 0.45 sand/mortar ratio by volume and a coarse aggregate volume of 0.317 m^3 per cubic meter (50% of the dry rodded bulk density).

The dosage of superplasticizer for each mix was determined by repeating the test on its respective mortar component because a different batch of cement was used, which resulted in some small difference. The dosages were such that spreads of 310-320 mm were achieved, which were slightly lower than those shown in **table 6-1.** The τ_0 was in a similar narrow range of 0.7-3.5 Pa, implying that it describes the same property as D_m. The T_V was slightly higher, but similar results were obtained for T_{250} and μ.

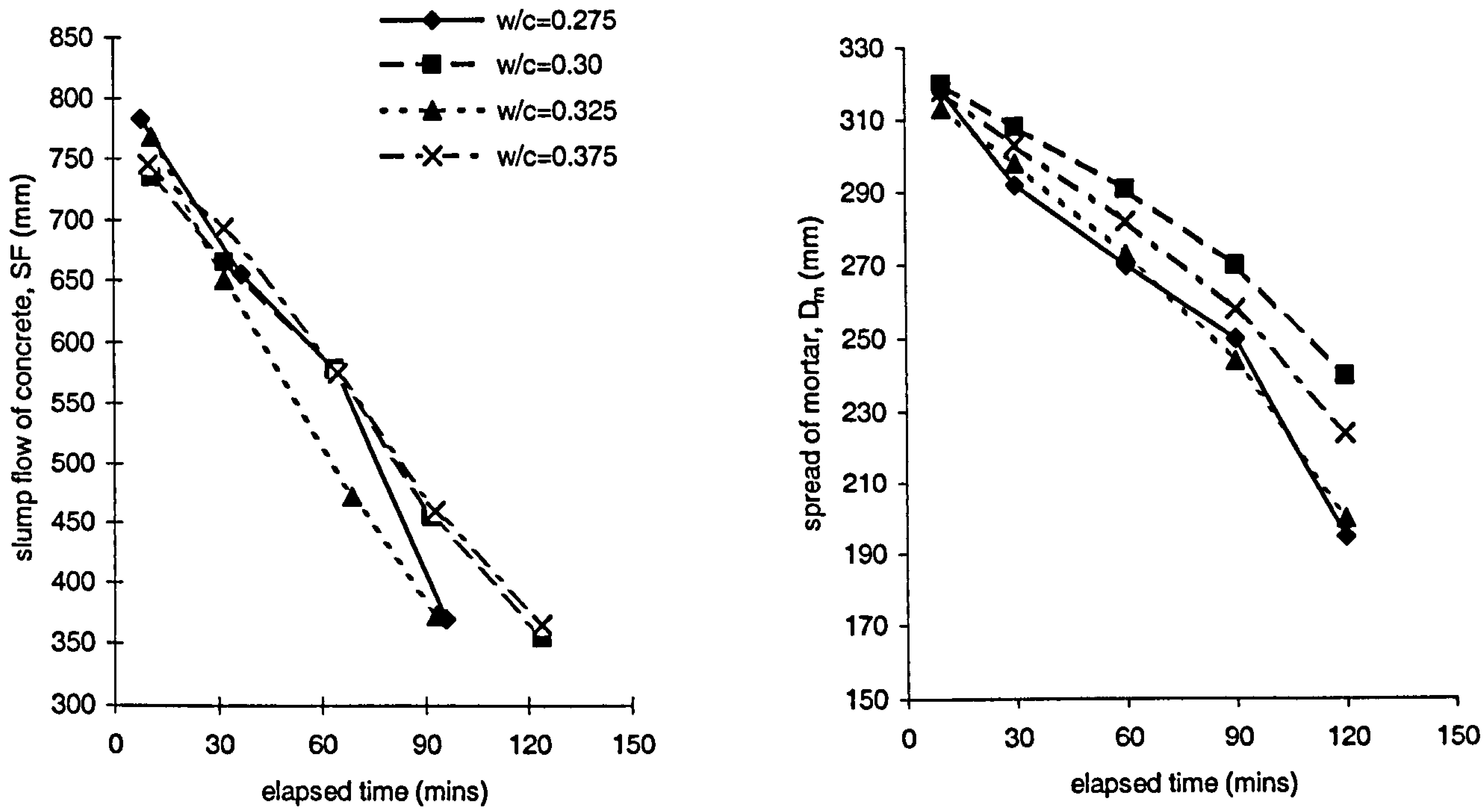
The slump flow (SF) of the concrete ranged from 740 to 790 mm, indicating the possibility of a relationship with spread of the mortar, and T_V, T_{500}, $T_{u\text{-}box}$ and μ consistently decreased with the increase of water/cement ratio suggesting they are measuring a similar property. All mixes had U box filling heights of between 330-340 mm, however, in mix C6-4 with water/cement ratio of 0.375, segregation was found at the bottom of two-point test machine bucket after the test, suggesting this is around the upper limit for a SCC mix without viscosity agent.

Table 6-3 Mix proportions and initial properties for concrete and mortar with various water/cement ratio*

Mix No.	w/c	Sp (%)	Mortar test					Concrete test						
			D_m (mm)	T_{250} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	SF (mm)	T_{500} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	U_H (mm)	$T_{u\text{-}box}$
C6-1	0.275	0.16	318	4.6	7.4	0.7	11.7	783	3.47	11.2	***	***	330	5.2
C5-1	0.30	0.13	320	3.4	4.4	1.0	5.7	735	3.22	7.53	***	78	340	2.9
C6-2	0.325	0.11	313	2.4	3.2	3.5	4.3	768	1.58	5.92	***	73	332	2.1
C6-3	0.375	0.087	318	1.3	1.9	3.2	2.2	745	1.22	3.09	10	26	332	1.6

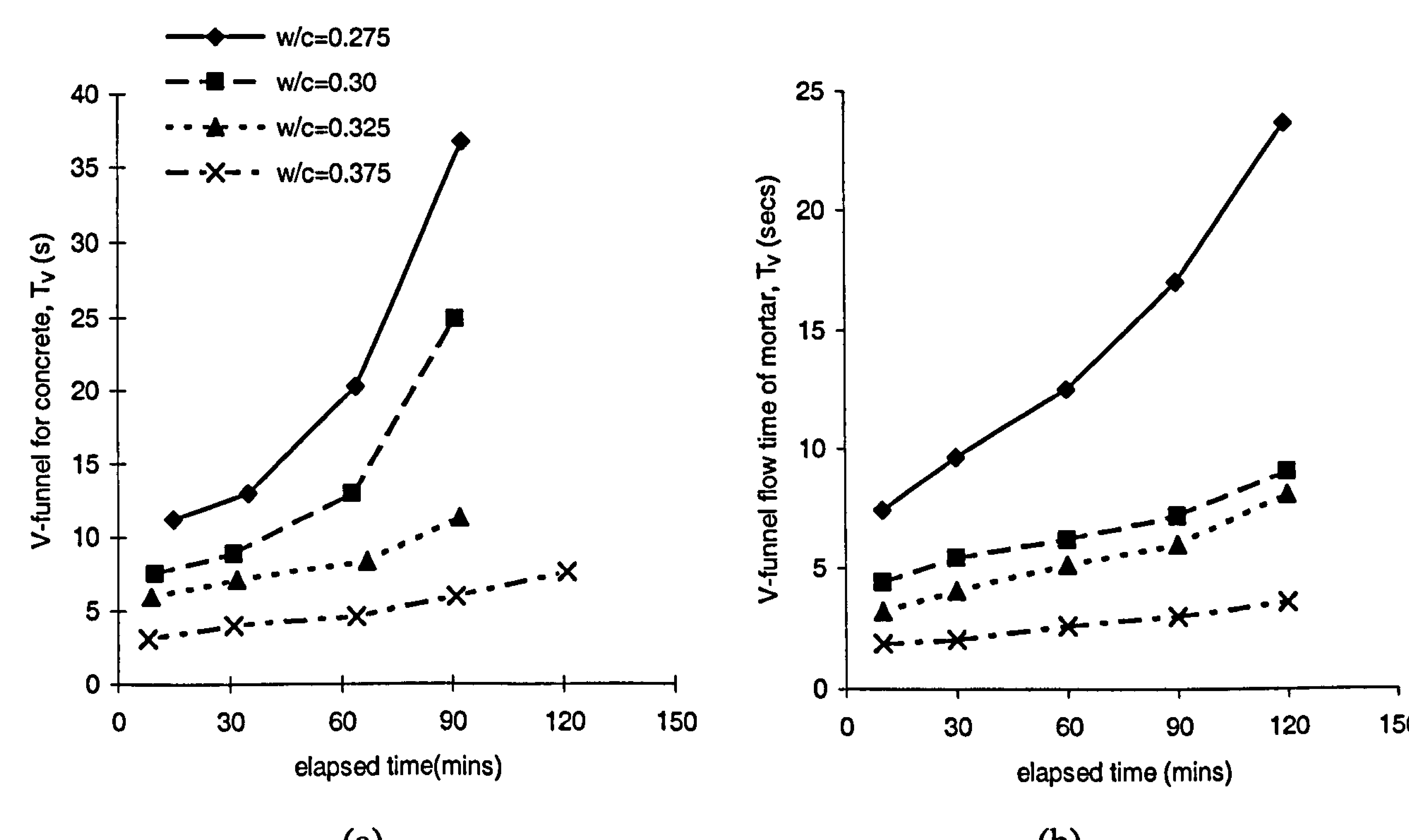
*100% PC4 was used as powder **by the weight of powder *** not measurable

Figures 6-5, 6-6, 6-7, 6-8 & 6-9 show the changes of concrete and respective mortar properties with time including SF/D_m, T_{500}/T_{250}, T_V, μ and U_H. Unfortunately, the yield stress was too low to be measured without significant error with the equipment available when the slump flow of concrete was higher than 600 mm, as discussed in section 4.4.2; hence it is not included in the figures. However, the measured values are tabulated in **Appendix 8.**



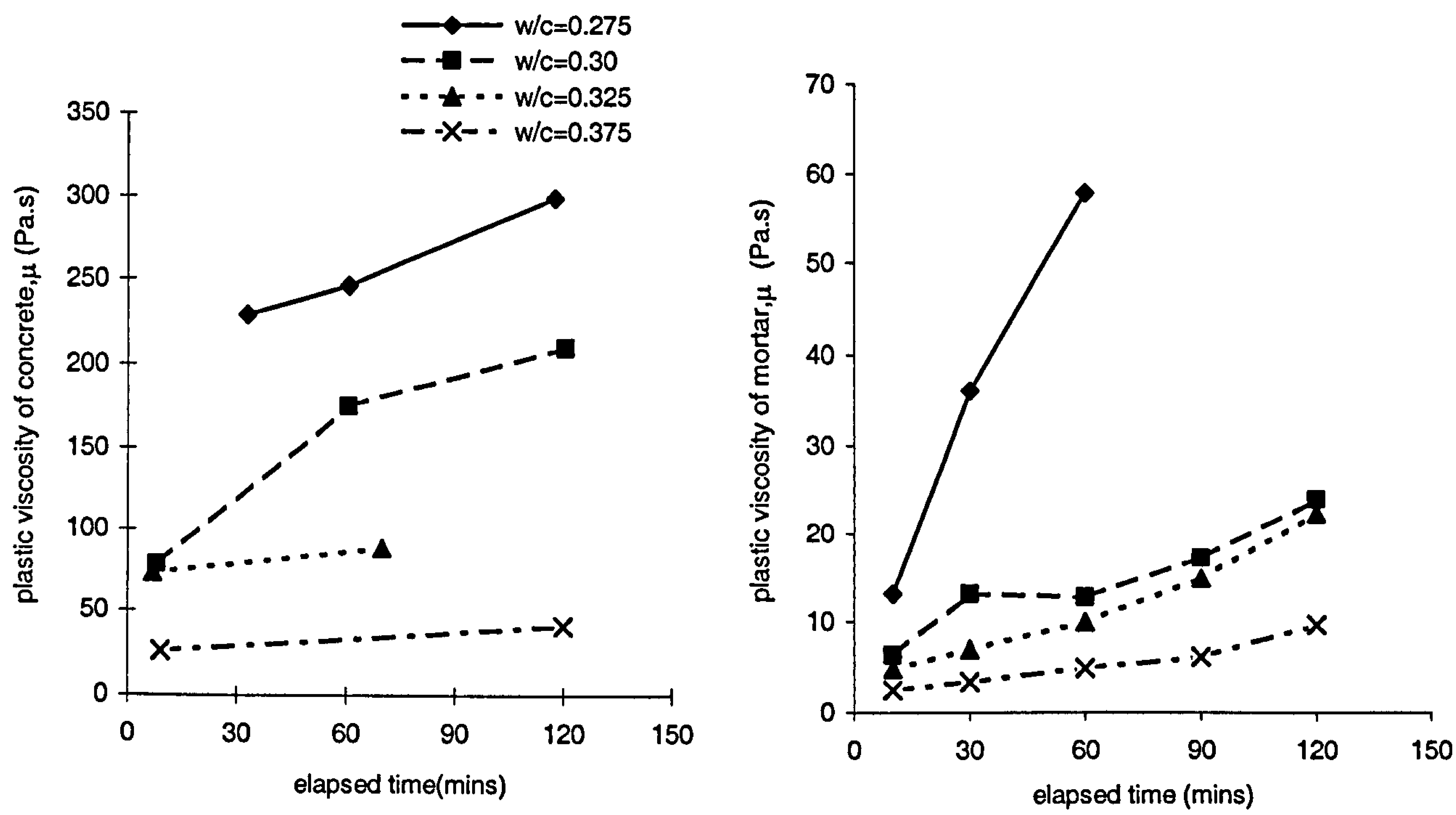
(a) (b)

Figure 6-5 Slump flow/spread retention of the concrete and mortar with various water/cement ratio



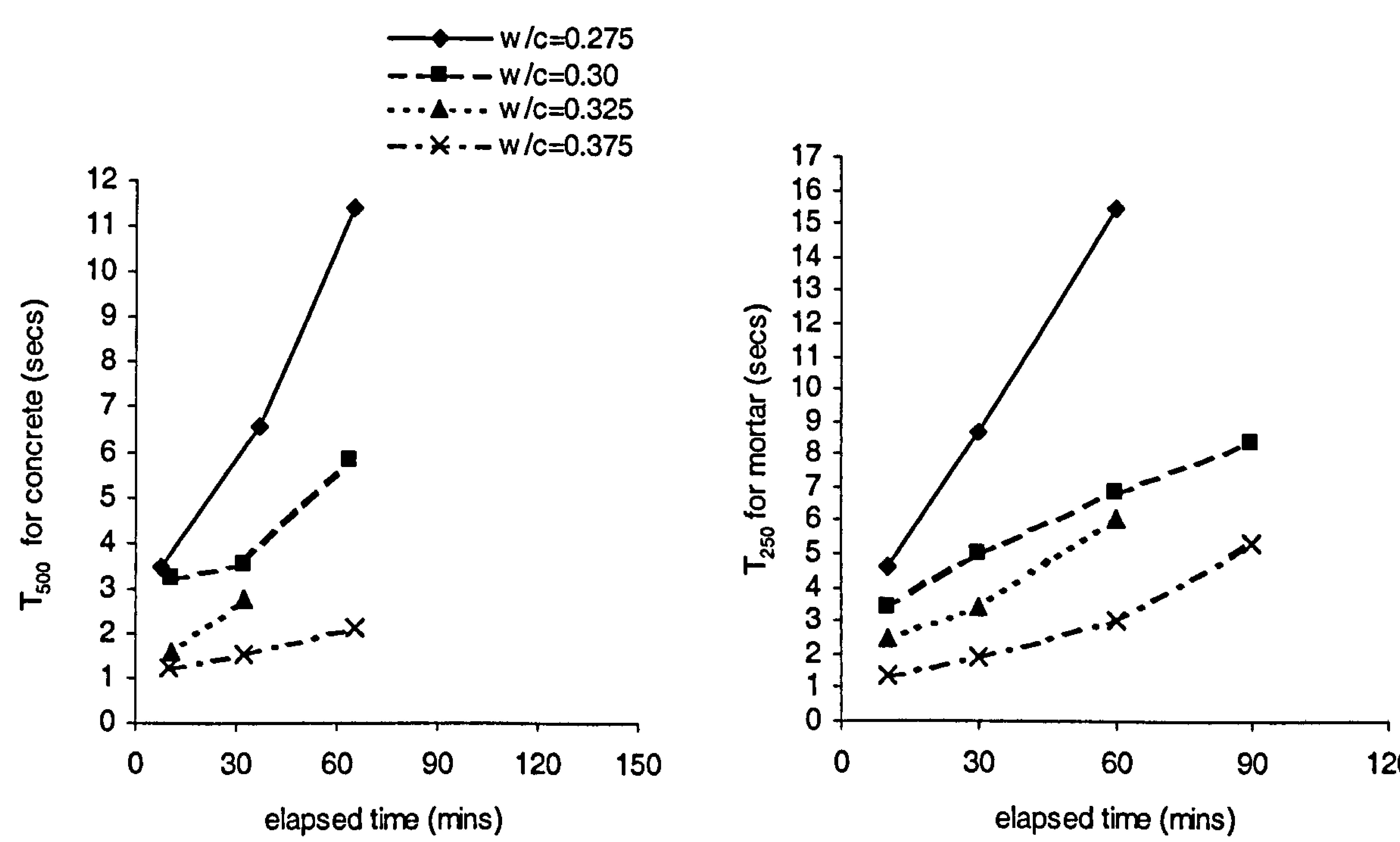
(a) (b)

Figure 6-6 The development of V-funnel flow time of the concrete and mortar with various water/cement ratio



(a) (b)

Figure 6-7 The development of plastic viscosity of the concrete and mortar with various water/cement ratio



(a) (b)

Figure 6-8 The development of T_{500} for concrete and T_{250} for mortar with various water/cement ratio

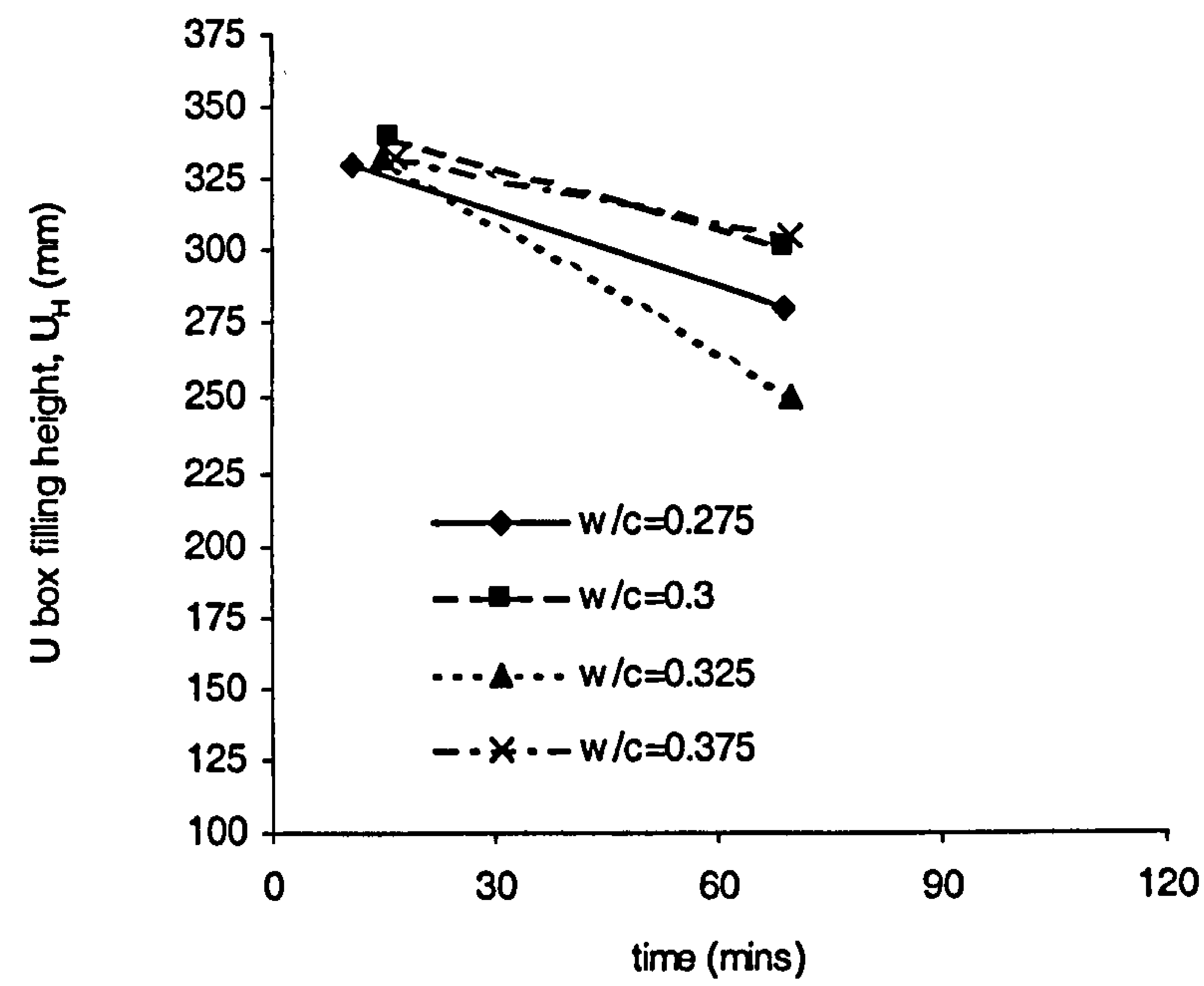


Figure 6-9 The change of U-box filling height with time for concrete with various water/cement ratio

The best workability retention in terms of slump flow shown in **figure 6-5** was obtained in the mixes with a water/cement ratio of 0.30 (the mix C6-2) and 0.375 (the mix C6-4), which had either high superplasticizer dosage or water/cement ratio. The slump flows at 90 minutes were about 90 mm higher than these for the other two mixes C6-1, C6-3. This is consistent with the test results on the mortar, but slightly different from the results of the mortar with different batches of cement (**figure 6-1**), which may be caused by the different composition of the cements (the C_3A content in PC4 is about 2% higher than that in PC2). The T_{500}, T_V and μ results (**figure 6-6, 6-7 & 6-8**) confirmed the finding from the mortar tests that the workability retention was improved with an increase of water/cement ratio. Overall, the best workability retention was obtained in mixes C6-2 and C6-4 (which had water/cement ratios 0.3 and 0.375); they both had U-box filling heights of over 300 mm at 60 minutes after mixing (**figure6-9**).

There is generally a good relationship between the mortar and concrete properties, which proves that it is possible to study the effect of water/cement ratio on the properties of fresh concrete using mortar tests. This will be discussed further in Chapter 10.

6.2 Effect of sand volume ratio

The effect of sand on the initial fresh properties of mortar has been thoroughly investigated in another programme, as summarised in chapter 2. Because the sand content is one of the important factors for mix design, the effect on workability retention was investigated in this programme.

6.2.1 Tests on mortar

Table 6-4 gives the mix proportions and initial properties. The sand/mortar ratio by volume was varied from 0.4 to 0.475, which is within the range for SCC according to the UCL mix design method [25,29]. The water/cement ratio was kept at 0.3 in all mixes. Glenium51 was used with one minute delayed addition time, and the dosage was such to achieve a spread between 310 and 320 mm. It can be seen that these slightly increased with sand content. A similar result was found by Naoki *et al* [84], as discussed in section 2.4.1.5. The μ, T_v and T_{250} were significantly increased, while the yield stress was in the range of 4.5-7.2 Pa.

Table 6-4 Mix proportions and initial properties for mortar with various sand contents*

Mix NO.	V_s/V_m	% sp**	D_m (mm)	T_{250} (s)	T_v (s)	τ_0 (Pa)	μ (Pa.s)
M6-11	0.4	0.115	310	2.6	2.28	6.2	3.9
M6-12	0.425	0.135	320	3.1	2.72	5.4	4.8
M6-2	0.45	0.145	315	3.5	3.26	4.5	6.9
M6-13	0.475	0.155	310	5.2	3.87	7.2	9.6

*All mixes with 100% PC2 as powder, ** By weight of powder

The test results for the two hours after mixing are presented in **figure 6-10.** All the mixes lost workability, and the degree of loss increased with sand content. The D_m showed similar behaviour to τ_0, as did T_v and T_{250} time to μ; this will be discussed in Chapter 10.

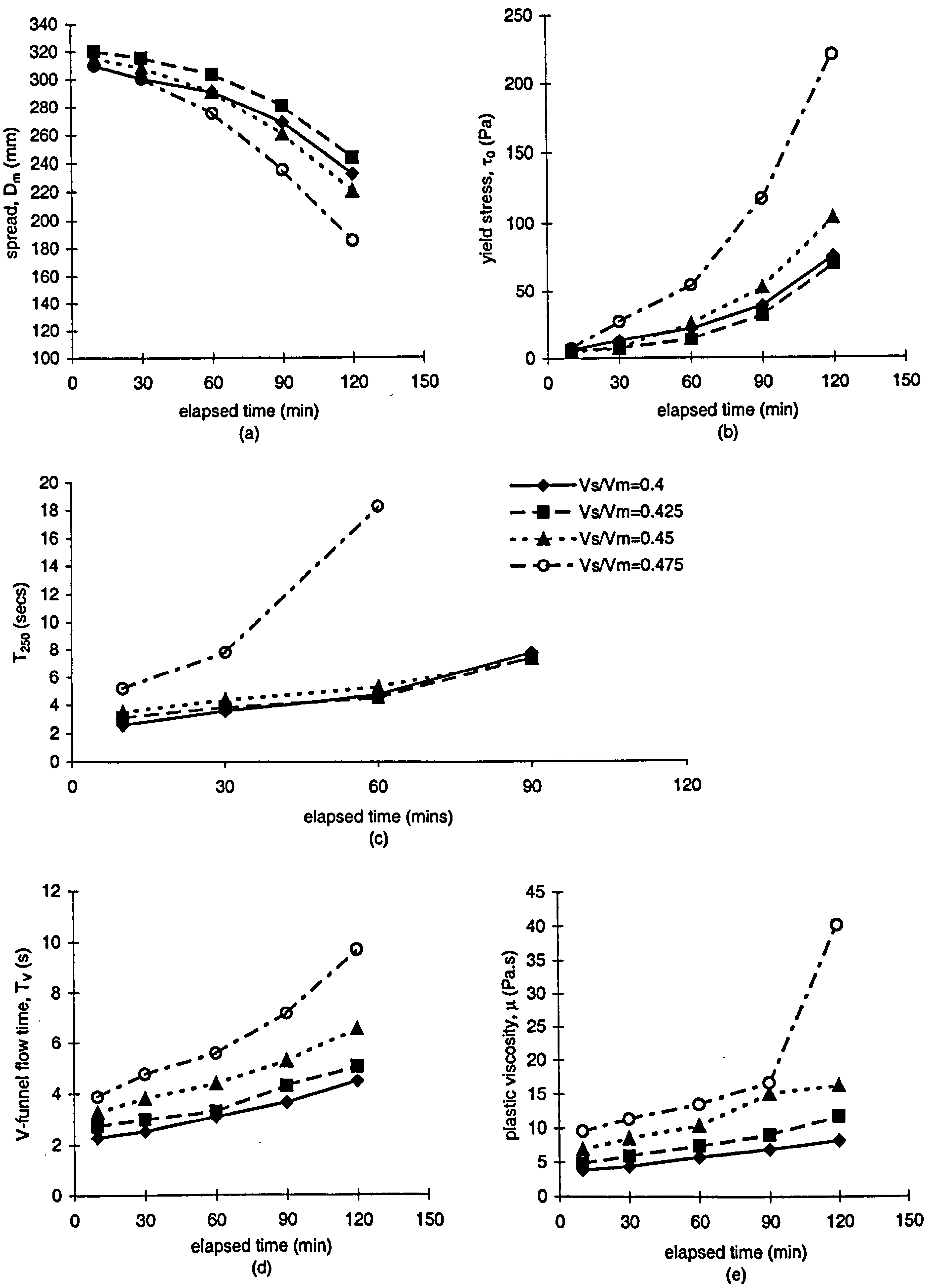
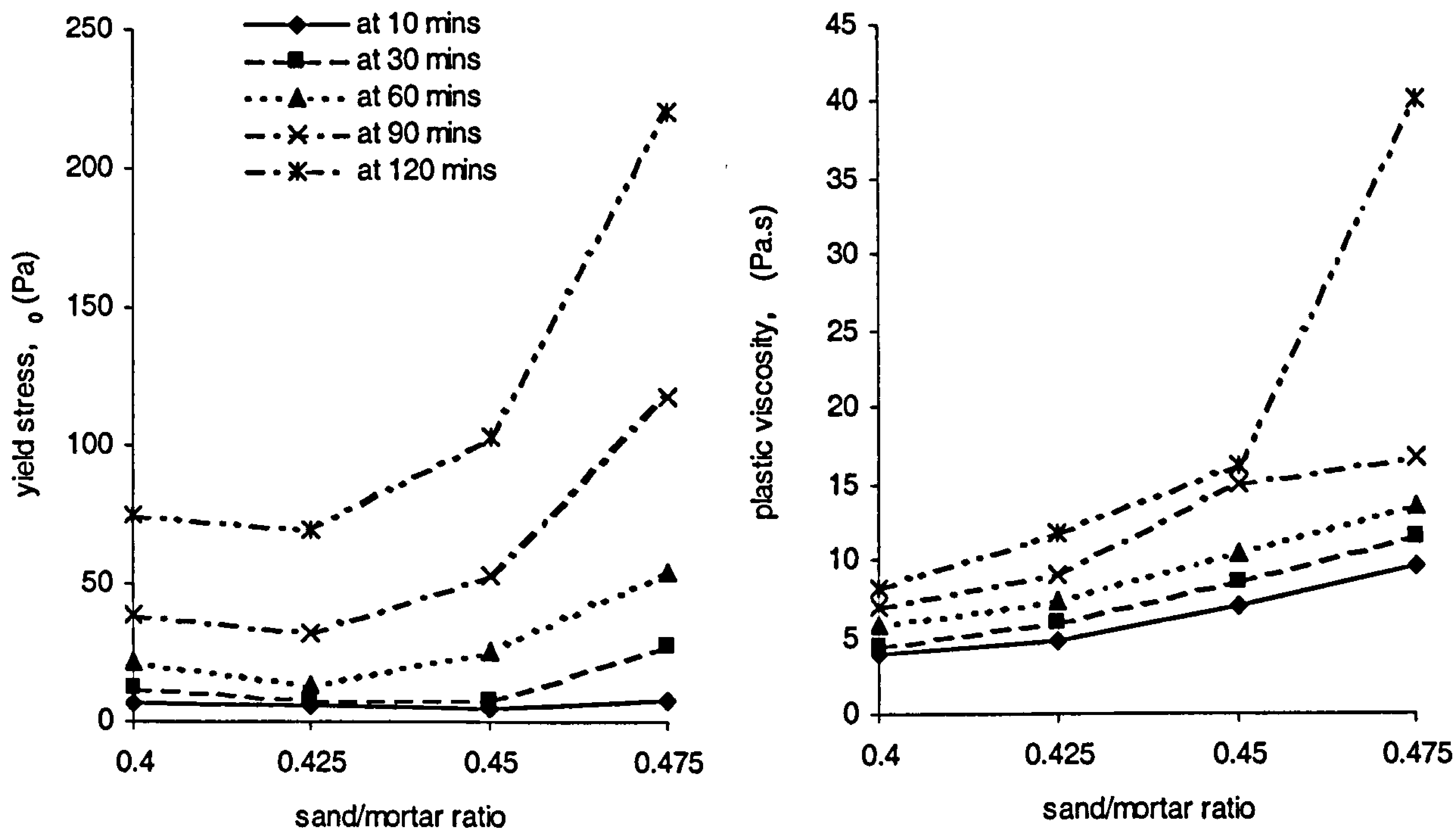


Figure 6-10 Development of properties of PC2 mortar mixes with various sand content for 2 hours after mixing: (a) spread (b) yield stress (c) T_{250} time (d) V-funnel flow (e) plastic viscosity

Workability loss of these mixes for 2 hours after mixing in terms of yield stress and plastic viscosity is shown in **figure 6-11.** Both mix M6-11 and M6-12 (0.4 and 0.425 sand/mortar volume ratio) had similar and the highest workability retention; the mix M6-2 (0.45 sand/mortar ratio by volume) showed slightly increased workability loss, but it was tripled in terms of yield stress and about eight times higher in terms of plastic viscosity for the mix M6-13 (0.475 sand/mortar ratio by volume) compared to mix M6-11.



(a) (b)

Figure 6-11 Comparison of the workability loss for the mortar with various sand contents in terms of (a) yield stress (b) plastic viscosity

As reviewed in chapter 2, Nishibayashi *et al* [109] found the relative plastic viscosity of mortar to its paste fraction is a power of the average thickness of the paste covering sand particles, meaning a power of the sand content. This implies that the same development of plastic viscosity for the paste fraction of mortar will result in greater increase for the mix with higher sand content. Therefore, it can be concluded that workability loss increases with increasing sand content, and the amount of loss is greater when the sand content higher; this was confirmed by the tests.

6.2.2 Tests on concrete

Concrete tests were carried out to confirm the results from the mortar tests. **Table 6-5** shows the sand/mortar ratios and initial properties of the concrete mixes. All used a powder of 100% PC4, a 0.3 water/cement ratio by weight and a coarse aggregate volume of 0.317 m^3 per cubic meter (50% of the dry rodded bulk density).

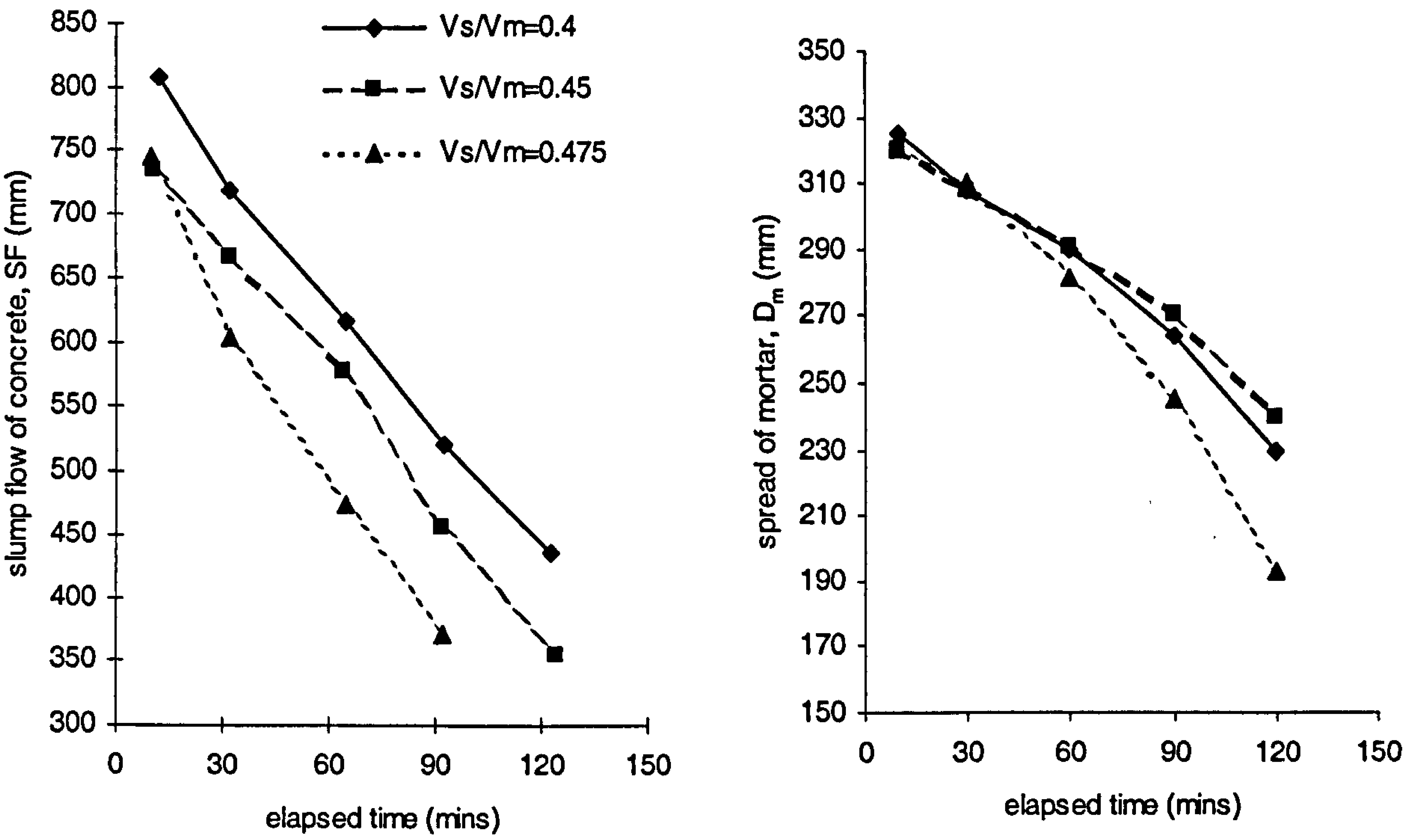
The dosage of superplasticizer for each mix was determined by repeating the spread test on the mortar component so as to give a spread of 310-320 mm. The dosages were slightly lower than those for the same mixes with PC2 (**table 6-4**). Again the τ_0 results were in a similar narrow range of 0.5-3.1 Pa; the T_V values were slightly higher and the T_{250} and μ similar. Clearly, there are only small differences with the different batch of cement.

The slump flow of the concrete ranged from 740-810 mm. The T_v, T_{500}, $T_{u\text{-}box}$ and μ consistently increased with the increase of sand content suggesting a possibility of a good relationship between them. The yield stress was too low to be measured with the two-point test equipment, while all mixes had excellent U box filling heights of between 330-340 mm.

Table 6-5 Mix proportions and initial properties of concrete and mortar with varying sand content *

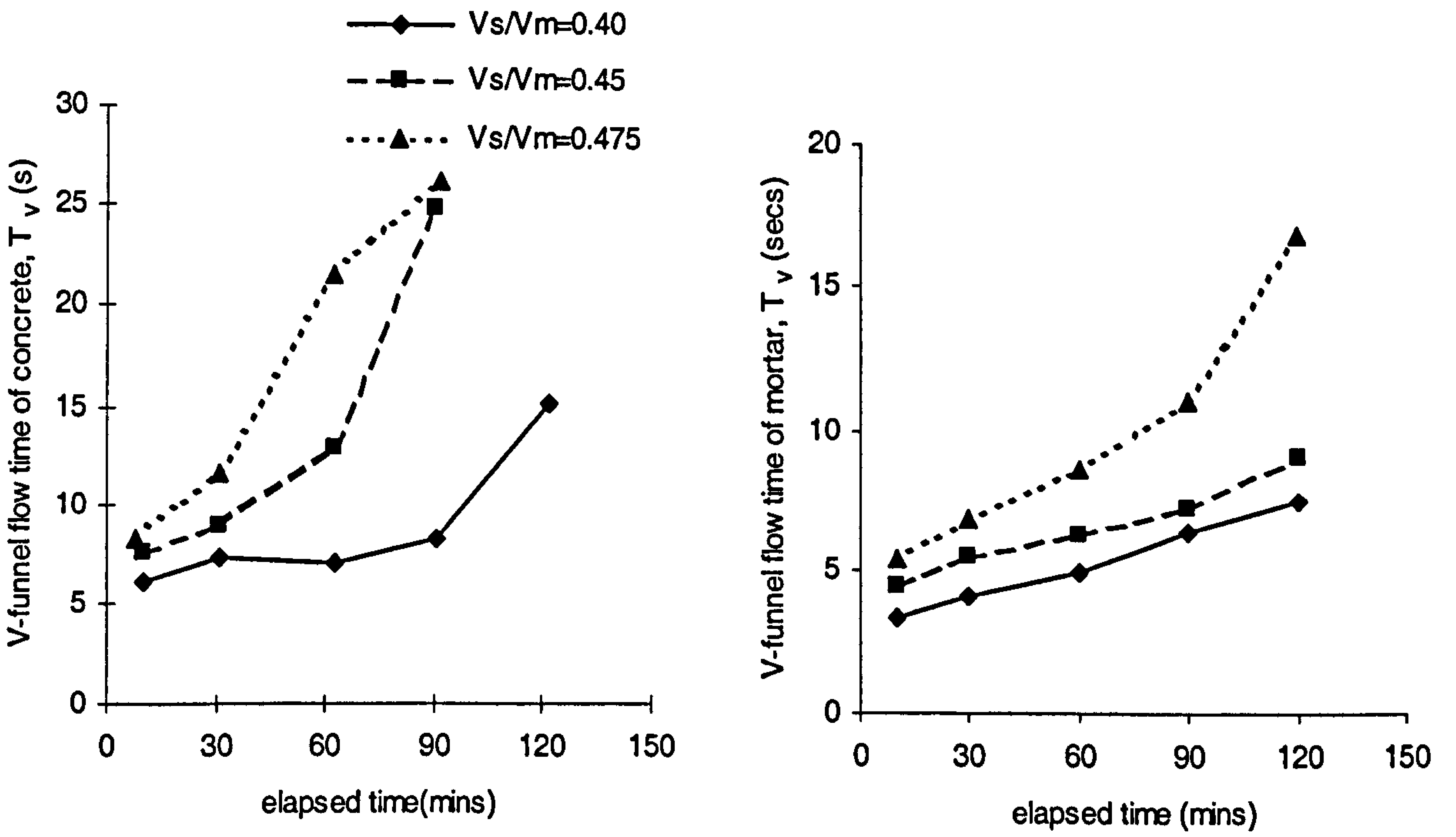
Mix No.	V_s/V_m	Sp ** (%)	Mortar test					Concrete test						
			D_m (mm)	T_{250} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	SF (mm)	T_{500} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	U_H (mm)	$T_{u\text{-}box}$ (s)
C6-4	0.4	0.115	325	2.5	3.25	3.1	3.5	808	2.25	6.0	***	59	340	2.25
C5-1	0.45	0.13	320	3.4	4.4	1.0	5.7	753	3.22	7.5	***	78	340	3.22
C6-5	0.475	0.145	320	4.1	5.34	0.5	8.7	745	4.29	8.3	***	104	335	4.29

*100% PC4 was used as powder **by the weight of powder *** not measurable



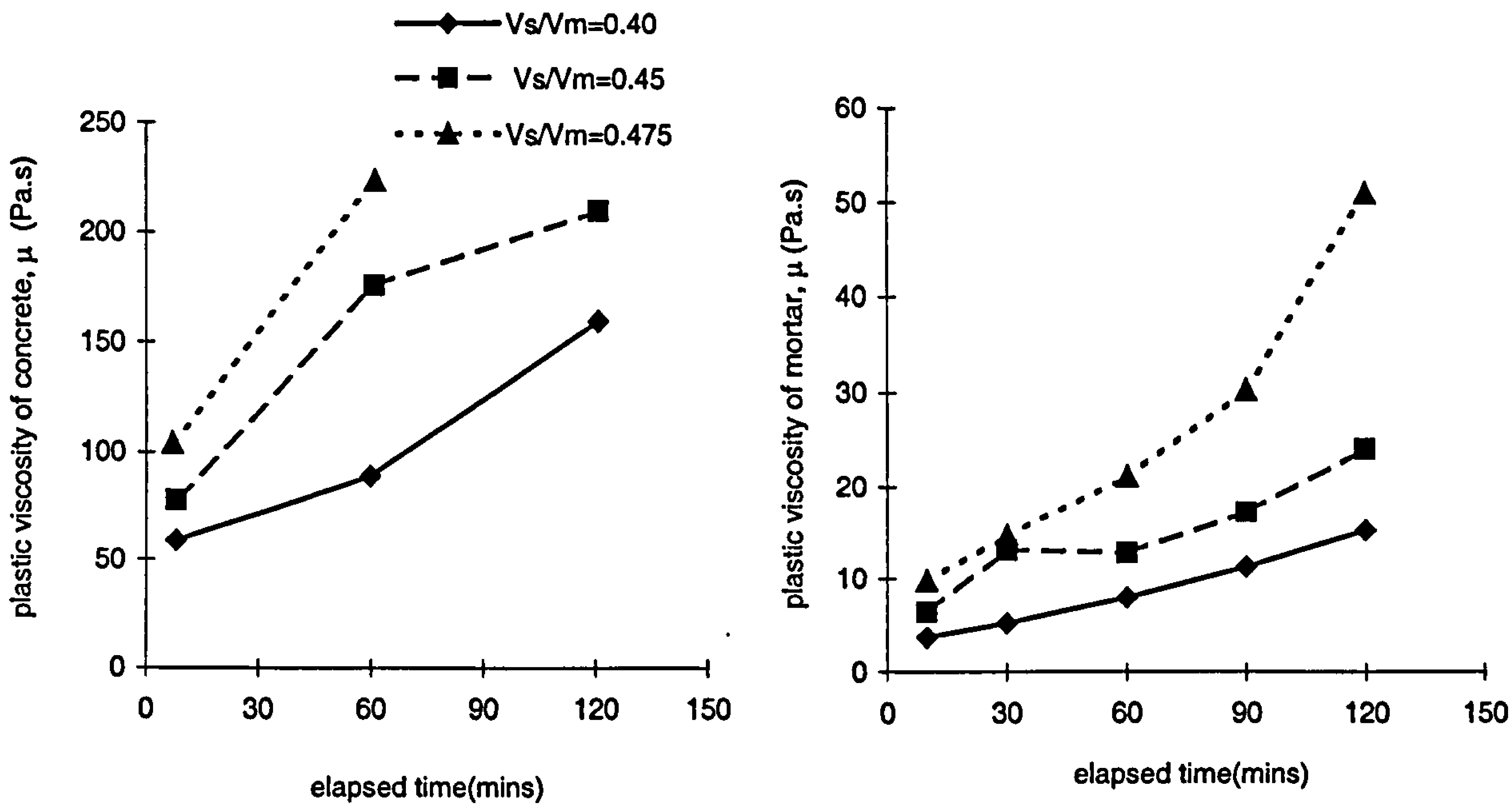
(a) (b)

Figure 6-12 Slump flow/spread loss of the concrete and mortar with various sand contents



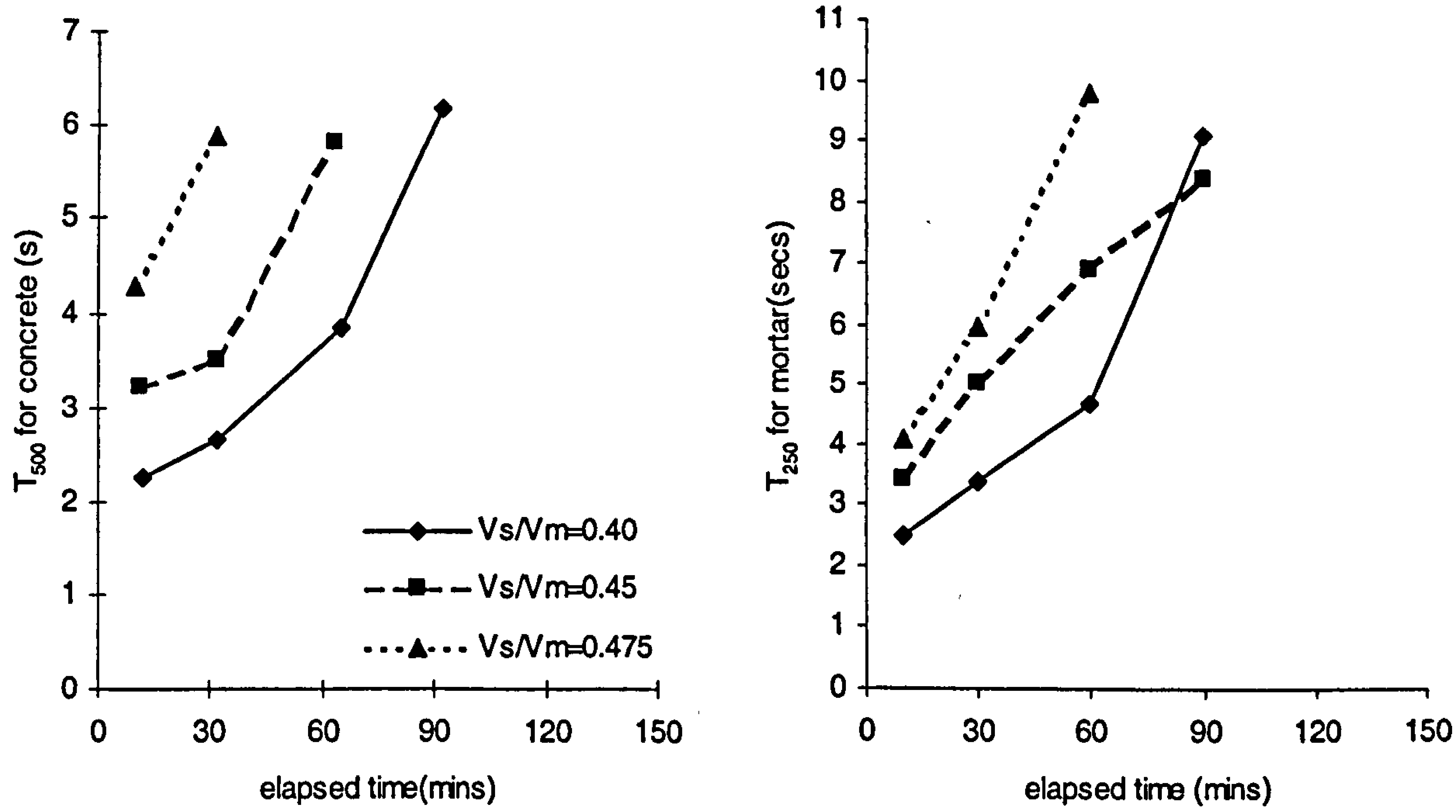
(a) (b)

Figure 6-13 Development of V-funnel flow time for the concrete and mortar with various sand contents



(a) (b)

Figure 6-14 The change of plastic viscosity with time for the concrete and mortar with various sand contents



(a) (b)

Figure 6-15 The change of T_{500} and T_{250} with time for the concrete and mortar with various sand contents

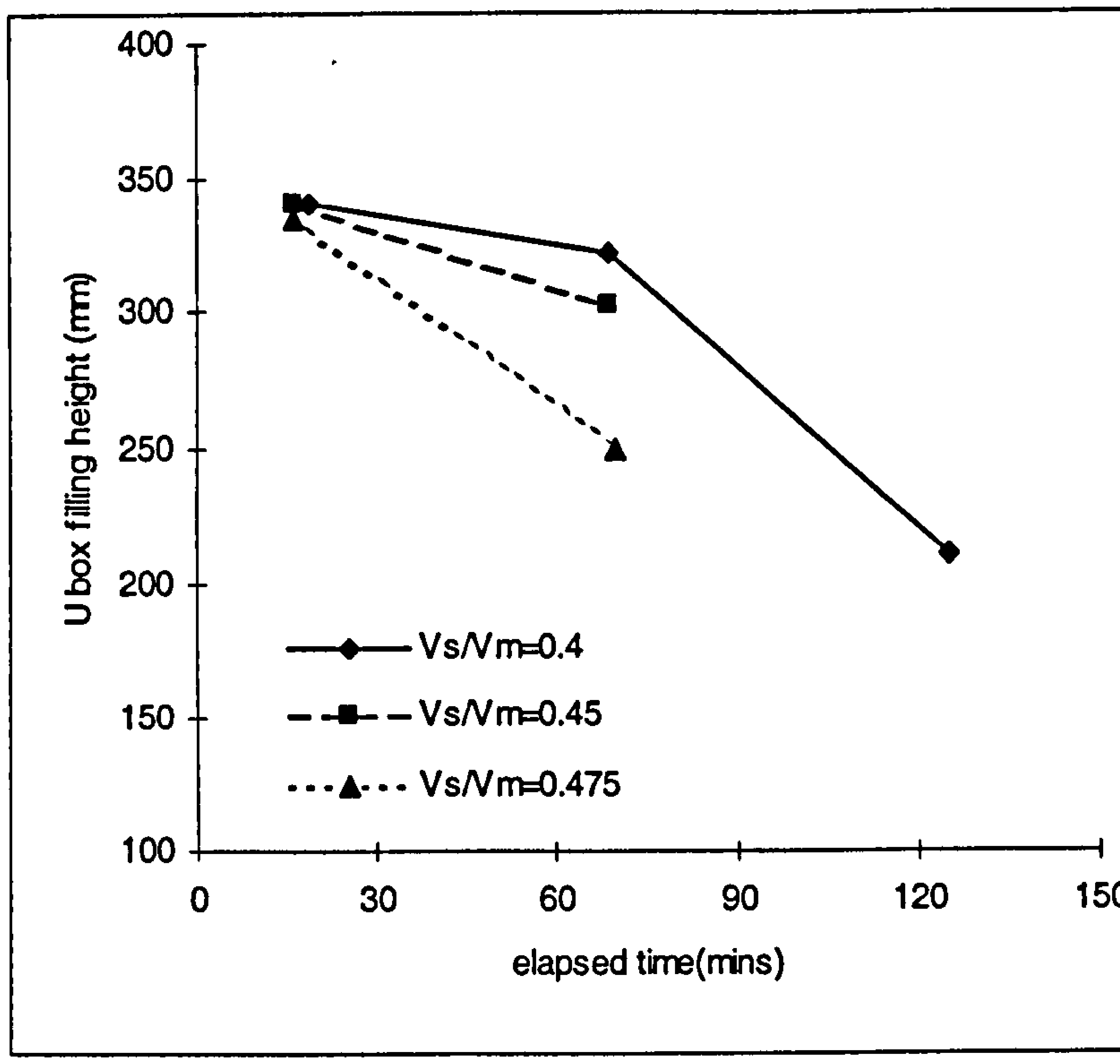


Figure 6-16 The change of U-box filling height with time for the concrete with various sand contents

Figures 6-12, 6-13, 6-14 6-15 & 6-16 show the development of the workability over the two hours after mixing for the concrete and mortar including SF/D_m, T_v, μ, T_{500}/T_{250} and U_H. Again yield stress is not included in the figures.

As with the mortar tests, the rate of slump flow loss (**figure 6-12**) was only slightly increased with an increase of sand content from 40% to 45% by volume of mortar, but a greater increase was observed at 47.5%. A similar performance was found in T_{500} test (**figure 6-15**), but it was not apparent in the V-funnel and plastic viscosity results (**figure 6-13 & 6-14**). In general, the best workability retention was obtained in mix C6-4 with a sand content of 40% mortar by volume; it maintained a U box filling height of 322 mm at 60 minutes, 20 mm higher than that for mix C5-1 (45% sand of mortar by volume), while the filling height for mix C6-3 with 47.5% of sand dropped to 250 mm for same period.

6.3 Effect of types of cement

In SCC, many types of cement have been used in single powder mixes, including low heat or moderate heat and high belite cement. Most of these materials are not available in UK market, however, the composition of SRC is very similar to a high belite cement; both have low C_3A content, but SRC may have high C_3S instead of C_2S content (**table 4-1**). The effect of using SRC on the fresh properties of SCC was therefore studied.

6.3.1 Tests on mortar

The properties of an SRC mix were studied by comparing it with a PC1 mix. **Table 6-6** shows the mix proportions and the initial properties. The superplasticizer dosage was chosen so as to achieve a spread of 310-320 mm, and both mixes had a similar dosage. The V-funnel flow times and yield stresses were also similar but the measured plastic viscosity of the PC mix was slightly lower than that of the SRC1 mix.

Table 6-6 Mix proportions of mortar with different types of cement

Mix NO.	Cement	% sp**	D_m (mm)	T_V (s)	τ_0 (Pa)	μ (Pa.s)
M6-14	PC1	0.15	311	3.92	9.0	8.1
M6-15	SRC1	0.145	310	3.8	5.5	5.8

Figure 6-17 shows the changes in properties with time after mixing. The SRC mix showed excellent workability retention. The workability hardly changed in terms of yield stress and spread and slightly increased in terms of V-funnel flow time and plastic viscosity. This is therefore a significant improvement of workability retention compared to a 100 % PC mix, suggesting potential advantage of producing SCC using SRC combined with Glenium51.

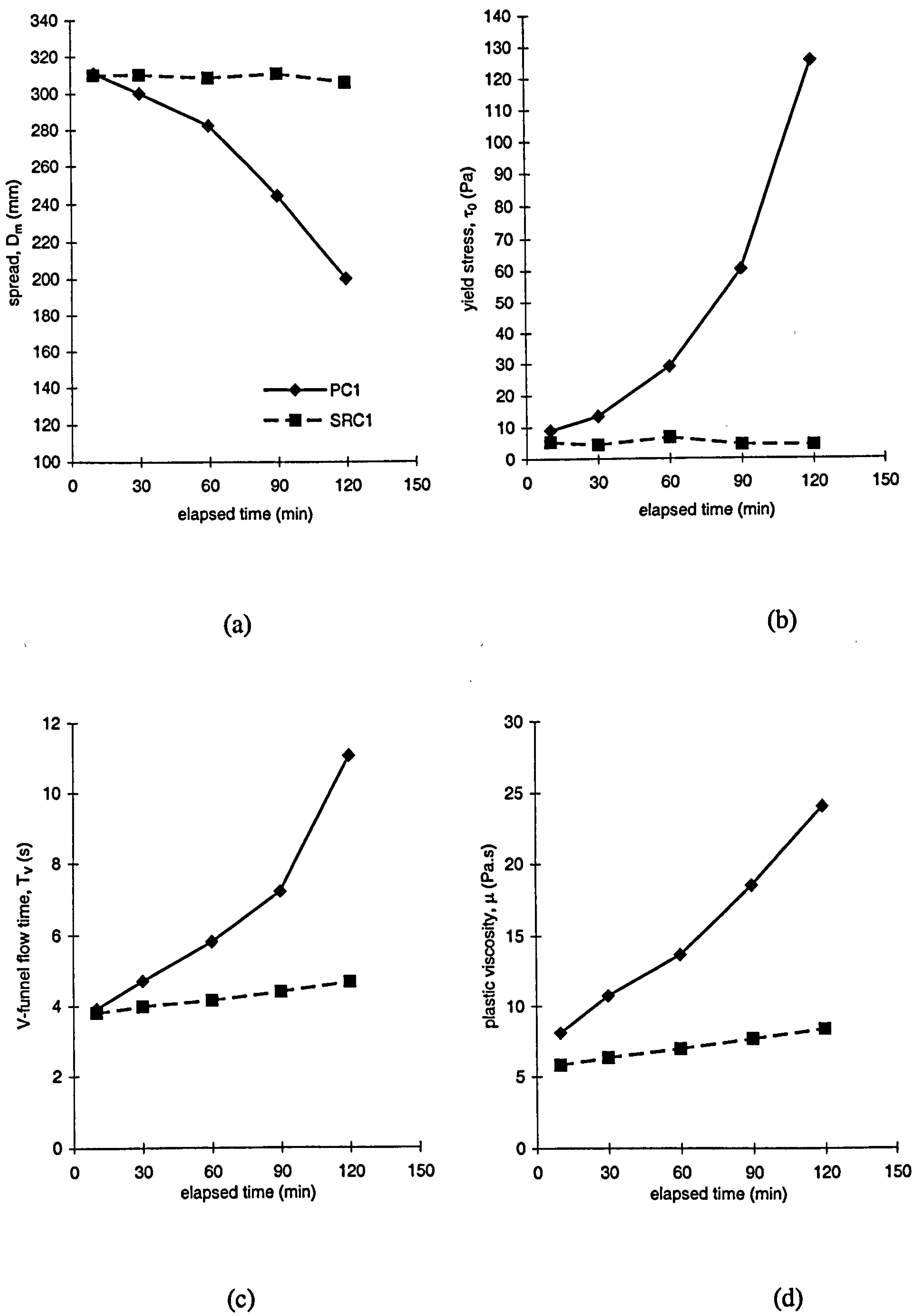


Figure 6-17 Development of properties of the mortar mixes with different types of cement for 2 hours after mixing: (a) spread (b) yield stress (c) V-funnel flow time (d) plastic viscosity

It is well known that SRC has low C_3A content which slows down hydration rate in the early stage, and this may improve the workability retention of SRC mix; it is however not clear how significant the effect of ionic strength is in this type of mix.

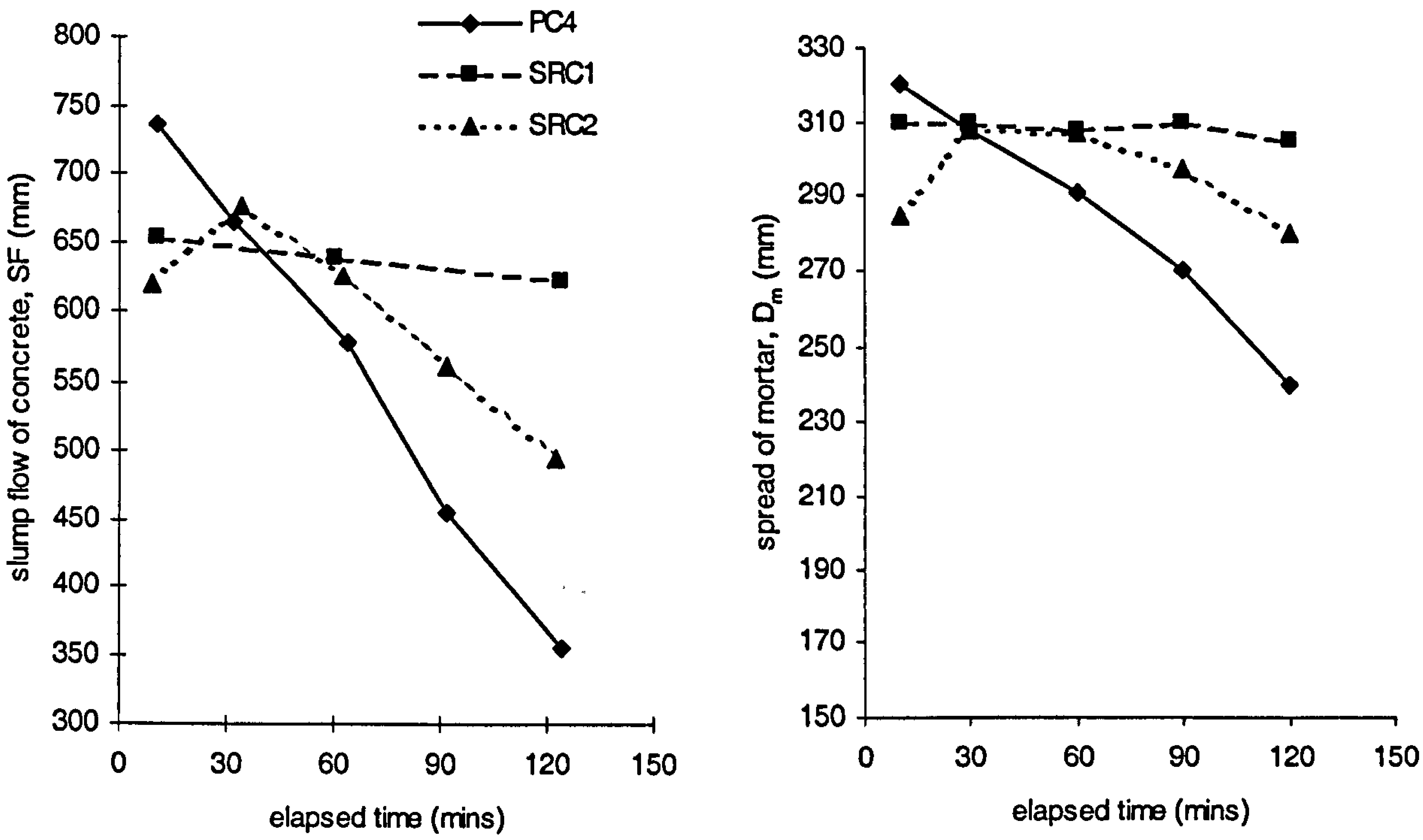
6.3.2 Tests on concrete

The excellent properties of the SRC mix were also confirmed by a concrete test. **Table 6-7** shows the mix proportions and initial properties. SRC from two batches were tested. Because the workability of the SRC2 mix was found to increase for 30 minutes after mixing the initial spread was controlled to 285 mm instead of 310-320 mm, otherwise bleeding and segregation occurred, but the initial yield stress was still in the range of 0-10 Pa. Different initial properties were found between the two SRC mixes suggesting an effect of the composition of SRC on workability.

Table 6-7 Mix proportions and initial properties of concrete and mortar with different types of cement

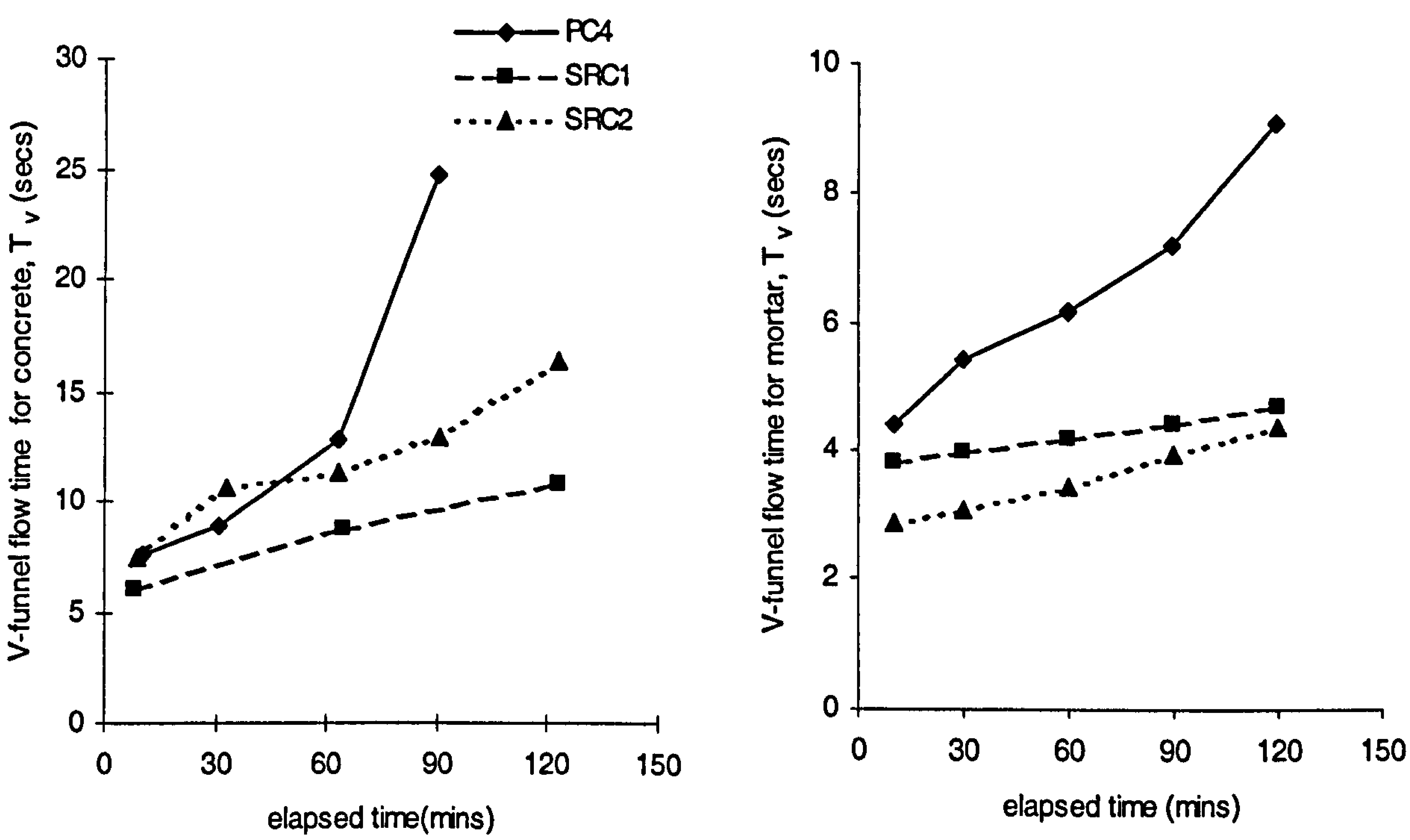
Mix No.	cement	Sp dose* (%)	Mortar test D_m (mm)	T_V (s)	T_{250} (s)	τ_0 (Pa)	μ (Pa.s)	Concrete test SF (mm)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	U_H (mm)
C5-1	PC4	0.13	320	4.4	3.4	1.0	5.7	735	7.53	**	78	340
C6-6	SRC1	0.145	310	3.8		5.4	5.8	653	5.95			337
C6-7	SRC2	0.13	285	2.87	2.3	7.3	3.8	618	7.37			340

*by the weight of powder ** not measurable



(a) (b)

Figure 6-18 Flow loss with time for concrete and mortar with different types of cement



(a) (b)

Figure 6-19 Development of V-funnel flow time with time for the concrete and mortar with different types of cement

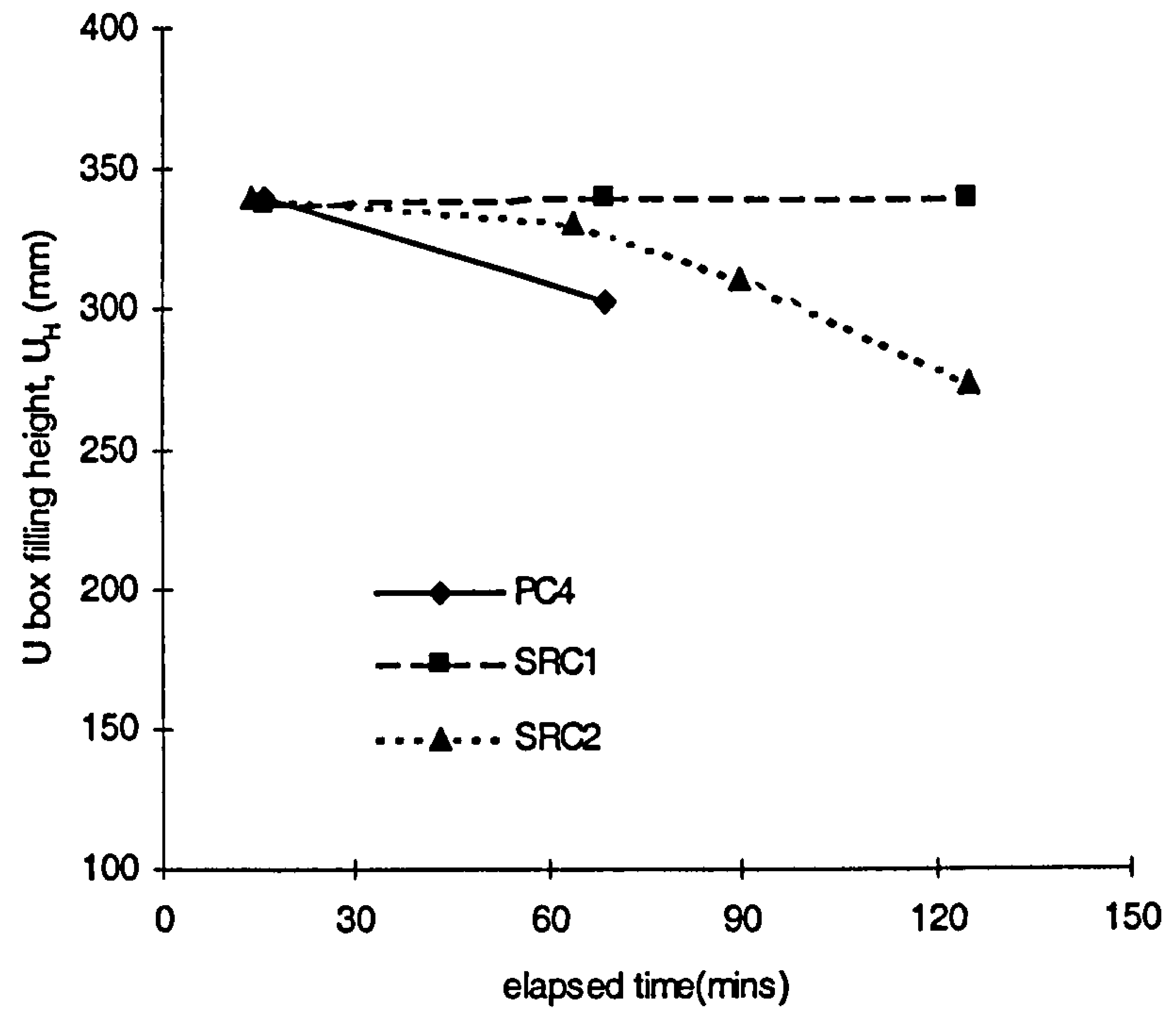


Figure 6-20 Change of U-box filling height with time for the concrete with different types of cement

Figures 6-18, 6-19 & **6-20** show the change in workability with time after mixing. The concrete results are consistent with those of the mortar, again suggesting a close relationship between them. In the two hours after mixing, the slump flow of SRC1 mix hardly changed while the V-funnel time increased from 5.95 seconds to 10.8 seconds. The performance of SRC2 mix was slightly inferior but still far better than the PC4 mix. The slump flow of SRC2 mix increased at 30 minutes after mixing and then decreased; similar behaviour has been found by others [82,89] with some PC mixes and the possible reason has been discussed by Yamada *et al* [91], as reviewed in section 2.4.2. Good passing ability was retained for two hours for SRC1 and 90 minutes for the SRC2 mix; but the PC4 mix could not be used as SCC just 60 minutes after mixing.

The different performance for two SRC mixes suggests the different properties of these two cements from different sources. SRC2 had higher C_3S and specific surface area (SSA) than SRC1 but both cements have similar total amounts of C_3S and C_2S. Both C_3S and C_2S adsorb similar amounts of superplasticizer but high C_3S and SSA are known to contribute to workability loss.

6.4 Conclusions

The effect of water/cement ratio, sand content and types of cement on the properties of mixes with single type of powder was investigated. It was found that

- Yield stress and plastic viscosity are two different properties and affected by different factors. Superplasticizer dosage and water content affect workability retention in terms of yield stress, and the best workability retention can be obtained with water/cement ratios between 0.275-0.3 or about 0.375. The plastic viscosity is mainly affected by water content, therefore the higher water/cement ratio the better workability retention.

- Workability loss increases with sand content, which greater increases of loss at higher sand content. The workability loss of the mix with sand/mortar volume ratio of 0.475 was three times in terms of yield stress and about eight times in terms of plastic viscosity of that with 0.4 at 2 hours after mixing.

- SRC mixes show excellent workability retention. This suggests the potential advantage of producing SCC with SRC combined with the new generation superplasticizer Glenium51.

- The concrete test results closely corresponded with the mortar tests illustrating the importance of mortar in SCC. This suggests the possibility of predicting concrete properties from its mortar tests (this will be discussed in more detail in chapter 10).

- The simple test method results show behaviour consistent with the rheological properties for mortar and concrete in most cases, and again this will be discussed in chapter 10.

Chapter 7

Fresh properties of mixes with binary blends of powder

Most SCC mixes contain blends of two or more powders, which have benefits for fresh, early age (e.g. heat of hydration) and long term properties (e.g. durability). Because of the different chemical and physical properties of the blended components, the fresh properties of the mixes can be very different to each other, even though they all satisfy the general SCC requirements. Clearly it is important to understand the effect of each component as well as the combined effect.

The objective of the work described in this chapter was to investigate the properties of mixes with binary powder combinations. As in the other parts of the programme, a range of variables were first assessed on mortars, and then selected variables were assessed in tests on concrete.

The factors studied were:

- blends of Portland cement, with a single typical blend of 40% for PFA, GGBS and LSP100, and 5% CSF (all by volume), and SRC with GGBS,
- the effect of particle size of LSPs (LSP100, LSP50 and LSP15),
- the effect of amount of LSP (LSP100 with 20, 40 and 60% by volume) and CSF (CSF with 5, 10 and 15% by volume).

This was followed by a discussion of the effect of superplasticizer and the initial plastic viscosity on the development of fresh properties.

The fresh properties which were measured during the two hour period after the start of mixing included:

- spread (D_m) and time to 250 mm spread (T_{250}), V-funnel flow time (T_V), yield stress (τ_0) and plastic viscosity (μ) for mortar;
- slump flow (SF) and the time for flow to 500 diameter (T_{500}), V-funnel flow time (T_V), yield stress (τ_0), plastic viscosity (μ), U-box filling height and the time to reach 250 mm height ($T_{U\text{-}box}$) for concrete.

Glenium51 was used and added 1 minute after the start of mixing.

Concrete cubes were also cast for compressive strength testing after the workability tests; the results will be reported in chapter 10.

7.1 Tests on mortar

7.1.1 Binary blends at a single replacement level

The mixes and their properties immediately after mixing are given in **table 7-1,** series 1 was the Portland cement (PC2) mixes, and series 2 the sulfate resisting cement (SRC2) mixes. All the powders had a similar particle size (see chapter 4), with the exception of the CSF. The water/powder ratio was constant at 0.945 (equal to 0.3 by weight) and the sand/mortar ratio at 0.45 by volume. In series 1 the superplasticizer (Glenium51) dosage was adjusted to give a spread value between 310-320 mm for each mix. In series 2 it was adjusted to give a spread of about 285 mm for SRC2 mix and 330 mm for the GGBS mix, and both spreads changed to between 310-320 mm at 30 minutes after the start of mixing, therefore their workability retention was compared from this time. The PFA, GGBS and LSP100 mixes all required a lower dosage than the 100% PC mix while the CSF mix required a much higher dose; this is consistent with the results of many other researchers [68, 69, 93]. The yield stress was in a narrow range of 0-9.0 Pa.

Two different groups of V-funnel flow times and plastic viscosity were obtained in series 1. The GGBS and the control mixes had similar flow time and plastic viscosity, but were both higher than the mixes with PFA, LSP and CSF which were in similar range within themselves.

Table 7-1 Mix proportions and initial properties of various binary mixes

series	Mix no.	Powder composition						Glenium51 dosage (% by wt.)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
		PC2	PFA	GGBS	LSP100	CSF	SRC2					
series 1	M7-1	100						0.15	310	3.9	9.0	8.1
	M7-2	60	40					0.125	325	3.1	4.5	4.4
	M7-3	60		40				0.1	325	3.8	0	7.3
	M7-4	60			40			0.09	325	2.5	4.0	4.2
	M7-5	95				5		0.2	320	2.49	5.4	4.3
series 2	M7-6						100	0.13	285	2.87	6.9	3.4
	M7-7			40			60	0.098	330	3.53	0	3.7

The change in properties with time after mixing for series 1 is shown in **figure 7-1**. It was expected that mixes containing CRM's would have improved workability retention due to slower hydration, but this is not the general pattern. The GGBS mix did not perform as well as the 100% Portland mix with the spread decreasing to 125 mm compared to 200 mm for the control at 120 minutes after the start of mixing. The LSP100 mix showed an inferior performance based on yield stress and spread results, but an improvement with V-funnel time and plastic viscosity. The PFA mix showed a slightly higher retention than the control, whereas the CSF mix had the highest retention of all with the spread at 120 minutes after the start of mixing as high as 280 mm. As with the cement only mixes, yield stress and spread showed similar patterns of behaviour, as did V-funnel flow time and plastic viscosity.

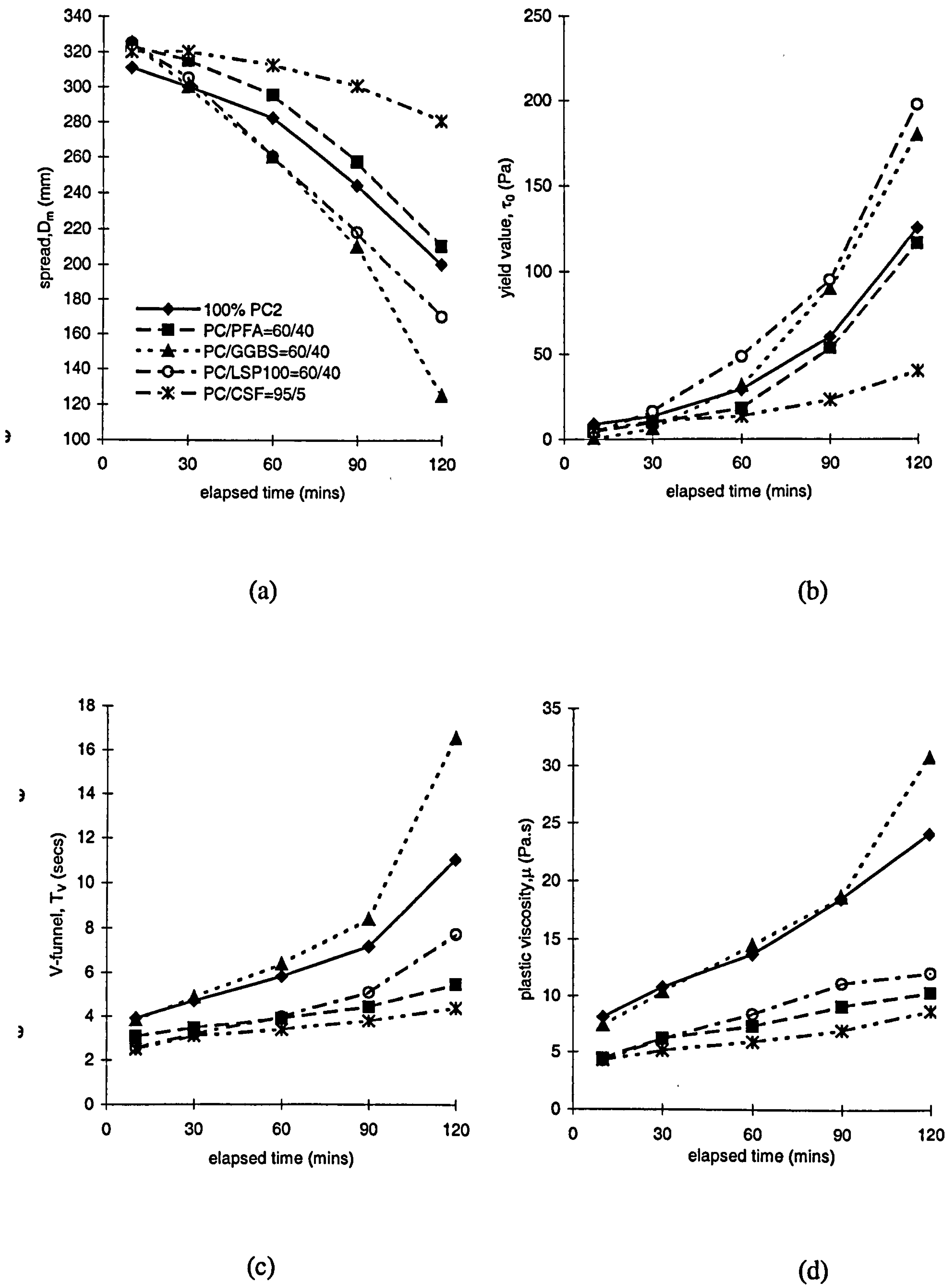
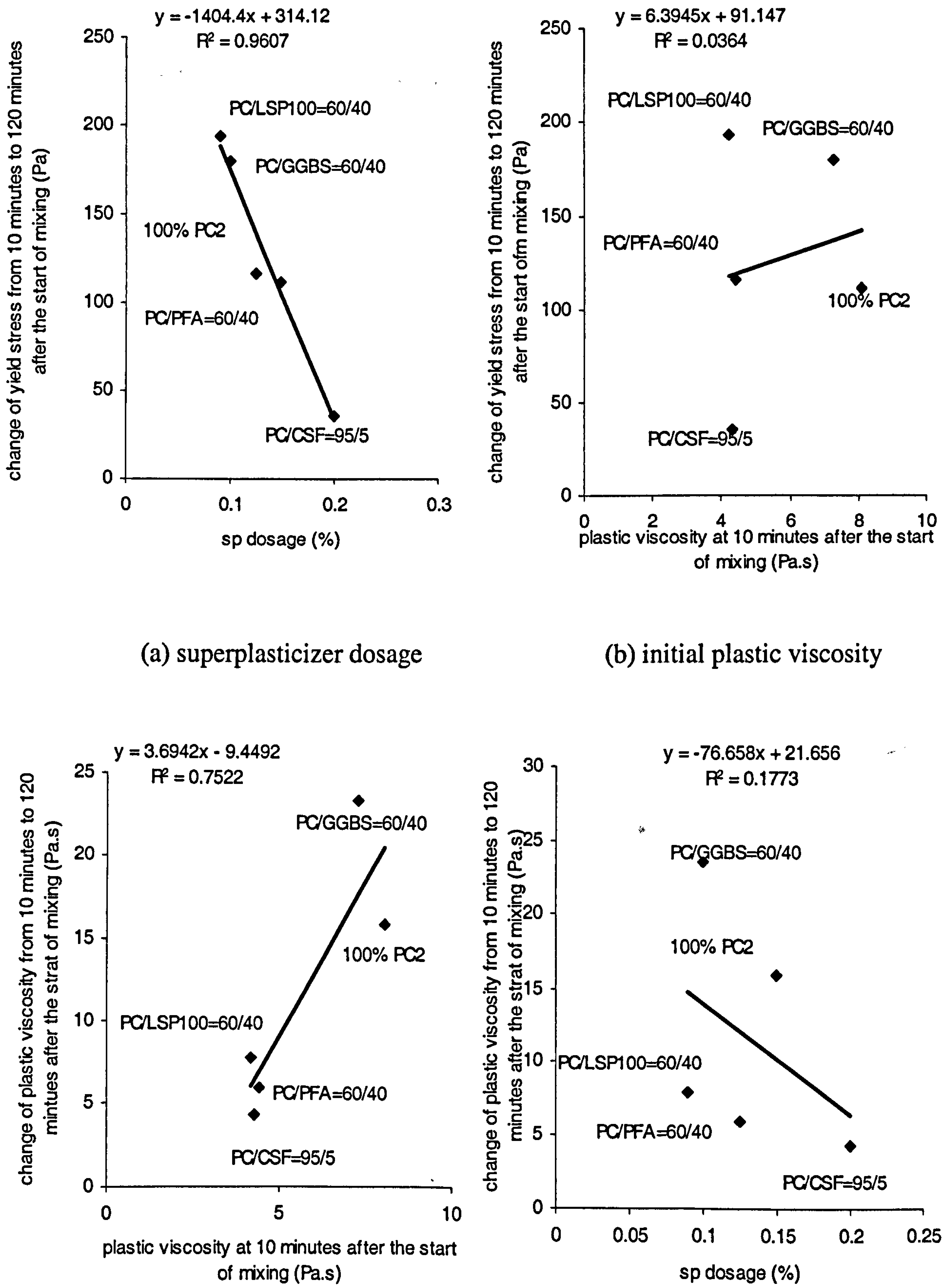


Figure 7-1 Workability retention of PC binary mixes in terms of (a) spread (b) yield stress (c) V-funnel (d) plastic viscosity

There were two general trends for workability retention depending on the properties measured, i.e. yield stress and plastic viscosity, which are shown in **figure 7-2**. Yield stress behaviour **(figure 7-2 (a) & (b))** was improved with increased superplasticizer dosage; the effect of blends was only apparent among the mixes with similar dosage of superplasticizer, (the PFA mix had slightly better workability retention than that of the 100% PC mix with similar dosage of superplasticizer). Plastic viscosity behaviour **(figure 7-2 (c) & (d))** was improved with its decreased initial value; the effect of the properties of yield stress was only seen among the mixes with similar initial values (the CSF mix had better workability retention than that of the PFA and LSP100 mix, all three mixes had similar initial plastic viscosity). These results are consistent with the conclusion in chapter 6 for single powder mixes: superplasticizer has significant effect on yield stress development, while the initial plastic viscosity affected by water content controls its development.

A possible significant effect of superplasticizer on workability retention in terms of spread and yield stress was also shown by the results of series 2, shown in **figure 7-3**. The workability retention of the GGBS mix with 0.098% of superplasticizer was inferior to the 100% SRC mix with 0.13% superplasticizer.

In general the workability retention of mortars for SCC is dependent on a combination of several factors including the powder composition, the type and dosage of superplasticizer, and the initial plastic viscosity *etc.* Mixes with GGBS or LSP100 do not necessarily have higher workability retention, whereas microsilica mixes can have excellent workability retention. This will be discussed in section 7.1.4.



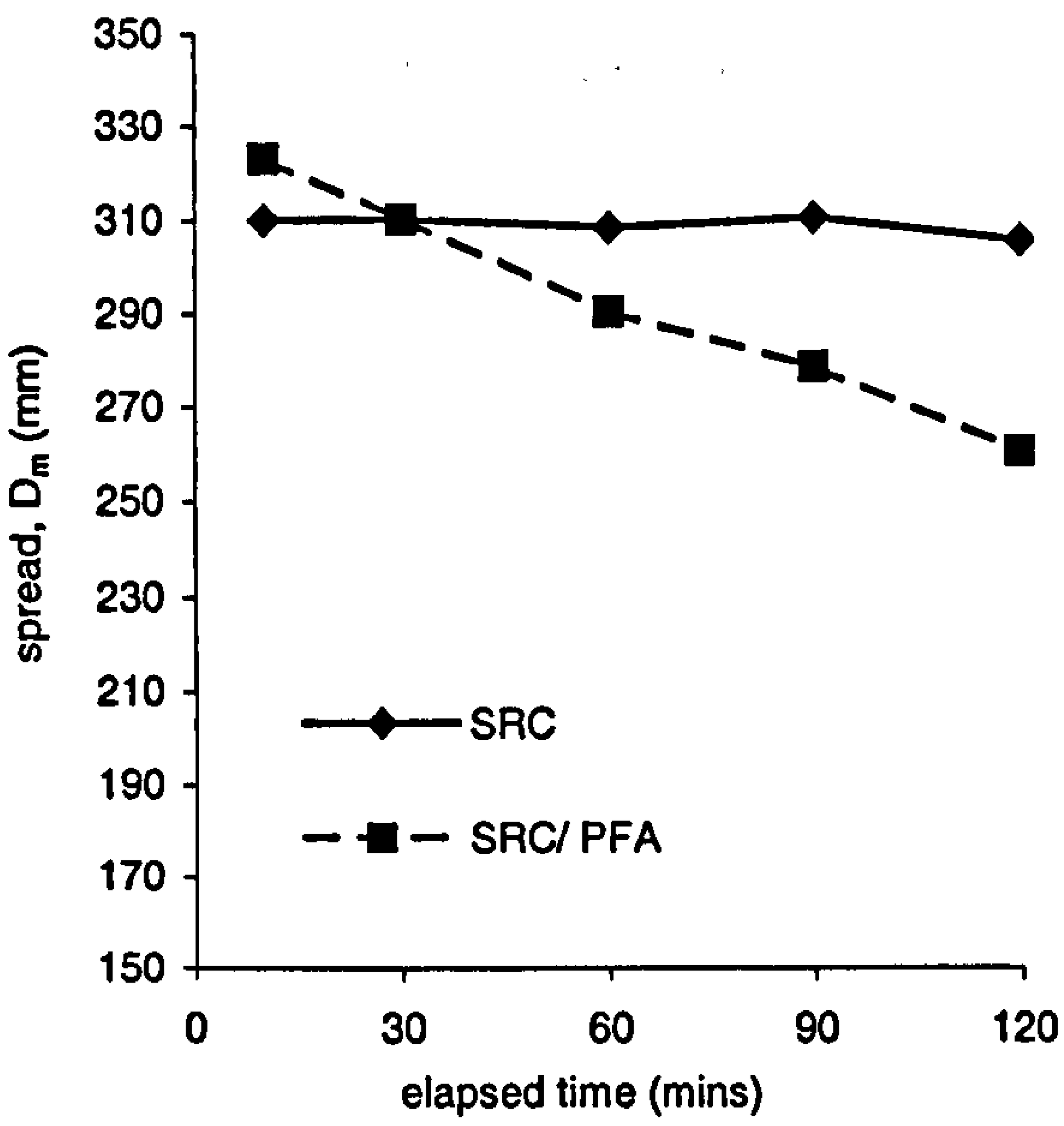
(a) superplasticizer dosage

(b) initial plastic viscosity

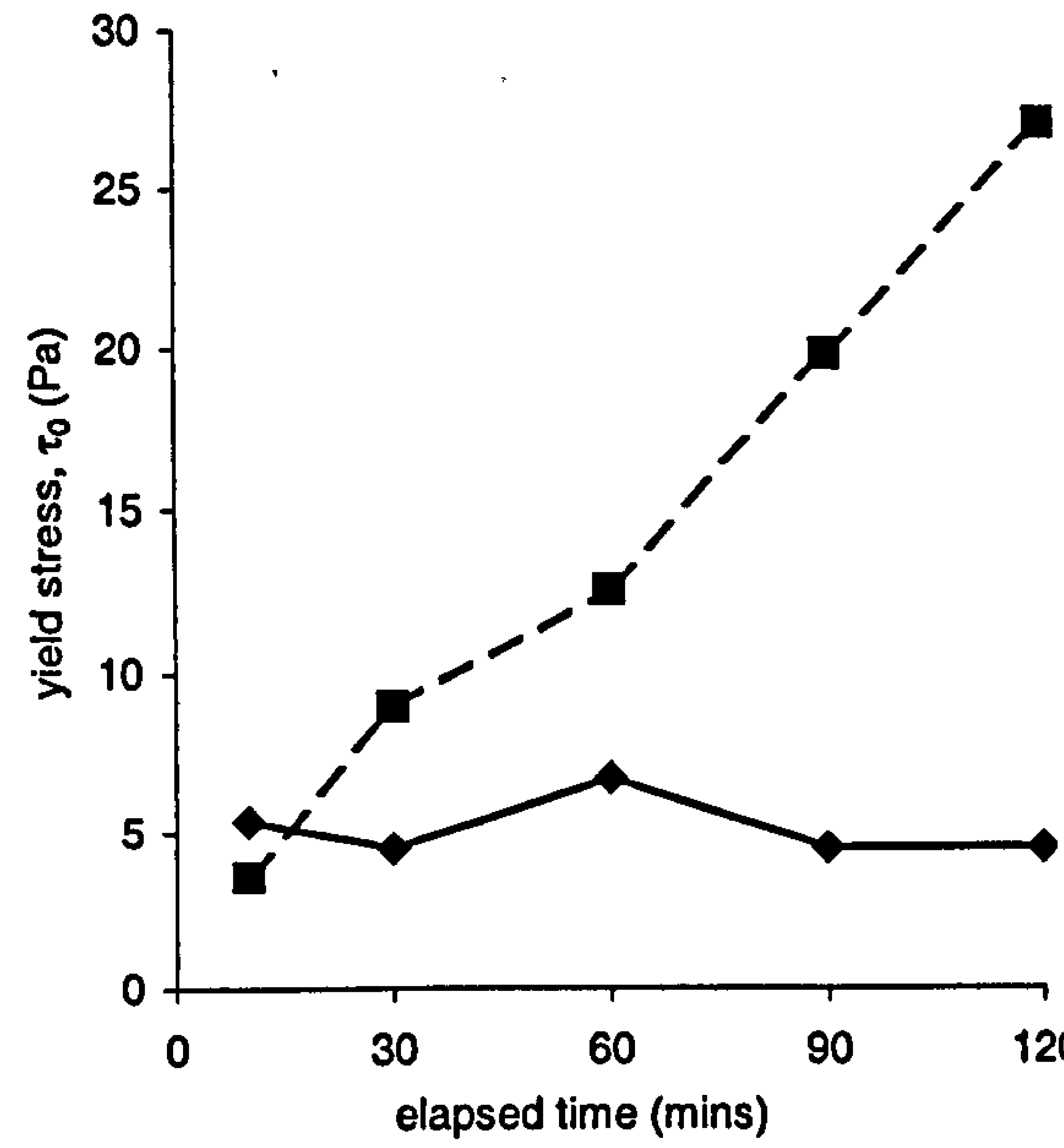
(c) initial plastic viscosity

(d) superplasticizer dosage

Figure 7-2 The factors affecting the change of yield stress and plastic viscosity



(a)



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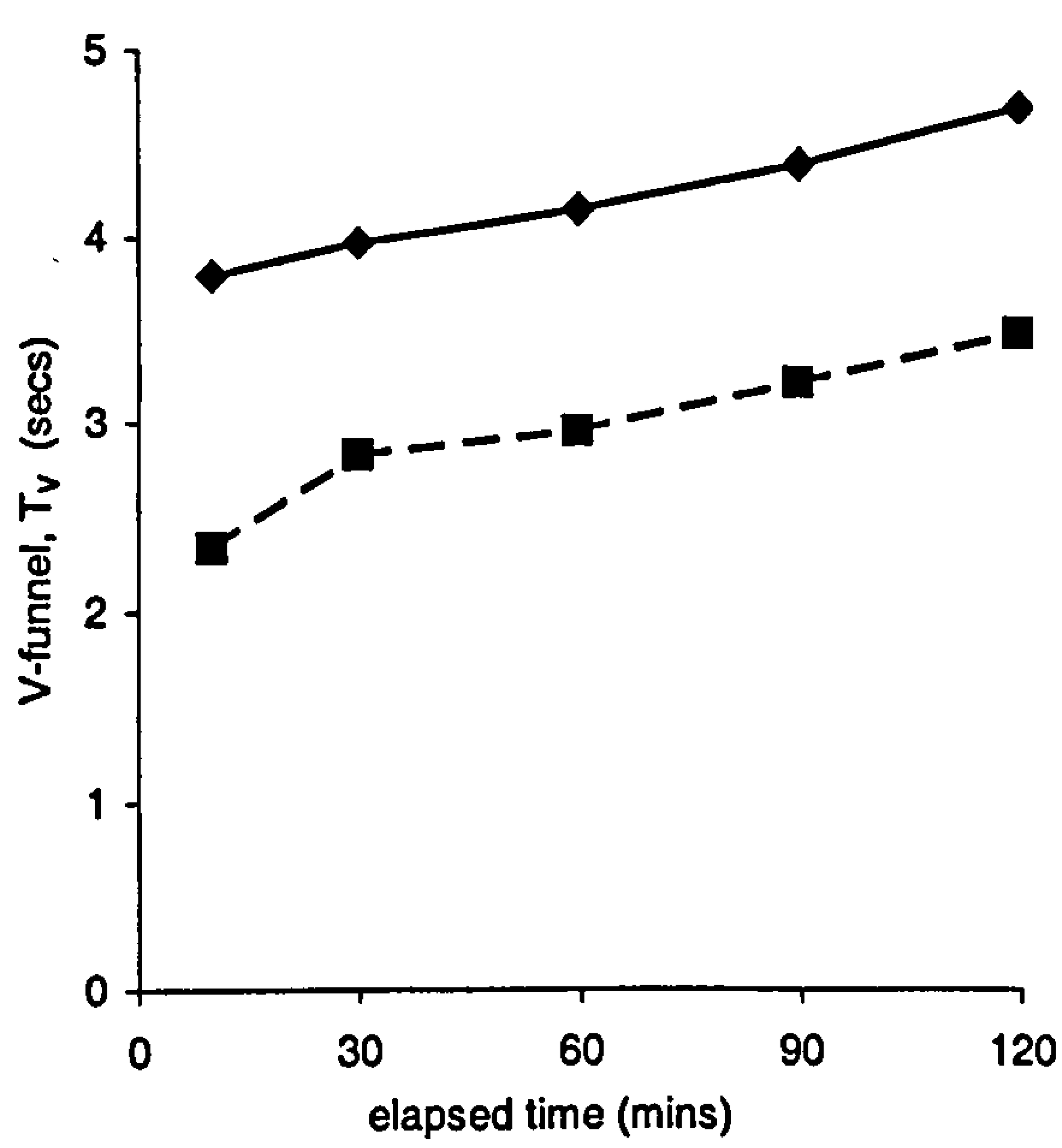
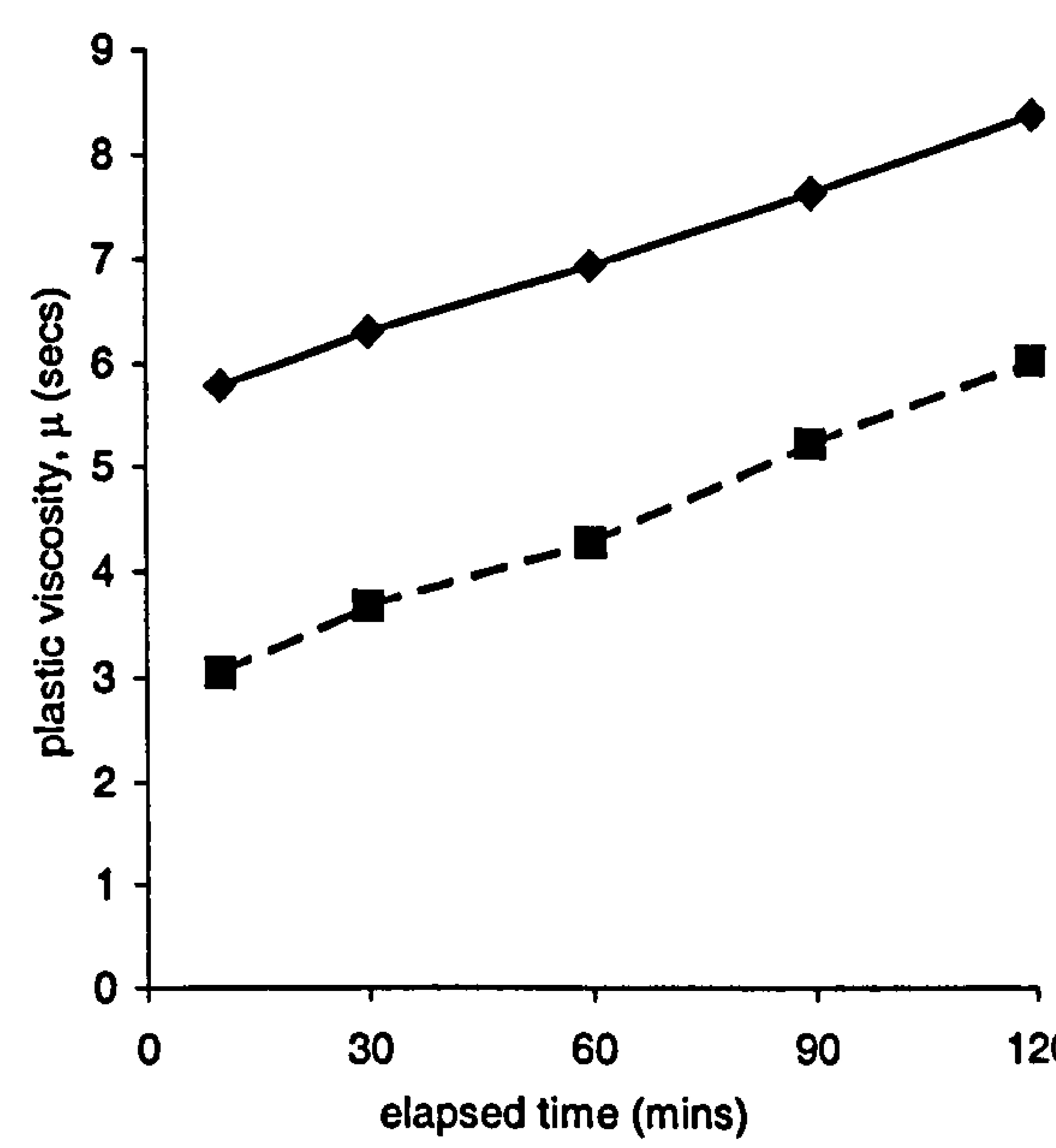


(c)



(d)

Figure 7-3 Workability retention of SRC binary mixes (a) spread (b) yield stress (c) V-funnel time (d) viscosity

7.1.2 Effect of the particle size of limestone powder

The effect of particle size on the workability of SCC has been reported in a few papers, as reviewed in chapter 2 [56, 59]. However, little study has been carried out on the workability retention. In this section, the effect of particle size on the workability during a two-hour period was studied using three different LSPs, i.e. LSP15, LSP50, and LSP100, which have 93-97% particles smaller than 10, 25 and 75 μm respectively. The material properties are given in **table 4-2.**

Table 7-2 Mix proportions and initial properties of LSPs binary powder mixes

Mix	Powder composition				Sp dos.	D_m	T_V	τ_0	μ
no.	PC3	LSP15	LSP50	LSP100	(% by wt)	(mm)	(secs)	(Pa)	(Pa.s)
M7-8	100				0.165	325	4.11	1.9	9.6
M7-9	60	40			0.085	323	3.01	7.7	5.2
M7-10	60		40		0.095	326	2.43	4.3	3.3
M7-11	60			40	0.1	320	1.78	8.6	2.0

Table 7-2 shows the mix proportions and initial properties of the mixes. The water/powder ratio was controlled to 0.945 by volume (equal to 0.3 by weight for 100% PC mix), and the sand/mortar ratio 0.45 by volume. Again, Glenium51 was used, and the dosage was adjusted so that a spread value between 310-320 mm was obtained for each mix. The mix M7-8 and M7-11 were repeats of the mix M7-1 and M7-4 respectively because a different batch of PC was used, and only a slight difference was found between these two series of mixes. The LSP mixes required much lower superplasticizer than the control but slightly increased dosages with the increase of fineness. The yield stress was between 1.9-8.6 Pa for all mixes. The V-funnel flow times and plastic viscosity were much lower than the control and decreased with increasing fineness; a time of less than 2 seconds was obtained in the LSP15 mix, which may cause segregation in the SCC. These differences are probably caused by the different maximum volume concentration of the powders. A higher maximum volume concentration of powder could be obtained in the LSP50 and LSP15 mixes compared to the LSP100 mix because of the combination of different particle sizes, suggesting more free water could be obtained resulting in reduced plastic viscosity.

Figure 7-4 shows the test results for workability retention. All three LSP mixes did not show better workability retention, in terms of spread and yield stress, than the control due to the lower superplasticizer dosage, but did in terms of V-funnel flow time and plastic viscosity due to lower initial values. The LSP15 mix was the best among the binary mixes, providing similar spread loss to the control, and this was followed by the LSP50 mix then the LSP100 mix. This suggests a significant effect of combinations of different particle sizes on both yield stress and plastic viscosity. The higher the maximum volume concentration of powder, the more free water and the bigger the distance between particles, and consequently better workability retention. This is also supported by Uchikawa *et al* [62] conclusion that a concrete mixed with powder containing a combination of different particle size of powder, such as 30-40% of coarse particles, 40-50% of medium particles and 10-20% of fine particles, may achieve good flowability.

It is noticed that the V-funnel flow time of the LSP15 mix increased to higher than 2 seconds after 30 minutes after the start of mixing suggesting that segregation could be avoided after this time. It was also found that the workability retention of the LSP100 mix M7-11 was inferior to that of the same mix in **figure 7-1** although the 100% PC3 mix M7-8 was similar to 100% PC2 mix M7-1. No specific reason was found except that these two series mixes with different batches of cement were tested in different seasons: one in winter with a room temperature of 18-20 ^{0}C, the other in summer with a room temperature of 21-22 ^{0}C. This highlights the importance of establishing the same experimental conditions when comparing the properties of different mixes.

It can be concluded that the workability retention of binary mixes may be improved by using different fineness blends such as the PC/LSP15 mix.

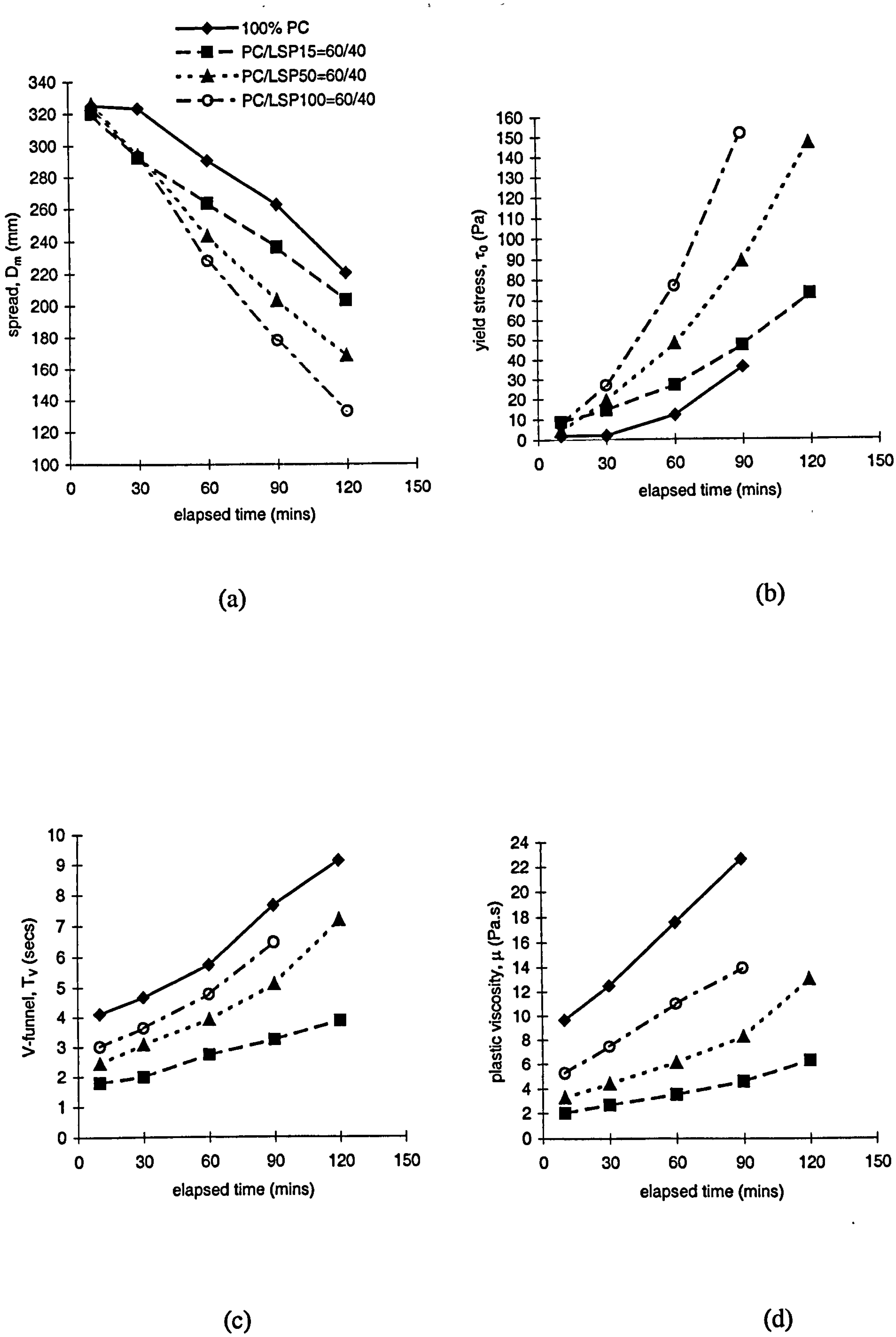


Figure 7-4 Effect of particle size on workability retention (a) spread (b) yield stress (c) V-funnel flow time (d) plastic viscosity

7.1.3 Effect of amount of CSF and limestone powder

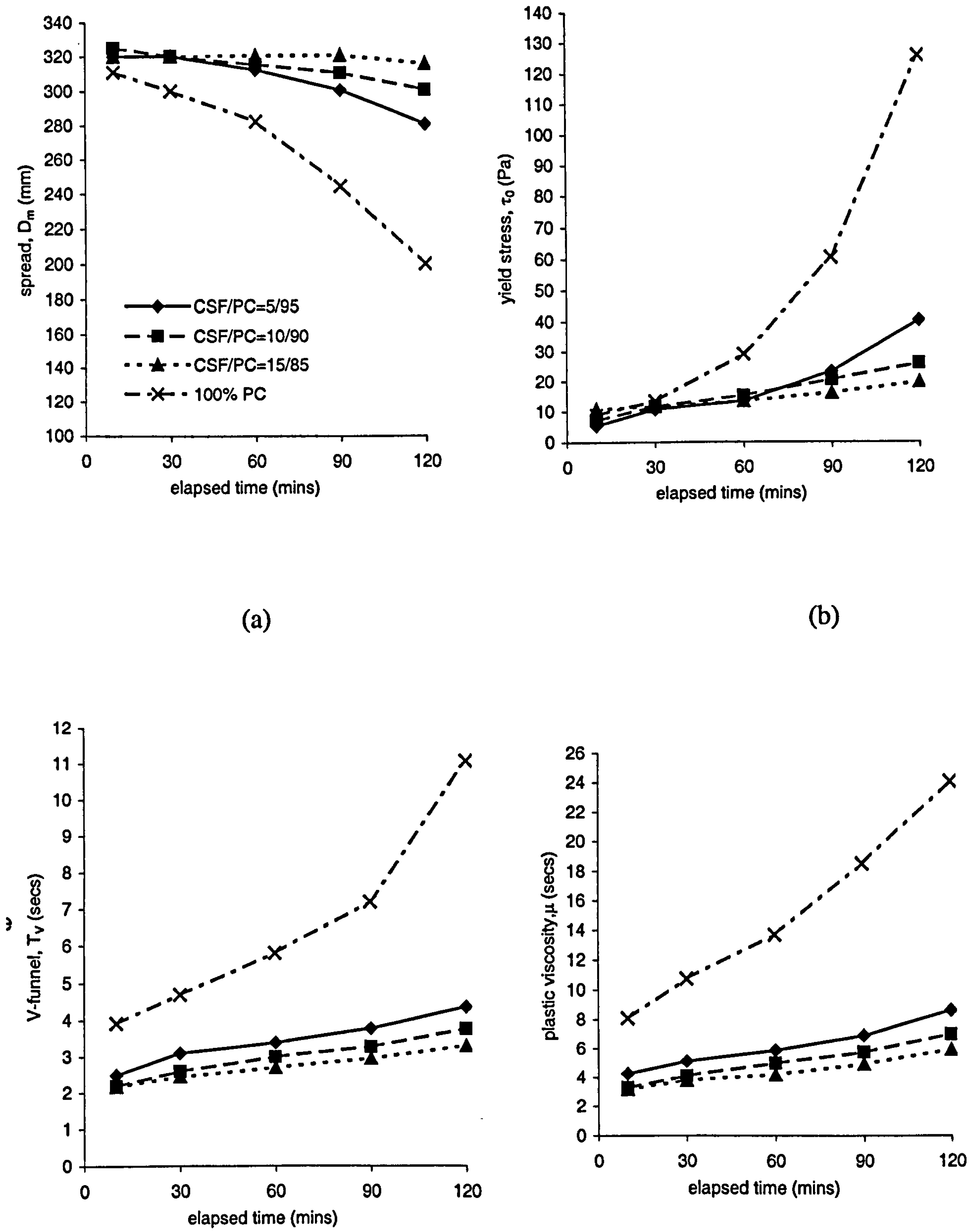
The effect of CRMs at a single level in the powder blends on the workability retention has been studied in section 7.1.1, e.g. CSF increased workability retention but LSP100 decreased. It can also be predicted that the higher the replacement, the more significant the effect should be. However, to confirm and quantify this, two groups of mixes were studied, one with CSF mix and the other with LSP100.

The CSF binary mix was studied because of the excellent fresh properties of the 5% replacement mix M7-5 already reported. **Table 7-3** shows the mix proportions and initial properties. The water/powder ratio was controlled to 0.945 by volume (equal to 0.3 by weight for a 100% PC mix) and the sand/mortar ratio to 0.45 by volume. Again the superplasticizer dosage was adjusted so that a spread value between 310-320 mm was obtained for each mix. This significantly increased with the CSF content. The yield stress was similar for all mixes, while the V-funnel flow time and plastic viscosity were much lower than the control but only decreased slightly with increased CSF content.

Table 7-3 Mix proportions and initial properties of CSF binary powder mixes

Mix no.	Powder composition		Sp dosage (% by wt powder)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
	PC2	CSF					
M7-1	100		0.15	310	3.9	9.0	8.1
M7-5	95	5	0.20	320	2.49	5.4	4.3
M7-12	90	10	0.25	325	2.19	7.2	3.3
M7-13	85	15	0.35	320	2.17	10.8	3.2

The workability retention results are shown in **figure 7-5**. There was a substantial improvement with the addition of CSF, and this continuously improved with increasing the content, on average the spread increased by 15-20 mm at 120 minutes after the start of mixing for every 5% further replacement of PC with CSF by volume. Amongst all the mixes, mix M7-13, with highest CSF content, showed the best workability retention with the least changes in properties over the two-hour period.



(a) (b)

(c) (d)

Figure 7-5 Workability retention of CSF binary mixes in terms of (a) spread (b) yield stress (c) V-funnel flow time (d) plastic viscosity

Table 7-4 shows the mix proportions and initial properties of the LSP100 mixes. Again the water/powder ratio was 0.945 and sand/mortar ratio was 0.45 for each mix by volume, and the superplasticizer dosage was adjusted to achieve a spread value 310-320 mm through out; the dosage reduced significantly with first 20% LSP100 replacement but not much further thereafter. The yield stress was in a range of 1.9-11.5 Pa while the V-funnel flow time and plastic viscosity decreased with the increase of LSP content.

Table 7-4 Mix proportions and initial properties of LSP100 binary powder mixes

Mix no.	Powder composition		Glenium51	D_m	Tv	τ_0	μ
	PC3	LSP100	dosage (% by wt)	(mm)	(secs)	(Pa)	(Pa.s)
M7-10	100		0.165	325	4.11	1.9	9.6
M7-13	80	20	0.115	320	3.88	5.8	8.3
M7-14	60	40	0.085	323	3.01	7.7	5.2
M7-15	40	60	0.072	318	2.65	11.5	3.5

Figure 7-6 shows the workability retention results. As expected from section 7.2.1, addition of LSP100 increased the workability loss, in terms of spread and yield stress, however, the significance of the loss was not proportional to the content of LSP100. The spread at 120 minutes after the start of mixing decreased from 160 to 130 mm when the amount of LSP100 replacement increased from 20% to 40%, which is a to 7.5 mm reduction in spread for every 5% LSP100 replacement. There was hardly any further loss when LSP100 content increased to 60% of powder by volume. The workability retention, in terms of V-funnel and plastic viscosity still followed the previous general of a lower initial plastic viscosity mix had better workability retention.

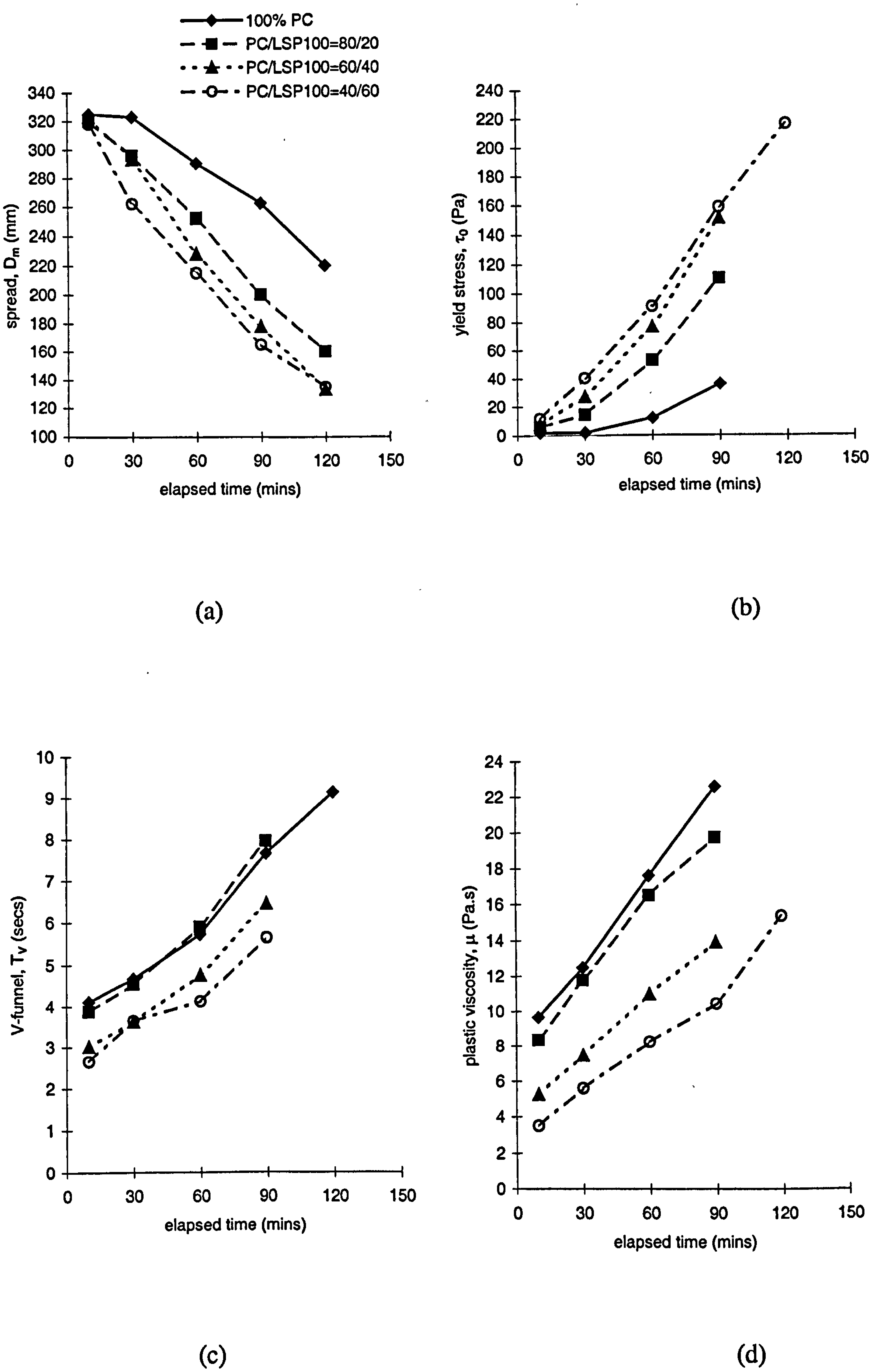


Figure 7-6 Effect of content of LSP100 blend on workability retention in terms of (a) spread (b) yield stress (c) V-funnel flow time (d) plastic viscosity

In summary, the effect of increasing CSF content on workability and workability retention of a binary mix is significant with a substantial increase of required superplasticizer dosage. In LSP100 mixes, no further effect of LSP100 content was seen above a level of 40% of powder by volume, which was consistent with the amount of superplasticizer required.

7.1.4 Discussion

It has been found that superplasticizer dosage has significant effect on spread and yield stress development while the initial value of V-funnel flow time and plastic viscosity on their own development. In order to understand this, further analysis was carried out to quantify these effects for all PC single and binary powder mortars presented in chapter 6 and chapter 7. **Figures 7-7** & **7-8** show the change of yield stress and plastic viscosity from 10 to 90 minutes after the start of mixing plotted against the superplasticizer dosage and the initial plastic viscosity respectively. As described earlier all these mixes had similar initial spread (310-320 mm) and yield stress (0-10 Pa) but different initial V-funnel flow time and plastic viscosity.

The significant effect of superplasticizer on the change of yield stress is clearly reflected in **figure 7-7**. For the mixes with similar water/powder ratio by volume the change is lower with an increase of superplasticizer; additionally, in the mixes with a similar dosage of superplasticizer the effect of other factors, e.g. sand content and types of blends *etc*, tends to be significant. For example, both binary mixes M7-3 (PC/GGBS = 60/40) and M7-9 (PC/LSP15 = 60/40) required 0.1% superplasticizer by weight of powder but M7-9 has a much lower change of yield stress. This is possibly due to higher maximum volume concentration of the powder in this mix (see also section 7.3), which increases the distance between powder particles, and hence reduces the degree of coagulation. Another example is that the development of yield stress for mix M6-11 (100% PC, $V_s/V_m = 0.40$) was significantly slower than that for the mix M7-14 (PC/LSP = 80/20, $V_s/V_m = 0.45$) because of the lower sand content, as discussed in chapter 6, although both contained 0.115% of superplasticizer. The significant effect of water/powder ratio is also clearly seen in the figure, the trend line for mixes with water/powder ratio of 1.42 (w/c = 0.45) is completely separated from the line for those mixes with water/powder ratio of approximately 0.945 (w/c = 0.3).

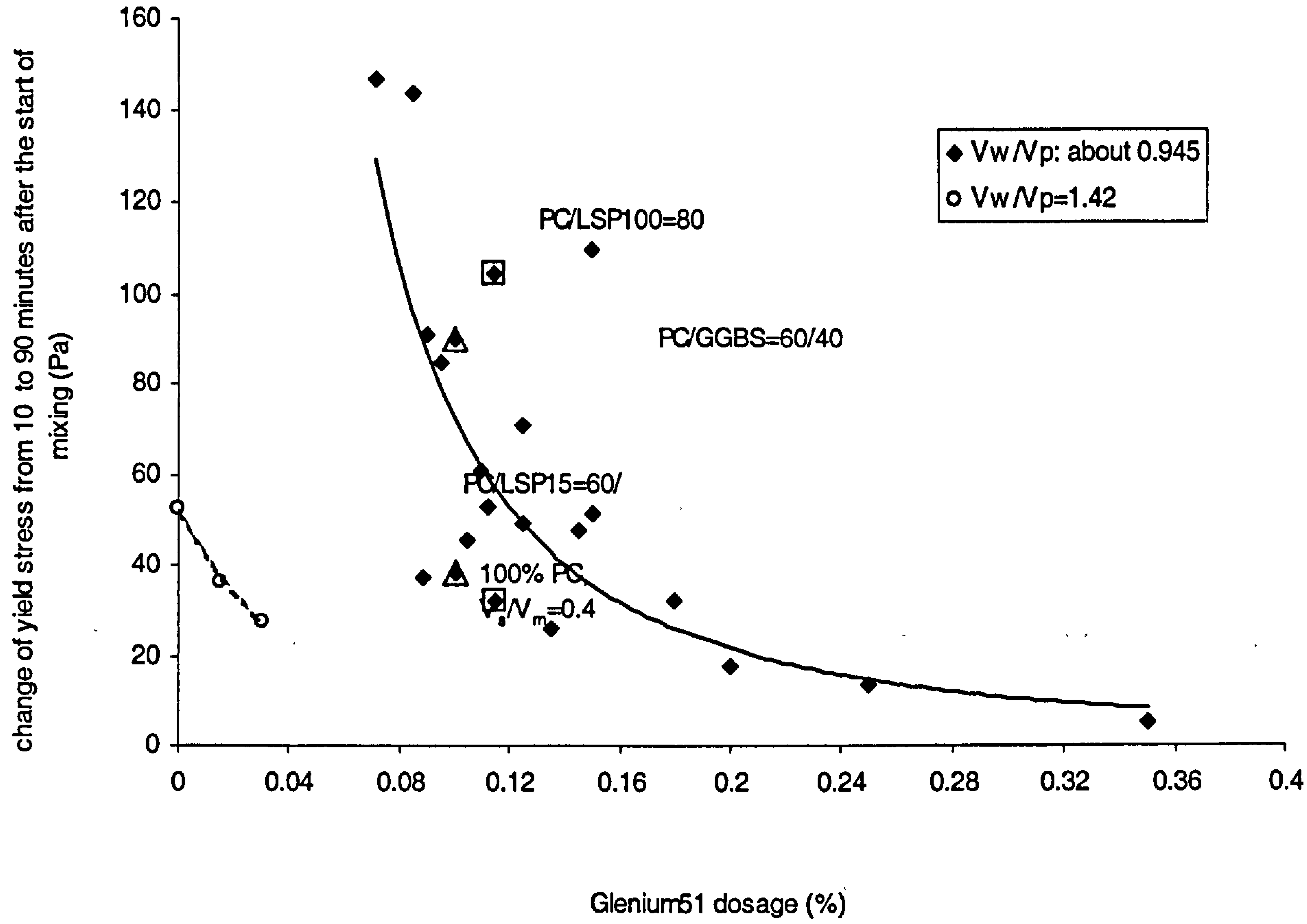


Figure 7-7 The change of yield stress from 10-90 minutes after the start of mixing vs. superpasticizer dosage

Figure 7-8 shows that workability loss in terms of V-funnel flow time and plastic viscosity appears to be strongly related to those factors which control their initial properties (see also **figure 7-2**). A higher initial value resulted in greater development for all the mixes (group 1). For those mixes with similar initial values but different composition the effect of workability retention in terms of yield stress is apparent. For example, the mix M7-14 (PC/CSF=95/5) had much lower plastic viscosity change than the mix M7-14 (PC/LSP100=60/40) because of better workability retention in terms of spread and yield stress.

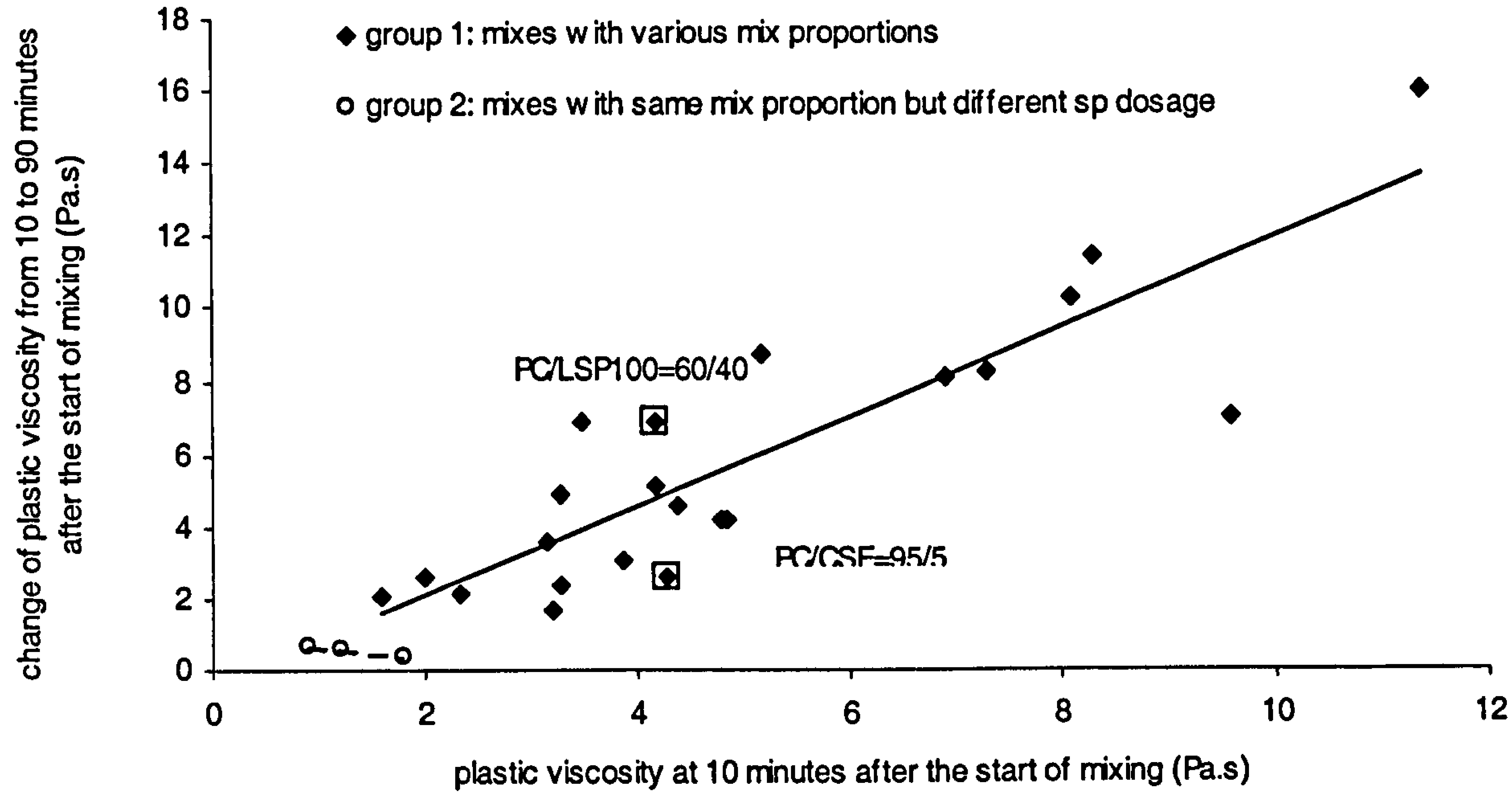


Figure 7-8 The change of plastic viscosity from 10-90 minutes after the start of mixing vs. their initial values

However, the effect of initial plastic viscosity was not shown in group 2 mixes. The initial plastic viscosity for group 1 mixes is caused by the different proportions of the particle components, and hence a different packing of the particles and distance between them; while it was caused by different dosage of superplasticizer for the mixes in group 2, which does not change the distance between the particles. This suggests that the distance between particles is the fundamental factor controlling the development of plastic viscosity. The higher distance between the particles the lower initial value, the less friction between them, and the slower the development of the plastic viscosity. The rheology equations can also confirm this by showing a close relationship between plastic viscosity and the particle concentration [110-114]. Therefore the different initial values caused by addition of different dosage superplasticizer has no significant effect on the development of plastic viscosity.

When a mortar is sheared at increasing rate, a minimum shear stress, i.e. yield stress, is needed to 'break' the reversible coagulated particles to make the mortar move; the shear stress then increases with increasing shear rate, and the rate of increase is thought to be related to friction between the particles. Therefore it is thought that coagulation and friction between particles, which increase with hydration time during the dormant period of cement hydration, are key factors controlling yield stress and plastic viscosity development respectively.

Bonen *et al* [93] suggested that, with a sulfonated naphthalene formadehyde superplasticizer, high strength pore solution in paste will induce a greater polarization of the double surface layer formed around the particles and this in turn, would probably generate more electrostatic bonds, which reduce fluidity. This means that coagulation of particles is greatly affected by the ionic strength in the pore solution, which is mainly governed by the presence of alkali sulfate or soluble calcium sulfate and alkali in a superplasticized mix. Jiang *et al* reported that there seems to be an optimum soluble alkali content in cements in terms of slump and slump loss of cement paste [137]. All these suggest that workability retention in terms of yield stress and spread may be significantly affected by soluble ion concentration in the solution, which is controlled by water content and ions from the powder and admixtures.

Bonen *et al* [93] have also found that silica fume addition increases the amount of superplasticizer adsorbed and decreases the ionic strength, and therefore reduces mini slump loss for cement paste. Similar results were found in **figure 7-1** for the microsilica mixes with the polycarboxylic admixture; however, it is not clear whether they have the same mechanism of workability loss, and further investigation for mixes with this type of superplasticizer would be useful.

The addition of CRMs such as PFA, GGBS and LSP reduces the cement content and therefore the C_3A content, but does not necessarily reduce the ionic strength or result in optimum soluble alkalies content. Moreover, the low requirement for superplasticizer dosage in these binary mixes reduced the contribution of glenimum51 to the workability retention.

The combination of different particle size powders will increase the maximum volume concentration of powder by packing and consequently increase the amount of free water and distance between particles. Moreover, particles with rounder surfaces such as PFA may reduce the surfaces area and friction between particles; and hence these will reduce the degree of coagulation. Decreasing sand content increases the distance between sand particles, and therefore reduces the friction between them. All these seemed to slow down the development of yield stress but the effect is much less significant than that of water content and superplasticizer.

On the other hand, plastic viscosity is thought to increase with the growth of cement particles due to increased hydrated surface layer, even at the low hydration rate during the dormant period. This increases the size of cement particles, and hence reduces the distance between them. Further study on this will be useful.

In summary, yield stress and plastic viscosity are two independent properties which develop with different mechanisms during the cement paste dormant period. They are affected by many factors among which the water/powder ratio and superplasticzer dosage are important to the development of yield stress, and the distance between particles to the development of plastic viscosity.

7.2 Tests on concrete

Concrete properties were examined for a few selected binary mixes. **Table 7-5** shows the mix proportions and initial properties. PC4 and SRC2 were used as the base cements, with 40% cement replacement for GGBS and LSP100, and 15% cement replacement by volume for CSF. Water/powder ratio by volume was 0.945 (equal to 0.3 by weight for a 100% PC mix), the ratio of sand to mortar was 0.45 by volume, and coarse aggregate volume was 0.317 m^3 per cubic metre, which is 50% of the dry rodded bulk density by weight.

As with the tests on concrete, reported in the previous chapter, in series 1 the dosage of superplasticizer was determined by repeating the respective mortar tests so as to obtain a spread of 310-320 mm in each mix in order to control the initial slump flow of the related concrete. The dosages required were slightly lower than those of the same mixes shown in **table 7-1**; the yield stress was again in a narrow range of 1-12.4 Pa. The V-funnel flow times were slightly higher than those for the same mixes in **table 7-1**, however, the plastic viscosities were similar. Generally although different batches of cement were used it was found that the properties of these two series of mortar mixes are similar. In series 2 the same dosages of superplasticizer as those for the same mixes in **table 7-1** were used because the materials were unchanged.

Table 7-5 Mix proportions and initial properties of binary mixes for concrete and mortar *

				Mortar test					Concrete test						
Series	Mix No.	Powder compos.	Sp** (%)	Dm (mm)	T_{250} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	SF (mm)	T_{500} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	U_H (mm)	Tu-box (s)
1	C5-1	PC	0.13	320	3.4	4.4	1	5.7	735	3.22	7.53	***	78	340	2.88
	C7-1	PC/GGBS	0.87	312	3.2	4.85	0.22	10.2	583	4.19	9.13	9	76	291	5.22
	C7-2	PC/LSP100	0.75	320	2.7	2.97	12.4	4.1	675	2.75	5.12	***	41	303	2.69
	C7-3	PC/CSF	0.3	328	2.3	2	10.5	2.6	740	2.65	4.78	68	8.3	333	1.91
2	C6-7	SRC2	0.13	285	2.3	2.87	6.9	3.4	618	****	7.37	****	****	340	****
	C7-4	SRC/GGBS	0.098	330	2.4	3.53	0	3.7	770	2.28	7.78	***	43	340	2.25

*100% PC4 was used as powder **by the weight of powder *** not measurable ****was not measured

It was expected that the initial slump flow of all these concrete mixes would be similar. However, those of the GGBS mix and the LSP100 mix were much lower than those of the 100% PC mix or the SRC mix; this might be because of the fast workability loss at the time of testing (15 minutes after the start of mixing). The GGBS mix had the highest T_V, T_{500}, $T_{u\text{-}box}$ and μ among them all, immediately followed by the 100% PC mix, and then the LSP100 mix and the CSF mix, suggesting that these test methods measure similar properties.

Figures 7-9, 7-10, 7-11 & 7-12 show the workability loss results of concrete and mortar mixes of series 1. The T_{500} and $T_{u\text{-}box}$ was not measured for workability loss because of fast workability loss for some mixes.

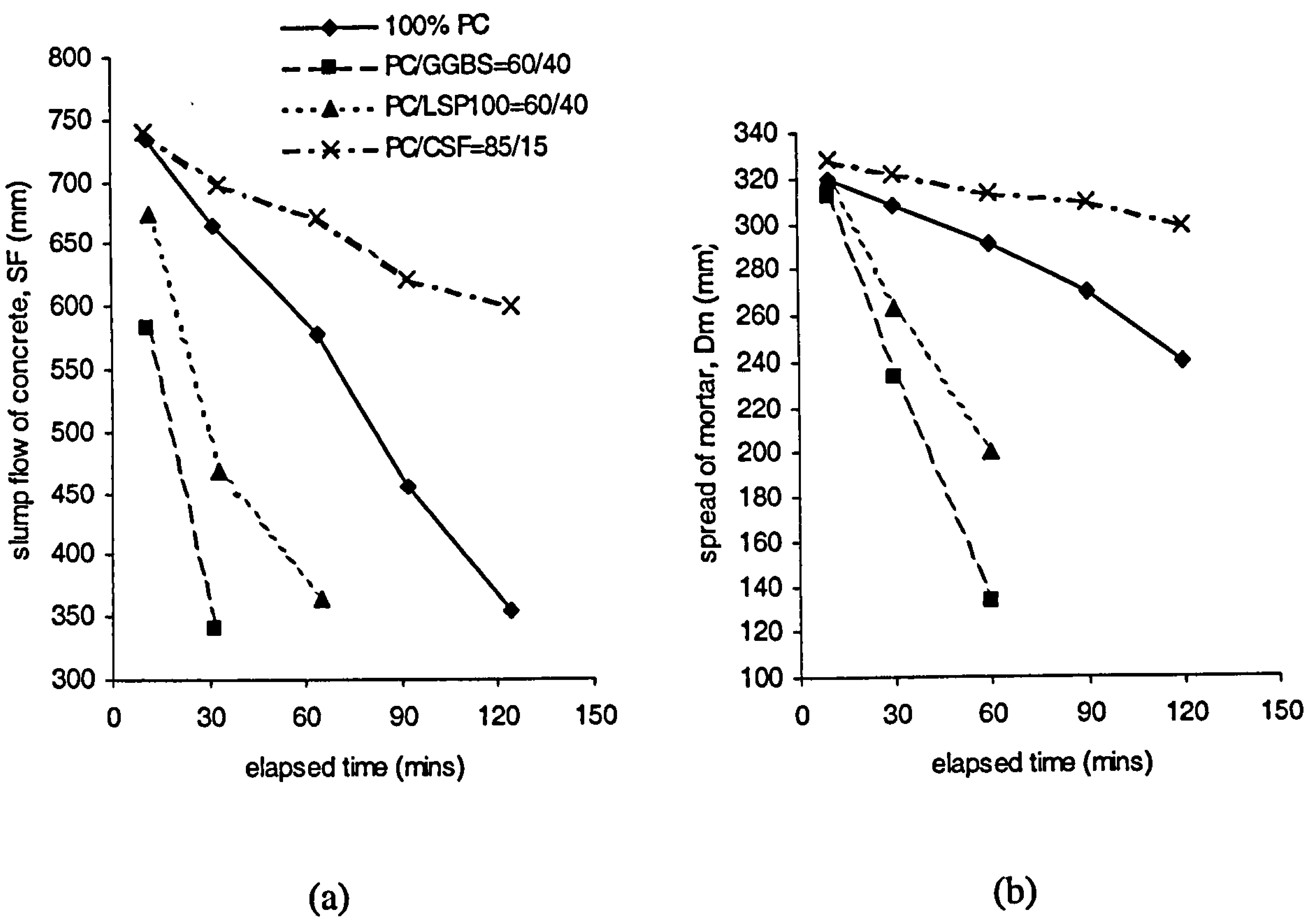


Figure 7-9 Slump flow and spread loss of binary mixes for concrete and mortar

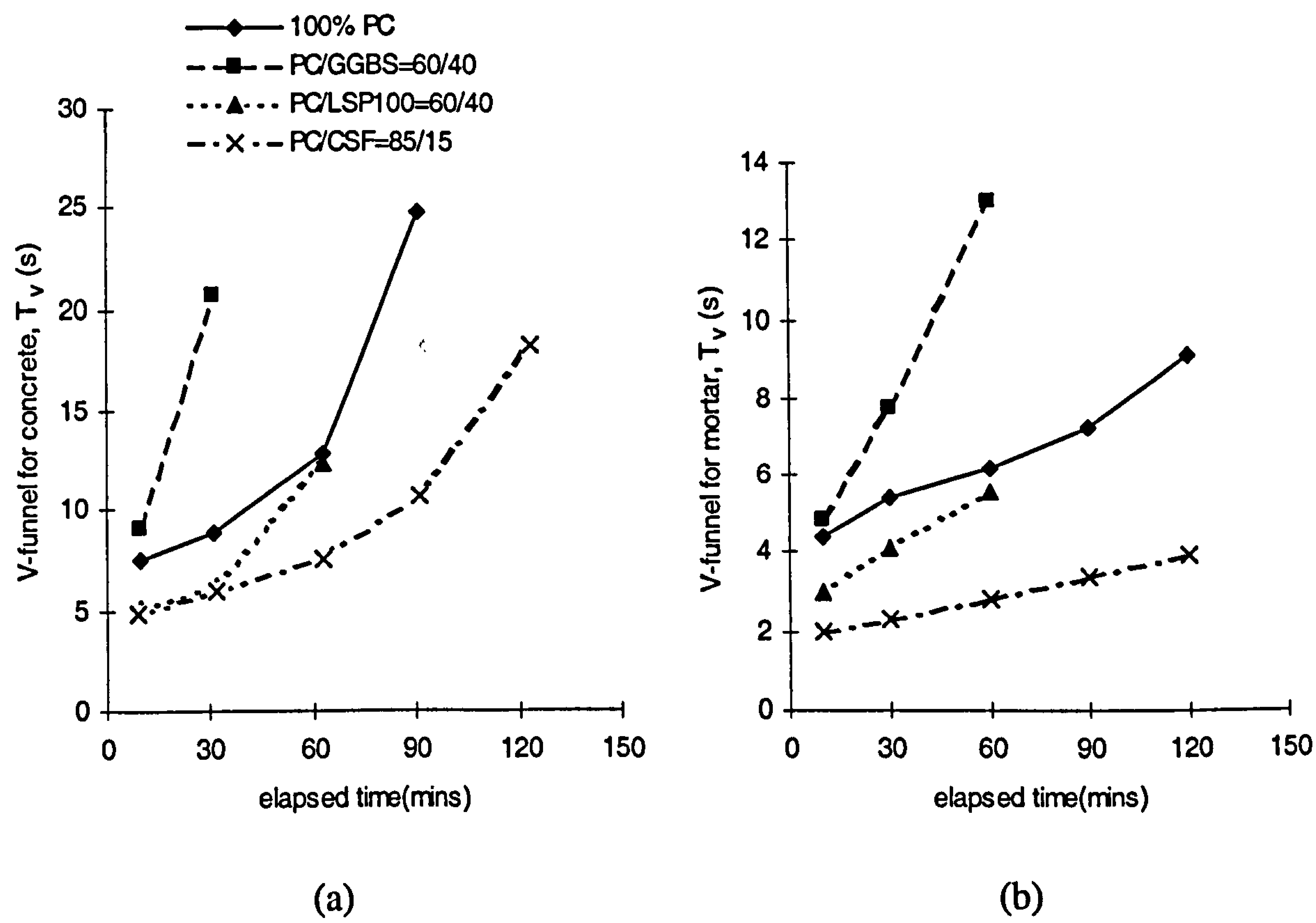


Figure 7-10 Development of V-funnel flow time of binary mixes for concrete and mortar

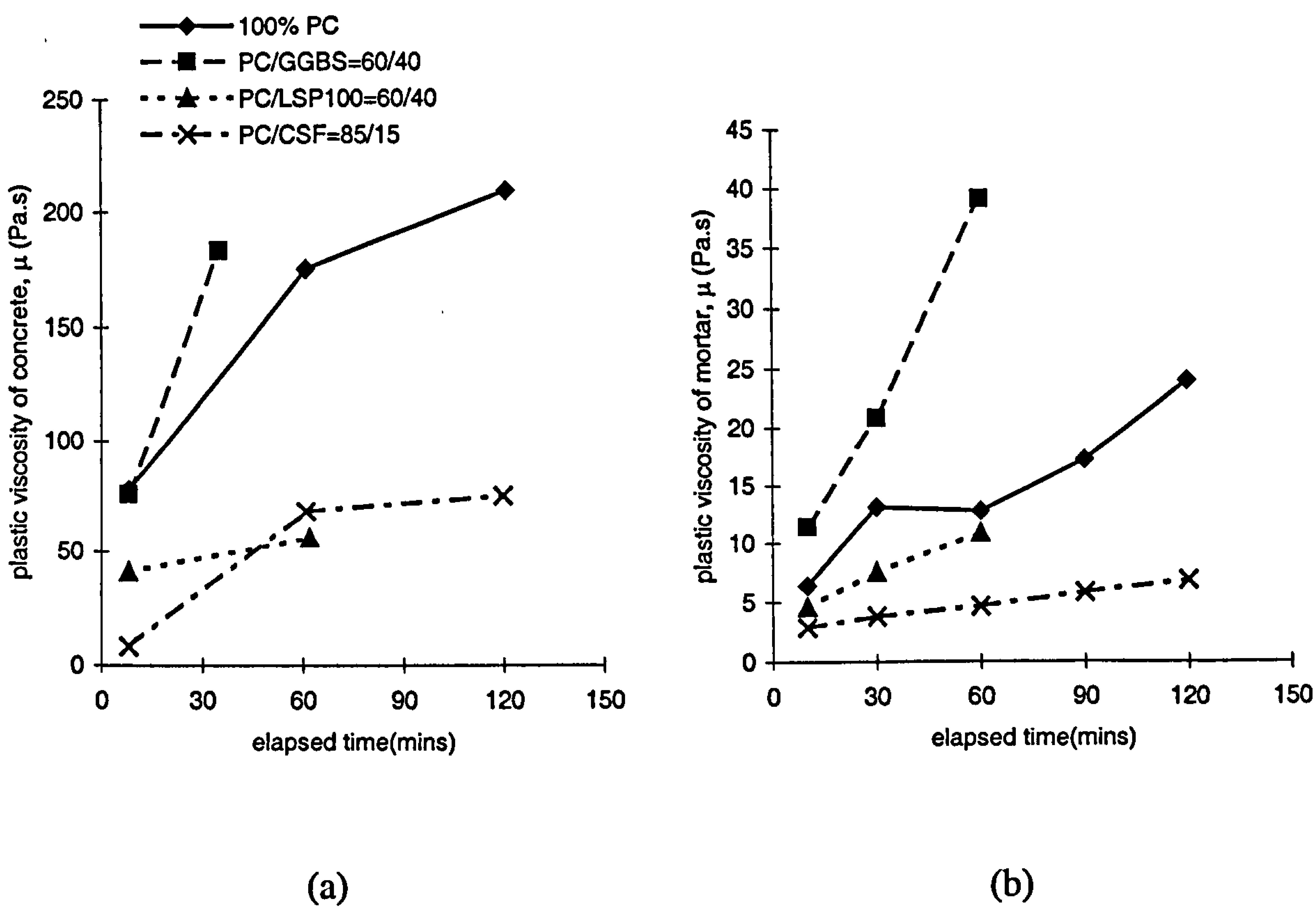


Figure 7-11 The development of plastic viscosity of binary mixes for concrete and mortar

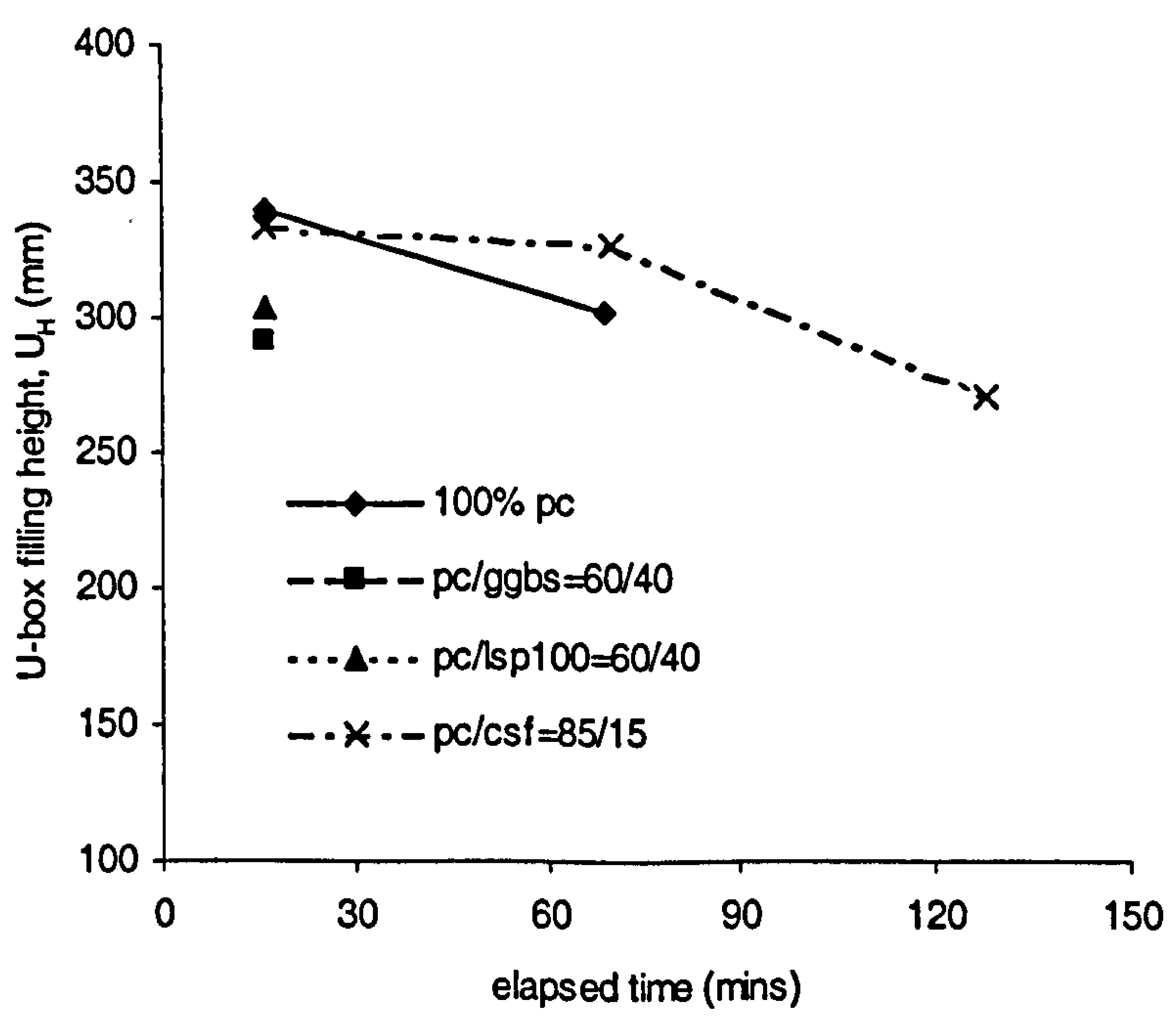


Figure 7-12 The change of U-box filling height with time for binary concrete mixes

As expected from the mortar properties, the rate of slump flow loss was different for each mix. The CSF mix showed the best performance, in terms of all the properties. The LSP100 mix had better performance in terms of V-funnel flow time and plastic viscosity than the 100% PC mix, but not as good as in terms of slump flow. The workability of the GGBS mix developed too fast to be measured just 30minutes after mixing. Overall the CSF mix maintained good passing ability (a U-box filling height higher than 300 mm) with this only dropping 5 mm below the requirement at 120 minutes after mixing, while the 100 PC mix and the LSP100 mix only lasted 60 and 30 minutes respectively. The GGBS mix could not achieve good passing ability even 20 minutes after the start of mixing.

A similar effect of GGBS was obtained in the SRC concrete mix, as shown in **figures 7-13 & 7-14** (the related mortar test results are shown in **figure 7-3**). The GGBS mix was inferior to the control mix although both mixes had U-box filling heights higher than 300 mm 90 minutes after mixing. It should be noted that the performance of the GGBS mix in series 2 was much better than in series 1 suggesting a significant advantage of SRC binary mixes.

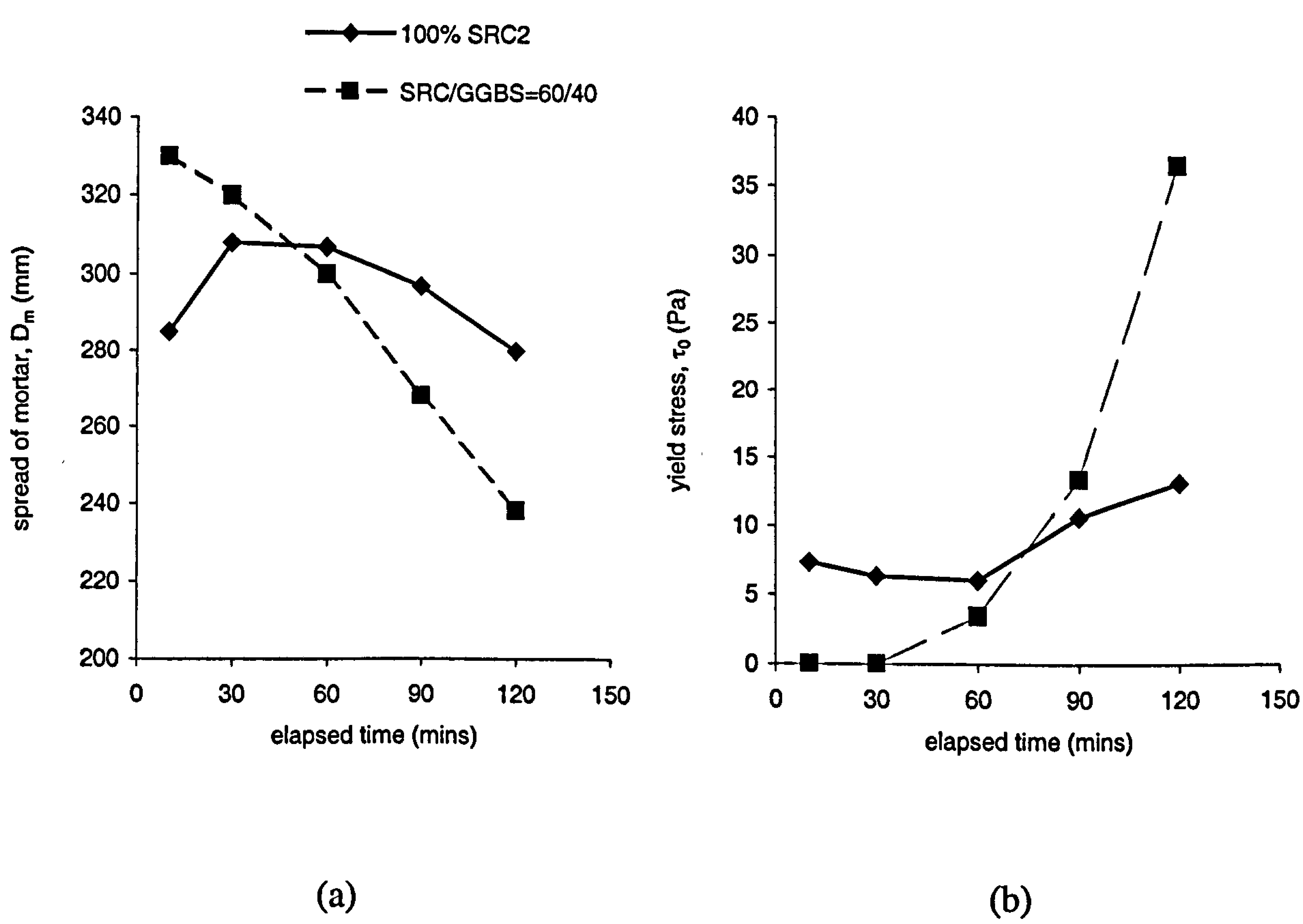


Figure 7-13 Workability retention of SRC binary concrete in terms of (a) slump flow (b) V-funnel flow time

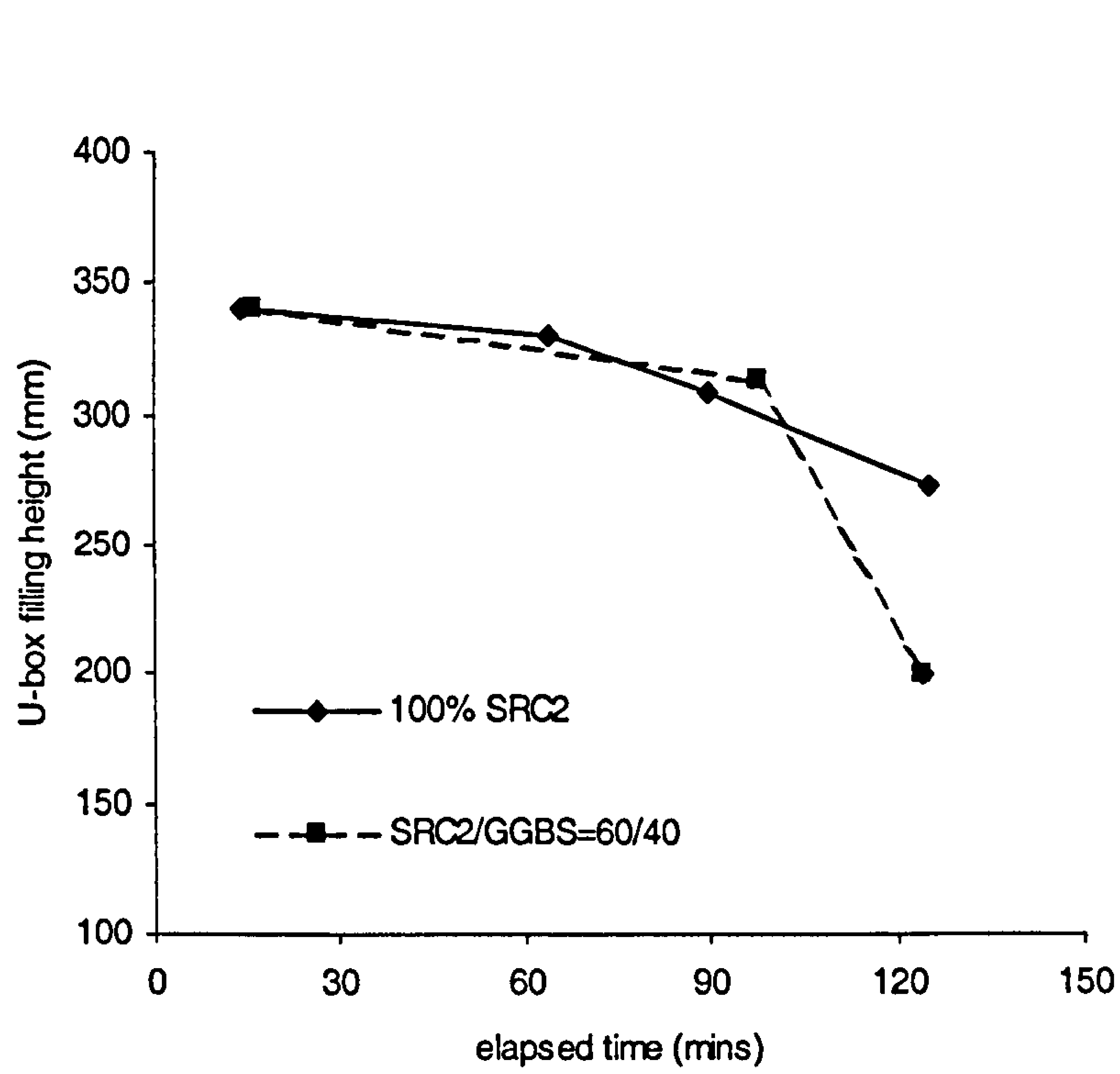


Figure 7-14 U-box filling height for SRC binary mixes

7.3 Conclusions

Fresh properties of binary mixes were studied. The factors studied included types of blends, particle size and content of blends, and the initial properties of a mix. It was concluded that:

- The type of blend has the most significant affect on the workability retention because of its effect on the dosage of superplasticizer required. The CSF binary mix can have little workability change for up to 2 hours, with double the amount of the superplasticizer than the control (100% PC mix), while the spread of the GGBS binary mix dropped to 125 mm with a requirement of 2/3 of the superplasticizer of the control.

- Particle size also has an effect on the workability retention due to the effect on maximum volume concentrations of powder and different packing. While LSP15 improved the workability retention, LSP100 reduced it compared to the control mix.

- The effect of the amount of CRM is dependent on the types of blends used. It was more significant for CSF blends showing a 15-20 mm increase for every 5% further replacement of PC, but 7.5 mm reduction for LSP100 blends at 120 minutes after the start of mixing.

- It is again shown that the yield stress and plastic viscosity are two independent properties which are affected by many factors. In particular the superplasticizer dosage, water content and the maximum volume concentration of solid phase are most important to the development of yield stress and plastic viscosity respectively.

Chapter 8

Fresh properties of mixes with ternary blends of powder

It was concluded in chapter 7 that, in mixes with binary blends of powder, the CSF mixes have shown excellent workability retention with a requirement for high dosages of superplasticizer. This indicates potential advantages in ternary blends in which one component is CSF, but little study has been carried out on the fresh properties of such mixes. This chapter reports the results of tests on the fresh properties of mixes with ternary blends of powder containing CSF, with a mix containing ternary blends of PC/PFA/LSP for comparison.

The variables studied were:

- ternary blends of PC/PFA/CSF, PC/GGBS/CSF, PC/LSP15/CSF and PC/PFA/LSP15,
- the effect of increasing CSF content in ternary blends of PC/GGBS/CSF.

As with tests reported in previous chapters, the fresh properties were measured for two hours after the start of mixing on mortars and selected concrete mixes. The tests were, as before,

- spread (D_m) and time to 250 mm spread (T_{250}), V-funnel flow time (T_v), yield stress (τ_0) and plastic viscosity (μ) for mortar;
- slump flow (SF) and time flowing to 500 mm in diameter (T_{500}), V-funnel flow time (T_V), yield stress (τ_0), plastic viscosity (μ), U-box filling height and the time flow to 250 mm height ($T_{U\text{-}box}$) for concrete.

Concrete cubes were also cast for compressive strength test after workability test; the results will be reported in chapter 10.

8.1 Mortar tests

8.1.1 Types of CSF ternary mixes

The mix proportions and the properties immediately after mixing for the full set of mixes and the control mixes are given in **table 8-1**. The control PC/CSF and the 100% PC mixes are similar to those tested previously, but made with PC3. The sand content and water/powder ratio were maintained at 0.45 of mortar and 0.945 (equal to 0.3 by weight for a 100% PC mix) by volume respectively. As with the binary mixes, glenium51 was used and the dosage was that to achieve a spread of 310-320 mm. All the CSF ternary mixes required a higher amount of superplasticizer than the other mixes without CSF, but much lower than that of the binary CSF mix, M8-6. Again, the yield stress was in a small range of 1.4-4.1 Pa. All the mixes had much lower V-funnel flow time and plastic viscosity than the 100% PC mix, the PC/GGBS/CSF and the PC/CSF mixes had the highest and the PC/LSP15/CSF mix the lowest values. It is known that a mortar with V-funnel flow time lower than 2 seconds will cause segregation for SCC [29] which was the case in three of the four mixes, the exception being PC/GGBS/CSF mix. In practice, this problem can be avoided by reducing the water content or adding a viscosity agent (see next chapter), or by allowing a short time for the V-funnel flow time and plastic viscosity to increase before the concrete is cast.

Table 8-1 Mix proportions and initial properties of CSF ternary mixes and reference mixes

Mix no	Powder composition					sp dosage (% by wt powder)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
	PC3	PFA	LSP15	GGBS	CSF					
M8-1	100					0.16	315	4.1	4.0	8.5
M8-2	50	25	25			0.09	313	1.8	10.8	2.2
M8-3	50	40			10	0.20	315	1.8	14.4	2.4
M8-4	50		40		10	0.18	320	1.4	10.8	1.4
M8-5	50			40	10	0.18	311	2.5	12.6	3.6
M8-6	90				10	0.25	325	2.6	17.9	3.8

The changes in properties with time after mixing are shown in **figure 8-1**. It can be seen that all the CSF ternary mixes had better workability retention than the 100% PC mix. The most significant improvement was obtained in the PC/LSP15/CSF mix, which showed the same retention as the CSF binary mix, but with much lower superplasticizer dosage. This was closely followed by the PC/PFA/CSF mix and the PC/GGBS/CSF mix. In contrast, the PC/PFA/LSP15 ternary mix was inferior to the control mix, the spread at 120 minutes after the start of mixing was 100 mm less than that for PC/LSP15/CSF mix while the yield stress was 3 times higher.

It was also noticed that the V-funnel flow times of all the CSF ternary mixes were greater than 2 seconds after 30-60 minutes from the start of mixing, suggesting that no segregation would occur if they were used after this time, which is reasonable for most construction practice.

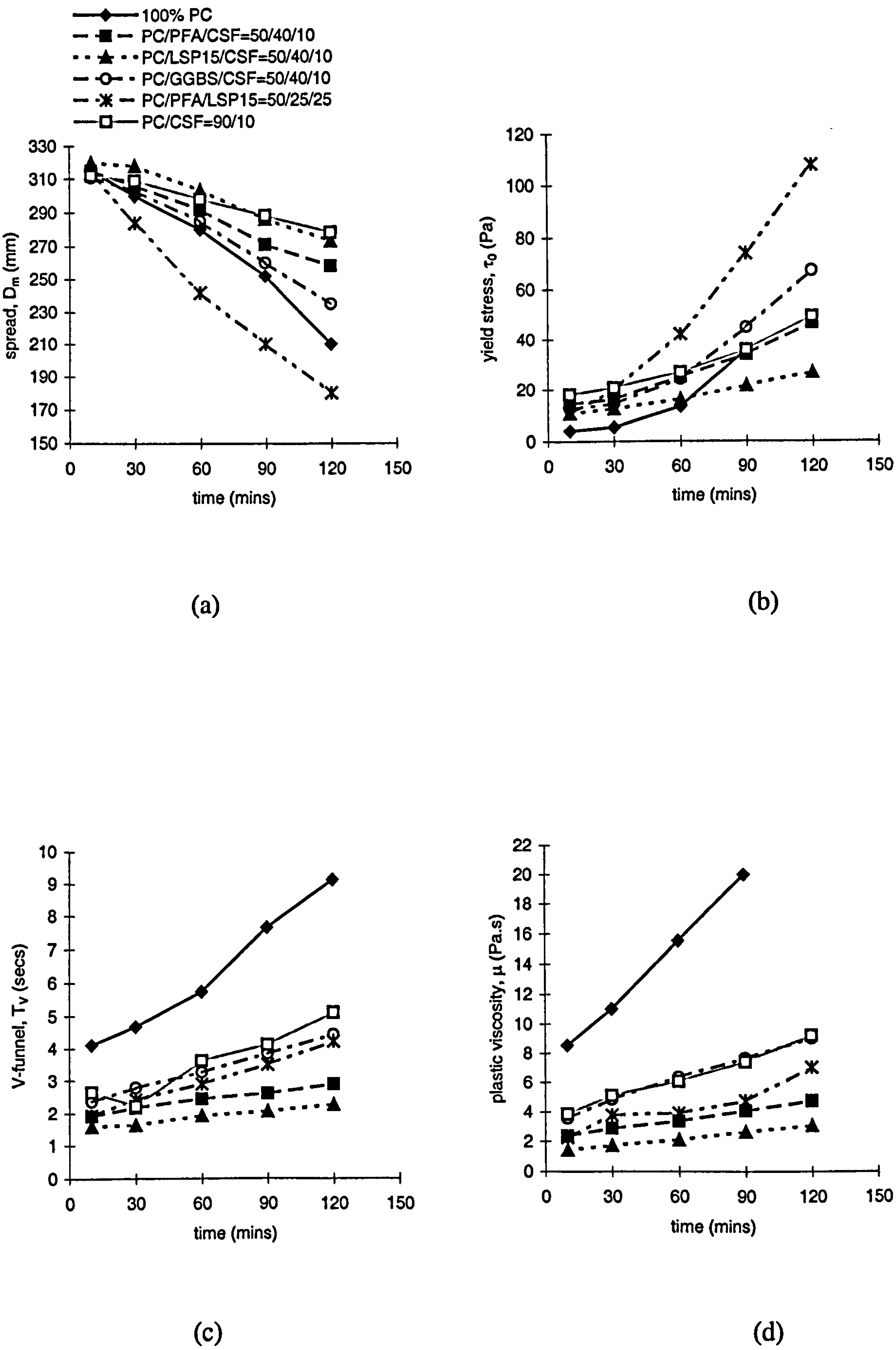
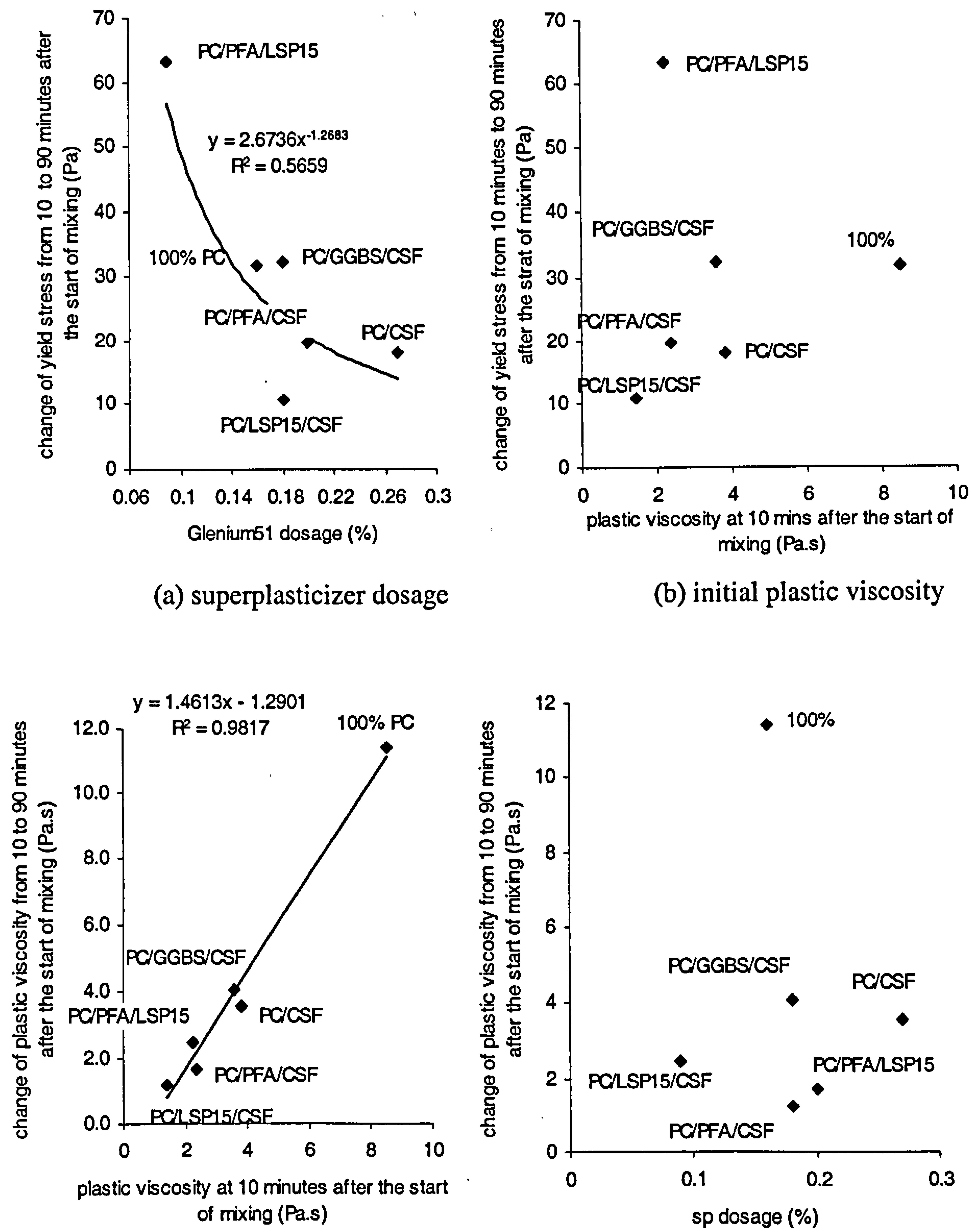


Figure 8-1 Workability retention of ternary mixes (a) spread (b) yield stress (c) V-funnel (d) plastic viscosity

Figure 8-2 plots the change of yield stress and plastic viscosity from 10 to 90 minutes after the start of mixing against their superplasticizer dosages and initial plastic viscosity. Again it was found that the degree of the change decreased with increase of superplasticizer dosage, but the mix with a combination of different particle size, the PC/LSP15/CSF mix, had significantly improved retention compared to the other mixes with similar superplasticizer dosage, which has also the case as reported in section 7.1.2. It was not surprising that the workability retention in terms of plastic viscosity was related to the initial values, and all the CSF ternary mixes obtained higher workability retention than the reference mixes because of their low initial values, reflecting the significant effect of maximum volume concentration of powder on the plastic viscosity development. In addition, the effect of superplasticizer dosage on the change of plastic viscosity, and the effect of the initial plastic viscosity on the change yield stress were not significant.

In general, it can be concluded that a ternary SCC mix in which one of the powders is CSF has potential advantages in terms of good workability retention and efficient use of superplasticizer.



(a) superplasticizer dosage

(b) initial plastic viscosity

(c) initial plastic viscosity

(d) superplasticizer dosage

Figure 8-2 Effect of superplasticizer dosage and initial plastic viscosity on the development of yield stress and plastic viscosity

8.1.2 Effect of CSF content

Further work was carried out to assess the effect of varying CSF content. A GGBS mix was selected, and the mix proportions and initial properties of the two CSF ternary mixes and a GGBS binary control mix are given in **table 8-2.** The CSF contents were 10% and 15%, i.e. a repeat of the previous mix plus a second mix at 15%. Because the PC/GGBS/CSF ternary mix M8-5 did not achieve as good workability retention as the PC/CSF binary mix with same amount (10%) of CSF (**figure 8-1**), a mix with 5% CSF was not tested. The sand/mortar and water/powder ratios were maintained at 0.45 and 0.945 by volume respectively. Glenium51 was used and the dosage was adjusted to achieve a spread of 310-320 mm. As with the CSF binary mixes (M7-12, M7-13) shown in **table 7-4**, the superplasticizer requirement significantly increased with the increase of CSF content, and was much higher than that needed for the GGBS binary mix, but still lower than the requirement for the CSF binary mixes with the same amount of CSF content, i.e. 10 and 15% of powder by volume respectively. The yield stress was in a small range of 0.0-12.6 Pa. All the CSF mixes had much lower V-funnel flow time and plastic viscosity than the GGBS binary mix, and the V-funnel flow time of mix M8-7 (with 15% of CSF content) was lower than 2 seconds suggesting attention is needed to avoid segregation for this type of mix.

Table 8-2 Mix proportions and initial properties of PC/GGBS/CSF ternary mixes and PC/GGBS binary mix

Mix no	Powder composition			sp dosage (% by wt powder)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
	PC3	GGBS	CSF					
M8-5	50	40	10	0.18	311	2.62	12.6	3.6
M8-7	45	40	15	0.25	325	1.84	6.3	2.4
M8-8	60	40		0.1	325	3.82	0	7.3

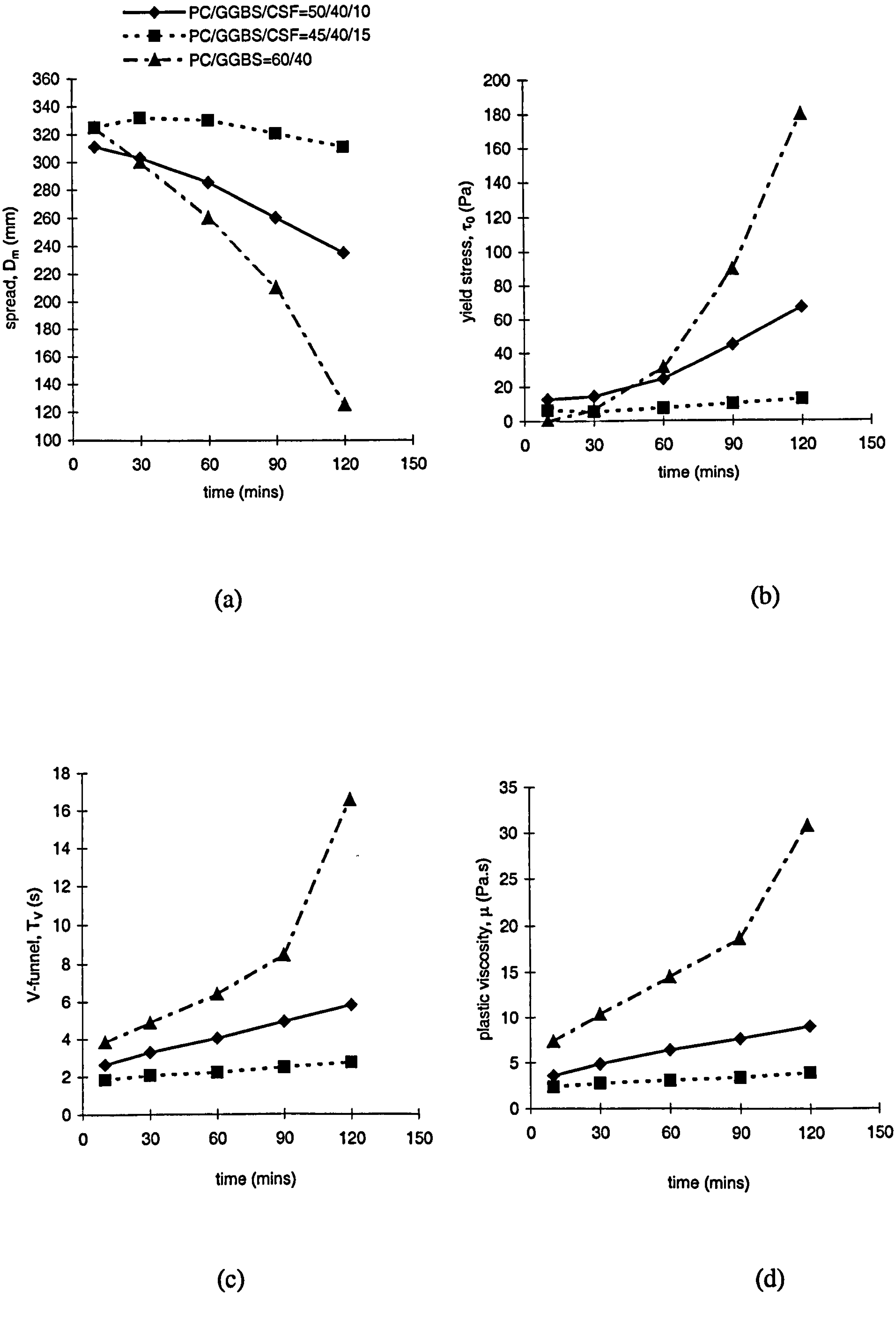


Figure 8-3 Workability retention of ternary mixes with various CSF content (a) spread (b) yield stress (c) V-funnel (d) plastic viscosity

The change in properties with time after mixing are shown in **figure 8-3**. Excellent workability retention was obtained in the mix that contained 15% CSF with hardly any change of spread and yield stress and only a slight increase of V-funnel flow time and plastic viscosity for two hours after mixing. The V-funnel flow time was higher than 2 seconds at 30 minutes after the start of mixing. This suggests that any required workability retention may be obtained for CSF ternary mixes by adjusting the CSF content without the addition of retarding admixtures.

It can be concluded that a CSF ternary mix retains the excellent retention properties of the binary PC/CSF mix but with a reduced superplasticizer dosage.

8.2 Concrete tests

The excellent performance of CSF ternary mixes was confirmed by concrete tests. Two ternary mixes were tested, PC/GGBS/CSF and PC/PFA/LSP15 mix, along with a 100% control mix. **Table 8-3** shows the mix proportions and initial properties of the concrete and mortar. The water/powder ratio was 0.945, which is equal to 0.3 water/cement ratio for 100% PC mix, and sand/mortar ratio 0.45 by volume, and coarse aggregate volume was 0.317 m^3 per cubic meter, which equals 50% of the dry rodded bulk density by weight. The dosage of superplasticizer was determined by repeating the tests on the respective mortar components so that a spread of 310-320 mm was achieved in each mix. This controlled the initial slump flow of the concrete to be in the range of 700-800 mm. When comparing the mortar properties with those of the same two ternary mortars M8-2 in **table 8-1** and M8-7 in **table 8-2**, it was found that similar properties were obtained except that the PC/GGBS/CSF mix in **table 8-3** required a much lower superplasticizer dosage, for no apparent reason. For concrete, both ternary mixes had similar V-funnel flow times, but lower than 4 seconds (the minimum requirement for SCC according to UCL mix design). However, the plastic viscosity of the PC/GGBS/CSF mix was much lower than that of the PC/PFA/LSP15 while the yield stress was much higher with no apparent reason. All the mixes had good U-box filling height; slight segregation was found in mixes C8-1 and C8-2, but this disappeared after 30 minutes.

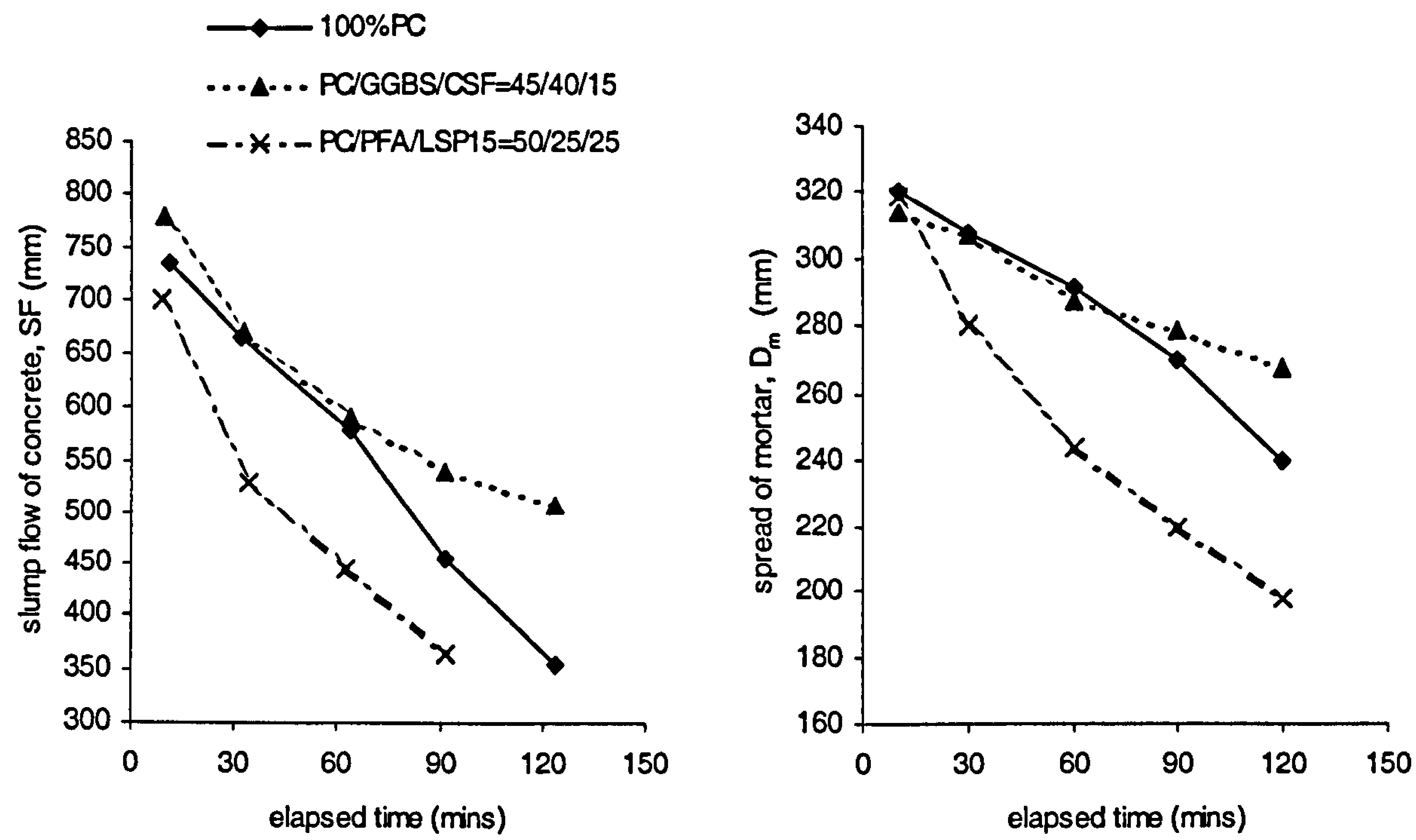
Table 8-3 Mix proportion and initial properties of ternary mixes for concrete and mortar*

			Mortar test					Concrete test						
Mix No.	Powder composition	Sp** (%)	D_m (mm)	T_{250} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	SF (mm)	T_{500} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	U_H (mm)	$T_{u\text{-}box}$ (s)
C5-1	PC	0.13	320	3.4	4.4	1	5.7	735	3.22	7.53	***	78	340	2.88
C8-1	PC/GGBS/CSF=45/40/15	0.225	314	2.69	2.06	14	2.64	778	1.22	3.68	50	8	335	1.75
C8-2	PC/PFA/LSP15=50/25/25	0.08	319	1.22	1.81	14	1.8	700	1.03	3.35	7.7	24	326	1.12

* PC4 cement was used, ** by weight of powder, ***: not measurable.

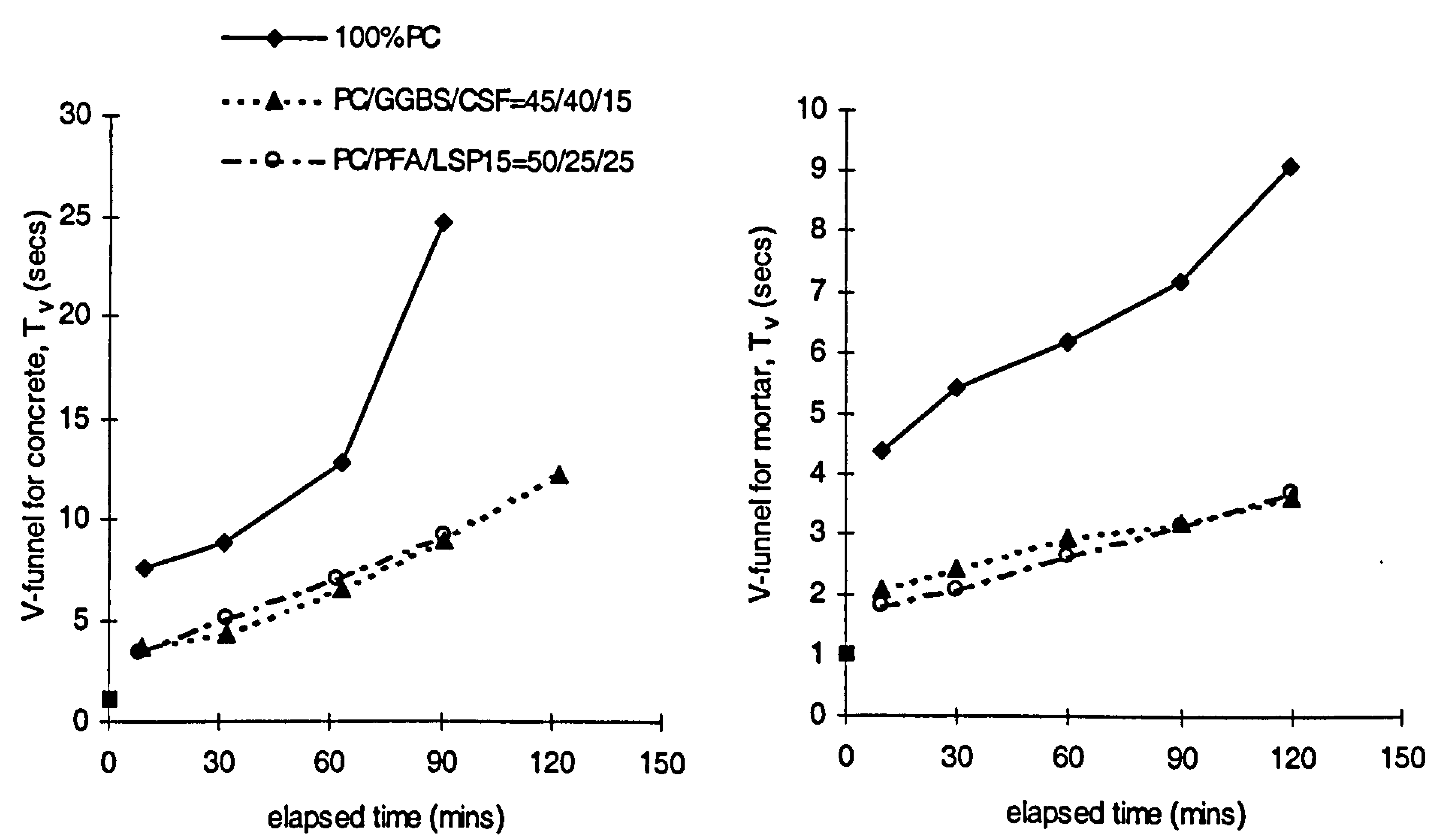
Figures 8-4, 8-5, 8-6 & **8-7** show the change in properties after mixing of the concrete and mortar mixes. It was noticed that the workability retention of the PC/GGBS/CSF mortar was inferior to that of same mix in **figure 8-3**, which may be caused by the lower requirement for superplasticizer. Nevertheless it had better workability retention than the other ternary mix and the control mix. The U-box filling height was still higher than 300 mm even 1 hour after mixing while for the PC/PFA/LSP15 ternary mix it had already dropped below 300 mm after 30 minutes. Similar trends were found for the same properties measured between mortar and concrete, indicating close relationship between the properties of mortar and concrete.

Many applications for high strength high performance concrete have used CSF, but normally to improve strength development and durability. The advantages of the CSF ternary mixes in their fresh stage have provided further reasons for their use.



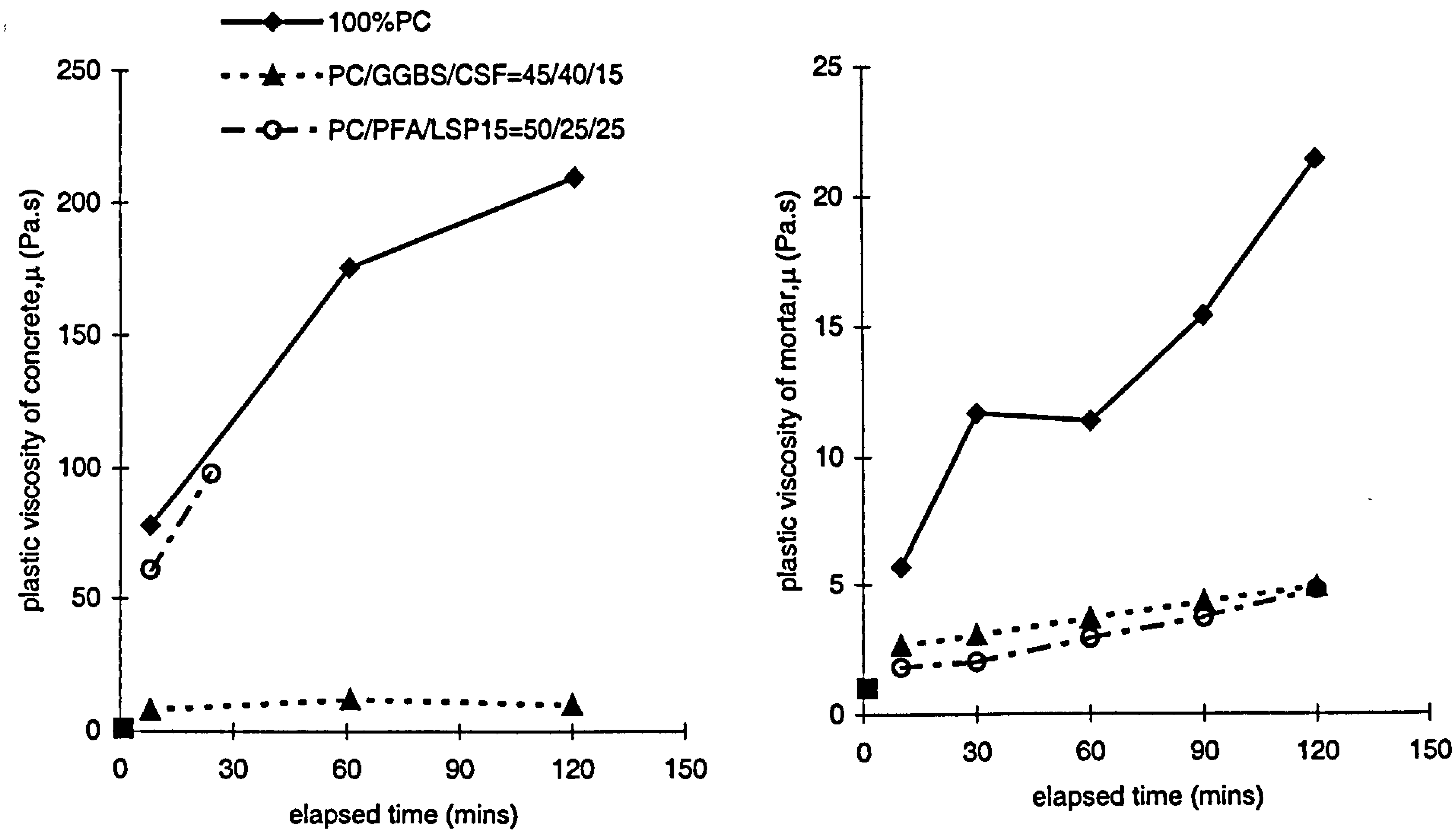
(a) concrete (b) mortar

Figure 8-4 Slump flow/spread development of ternary mixes for concrete and mortar



(a) concrete (b) mortar

Figure 8-5 V-funnel flow time development of ternary mixes for concrete and mortar



(a) concrete (b) mortar

Figure 8-6 Plastic viscosity development of ternary mixes for concrete and mortar

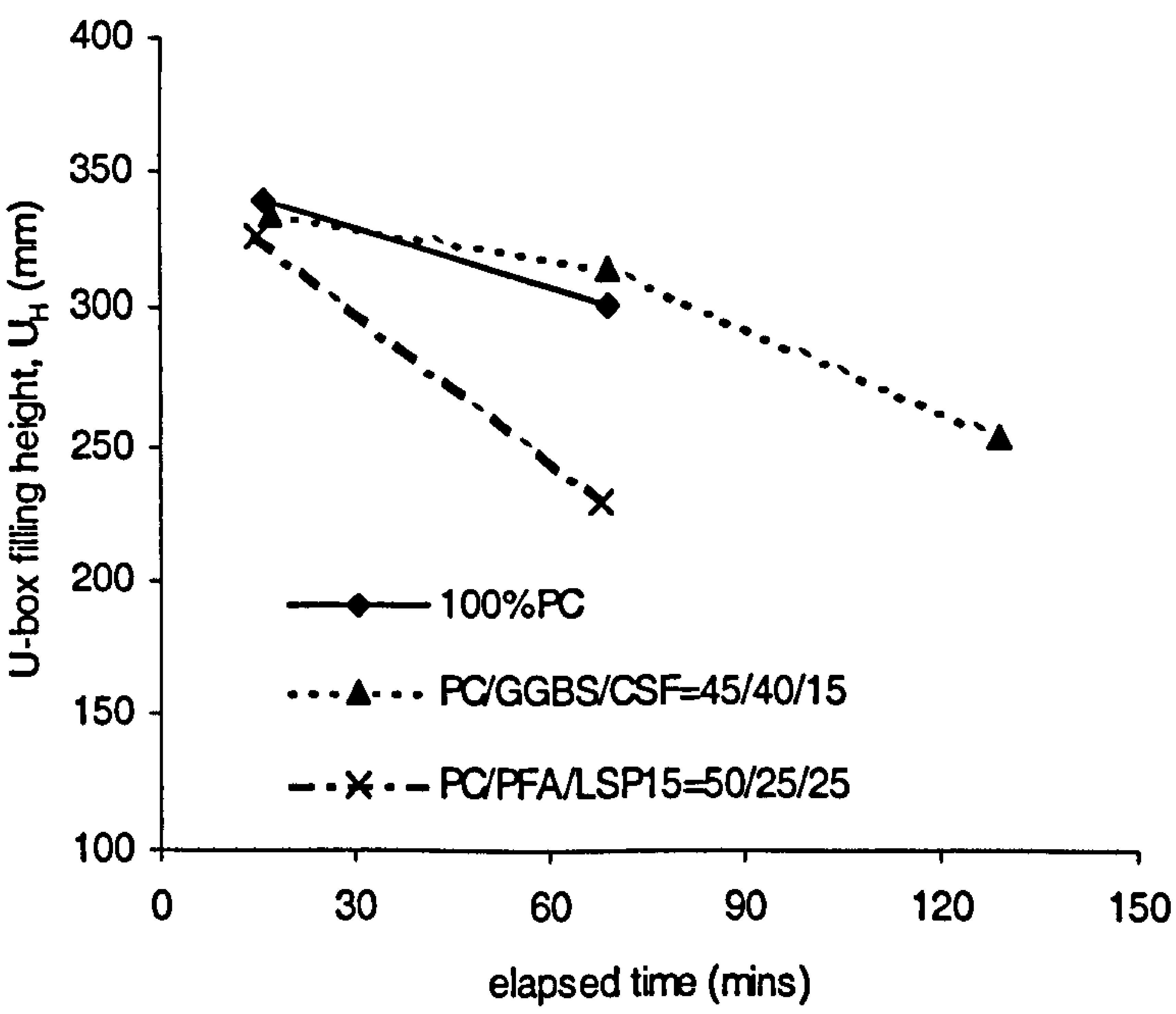


Figure 8-7 The change of U-box filling height with time for ternary mixes

8.3 Conclusion

The fresh properties of CSF ternary mixes were studied by mortar and concrete tests. The results confirmed that these have as good workability retention as CSF binary mixes, but with lower superplasticizer dosages. The spread of PC/LSP15/CSF mortar mix was 100 mm higher than the ternary mixes without CSF at 120 minutes after the start mixing. Excellent workability can be achieved with hardly any change in terms of spread and yield stress for the mixes with a high content of CSF. The use of CSF in SCC should not only be considered for strength and durability reasons but also for good fresh properties.

Chapter 9

Properties of mixes containing viscosity agents

As reviewed in chapter 1, SCC can be classified into three types: powder based SCC, which was investigated in the tests presented in chapter 6, 7 & 8, viscosity agent based SCC and a combined type. The latter two can be considered as one type in terms of component materials because both include a viscosity agent. The fresh properties and strength development of SCC containing two types of viscosity agent were studied. The types of viscosity agent used were Welan gum, commonly used in SCC, and a cellulose based agent as a comparison.

The programme was as follows,

- Preliminary study of:
    - the basic properties of Welan gum solutions compared to cellulose based solutions,
    - the effect of mixing procedure on the efficiency of Welan gum; two mixing methods and various mixing times between 3-10 minutes were tested,
    - the compatibility of Welan gum with superplasticizers, including Conplast430, Darcem2001, Sika10 and Glenium51 (details of these have been given in table 4-3),
    - the effect of Welan gum on the superplasticizer saturation dosage and the maximum workability.
- A full investigation of the compatibility of Welan gum with the superplasticizers. The superplasticizers included all the types above and ConplastM1. The compatibility of the cellulose-based agent with two types of superplasticizer, Conplast430 and Glenium51, was also investigated.
- Research on the effect of Welan gum on the properties of mixes with a single type of powder; the types of cement used were PC and SRC, and the dosage of Welan gum was varied between 0 and 0.1%.

- A study of the properties of the binary mixes with Welan gum; the binary blends of powder included PC/GGBS, PC/PFA, PC/LSP100 and PC/CSF.

It can be seen that the cellulose based viscosity agent was only studied for its solution properties and compatibility with superplasticizers because it was found to be less advantageous than Welan gum.

As before, mortar tests were first carried out, and then important findings were confirmed by concrete tests. All mortar and concrete were considered as Bingham materials. The fresh properties that were measured included:

- spread (D_m) and time to 250 mm spread (T_{250}), V-funnel flow time (T_V), yield stress (τ_0), plastic viscosity (μ) for mortar;
- slump flow (SF) and time to 500 mm slump flow (T_{500}), V-funnel flow time (T_V), yield stress(τ_0), plastic viscosity (μ), U-box filling height and the time flow to 250 mm height ($T_{U\text{-box}}$) for concrete.

Both mortar and concrete cubes were cast for compressive strength testing, and setting time tests were also carried out on the mortar.

9.1 Preliminary study

The properties of Welan gum depend on its molecular structure and molecular weight. These properties, which have a significant effect on SCC, were examined before the more rigorous tests. This included assessment of:

- rheological properties of Welan gum (WG) solutions compared to Carboxy Methyl Cellulose (CMC) solutions,
- effect of mixing procedure on the efficiency of theWelan gum,
- Welan gum and superplasticizer compatibility,
- effect of Welan gum on the superplasticizer saturation dosage and maximum workability.

9.1.1 Properties of Welan gum solutions

The pseudoplastic and stability properties of Welan gum solution in water were examined, since these show the major characteristics of Welan gum.

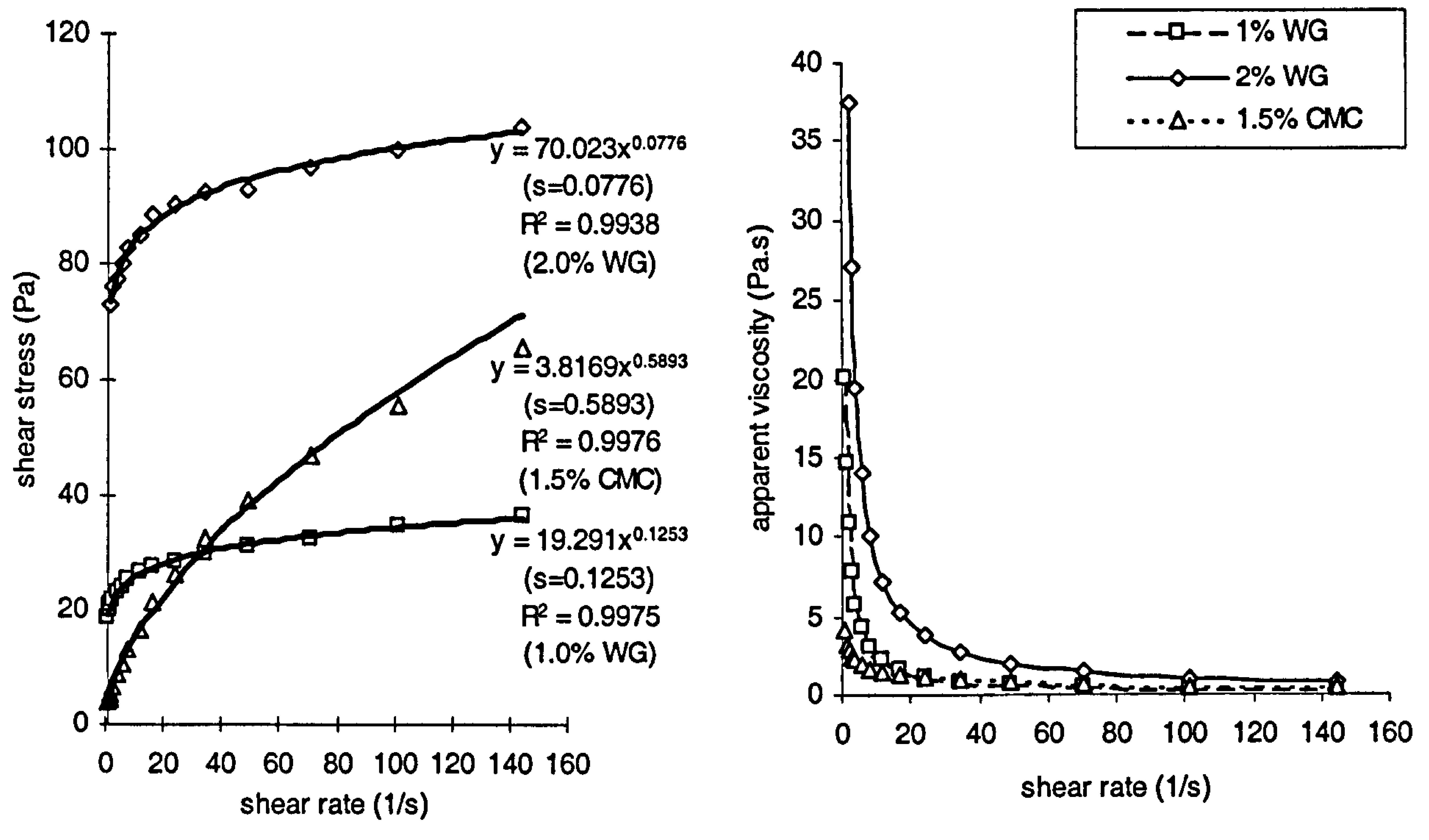


Figure 9-1 Rheological property of Welan gum and cellulose solutions

Figure 9-1 shows the rheology property of Welan gum and Carboxy Methyl Cellulose solutions measured with the concentric cylinder viscometer **(figure 4-4)**. Rheology of both solutions followed power law, $\tau = r\dot{\gamma}^{s}$, meaning pseudoplastic behaviour. Welan gum showed a much higher pseudoplastic property than the cellulose solution with much lower 's' values, meaning fast increasing apparent viscosity with a decrease in shear rate. This property is very similar to that of the Welan gum solution described in **figure 2-15.**

Another characteristic of Welan gum is its stability in various types of solutions. **Figure 9-2** shows that the apparent viscosity hardly changed in deionized water or filtered cement water solutions, but that this significantly changed for solutions of the cellulose viscosity agent. This suggests that the properties of Welan gum will be maintained with different cements. This is highly beneficial for cement paste, mortar and concrete, as reviewed in chapter 2.

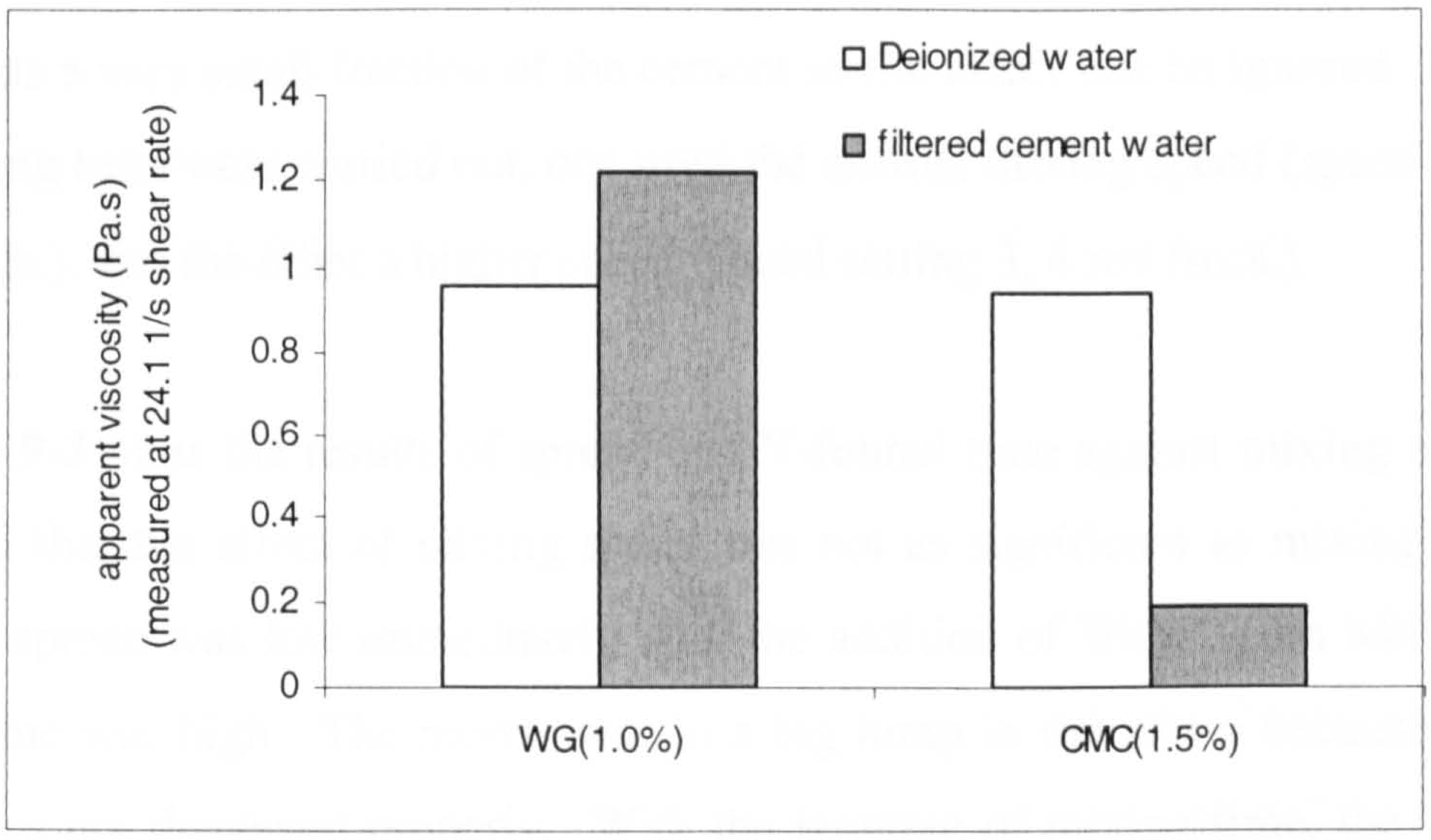


Figure 9-2 Apparent viscosity of Welan gum in various solutions compared to cellulose

9.1.2 Effect of mixing procedure on the efficiency of Welan gum

It was reported in chapter 2 that the efficiency of Welan gum is much dependent on the mixing procedure, product form, and mixing conditions. If high flowability with controlled bleed and flow loss is required, the optimal use of Welan gum is achieved by being added as a solution after superplasticizer; or in a powder form at the same time as, or after, the superplasticizer [133]. It was found very difficult in the laboratory to make Welan gum solutions with powder with precise concentrations and then store the solution. Therefore it was decided to add Welan gum in powder form during mixing after the addition of superplasticizer. The mixing time with different mixing speeds to obtain the highest efficiency of the Welan gum in the mortar was studied. A mix with water/cement ratio of 0.5 by weight, sand/mortar ratio of 0.45 by volume, Glenium51 at 0.4% of cement by weight, and Welan gum at 0.1% of water by weight was used for this. Glenium51 was chosen because of its good performance in SCC without Welan gum; it was however subsequently found not to perform well with Welan gum, this will be discussed in section 9.1.3 and 9.2.

When mixing, Welan gum was always added 1 minute after the superplasticizer which was added 1 minute after the start of mixing. The Welan gum was premixed with dry PFA by 1:10 by weight for more efficient dispersal. The amount of PFA used was a very small fraction of the cement so the effect can be ignored. Two series of mixing tests were carried out, one used the normal mixing speed (speed setting 1, 1 rev./secs.), and the other a higher speed (speed setting 3, 4 rev./secs.).

Figure 9-3 plots the results of spread and V-funnel time against mixing time. It can be seen that the effect of mixing speed was not as significant as mixing time. The mortar spread was low immediately after the addition of Welan gum while V-funnel flow time was high. The mortar was in a big lump in the mixer because the Welan gum was not dispersed properly. With the increase of mixing time, the Welan gum gradually dissolved in mortar and dispersed, and the mortar tended to be more homogenous; the spread increased and V-funnel flow time decreased. The maximum spread and the lowest V-funnel flow time were both achieved at 6-8 minutes for both mixing conditions. Therefore 6 minutes mixing time with normal mixing speed was chosen for the remaining tests.

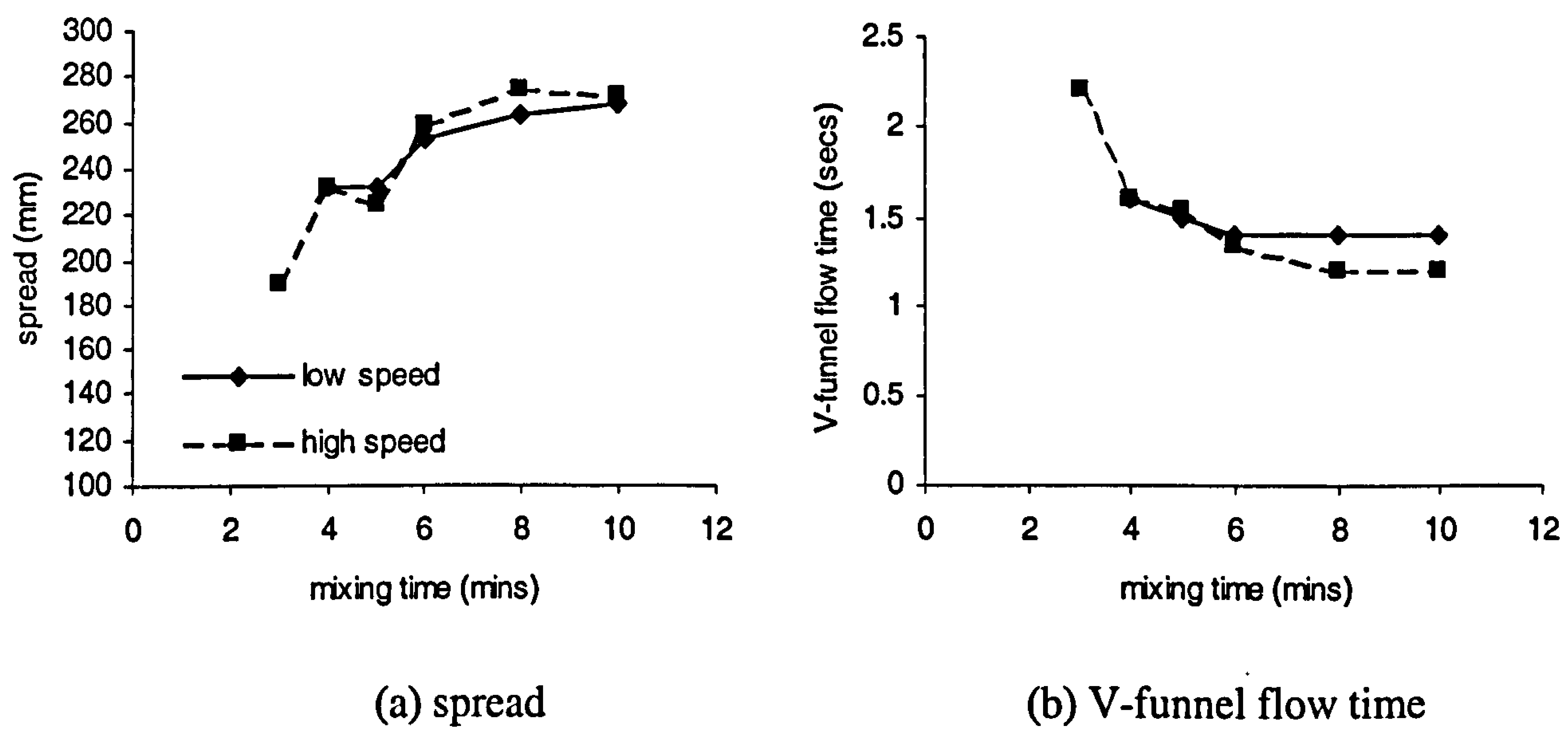


Figure 9-3 Effect of mixing speed and time on workability of Welan gum mixes

9.1.3 Welan gum and superplasticizer compatibility

The compatibility of any two components added to concrete is always of concern. As reviewed in chapter 2 both Welan gum and superplasticizer work on powder and water, and the interaction between them is much dependent on their individual properties. For this reason a preliminary study was carried out to investigate the compatibility of Welan gum with superplasticizers, using mortar tests. A mix with a water/cement ratio of 0.4 by weight and sand/mortar ratio of 0.45 by volume was used. The dosages of Welan gum were 0%, 0.05% and 0.1% by weight of water. Four types of superplasticizers were chosen, i.e. Conplast430, Darcem2001, Sika10 and Glenium51. The dosage to achieve a spread of 280 ± 5 mm was determined for in each mix.

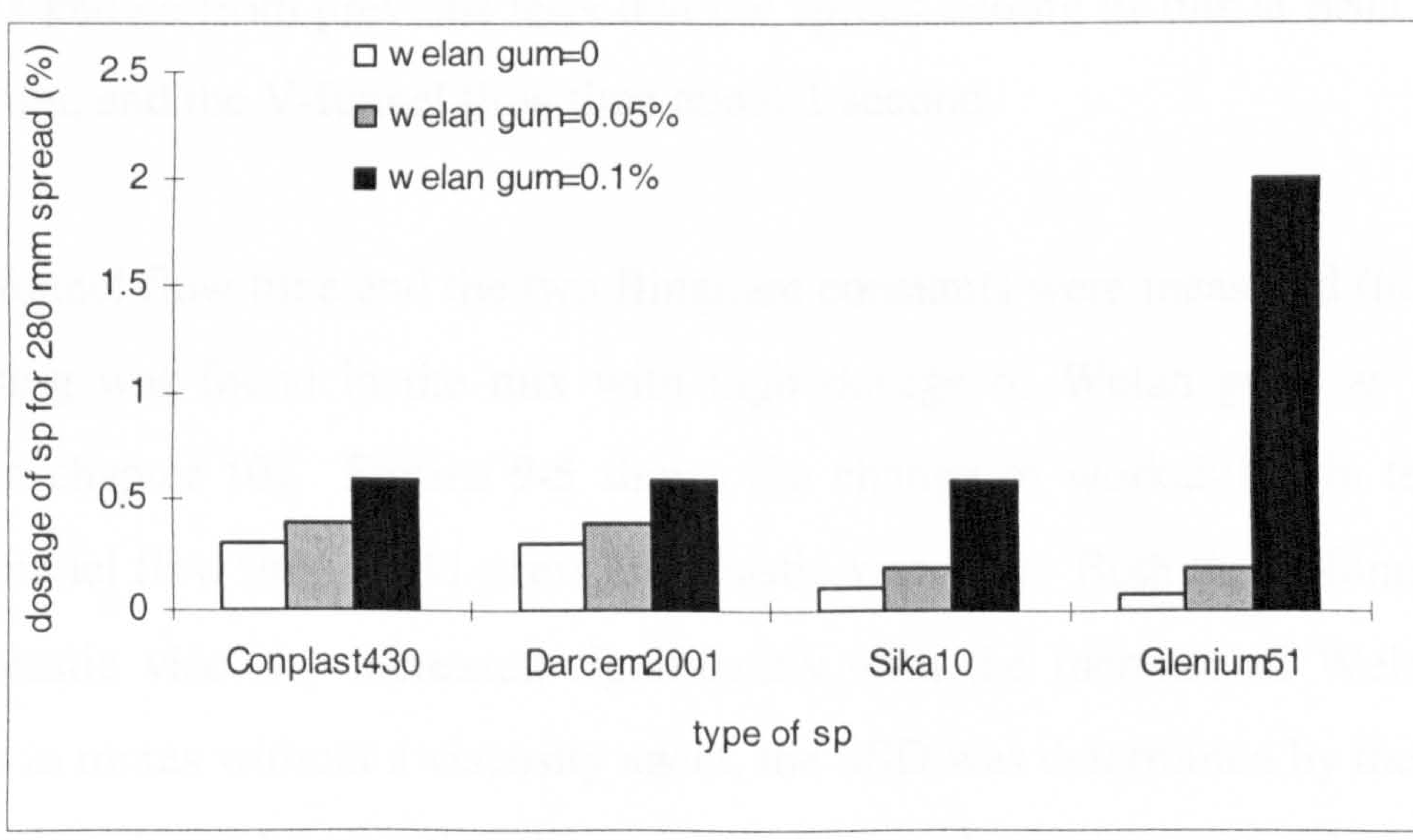


Figure 9-4 The effect of Welan gum level on the dosage of superplasticizers in mortar to achieve a spread of 280 ± 5 mm

The results are shown in **figure 9-4**. In all cases, the addition of Welan gum resulted in an increased requirement for superplasticizer to achieve the same spread. At 0.05% Welan gum, the increases were modest for all the superplasticizers. With 0.1%, the increase for Conplast430 and Darcem2001 was a factor of about two; for Sika10 it was about six times, but for Glenium51 about twenty times as much superplasticizer was required. Clearly this indicates the different compatibilities between Welan gum and different types of superplasticizer. Conventional superplasticizers seemed to have better compatibility with Welan gum than the 'new generation' types, at least in terms of the relative amount to achieve the same spread. Further study of this is reported in section 9.2.

9.1.4 Effect of Welan gum on SSD and maximum workability

The above results confirm that Welan gum increases the required superplasticizer dosage for a given workability, as reviewed in Chapter 2. However, it is not clear by how much the maximum possible workability changes. This was examined by testing mortar with dosages of Welan gum between 0.05 and 0.15%. The water/cement ratio was 0.4 and sand/mortar ratio 0.45 by volume. Conplast 430 was used and the dosage was increased until the maximum workability was obtained for each mix. This was not a complete set of tests because a control mix with no Welan gum was not carried out, but it is known from previous tests that the spread ceiling of this at SSD will be about 310 mm, and the V-funnel flow time about 1 second.

Spread, V-funnel flow time and the two Bingham constants were measured (however, shear thinning was found in the mix with high dosage of Welan gum, as will be discussed in chapter 10). **Figure 9-5** shows the change of workability in terms of spread, V-funnel flow time, yield stress and plastic viscosity. Both the V-funnel flow time and plastic viscosity increased significantly with the increase of Welan gum dosage. As in mixes without a viscosity agent, the SSD was determined by the spread and yield stress. It can be seen that the amount of superplasticizer required to achieve the maximum value of these was significantly increased with increasing Welan gum dosage. While 0.6% Conplast430 was needed for the mix with 0.05% Welan gum, double the amount was required for the mix with 0.1% and six times for the mix with 0.15% Welan gum. Also the spread ceiling decreased and the corresponding yield stress increased with increasing Welan gum dosage, which is consistent with the results found by Yuragi *et al* as shown in figure 2-26 [76]. This suggests that there is a limit of the Welan gum dosages for SCC, beyond which it may not be feasible to produce SCC due to insufficient flowing capacity.

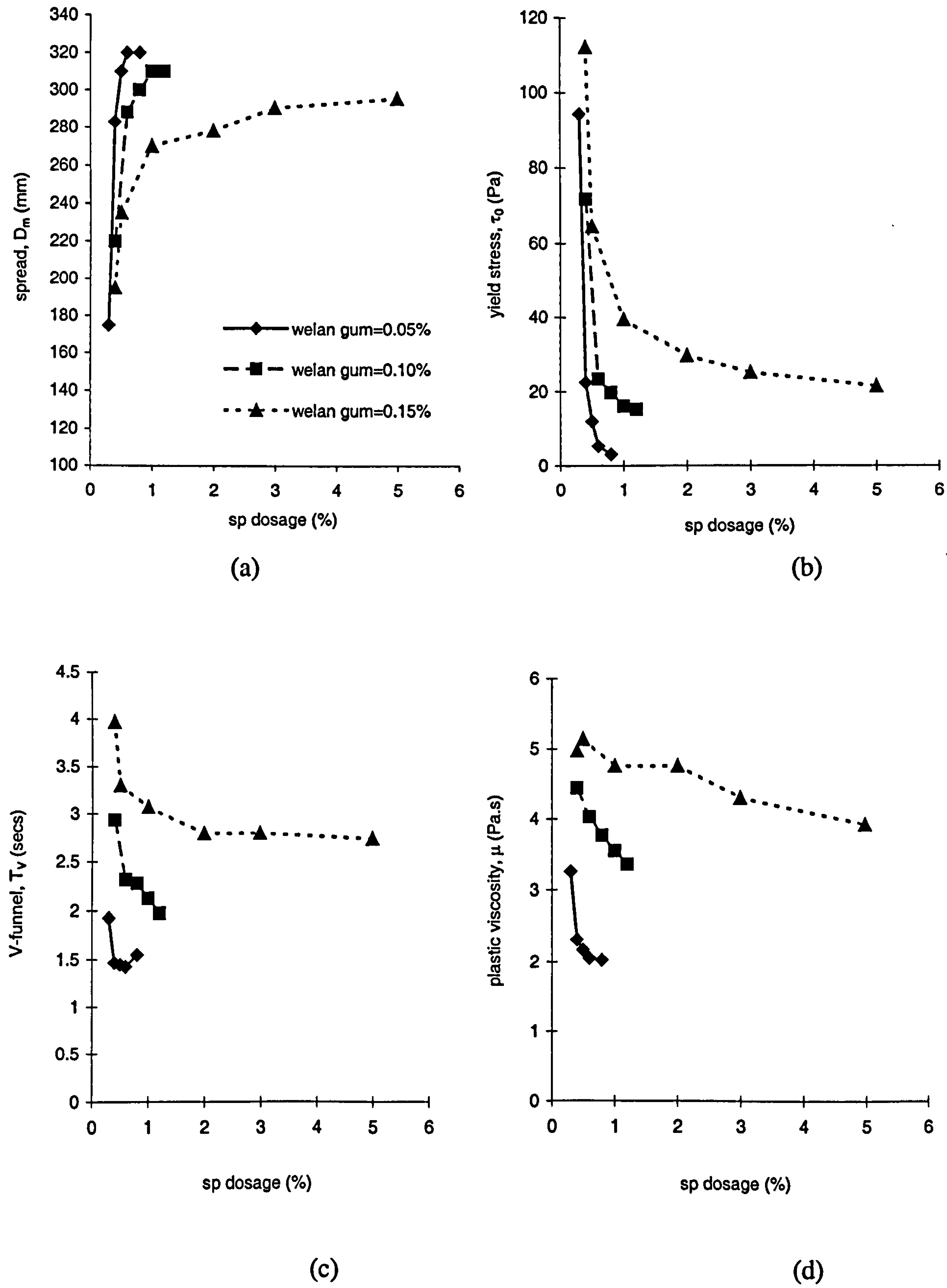


Figure 9-5 Effect of Welan gum and superplasticizer dosage on (a) spread (b) yield stress (c) V-funnel flow time (d) plastic viscosity

9.2 Welan gum superplasticizer compatibility

As reviewed in chapter 2, the purpose of adding a viscosity agent to SCC is to increase plastic viscosity and stability while keeping yield stress unchanged; however most viscosity agents increase yield stress and hence require more superplasticizer. The best Welan gum/superplasticizer combination would be the pair with the least effect on yield stress, but increasing plastic viscosity, as well as little effect on other properties such as workability retention, setting time and strength development. These were investigated, first by mortar tests, and then by concrete tests.

9.2.1 Mortar

Welan gum/superplasticizer compatibility was first examined in terms of initial fresh properties to find the group with the least increase of yield stress with increasing plastic viscosity. Five different types of superplasticizer were tested: Conplast430, ConplastM1 and Darcem2001; and two of the new generation: sika10 and Glenium51 (the detail of these have been given in table 4.3). The properties examined included initial fresh properties, workability retention, setting time, and strength development.

Table 9-1 shows the mix proportions and the fresh properties for the reference mixes with different types of superplasticizer without Welan gum. 100% PC2 was used, the water/cement ratio was 0.35 by weight instead of 0.4, sand/mortar ratio 0.45 by volume, and the superplasticizer dosage was that to achieve a 310-320 mm spread. It was found that measuring the properties of the reference mix with 0.4 water/cement ratio was difficult because of the segregation caused by the low plastic viscosity.

It can be seen that the yield stress of all the mixes was between 10-13 Pa, and the V-funnel flow times and plastic viscosities for the mixes with conventional types of superplasticizer were similar but slightly lower than those for the mixes with the new generation superplasticizers.

Welan gum was added to each reference mix at dosages of 0.025%, 0.05%, 0.075% and 0.1%. **Figure 9-6** presents the change of workability with the increase of Welan gum dosage. In all cases, the addition of Welan gum resulted in an increase in V-funnel flow time and plastic viscosity and a decrease of workability in terms of spread and yield stress. However, as shown in **figure 9-7**, there was less reduction of the workability with increased plastic viscosity in conventional superplasticizer mixes compared to the new generation superplasticizers. Clearly, Conplast430, ConplastM1 and Darcem2001 are more compatible with Welan gum than the new generation types.

Table 9-1 Mix proportions of reference mixes with various types of superplasticizer and their properties

Series	Mix No	Types of superplasticizer	Dosage (% by wt powder)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
	Mix 9-1	Conplast430	0.47	309	1.56	13.0	2.7
	Mix 9-2	ConplastM1	0.65	313	1.71	11.7	3.0
Series 1	Mix 9-3	Darcem2001	0.52	310	1.64	11.7	3.0
	Mix 9-4	Sika10	0.19	313	1.85	12.6	3.5
	Mix 9-5	Glenium51	0.11	313	1.90	10.8	3.4

It is known that the dispersion mechanism of Glenium51 is mainly steric hindrance repulsion. The ethylene oxide chains (EO chains) in the molecules have a strong ability to hold water, due to a bulky and thick adsorption layer formed on the cement surface [6]. Polysaccharide polymers (such as Welan gum) adsorb water and swell to impart viscosity, which suggests that Glenium51 and Welan gum might, in effect, be competing for the same water causing poor compatibility. Sika10 has a similar dispersing mechanism to Glenium51, suggesting similar poor compatibility with Welan gum, as confirmed by the results.

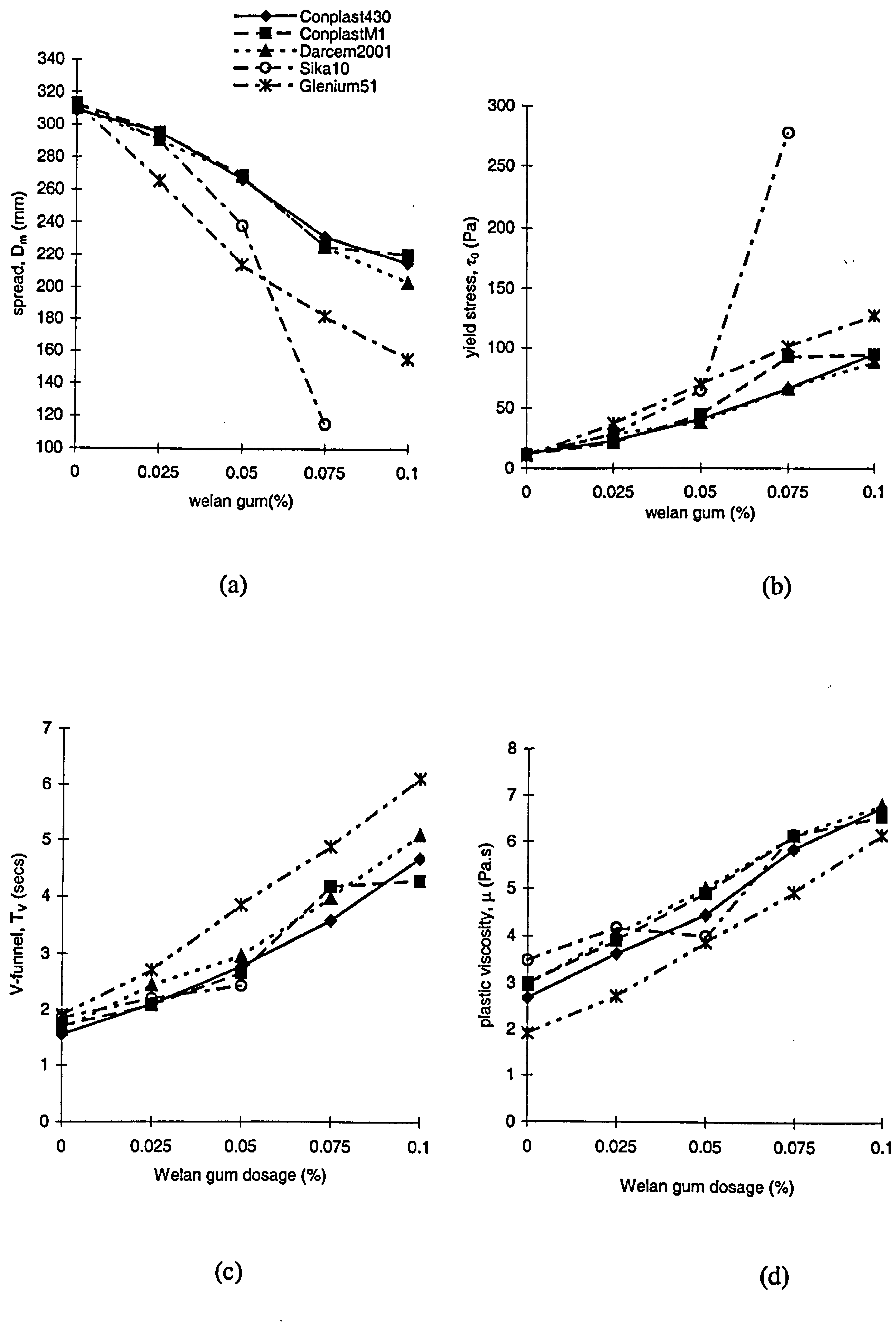


Figure 9-6 Welan gum and superplasticizer compatibility in terms of (a) spread, (b) yield stress (c) V-funnel flow time (d) plastic viscosity

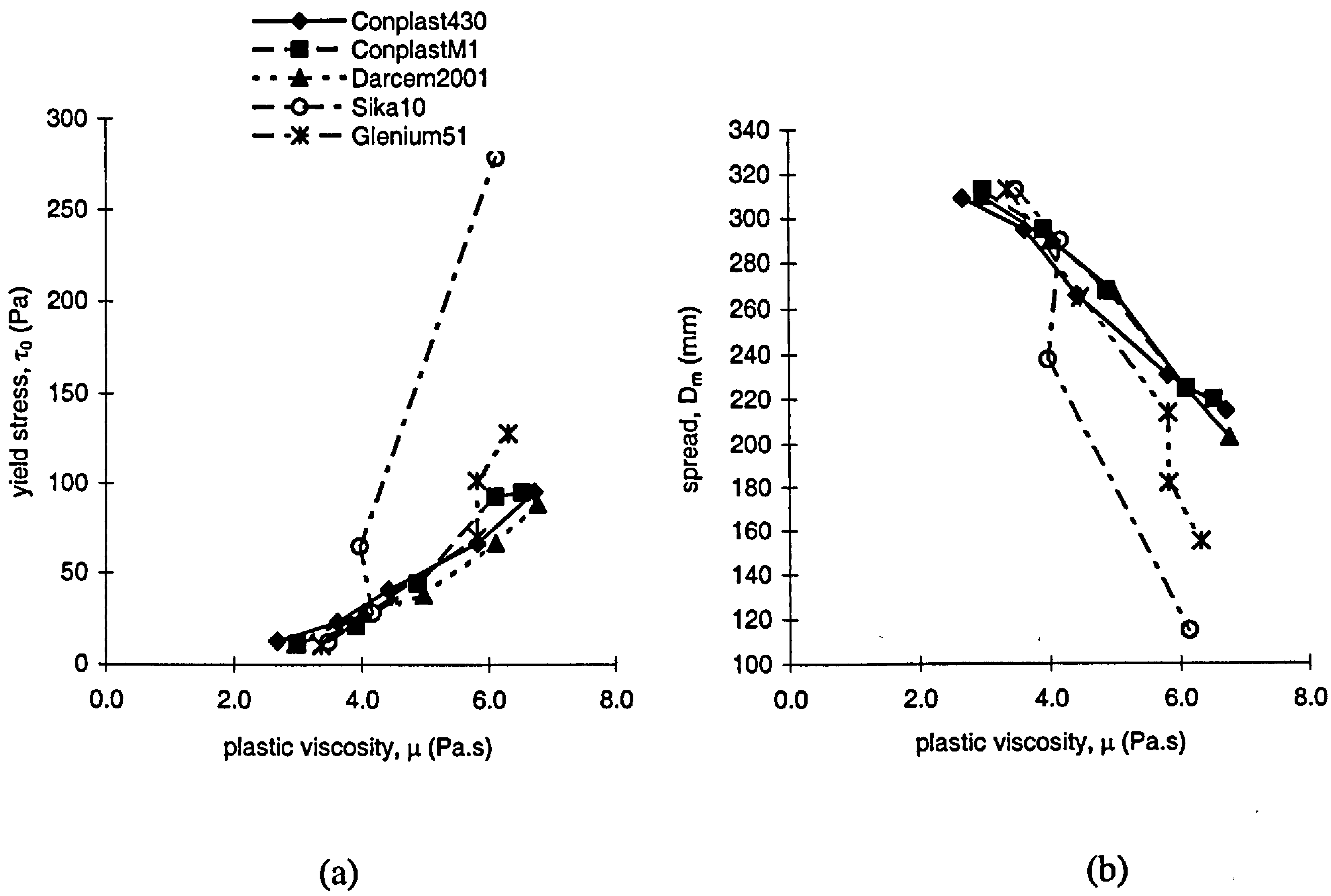


Figure 9-7 Welan gum and superplasticizer compatibility in terms of the relationship between (a) yield stress and plastic viscosity, (b) spread and plastic viscosity

The poor compatibility between some superplasticizers and viscosity agents is not confined to Welan gum. It has been reported that cellulose-based water-soluble polymers have a poor compatibility with naphthalene sulfonate because the interaction between the two becomes extremely weak due to the conversion of sodium naphthalene sulfonate to calcium naphthalene sulfonate [8]. However, a two-point test for cellulose (available in UK) with Conplast430 and Glenium51 compatibility showed that the compatibility between Glenium51 and cellulose was still inferior to that with Conplast430 (**figure 9-8**).

It has been reported that a new type of viscosity agent, called non-adsorptive, has been produced. This does not compete with the superplasticizer for adsorption sites and the amount of superplasticizer required is the same as that without a viscosity agent; however, it is not yet available yet in the UK. Another new type of viscosity agent, called colloidal silica, seems to be in use; but its properties have not been reported.

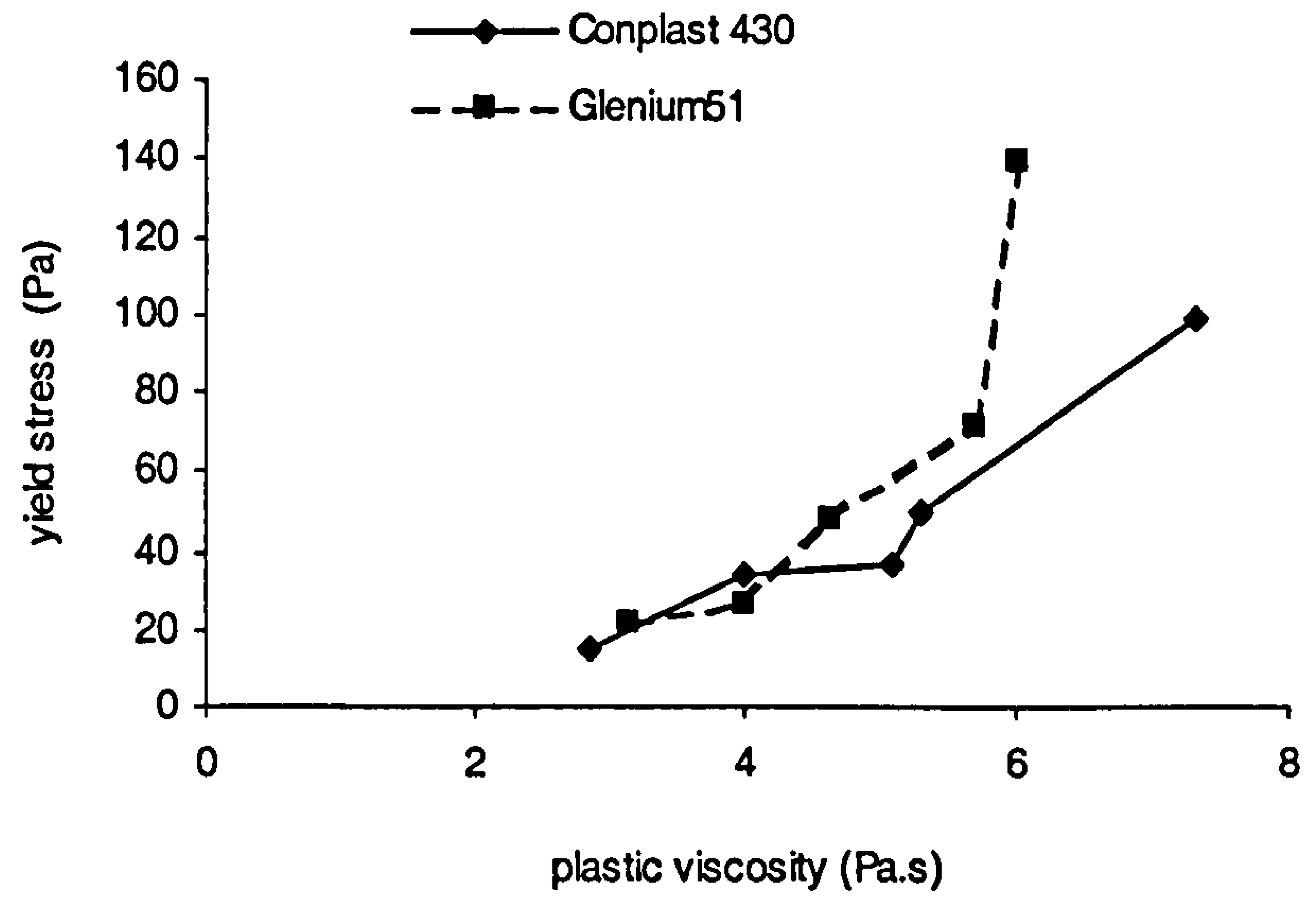


Figure 9-8 Cellulose and superplasticizer compatibility in terms of the relationship between yield stress and plastic viscosity

Further assessment of compatibility was carried out by workability retention, setting time and strength development tests. From the above results, three superplasticizers were selected, Conplast430, ConplastM1 and Darcem2001. **Table 9-2** shows the mix proportions and initial properties immediately after mixing. All the mixes had a water/cement ratio of 0.35 by weight, a sand/mortar ratio 0.45 by volume and a Welan gum dosage of 0.05% by weight of water. The superplasticizer dosage was such that a spread value between 310-320 mm was achieved for each mix, and hence three mixes had very similar initial workability.

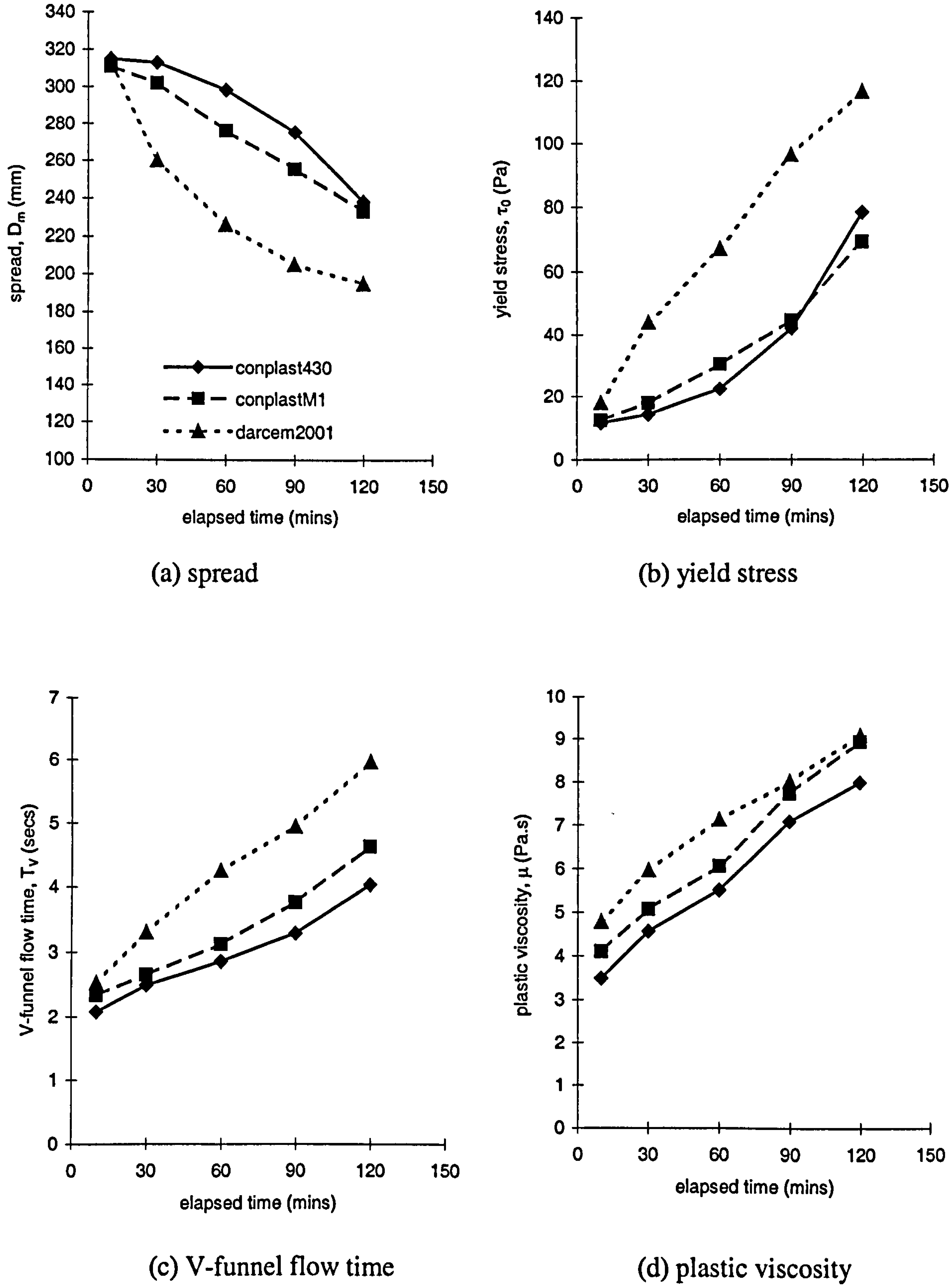
Table 9-2 Mix proportions and initial properties of Welan gum mixes with three different types of superplasticzer

Mix no.	Welan gum (%)	Types of superplasticizer	Dosage (% by wt powder)	D_m (mm)	Tv (secs)	τ_0 (Pa)	μ (Pa.s)
M9-6		Conplast430	0.7	315	2.08	11.7	3.5
M9-7	0.05	ConplastM1	1.1	311	2.34	12.6	4.1
M9-8		Darcem2001	0.7	313	2.53	17.9	4.8

It could be expected that all three superplasticizers have similar effect on the mix without Welan gum in terms of workability retention setting time and strength development because all three belong to the same generation type. **Figure 9-9** shows the change of workability for two hours after the start of mixing. The Conplast430 and ConplastM1 mixes showed very similar performance in terms of spread and yield stress; both have better workability retention than the Darcem2001 mix. The plastic viscosity results showed very similar performance while the V-funnel results indicated that Darcem2001 mix was inferior.

The setting times and strength developments of these mixes are given in **figure 9-10** & **9-11**. It was thought that Conplast430 and ConplastM1 mixes might have longer setting time and slower strength development because of their better workability retention. However, while the Conplast430 mix had a similar setting time to ConplastM1 mix, it had higher early strength and 28 day strength. In contrast, the Darcem2001 mix showed much longer setting times, lower early strength and similar 28 day strength to the other two. This implies that there is no significant effect of workability retention on setting time because the workability retention concerned is only for the first two hours after the start of mixing which is during the dormant period of cement hydration.

In summary, among the superplasticizers, Conplast430 showed the best compatibility with Welan gum and the best performance in terms of workability retention, setting time and strength development. However, it can be argued that the different behaviour of these three mixes may be caused by different properties of superplasticizers, not the compatibility of Welan gum with them. This could be proved by comparing these results with those of reference mixes without Welan gum, but unfortunately this was not carried out.



(a) spread

(b) yield stress

(c) V-funnel flow time

(d) plastic viscosity

Figure 9-9 Workability retention of Welan gum mixes with different types of superplasticizer

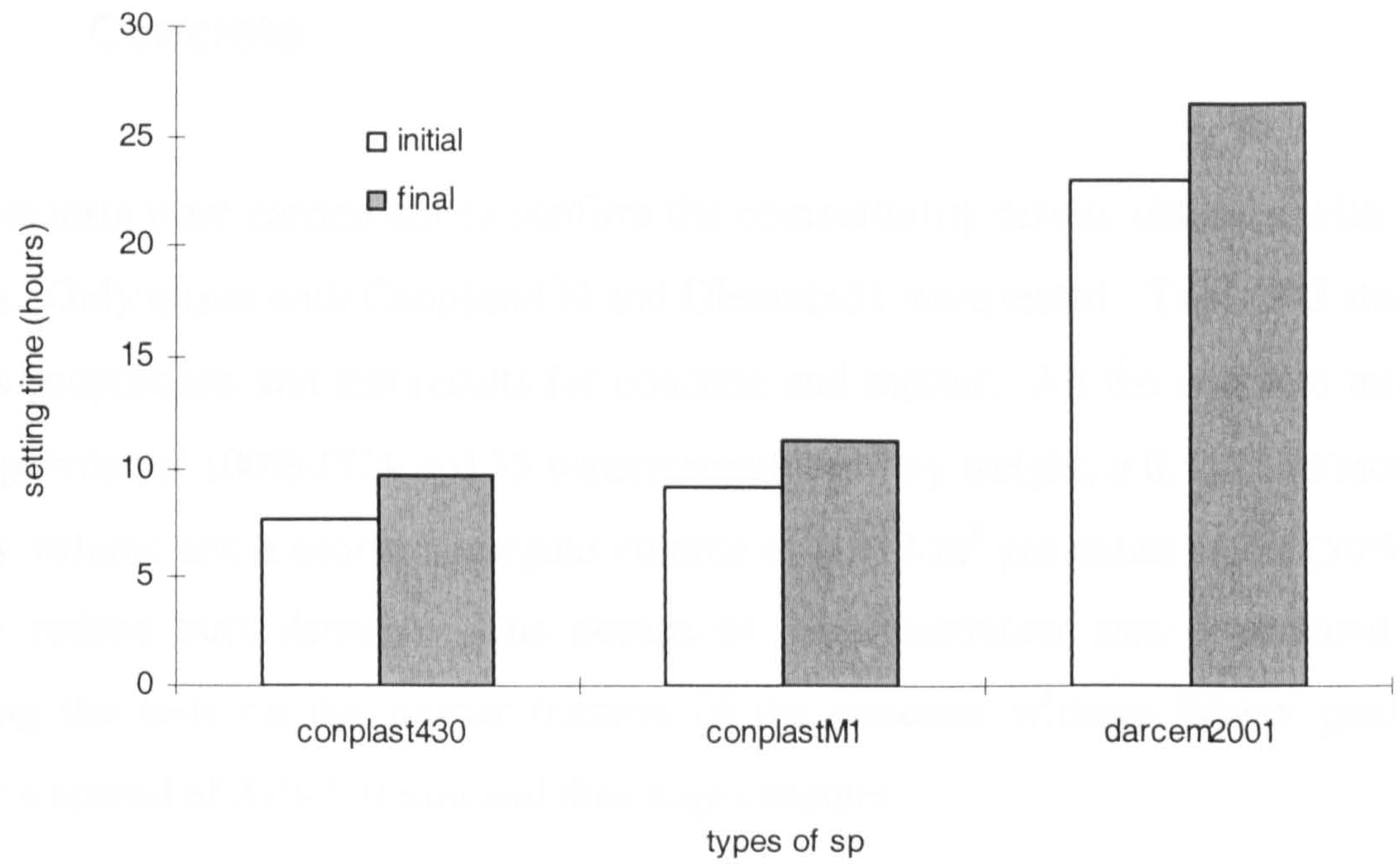


Figure 9-10 Setting time of Welan gum mixes with different types of superplasticizer

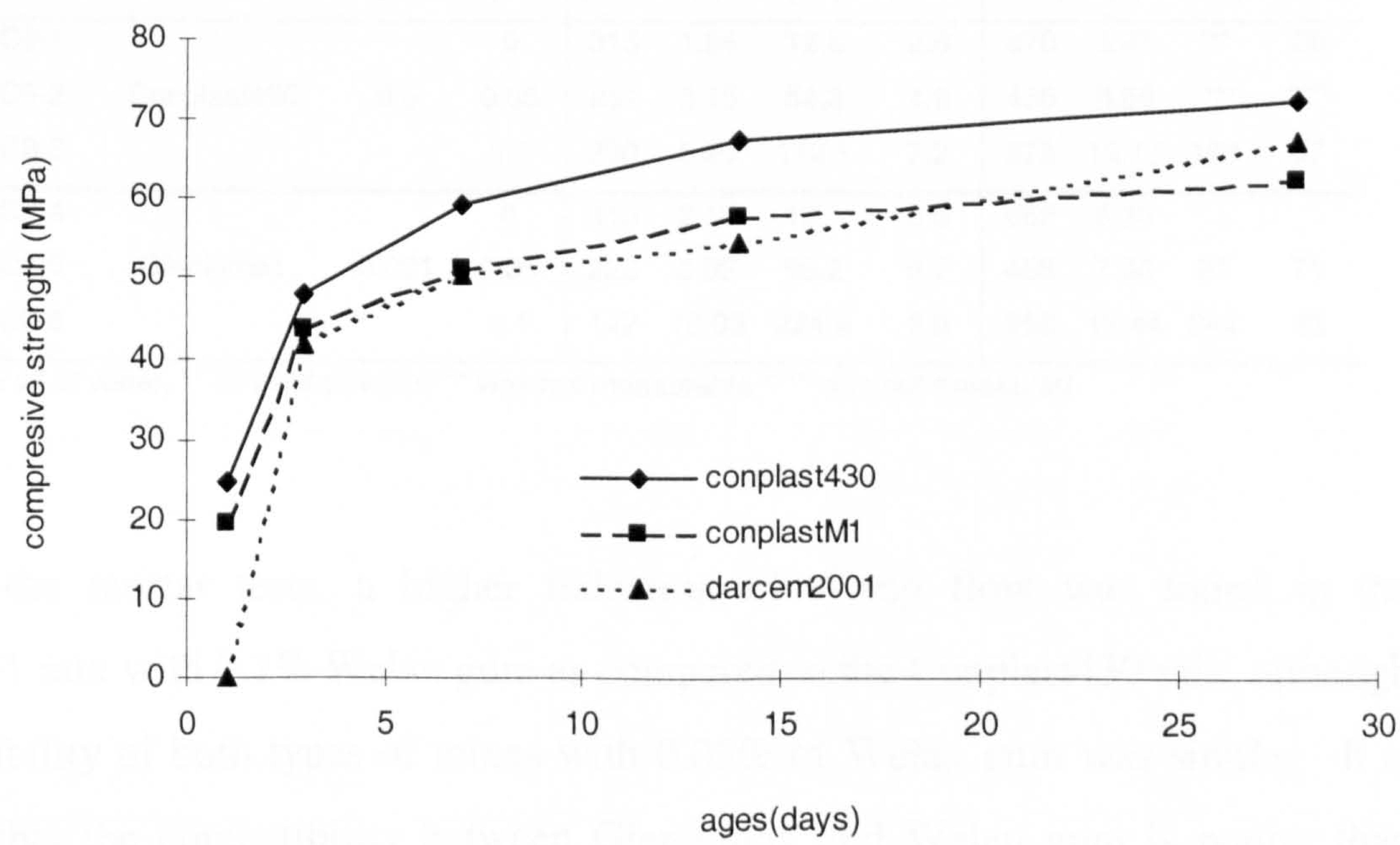


Figure 9-11 Strength development of Welan gum mixes with different types of superplasticizer

9.2.2 Concrete

Concrete tests were carried out to confirm the compatibility results obtained with the mortars. Only mixes with Conplast430 and Glenium51 were tested. **Table 9-3** shows the mix proportions and test results for concrete and mortar. All the concrete mixes used a powder of 100% PC4, a 0.35 water/cement ratio by weight, a 0.45 sand/mortar ratio by volume and a coarse aggregate volume of 0.317 m^3 per cubic meter (50% of the dry rodded bulk density). The dosage of superplasticizer was determined by repeating the tests on the mortar fraction of the concrete without Welan gum to achieve a spread of 310-320 mm and then kept constant.

Table 9-3 Mix proportion and fresh properties of Welan gum mix with two types of superplasticzers

series	Mix No.	Types of superplasticizer	Sp** (%)	WG* (%)	Mortar test D_m (mm)	Tv (s)	τ_0 (Pa)	μ (Pa.s)	Concrete tests SF (mm)	Tv (s)	τ_0 (Pa)	μ (Pa.s)
1	C9-1	Conplast430	0.5	0	313	1.94	12.8	2.6	670	3.81	***	39
	C9-2			0.05	251	3.15	54.3	4.9	455	8.59	****	****
	C9-3			0.1	200	5.20	112.1	7.2	375	19.13	186	67
2	C9-4	Glenium51	0.091	0	310	2.19	18.1	3.5	659	5.10		
	C9-5			0.05	223	3.99	99.2	6.7	458	7.66	91	71
	C9-6			0.1	142	10.03	224.8	8.9	293	15.44	344	43

* % wt of water, ** % wt of powder,*** was not measurable **** was not measured

As with the mortar tests, a higher reduction of slump flow was found in the Glenium51 mix with 0.1% Welan gum as compared to the Conplast430 mix, although the workability of both types of mixes with 0.05% of Welan gum was similar. It is apparent that the compatibility between Glenium51 and Welan gum is poorer than Conplast430. Therefore, Conplast430 was chosen for Welan gum mixes for the remaining tests because of its general better performance than the other superplasticizers in terms of the properties tested above.

9.3 Effect of Welan gum on the properties of the mixes with a single type of powder

9.3.1 Mortar

Table 9-4 presents the mix proportions and initial properties of the mixes with varying content of Welan gum. Two types of cement were used, i.e. PC2 and SRC1, all the mixes used a water/cement ratio of 0.35 by weight and sand/mortar ratio of 0.45 by volume. The superplasticizer dosage was adjusted to achieve a spread of 300-310 mm, which is higher than the minimum requirement for SCC according to the UCL mix design method but slightly less than the spread ceiling at saturation dosage for each mix. Again the required superplasticizer dosage significantly increased with increased Welan gum dosage. Both V-funnel flow time and plastic viscosity increased with Welan gum dosage, but there was no further increase beyond a Welan gum dosage exceeding 0.075%.

Table 9-4 Mix proportion and initial properties of mortar with different content of Welan gum

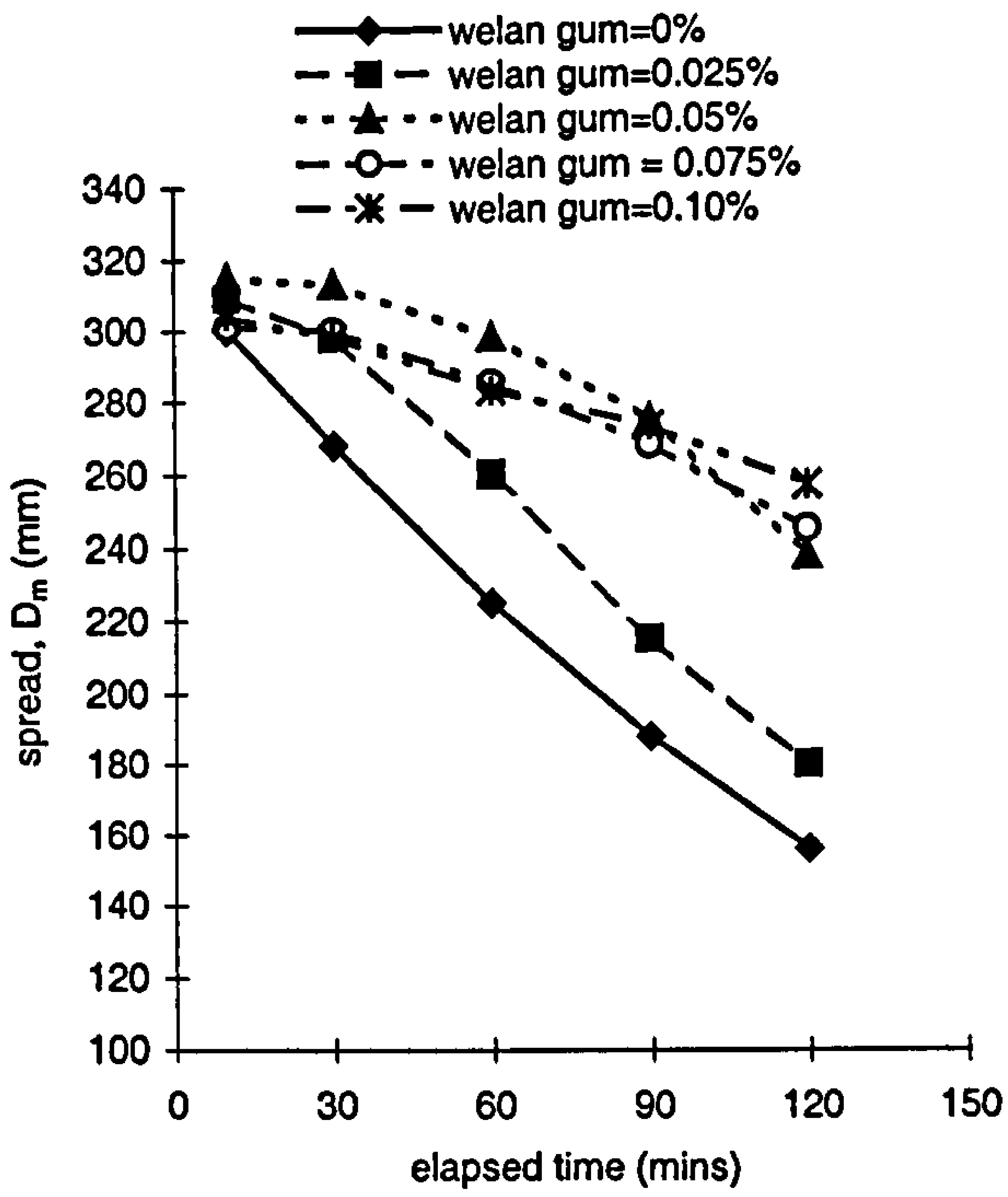
Mix no.	Types of cement	Welan gum dosage (% by wt. of water)	Sp dosage (% by wt powder)	D_m (mm)	T_v (secs)	τ_0 (Pa)	μ (Pa.s)
M9-9		0	0.45	300	1.49	13.9	2.5
M9-10		0.025	0.5	309	1.6	11.7	3.0
M9-11	PC2	0.05	0.7	315	2.08	11.7	3.5
M9-12		0.075	1.0	301	2.8	19.7	5.5
M9-13		0.1	1.6	304	2.88	25.1	4.6
M9-14	SRC1	0.05	0.6	313	2.14	14.4	3.5

Figure 9-12 shows the workability retention of the PC mixes. The addition of Welan gum improved the workability retention significantly in terms of spread and yield stress, but this may be a result of delay hydration and the increased superplasticizer dosage. However, there seems to be a limiting dosage beyond which no further improvement was achieved, and in this case this was 0.05%-0.075% (**figure 9-12 (a)**

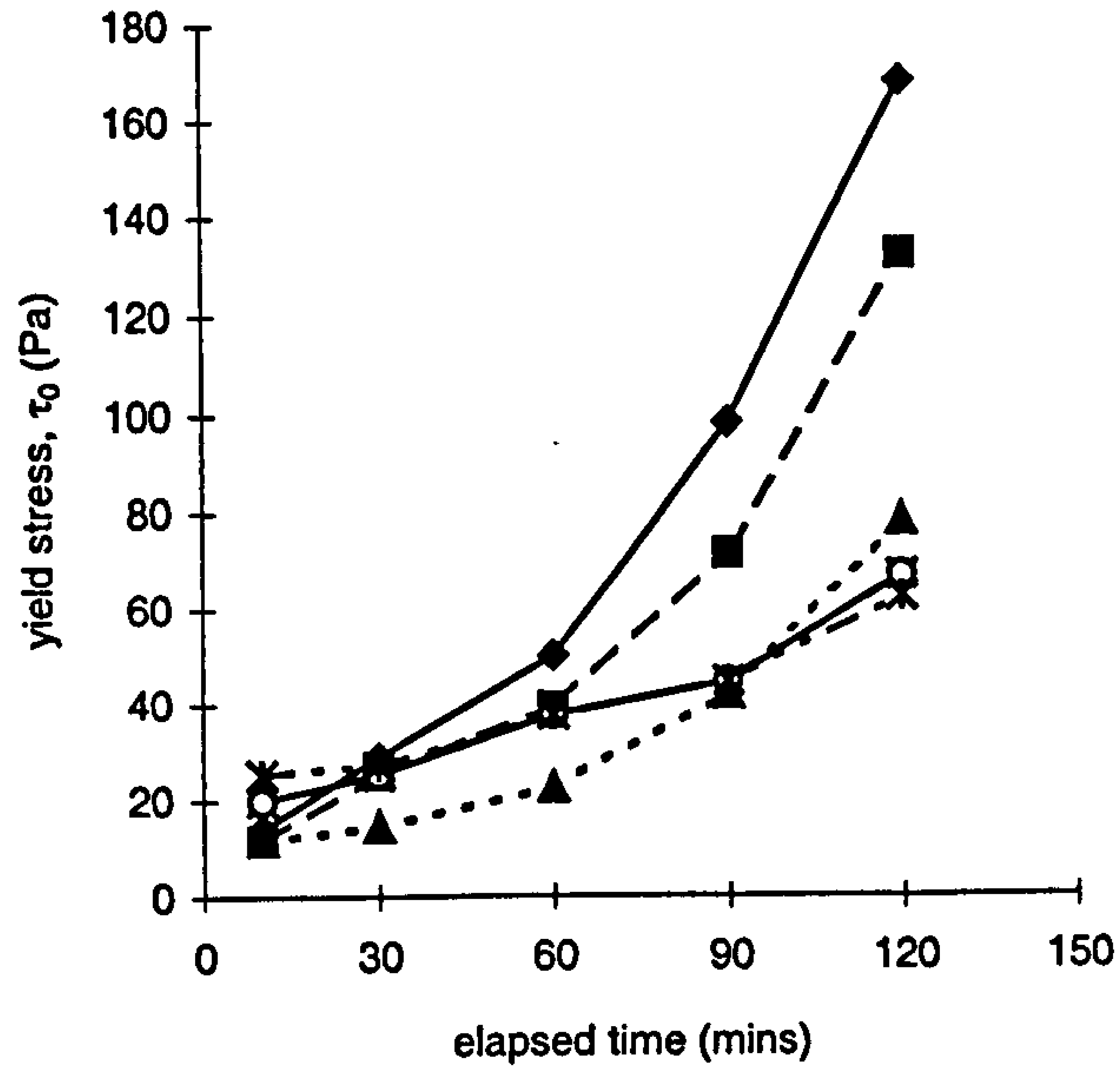
& (b)). This performance is consistent with results from others as shown in **figure 2-26.**

A different result of workability retention was obtained in terms of V-funnel flow time and plastic viscosity, shown in **figure 9-12 (c) & (d).** All the Welan gum mixes had a very similar trend of workability retention although they have different initial values, reflecting little effect of the dosage of Welan gum. It was concluded in chapter 7 that the fundamental factors controlling the initial value and development of plastic viscosity for a mix is the particle concentration and the distance between particles. Welan gum did change the initial plastic viscosity by increasing the viscosity of water but the particle concentration was constant and the distance between them therefore has little effect on the plastic viscosity development. This is similar to the effect of superplasticizer as discussed in chapter 7.

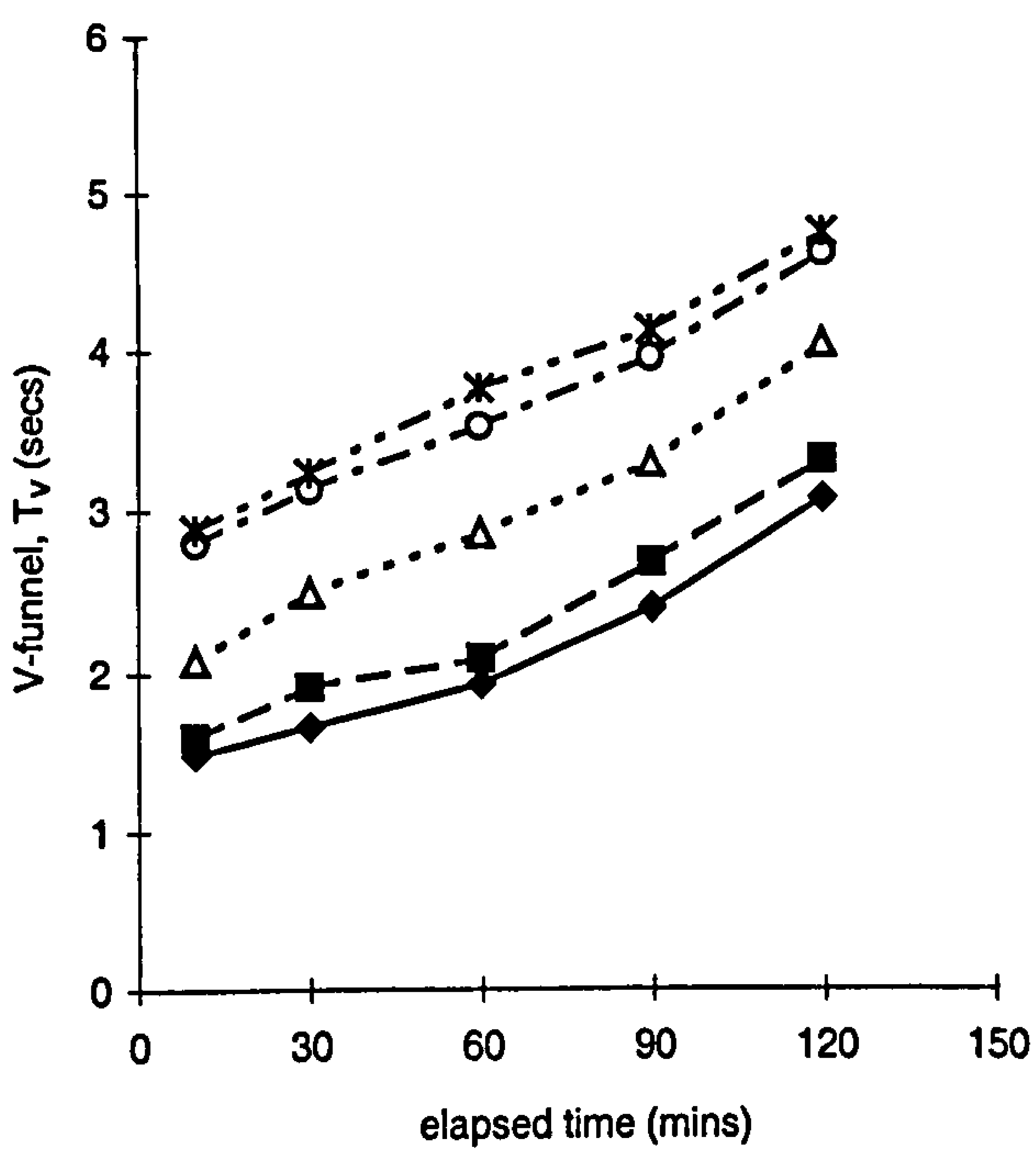
Figure 9-13 shows the comparison of workability retention between the PC2 mix and SRC1 mix with the same dosage of Welan gum. It would be expected that SRC mix has better performance than PC mix, as found for the mixes with Glenium51 without a viscosity agent. Surprisingly this is not the case for these mixes. This might be for two reasons: Glenium51 has a significant influence on workability retention in SCC without a viscosity agent; and or the effect of the low C_3A content in SRC is not significant compared to that of Welan gum. However, further investigation is needed to confirm this.



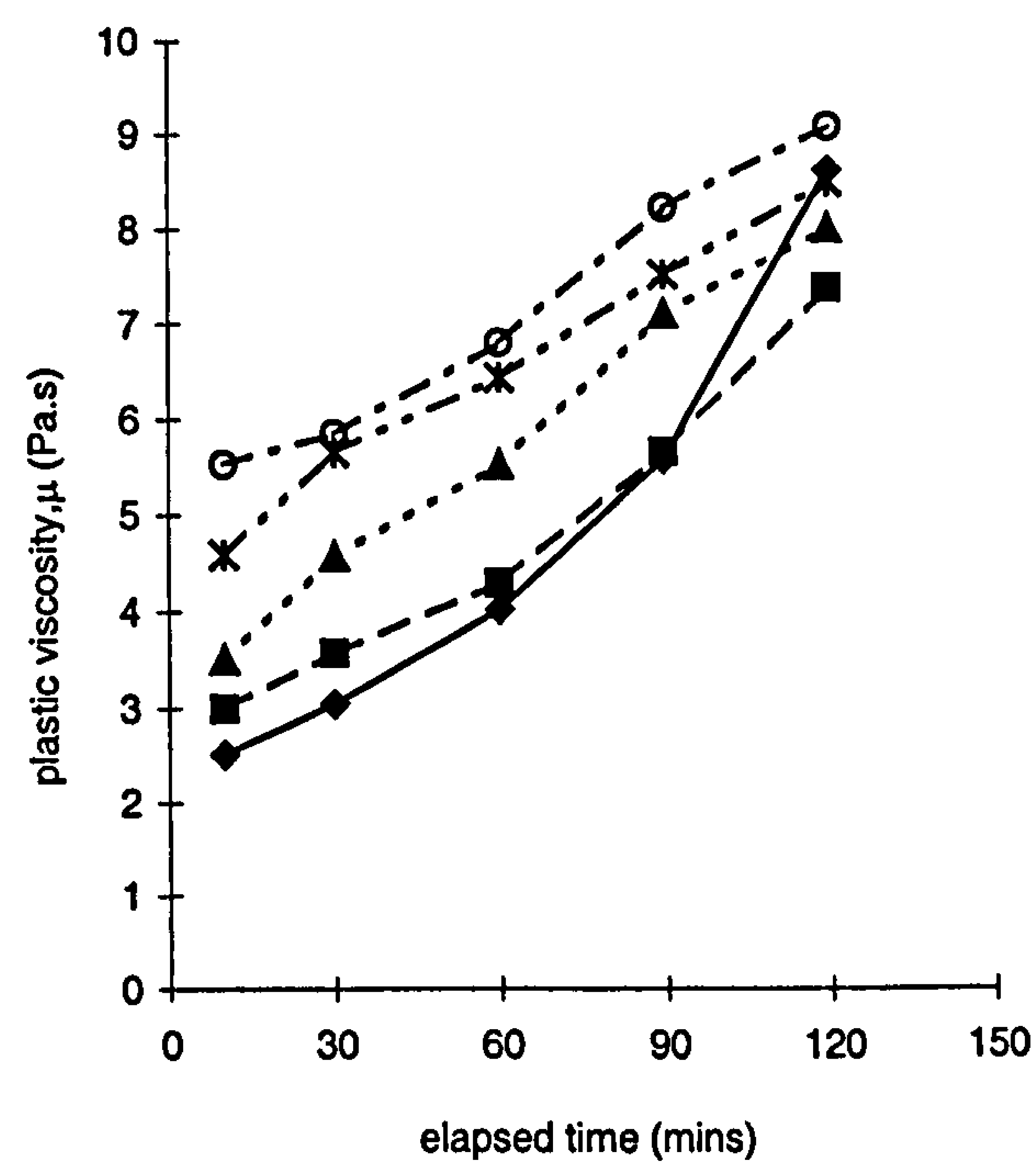
(a) spread



(b) yield stress

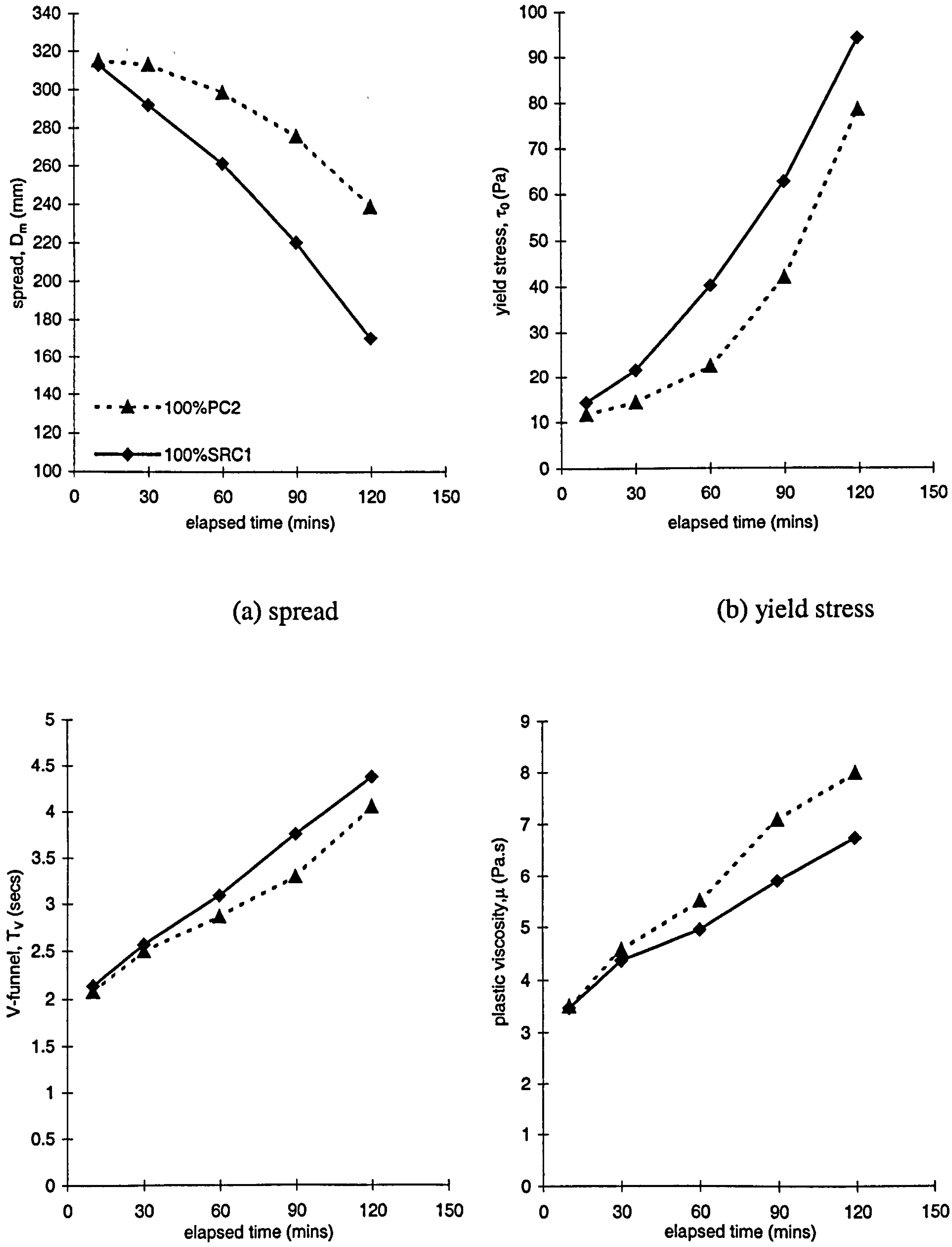


(c) V-funnel flow time



(d) plastic viscosity

Figure 9-12 Workability retention of single powder mix with various dosages of Welan gum



(a) spread

(b) yield stress

(c) V-funnel flow time

(d) plastic viscosity

Figure 9-13 Comparison of workability retention of SRC mix and PC mix

Setting time and strength development were also tested for all the mixes, and **figure 9-14** & **9-15** show the results. Clearly, the setting time was delayed with the increased Welan gum dosage, and this is more significant at high dosage, for example, there is little delay at 0.025% level; but the initial and final setting times increased by about 2 and 3 hours at 0.05% level, and 7 and 8 hours at 0.1% level respectively. The early strength and 28 day strength also decreased. This is consistent with Khayat *et al* [75] results that the coupled effect of Welan gum and superplasticizer delays the onset of initial setting of cement paste. The SRC1 mix had similar setting time to the PC2 mix but much lower 28 day strength.

In general, Welan gum improves workability retention in terms of spread and yield stress but has little effect on the development of V-funnel flow time and plastic viscosity. Welan gum also delays setting time and slows down strength development, therefore, the final strength may be affected.

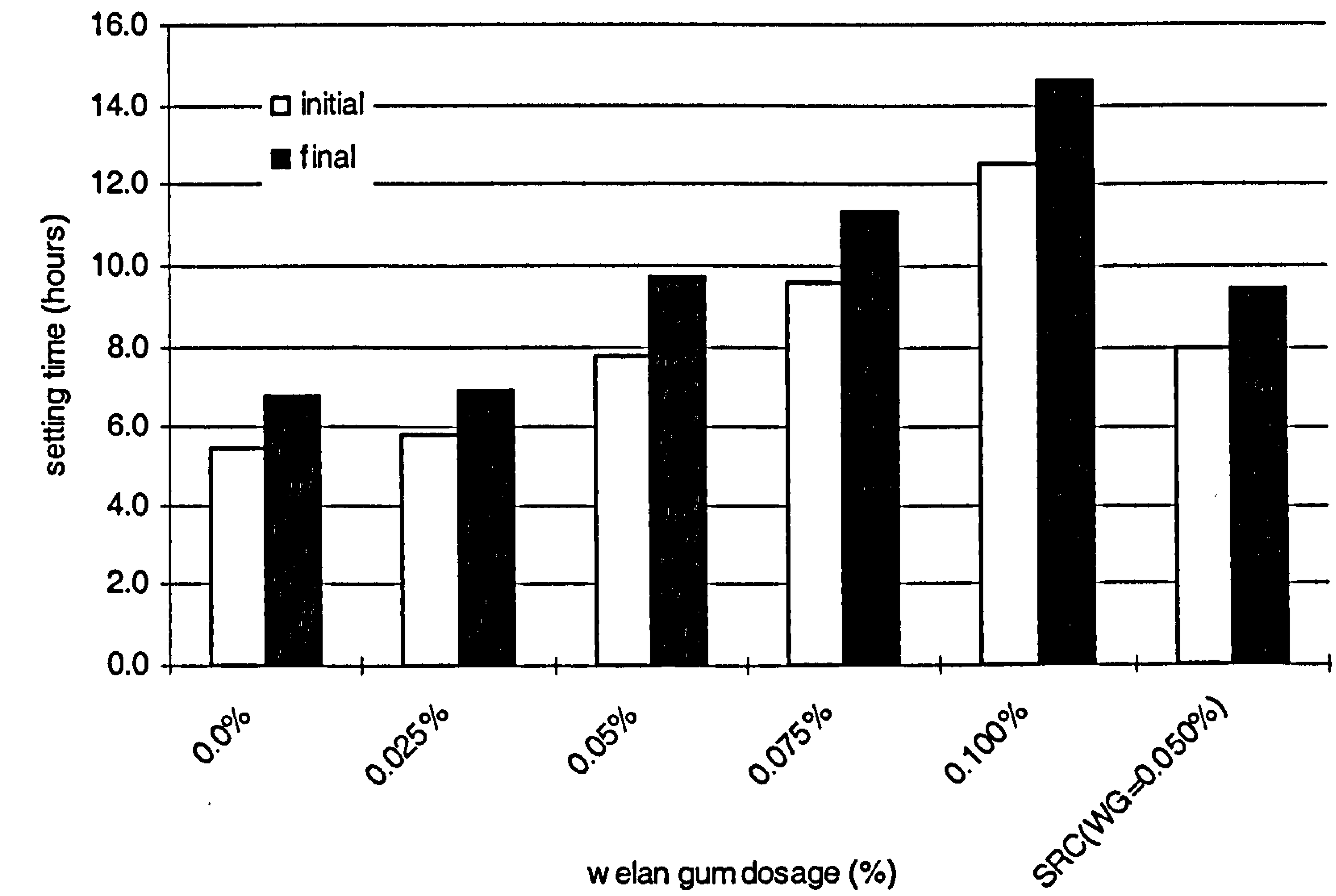


Figure 9-14 Effect of Welan gum content on setting time of mortar

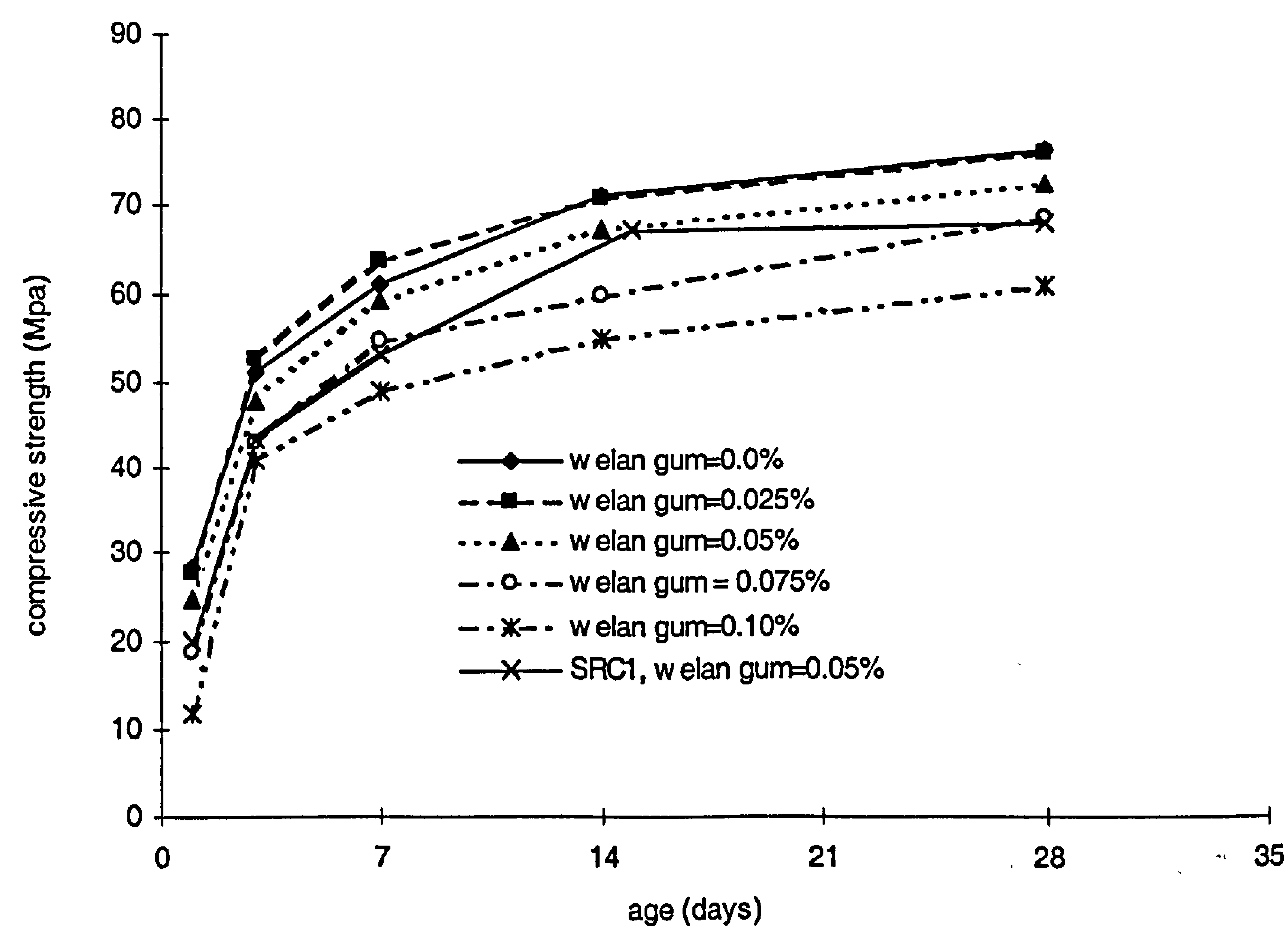


Figure 9-15 Effect of Welan gum on compressive strength development for mortar

9.3.2 Concrete

Concrete tests were carried out to further confirm the findings from mortar test results. **Table 9-5** shows the mix proportions and initial properties. All the concrete mixes used a powder of 100% PC4 or 100% SRC2, a water/cement ratio of 0.35 by weight, a 0.45 sand to mortar ratio by volume and a coarse aggregate volume of 0.317 m^3 per cubic meter (50% of the dry rodded bulk density). Conplast430 was used, and the dosage of superplasticizer was determined in the same way as before but for the mortar component of the concrete, so as to achieve a spread of 300-310 mm. Comparing the initial properties for the same mixes shown in **table 9-4** shows that all the PC4 mortar mixes had similar superplasticizer dosage requirements and initial properties to that of the PC2 mixes. As in previous tests, τ_0 was not measurable. The concrete slump flow (SF) was in a range of 670-750 mm, and the T_V, T_{500} and μ increased with the increase of Welan gum dosage, however, no conclusive results were given by the $T_{u\text{-box}}$ test. All mixes had higher than 300 mm filling height in the U-box tests.

Table 9-5 Mix proportions and initial properties for concrete and mortar with various Welan gum dosage

		WG dosage		Mortar test					Concrete test						
Mix No.	Types of cement	(By wt of Water %)	sp* (%)	D_m (mm)	T_{250} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	SF (mm)	T_{500} (s)	T_V (s)	τ_0 (Pa)	μ (Pa.s)	U_H (mm)	$T_{u\text{-box}}$ (s)
C9-5	PC4	0	0.5	313	2	1.94	12.0	2.9	670	1.41	3.81	**	39	316	1.67
C9-6		0.05	0.75	313	3.88	2.91	17.3	4.9	740	1.72	4.35	**	58	334	1.47
C9-7		0.075	1.2	301	6.34	3.38	26.2	6.3	698	2.87	5.69	**	71	328	2.31
C9-8	SRC2	0.075	1.0	318		2.46			753		3.31			336	

*by the weight of powder ** not measurable

The change in properties with time after mixing can be seen in **figure 9-16, 9-17, 9-18 & 9-19**. The change of slump flow time and spread flow time was not plotted because of fast workability loss with few data obtained for each mix. As expected from the mortar the test results, the workability retention was improved significantly in terms of slump flow with the addition of Welan gum, but not much difference was found for the retention in terms of V-funnel and plastic viscosity. The workability retention of the mixes with 0.05% and 0.075% Welan gum content are very close, suggesting that there may be a limiting value of Welan gum dosage beyond which increase of dosage did not induce further improvement. This is consistent with the mortar tests results from previous section. The SRC2 mix had the same workability retention as the PC4. In summary the fresh properties of the SRC was similar to that of 100% PC for Welan gum mix. All the Welan gum mixes retained satisfactory passing ability for more than1 hour while the control mix retained for less than 30 minutes after mixing.

Figure 9-20 shows the strength development. It can be seen that both 1 day and 28 days strength were decreased with the addition of Welan gum, and the reduction of early strength (about 25% reduction at 0.075% Welan gum dosage) was relatively higher than that at 28 days (about 10% reduction at 0.075% Welan gum dosage).

It can be concluded that the dosage of Welan gum has the following effects on SCC properties with a single type of powder:

- It improves workability retention in terms of spread and yield stress with little effect in terms of V-funnel flow time and plastic viscosity, but there is a limiting dosage beyond which no further improvement is achieved.
- It delays setting time and decreases early and 28 day strength.
- The workability retention of the SRC mix does not show any improvement compared to the PC mix with Conplast430 and Welan gum.

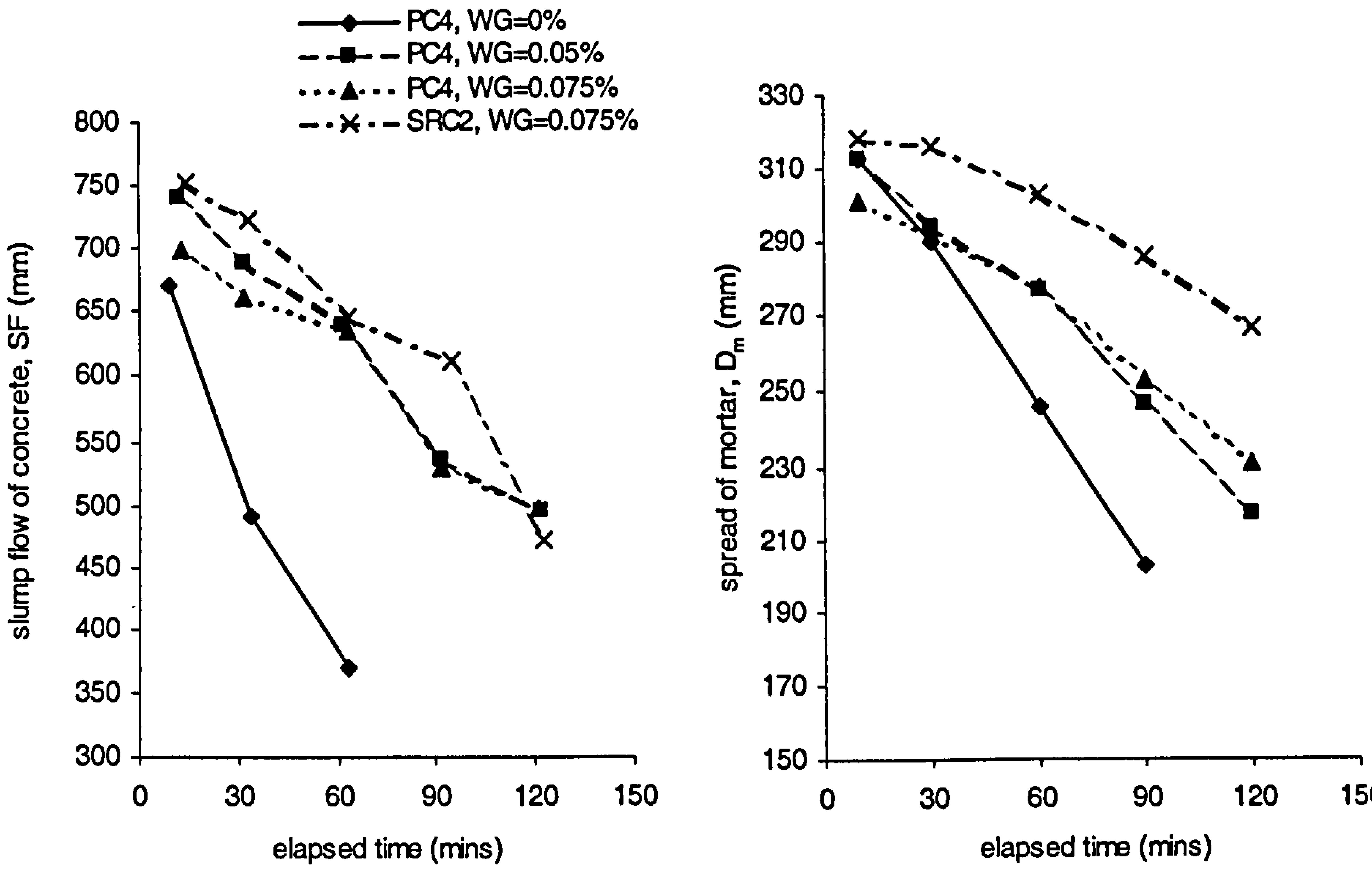


Figure 9-16 Effect of Welan gum dosage on slump flow loss for concrete and spread loss for mortar

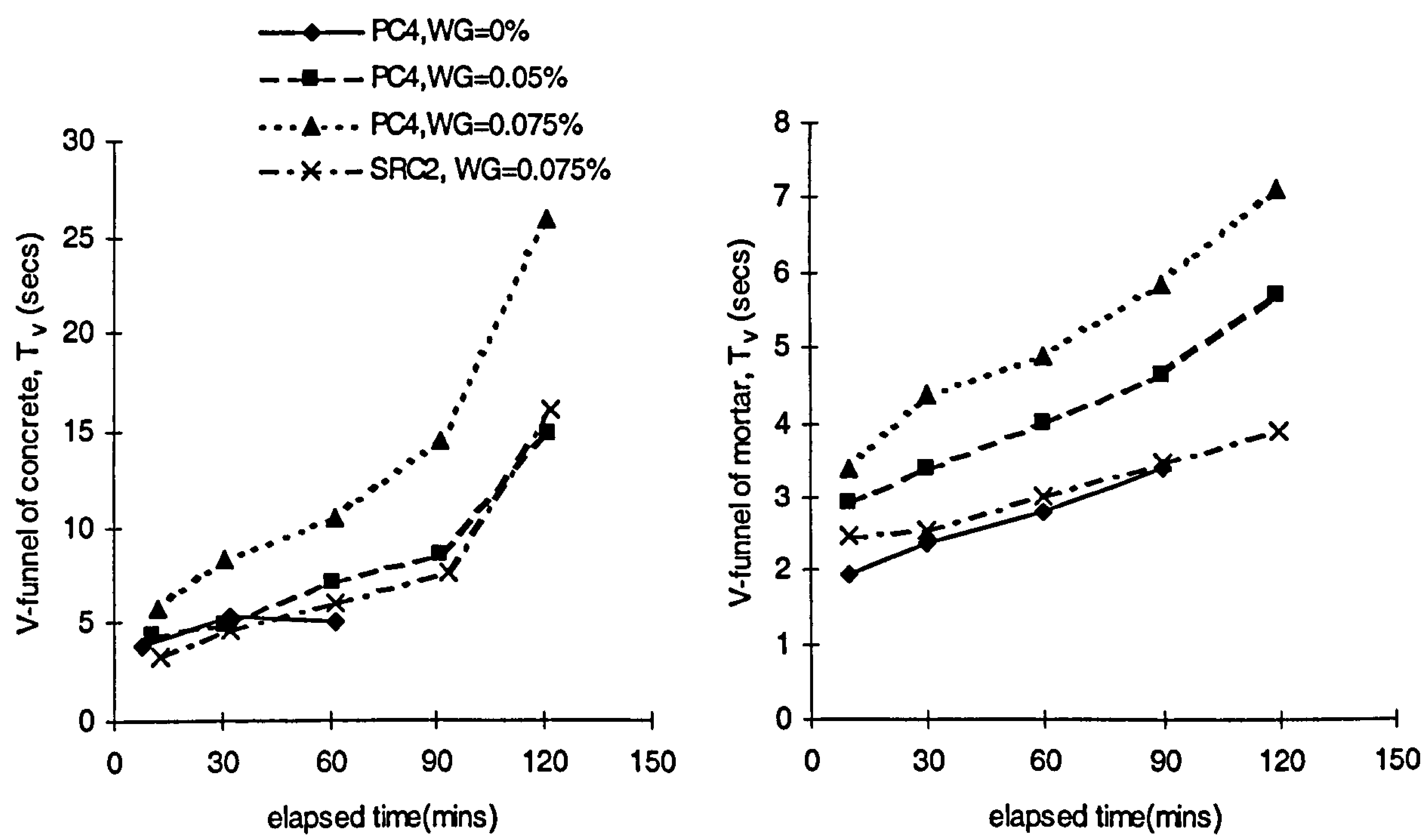


Figure 9-17 Effect of Welan gum dosage on the development of V-funnel flow time for concrete and mortar

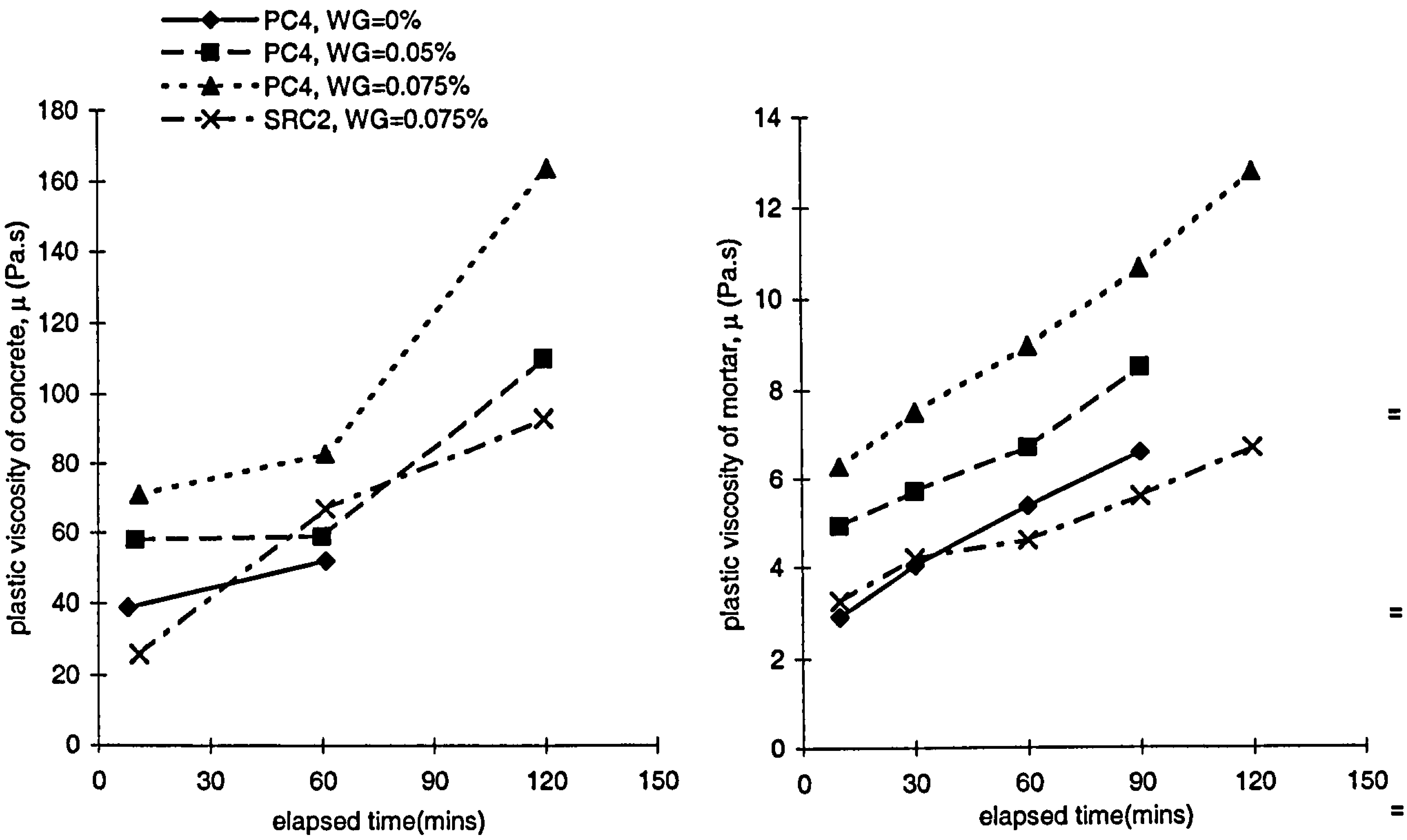


Figure 9-18 Effect of Welan gum dosage on the development of plastic viscosity for concrete and mortar

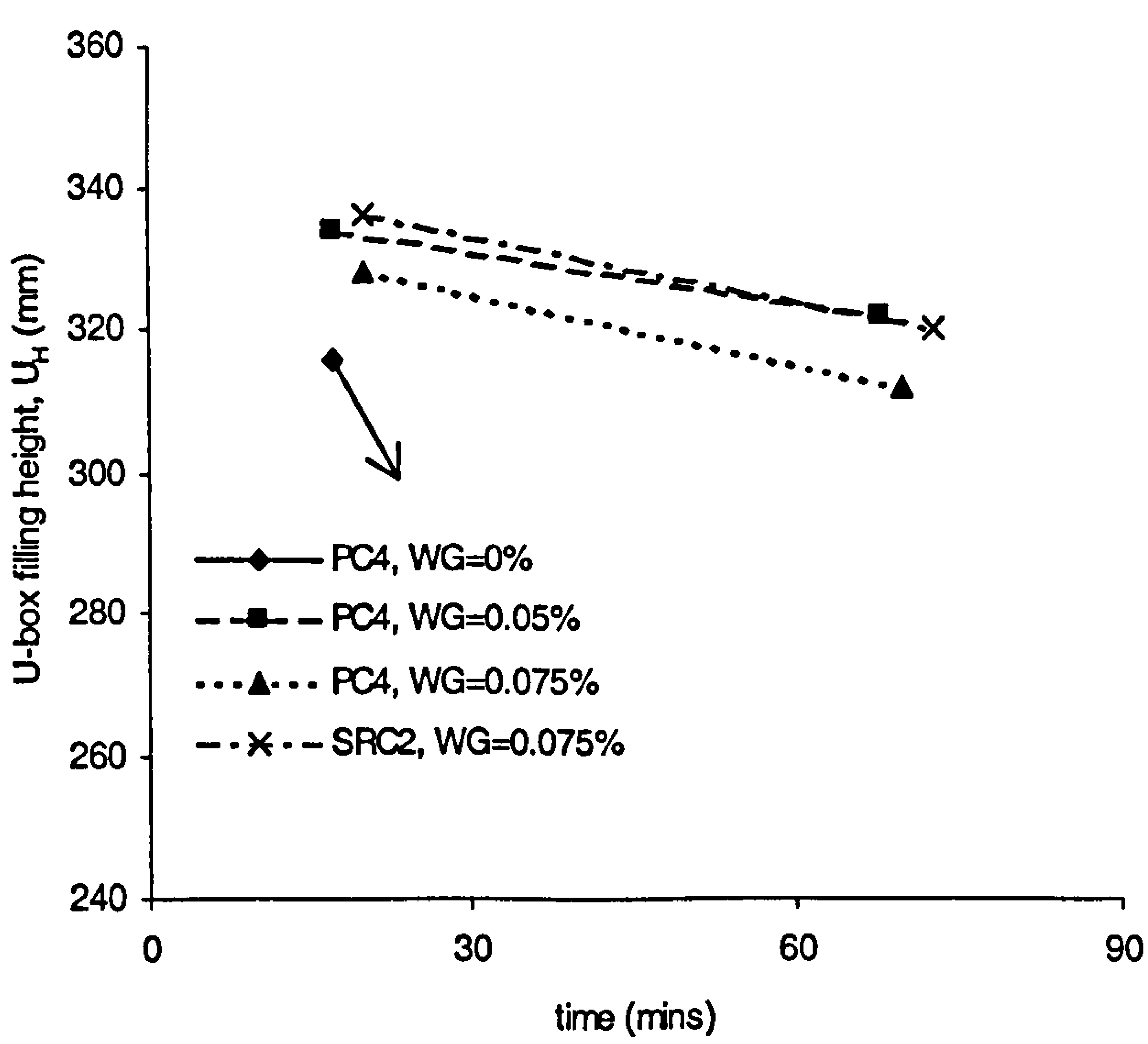


Figure 9-19 U-box filling height for the concrete with various Welan gum dosages

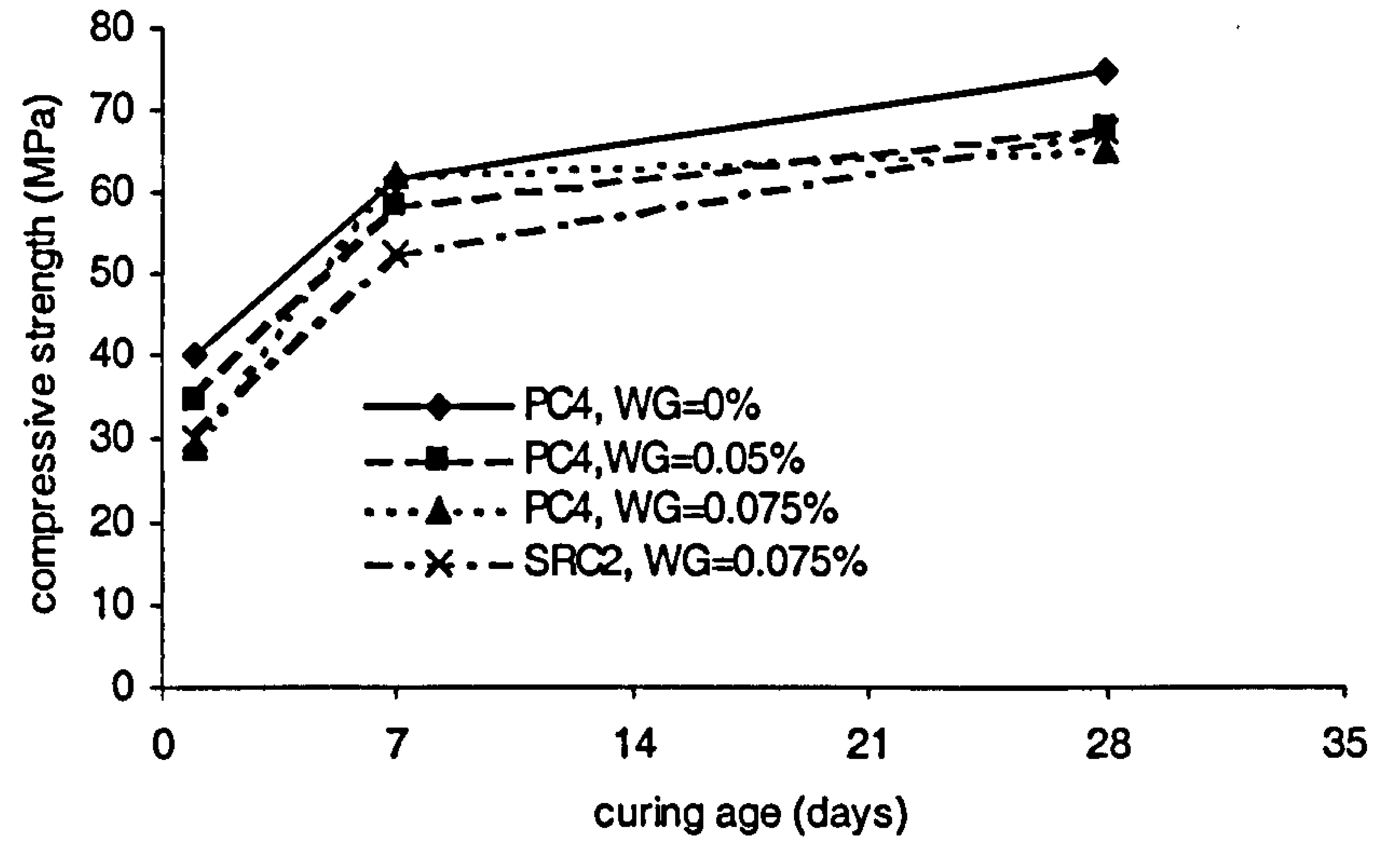


Figure 9-20 Strength development of Welan gum mixes

9.4 Effect of Welan gum on the properties of the mixes with binary blends of powder

9.4.1 Mortar

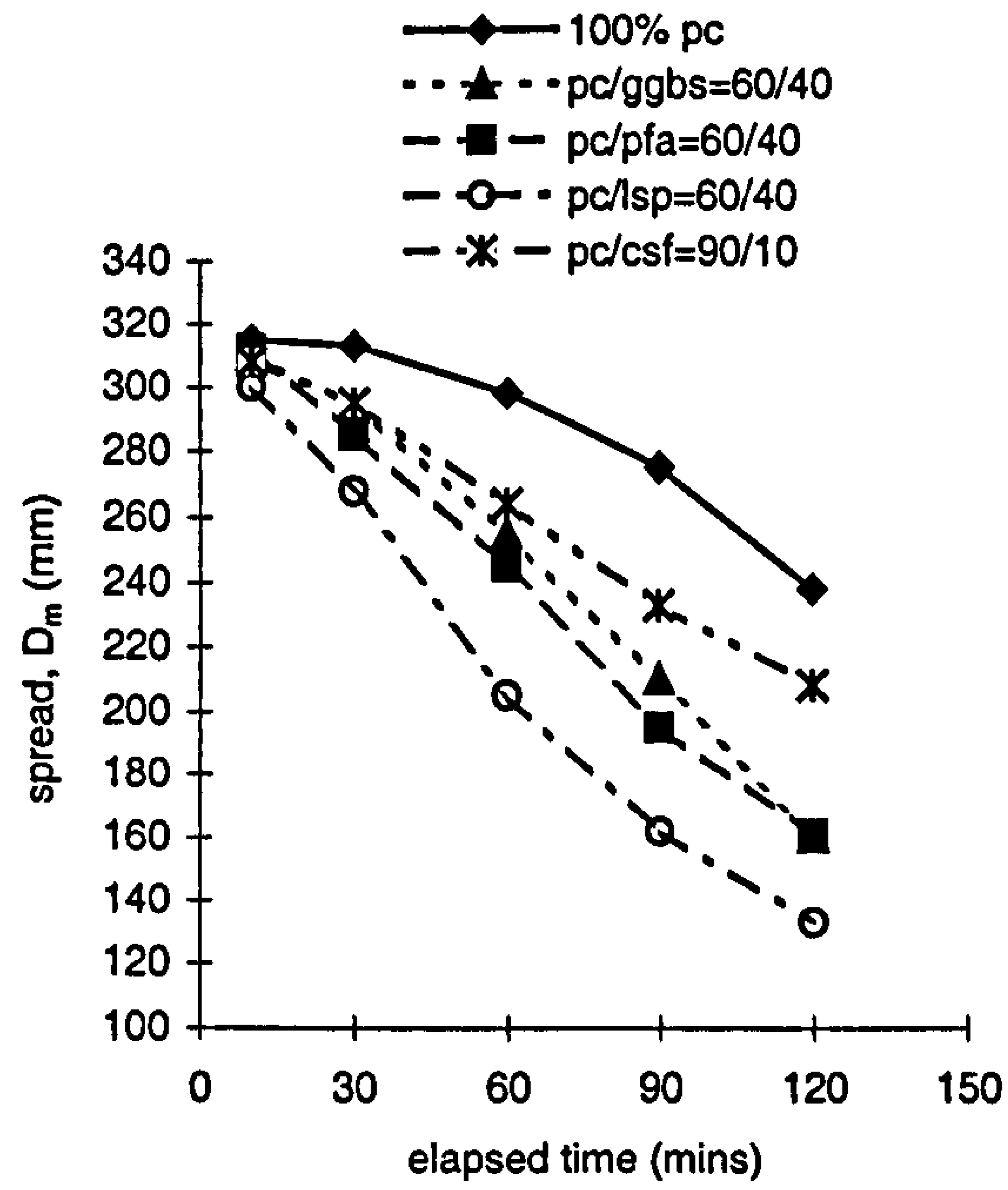
The properties of Welan gum mixes with binary blends of powder were studied. **Table 9-6** shows the mix proportion and initial properties. The water/powder ratio was maintained at 1.103, which is the equivalent to a water/cement ratio of 0.35 by weight, which is the same as for the single powder mixes, and the sand/mortar ratio was 0.45 by volume. The Welan gum dosage was chosen as 0.05% by the weight of water in all mixes, according to its performance in single powder mix, and Conplast430 dosage was adjusted such that a spread value between 300-310 mm was obtained for each mix. As expected from previous tests on similar mixes with Glenium51, the PFA, GGBS and LSP100 mixes required a lower superplasticizer dosage than the 100% PC mix. The CSF mix also required a higher dose, but not as high as that with Glenium51 in the similar mix without Welan gum, which may be due to the higher water/powder ratio and the different type of superplasticizer used. Again, significantly different V-funnel flow times and plastic viscosities were obtained; the GGBS mix had the highest, closely followed by mixes with PC SRC, PFA, LSP, and much lower for the CSF mix.

Table 9-6 Mix proportions of and initial properties of Welan gum mixes with various types of binary blends of powder

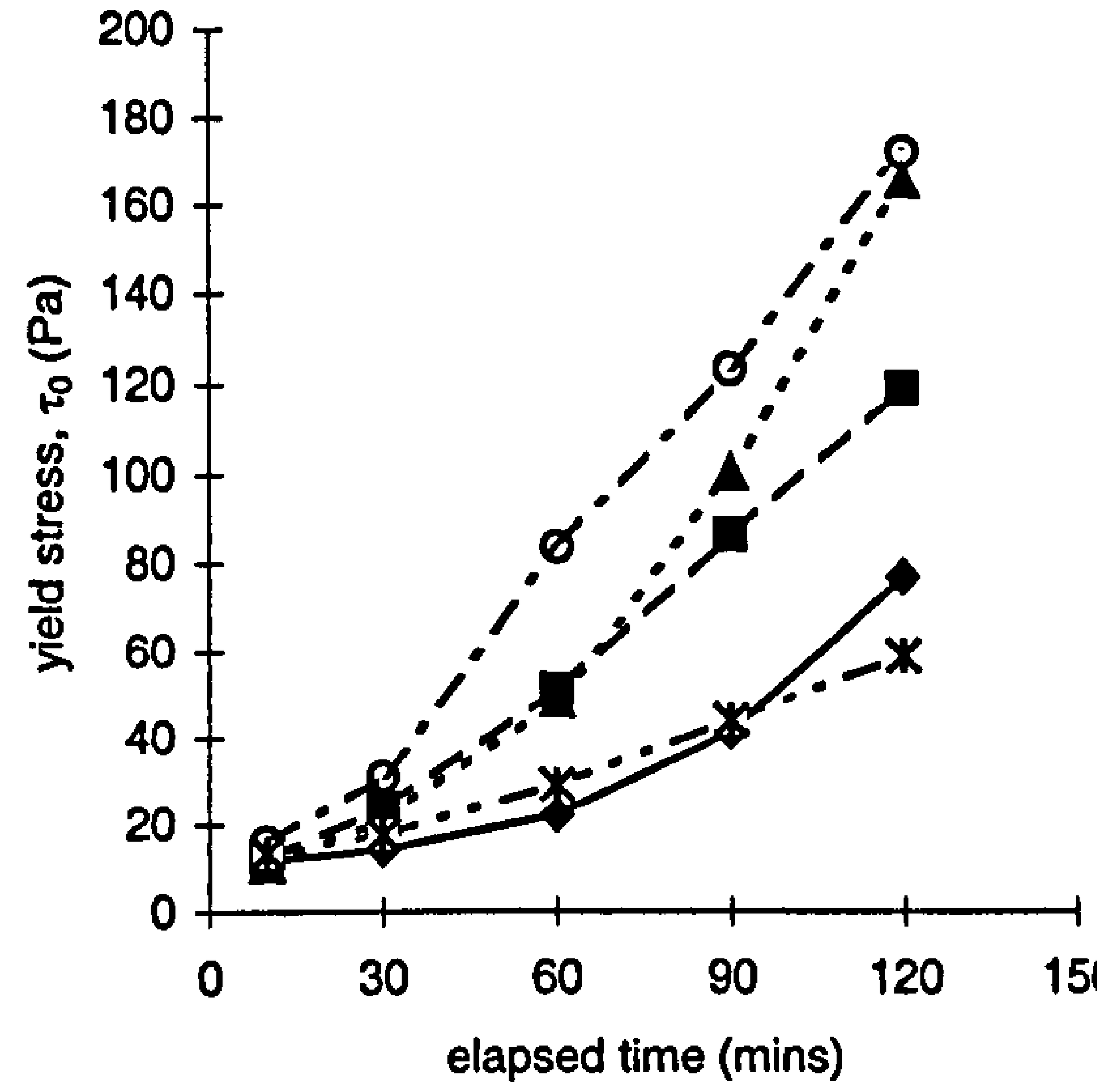
Mix	Powder composition					Sp dosage	D_m	T_v	τ_0	μ
no.	PC2	GGBS	PFA	LSP100	CSF	(% by wt)	(mm)	(secs)	(Pa)	(Pa.s)
M9-15	100					0.7	315	2.08	11.7	3.5
M9-16	60	40				0.55	310	2.38	10.8	4.2
M9-17	60		40			0.46	312	1.78	12.6	2.8
M9-18	60			40		0.42	300	1.88	16.2	3.1
M9-19	90				10	0.8	308	1.24	13.5	1.5

Figure 9-21 shows the results for workability retention. The CSF mix was similar to the 100% PC mix in terms of spread and yield stress, which may be due to the lower requirement for superplasticizer dosage compared to the Glenium51 mixes without Welan gum. This is followed by the GGBS and PFA mixes, and the LSP mix which had least workability retention. This is consistent with the properties of these binary mixes without Welan gum, but different from the results obtained by Sakata [74] in which LSP binary mortar showed the best spread retention among those binary mixes as reviewed in **figure 2-46**. The reason may be due to different properties of raw materials from different sources. Apparently, there is an effect of the dosage of superplasticizer, but the influence of Conplast430 is not as great as that of Glenium51.

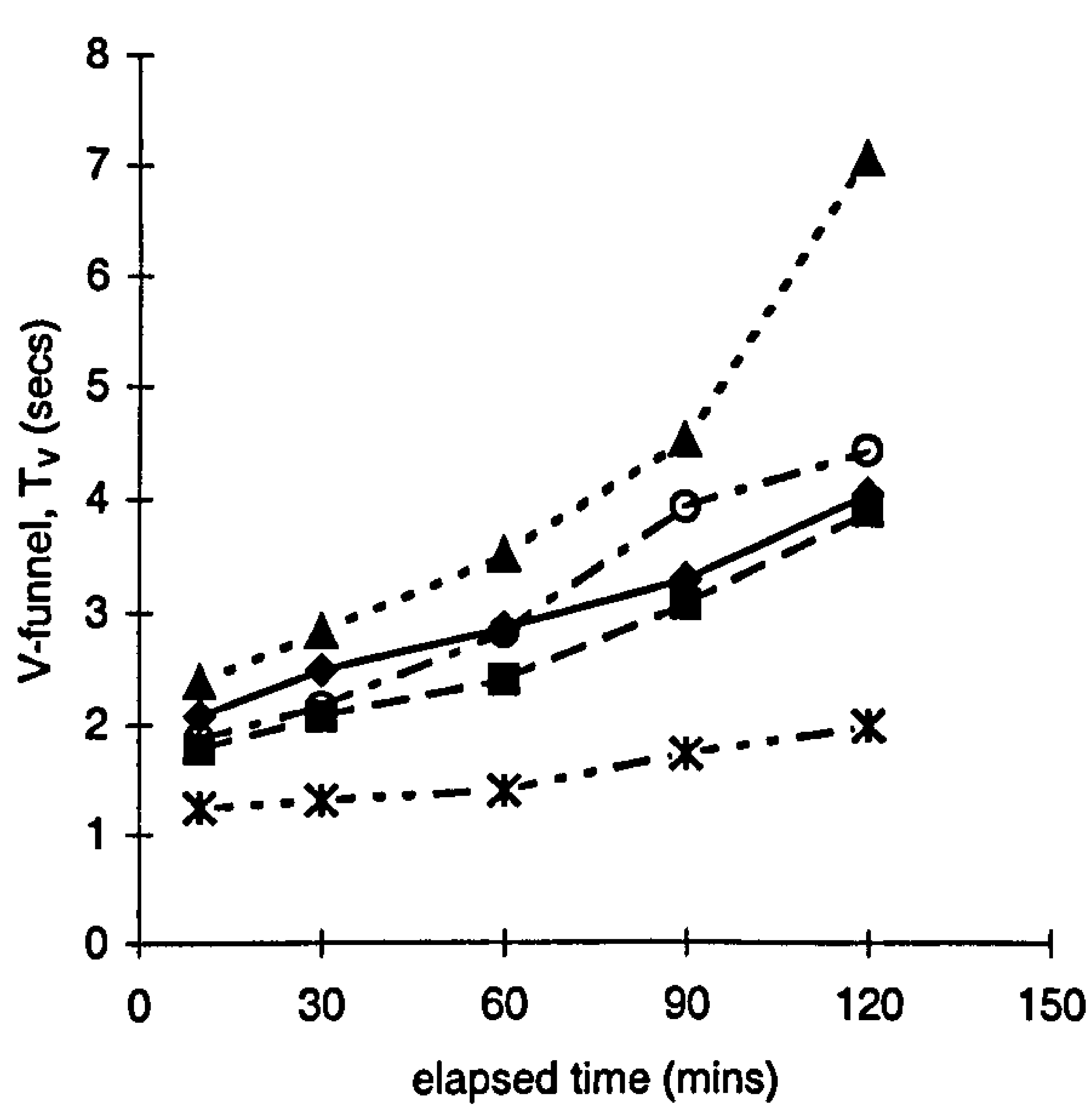
The workability retention in terms of V-funnel flow time and plastic viscosity again followed the trend of their initial values, which can be explained by different packing density for the different blends. Therefore the best workability retention was obtained in the CSF mix.



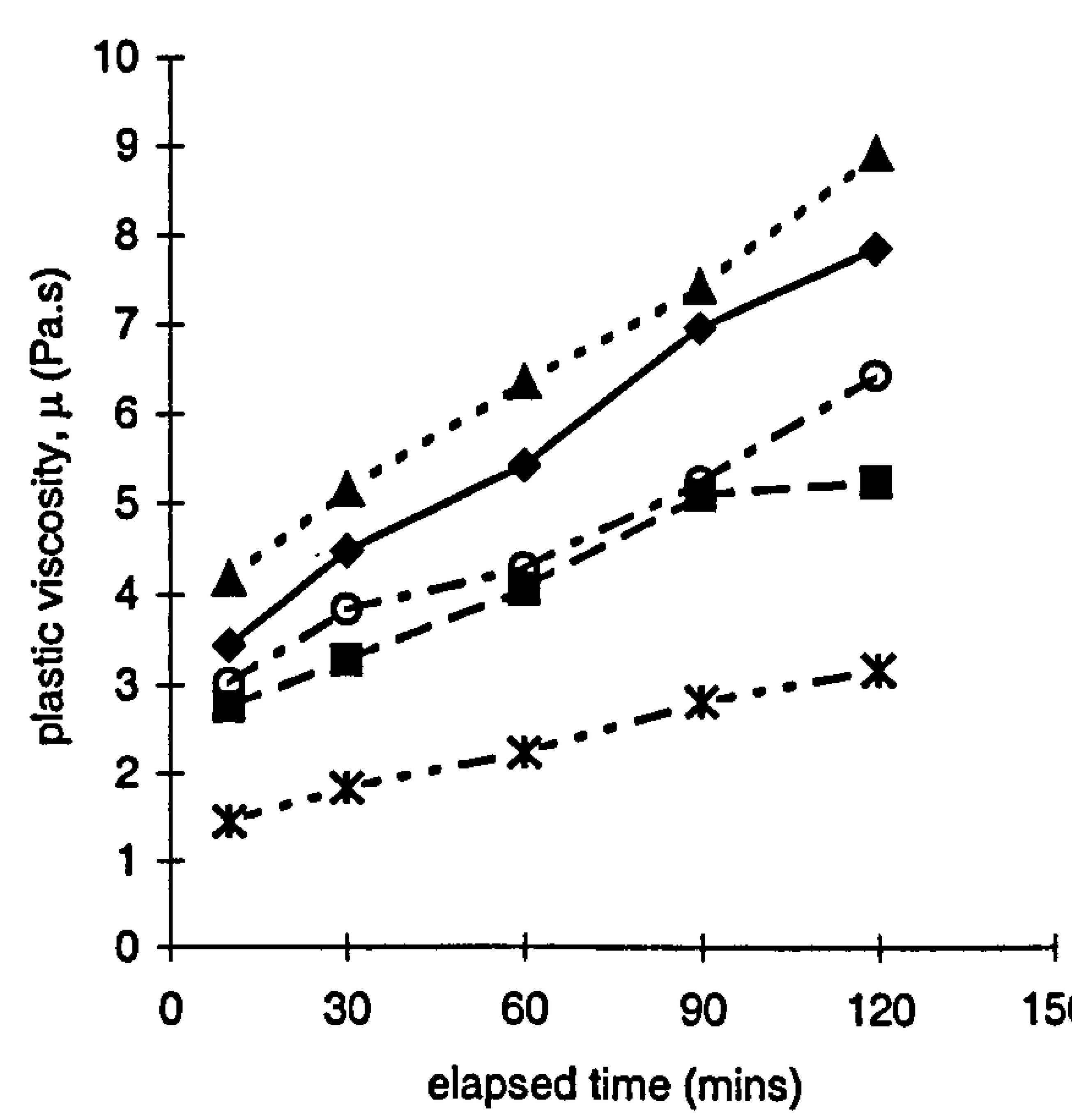
(a) spread



(b) yield stress



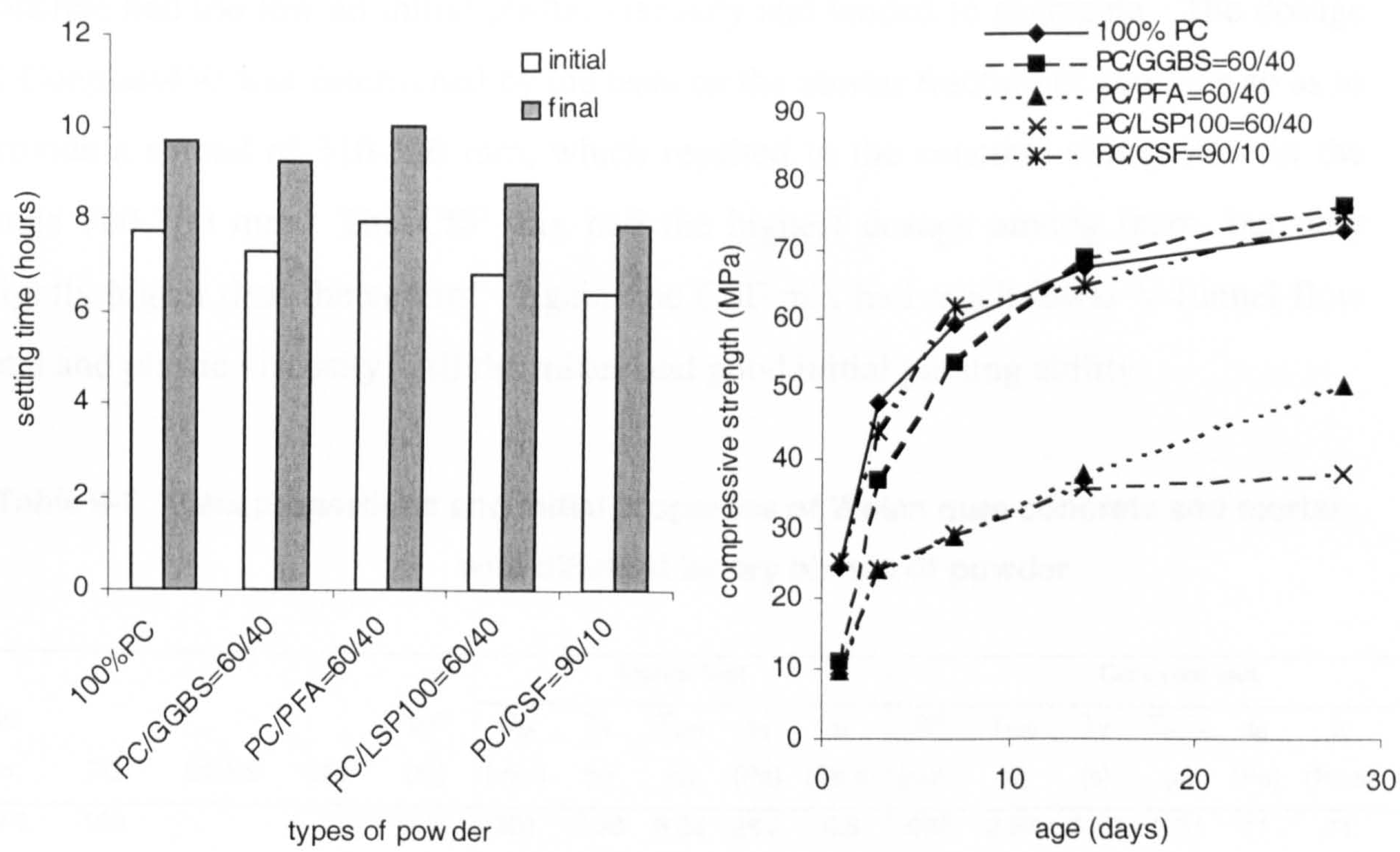
(c) V-funnel flow time



(d) plastic viscosity

Figure 9-21 Workability retention of Welan gum mixes with various binary blends of powder

The results for setting time and strength development of these mixes are shown in **figure 9-22**. Again there is no relation between workability retention and the setting times. The CSF had the shortest setting time, followed by the LSP100, GGBS mixes, the 100% PC and PFA mixes. The strength development was closely related to water/cement ratio and the types of blends. The 100% PC, GGBS and CSF mixes had similar 28 day strength with the GGBS mix having a lower 1 day strength; the PFA mix had both lower 1 day and 28 day strength compared to the 100% PC mix, but higher strength than the LSP100 mix. The relationship between strength and the mix composition will be discussed in chapter 10.



(a) setting times (b) strength development

Figure 9-22 Setting times and strength development for Welan gum mixes with binary blends of powder

9.4.2 Concrete

Concrete tests were carried out to confirm the mortar test results. Two binary mixes were chosen, a GGBS and a CSF mix; **table 9-7** shows the mix proportions and initial properties. As before the concrete mixes all contained 1.103 water/powder ratio (equal to 0.35 water/cement ratio by weight) and 0.45 sand/mortar ratio by volume and a coarse aggregate volume of 0.317 m^3 per cubic meter (50% of the dry rodded bulk density). The Welan gum dosage was 0.075% by weight of water instead of 0.05% used in previous mortar test because it was found in a trial mix that the CSF concrete had too low an initial plastic viscosity and tended to segregate. The dosage of Conplast430 was determined by the tests on the mortar fraction of concrete so as to provide a spread of 310-320 mm, which resulted in the concrete slump flow in the range 700-760 mm. The CSF mix had the highest dosage among them, but only slightly higher than the control. Again, the CSF mix had much lower V-funnel flow time and plastic viscosity. All the mixes had good initial passing ability.

Table 9-7 Mix proportions and initial properties of Welan gum concrete and mortar with different binary blends of powder

					Mortar test					Concrete test						
Mix No.	PC	GGBS	CSF	sp* (%)	D_m (mm)	T_V (s)	T_{250} (s)	τ_0 (Pa)	μ (Pa.s)	SF (mm)	T_{500} (s)	T_V (s)	$T_{u\text{-}box}$ (s)	τ_0 (Pa)	μ (Pa.s)	U_H (mm)
C9-7	100			1.2	301	3.38	6.34	26.2	6.3	698	2.87	5.69	2.31	**	71	328
C9-9	60	40		0.9	318	4.74	4.29	11.7	6.8	755	2.49	6.95	2.32	**	121	325
C9-10	90		10	1.3	320	1.72	2.19	13.7	2.6	750	1.03	2.5	1.22	**	36	327

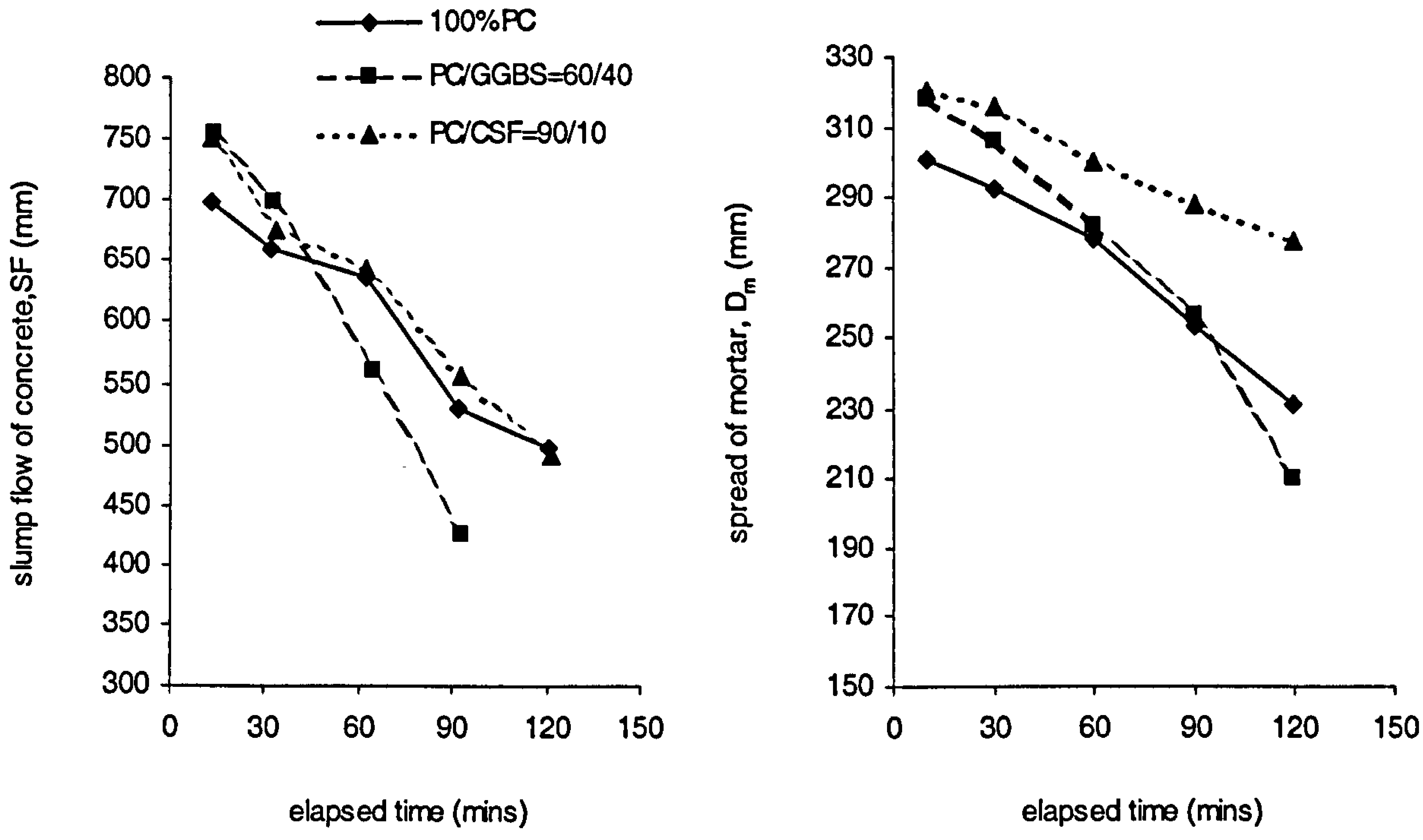
*by the weight of powder ** not measurable

Figures 9-23, 9-24, 9-25 & **9-26** show the test results for workability retention of the binary mixes and the 100% PC reference mix. Similar workability retention was obtained, in terms of slump flow, for the CSF mix compared to the reference mix, as was found with mortar, but that for the GGBS mix was much lower than the reference mix. The general trend for workability retention to be improved with superplasticizer dosage was still followed; however, this effect was not as significant as in the mixes with Glenium51.

The V-funnel and plastic viscosity results demonstrated again the advantage of low initial viscosity for better workability retention. Both binary mixes had a U-box filling height higher than 300 mm at 60 minutes after the start of mixing but that for CSF mix was 20 mm higher. Overall, the CSF mix showed better passing ability than the GGBS mixes.

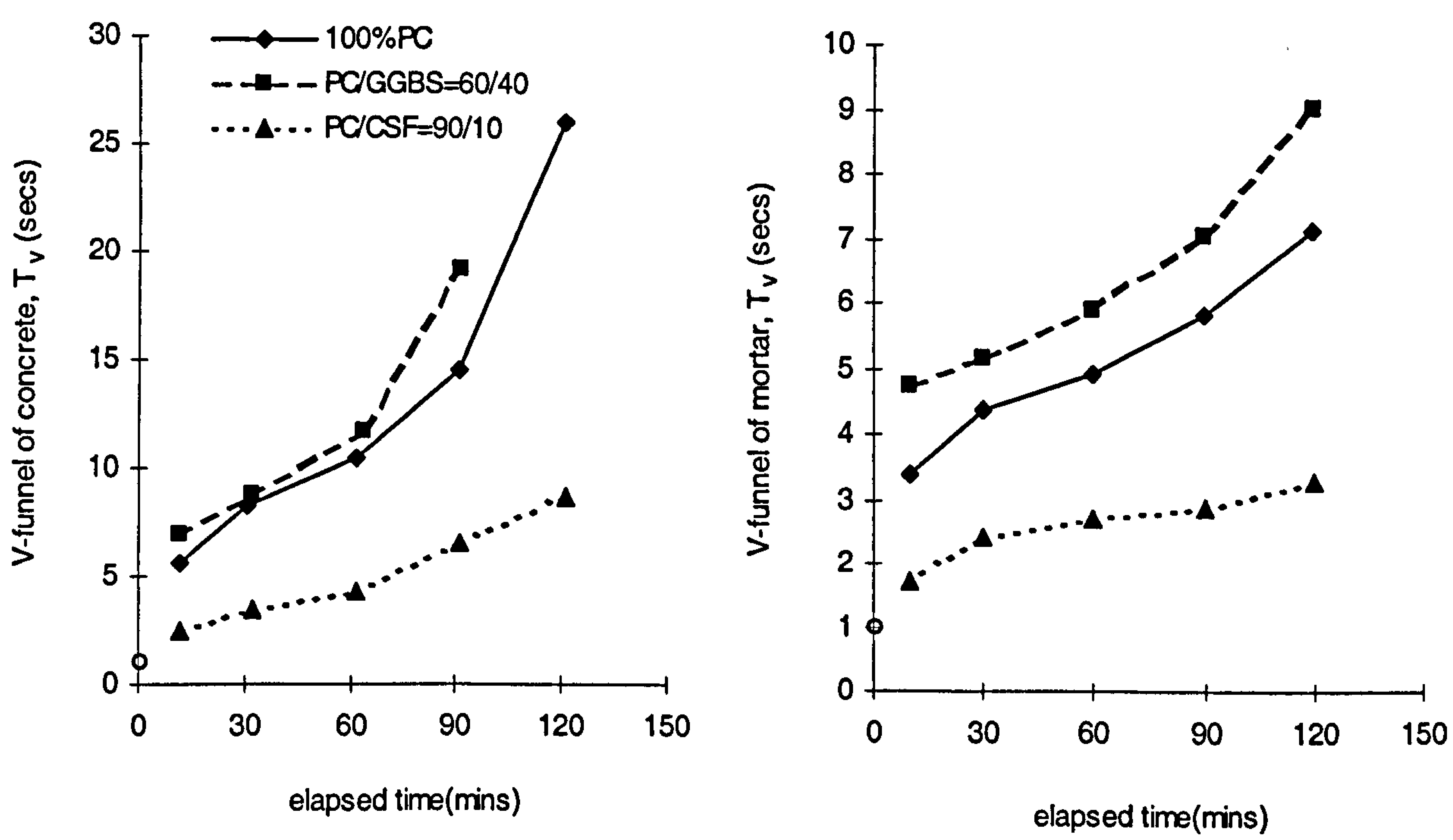
To summarise, there is general trend for workability retention in terms of yield stress to be improved with increase of superplasticizer dosage; while the workability retention in terms of plastic viscosity follows with decreased initial values due to increased packing density of the blends in the powder, but this effect was not as significant as in the mixes with Glenium51.

Extension of the tests to ternary mixes is not necessary because none of the binary mixes has significant advantage in terms of workability retention compared to single powder mixes, suggesting little benefit from the blends of powder.



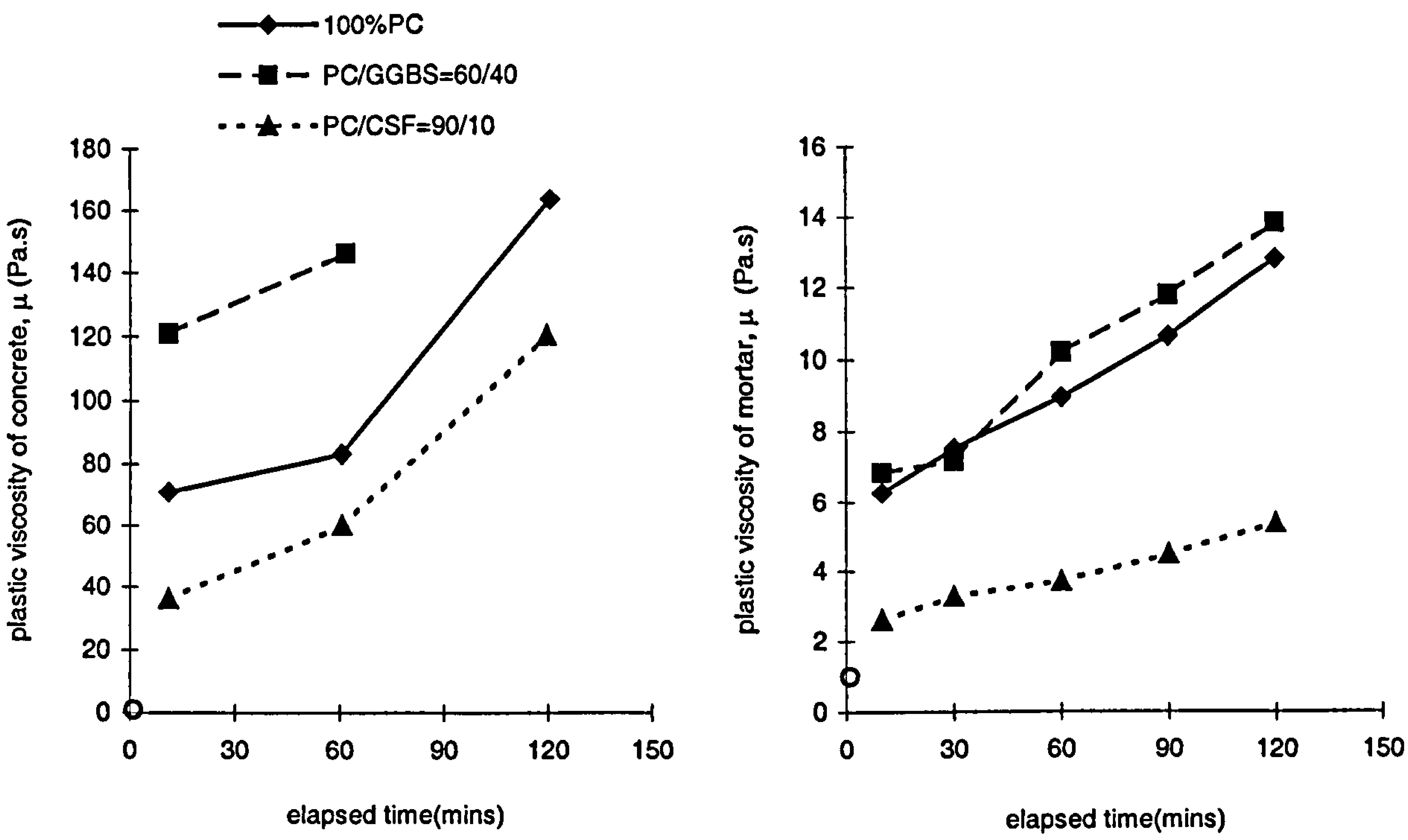
(a) concrete (b) mortar

Figure 9-23 workability retention of Welan gum mixes with various binary blends of powder in terms of Slump flow/spread



(a) concrete (b) mortar

Figure 9-24 workability retention of Welan gum concrete and mortar mixes with various binary blends of powder in terms of V-funnel flow time



(a) concrete (b) mortar

Figure 9-25 workability retention of Welan gum concrete and mortar mixes with various binary blends of powder in terms of plastic viscosity

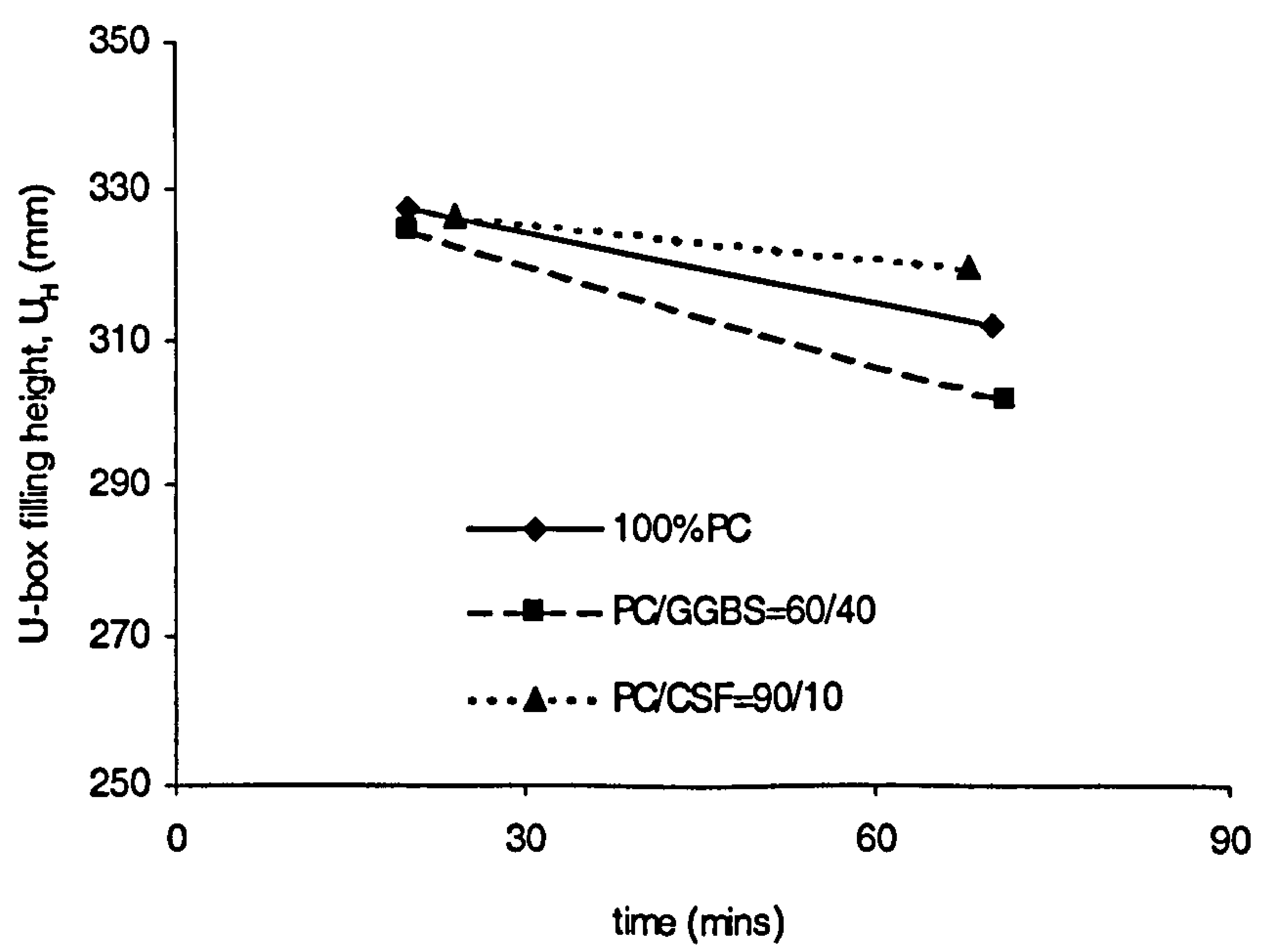


Figure 9-26 The change of U-box filling height with time for Welan gum mixes with various types binary blends of powder

9.5 Conclusions

From studying the properties of mortar and SCC with viscosity agent the following conclusions were made:

- Welan gum had a better compatibility with Conplast430 than with Glenium51.

- Welan gum does not only increase plastic viscosity but also yield stress, hence requires more superplasticizer to achieve the same yield stress as the mix without viscosity agent. The maximum spread at superplasticizer saturation dosage for mortar is reduced with increasing dosage of Welan gum. Too much dosage of Welan gum will reduce the maximum spread below 300 mm, which is the low limit for a mortar for SCC. For 100% PC mix with water/cement ratio of 0.4 Welan gum dosage should be no more than 0.1% by weight of water.

- Welan gum can improve workability retention due to delayed hydration and increased superplasticizer dosage. However, there is limiting dosage beyond which no further improvement with increase of Welan gum content, for example as 0.05-0.075% for the mix with water/cement ratio of 0.35.

- Setting time is delayed by the addition of Welan gum; the initial and final setting times increased about 2 and 3 hours at 0.05% level, 7 and 8 hours at 0.1% level respectively for mortar. Early strength decreased more significantly than 28 day strength, about 25% reduction at 0.075% Welan gum dosage compared to about 10% reduction at 0.075% Welan gum dosage for 28 day strength.

- In binary mixes the workability retention of CSF mixes showed performance similar to 100% PC mix in terms of yield stress but better workability retention in terms of plastic viscosity. There is an effect of superplasticizer dosage on the slump flow or spread retention, and the initial plastic viscosity on its development, but this is not as significant as that in Glenium51 mixes.

- The addition of a viscosity agent can allow SCC mix designs to use a wider range of water/cement ratio. Addition of Welan gum as a viscosity agent has many advantages but such non-adsorptive viscosity agent may be better. Further study on new types of viscosity agents is necessary.

Chapter 10

Further analysis and discussion of the test results

In previous chapters the results of tests investigating the effect of components of mortar on the properties of SCC were reported. In this chapter the whole set of test results are combined and analysed in terms of

- Rheological models. In particular, the applicability of the Herschel-Bulkley model for some types of mortar was considered. For this, some further testing was carried out. The details are presented in section 10.1.
- The relationships between the test results for
  - mortar properties,
  - concrete properties,
  - mortar and respective concrete properties.

  The details are described in section 10.2.
- Feret's rule for the prediction of compressive strength. The details are reported in section 10.3.

The test data are presented in **Appendices 7-14.**

10.1 Rheology of mortar

Throughout this research both mortar and concrete were considered as Bingham materials, and the analysis in previous chapters was based on this. However, it has also been suggested that SCC could be better described by Herschel-Bulkley model [108]. The flow curves obtained in this programme therefore were analysed for this type of behaviour.

10.1.1 Shear thickening

Shear thickening, i.e. the shear stress increasing more rapidly than the shear rate, occurred in two situations.

One consistent but small effect occurred when a mortar had an overdose of superplasticizer. A typical example is shown in **figure 10-1**. This apparent shear thickening may be caused by segregation. During testing, aggregate particles may start to settle to the bottom of the cup, with consequent "diluting" of the remainder of the mortar; as a result, during the shear rate reduction (i.e. on the down curve) the shear stress decreased more rapidly. This suggests that the apparent shear thickening is not a true mortar property but is caused by segregation.

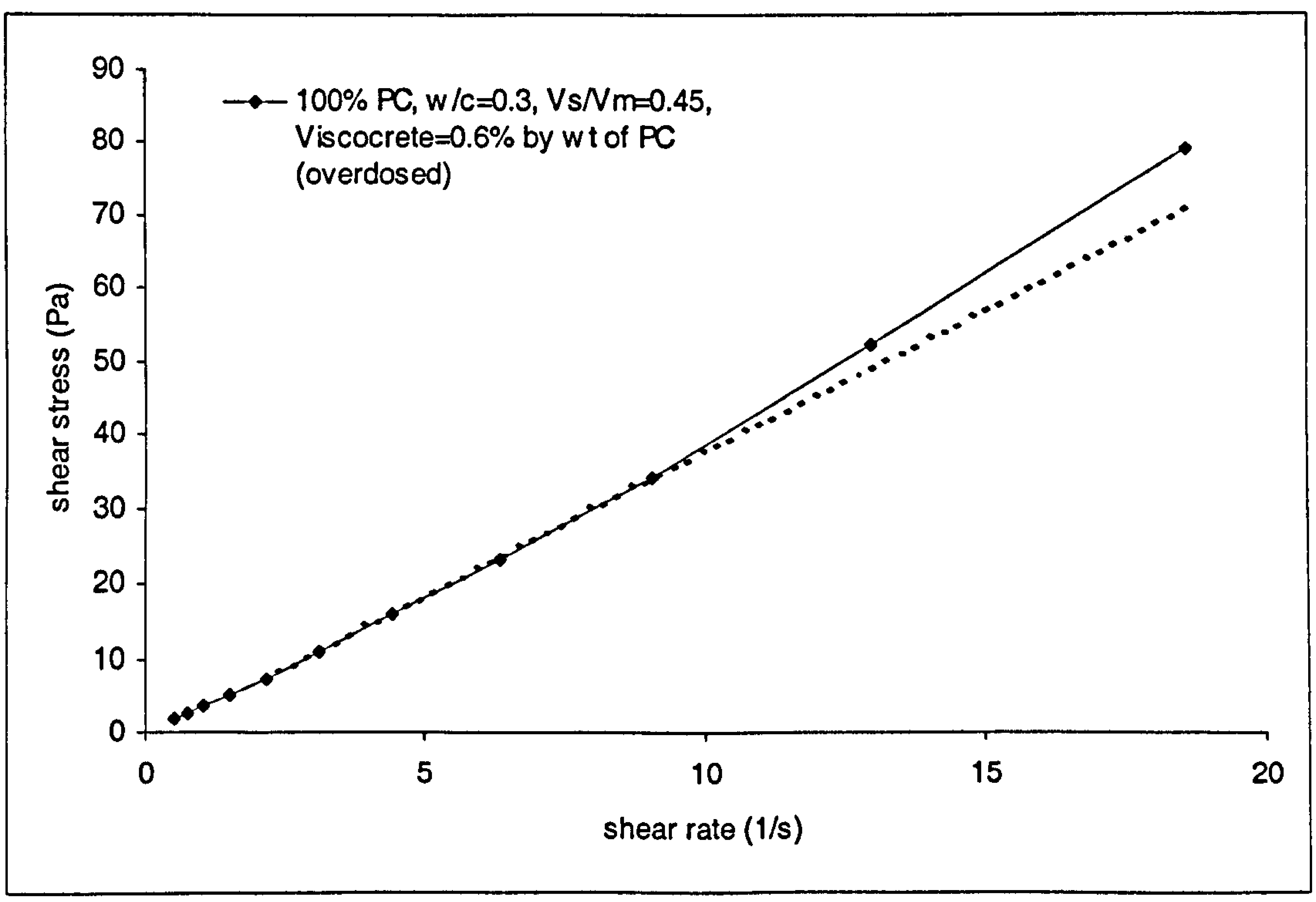


Figure 10-1 The measured rheology of a mortar with overdosed superplasticizer

Cyr *et al* [133] also obtained shear thickening in paste and claimed this to be due to high doses of superplasticizer; however, this also may have been overdosed superplasticizer (as above) but no detailed information was given.

The other shear thickening behaviour, which was more significant, was in the binary mixes with high contents of GGBS. An example is mix M7-3 (with 40% GGBS), and therefore three further extra mixes with different GGBS contents were tested. **Table 10-1** shows the mix proportions and properties of these three mixes together with mix M7-3 and M6-2 (used as control). Glenium51 was also used to achieve high flowability, and the dosage was controlled to ensure that no bleeding and segregation occurred in the mix.

Table 10-1 Mix proportions for GGBS mixes and flowing properties

Mix No.	Composition of powder*		Sp	D_m	T_V
	PC	GGBS	(% of powder by wt.)	(mm)	(secs)
M6-2	100	0	0.145	315	3.26
M10-1	80	20	0.115	315	4.1
M7-3	60	40	0.1	325	3.82
M10-2	40	60	0.09	290	4.44
M10-3	20	80	0.08	245	12.92

*: $V_w/V_p = 0.945$, $V_s/V_m = 0.45$

Figure 10-2 shows the relationship between the shear stress and the shear rate for each mix (the data are given in appendix 14). It can be seen that the rheology of the mortars with a GGBS content of no more than 40% still followed the Bingham model, however, significant shear thickening was found in the mixes with GGBS content of 60% and 80%.

Therefore the Herschel-Bulkley model

$$\tau = \tau_0' + k\dot{\gamma}^n$$

where

τ_0' : Herschel-Bulkley yield stress,

k, n: Herschel-Bulkley parameters,

was fitted to these curves, and it was found that the value of 'n' was very close to 1 when the GGBS content was low but increased with increasing GGBS content, suggesting an increase of shear thickening behaviour. The yield value also is increased, but as discussed later, this is consistent with the reduction in spread.

The shear thickening property was not found during the two-point test for concrete with GGBS content 40%. Further investigations at higher GGBS content would be therefore useful. In this project all GGBS mixes apart from these in **table10-1** had a content not more than 40% by the volume of powder, therefore the behaviour was still considered as following the Bingham model.

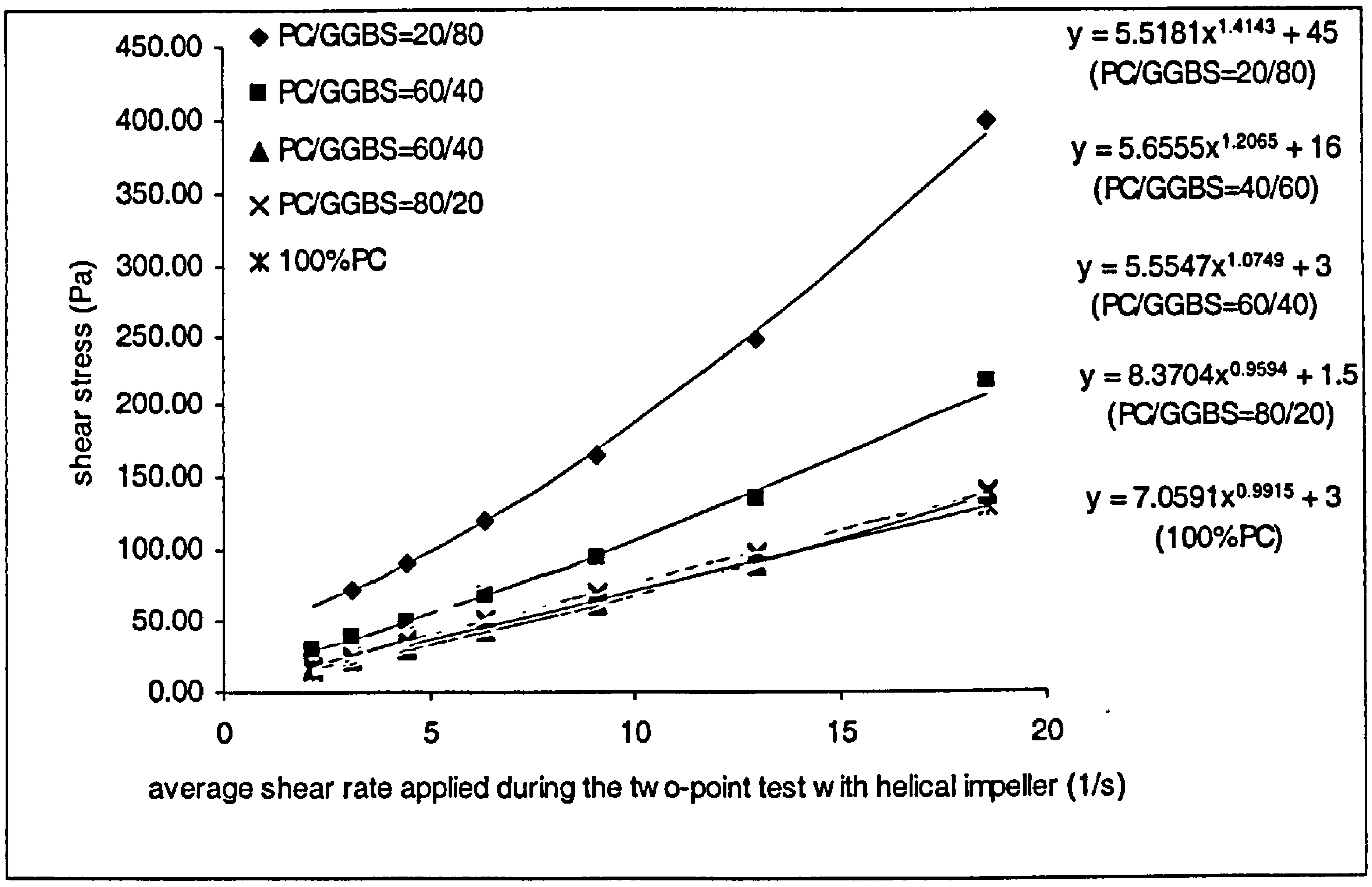


Figure 10-2 Rheology of the mortars with varying GGBS content

It is known that a shear thickening material flows with difficulty at higher shear rate and has tendency to bleed at lower shear rate. In general it is often found that concretes with high GGBS content are more difficult to handle and more sensitive to variations in the water content than 100% PC mixes; this can be explained by their shear thickening property. The performance may be related to GGBS particle shape and size distribution, but further work to clarify this is needed.

10.1.2 Shear thinning

In a two-point test on a Bingham material, the shear stress vs shear rate relationship is not linear until shear rate is sufficient for the whole sample sheared; the relationship is therefore easily confused with the curve for a shear thinning material, which is a concave towards the shear rate axis as shown in **figure 10-3**. Clearly there is some difficulty in distinguishing shear thinning materials from Bingham materials.

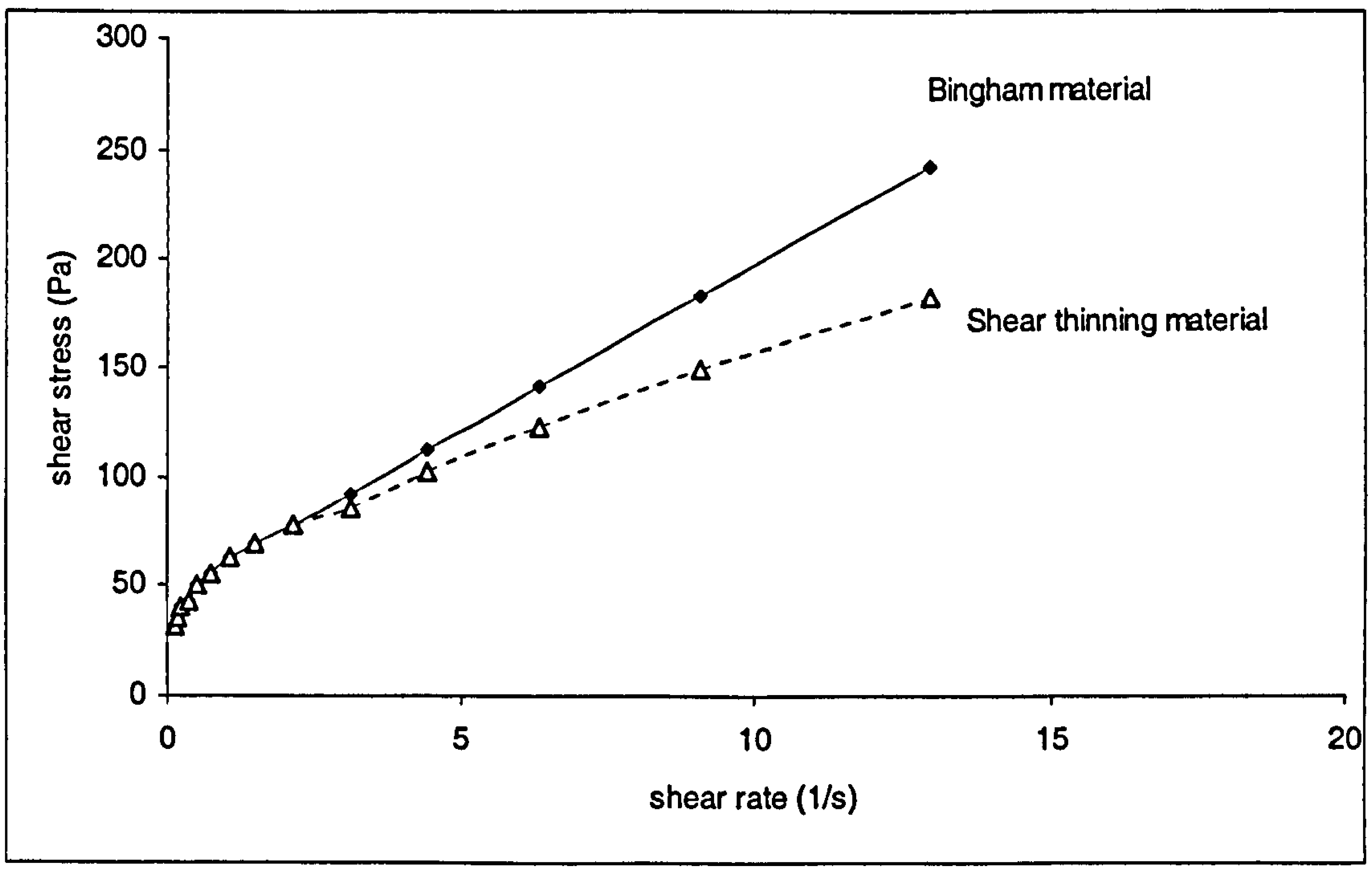


Figure 10-3 Bingham material and shear thinning material in two-point test

Shear thinning behaviour was first found in a mix with a high CSF content of 15%, as shown **figure 10-4**. Applying the Herschel-Bulkley model gave a value of "n" well below 1 while that for the 100% PC mix was very close to 1. This is consistent with the results by Cyr *et al* who found that CSF pastes with superplasticizer were shear thinning [102].

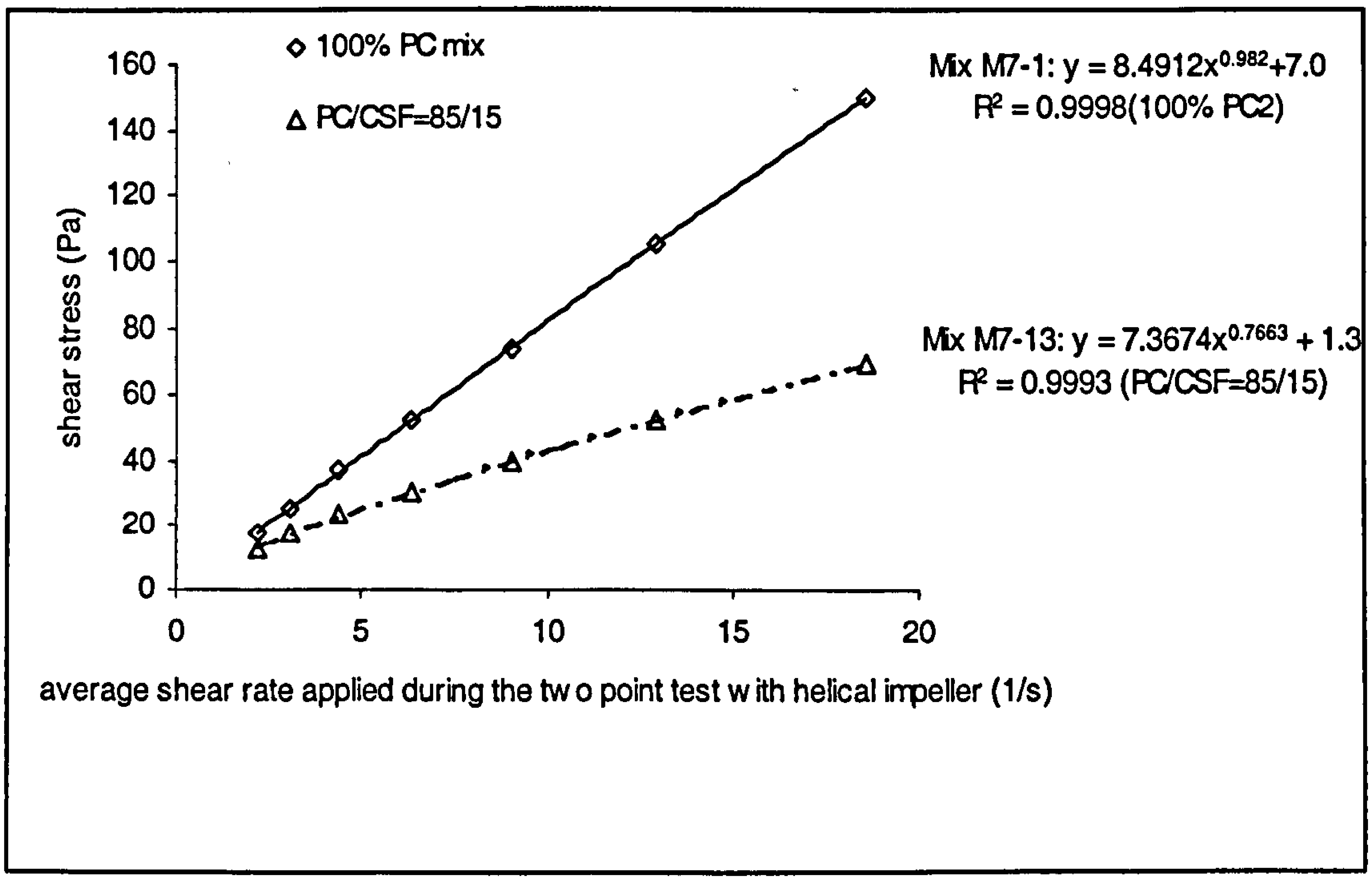


Figure 10-4 Rheology of the CSF mix compared to the 100% PC mix

As reviewed in chapter 2, Welan gum solutions have a pseudoplastic (shear thinning) property, and also Viscocrete can improve stability and segregation resistance, which may also be due to shear thinning behaviour. Therefore, their rheological behaviour was examined and compared with other superplasticizers, using mortar tests. **Table 10-2** shows the mix proportions and fresh properties. The spread was controlled to 310 mm for the mixes in series 1, and 305 mm in series 2. No segregation was found in either series. **Figures 10-5** & **10-6** show the flow curves of series 1 and series 2 respectively (detailed data is given in appendix 16). Shear-thinning was found in the mixes with Viscocrete (n=0.82) the mixes with Glenium51 or Conplast430 still followed Bingham model (n≅1). The mixes with the higher water/cement ratio also showed apparent shear thinning (n=0.82), (the reason is not clear), but increasing Welan gum clearly increased the tendency of shear thinning (n=0.69) (**figure 10-6**).

Table 10-2 The mix proportions and fresh properties for the mix with various types of admixtures

Series	Mix No.	w/c	Types of admixtures	WG dosage (%)	Sp dosage (%)	Dm (mm)	Tv (secs)
	M7-1	0.3	Glenium51		0.15	311	3.92
Series1	M10-4		Viscocrete		0.33	311	3.22
	M10-5		Conplast 430		0.6	313	3.49
	M10-6	0.35	Conplast430	0	0.45	305	1.58
Series2	M10-7		Welan gum	0.05	0.7	307	2.72
	M10-8			0.1	1.6	305	2.88

It is known that shear thinning behaviour is beneficial for SCC. The concrete is easily handled and pumped, and has good surface finishing. It was suggested by Chai, who studied SCC in UCL, that SCC samples cast containing CSF have less blow holes at the surface than that with 100% PC mix. This was also observed during the tests in the current programme, although no systematic measurements were made.

In summary, it is confirmed that the rheology of SCC would be better described by the Herschel-Bulkley model, as suggested by de Larrard *et al* [108].

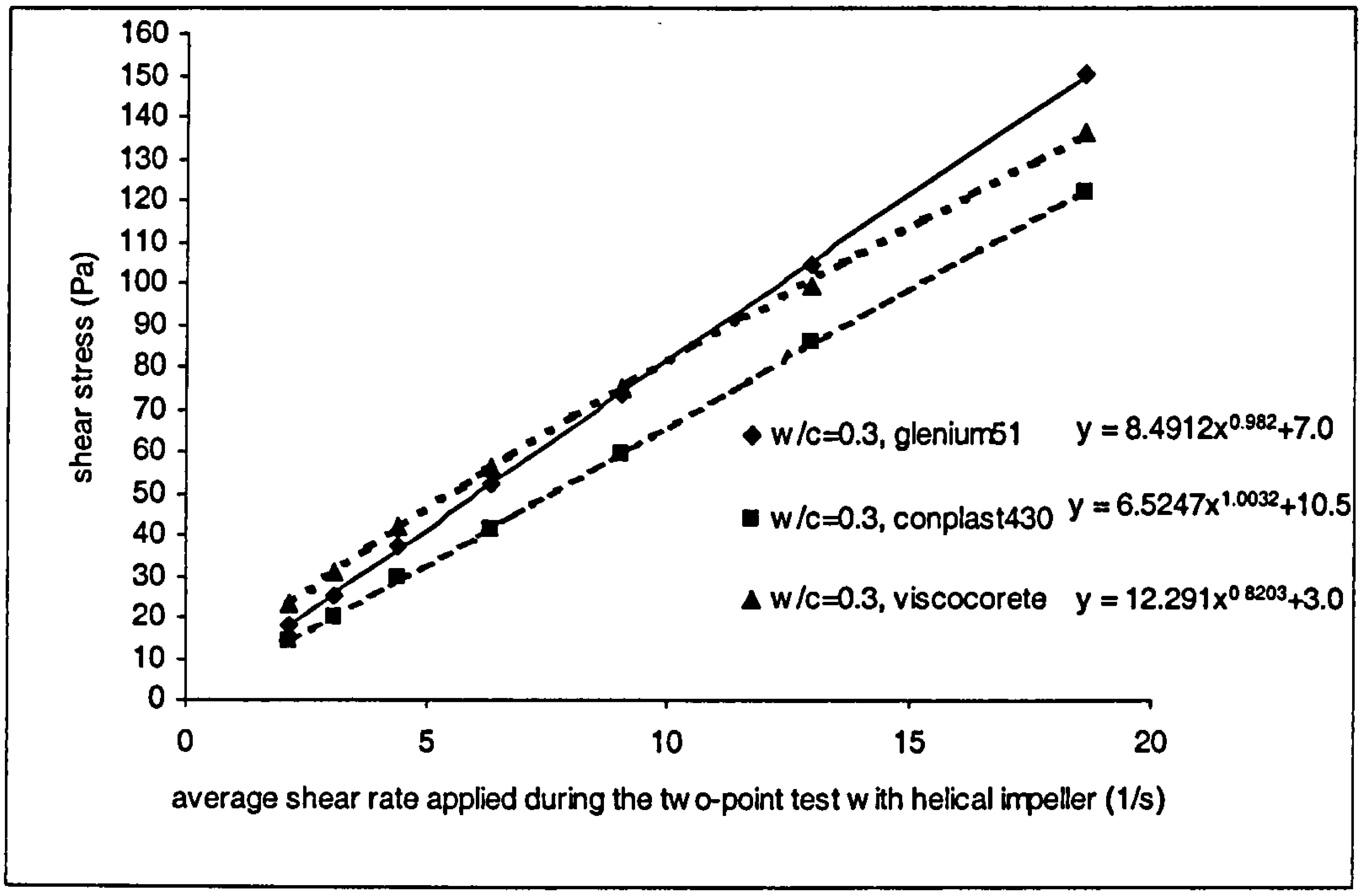


Figure 10-5 The relationship between shear stress and shear rate for the mixes with various types of superplasticizer

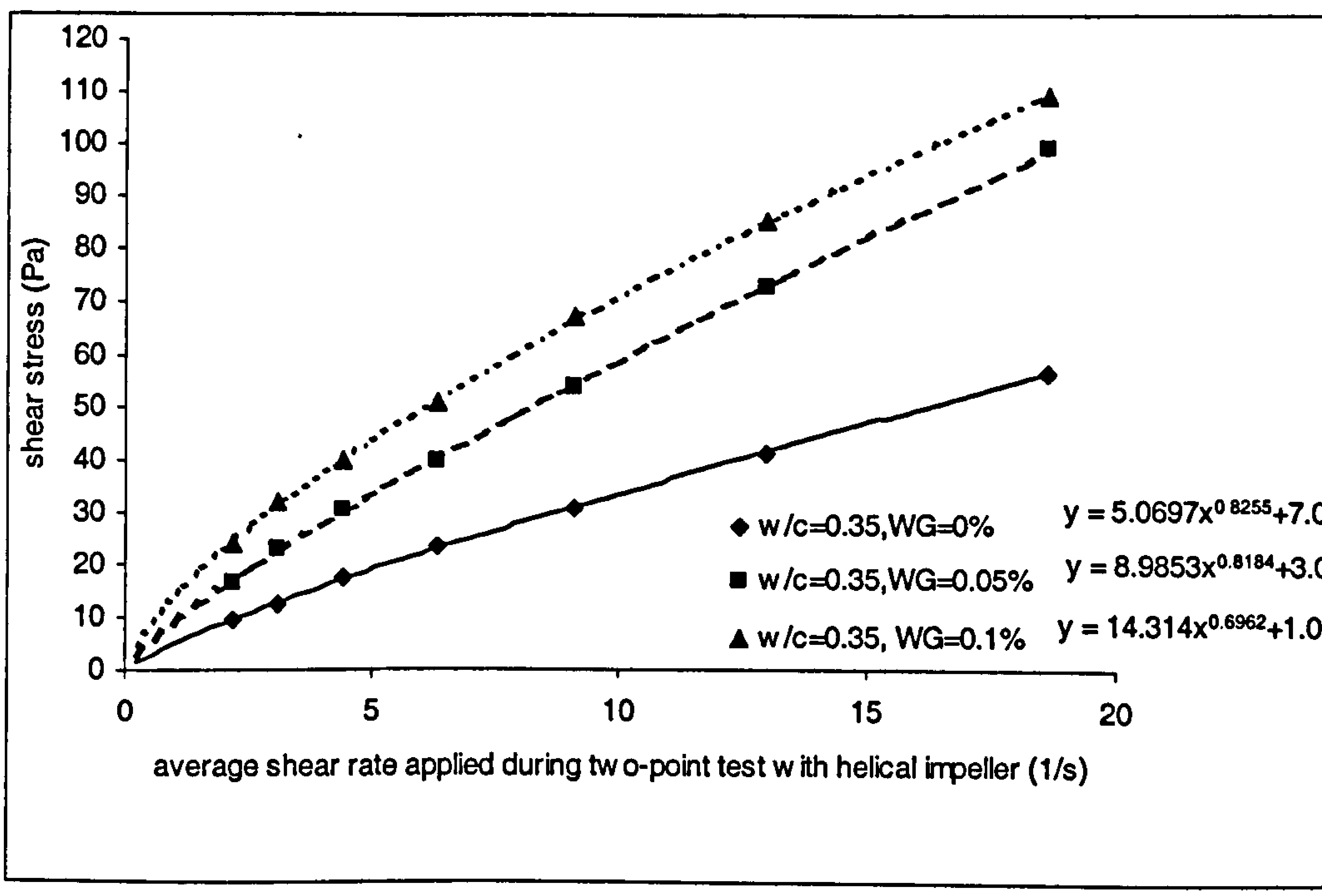


Figure 10-6 Effect of Welan gum dosage on the relationship between shear stress and shear rate

10.2 Relationships between the fresh properties for mortar and concrete

As reviewed in chapter 2, there are close relationships between the rheological properties and the single point test results. It was also shown in previous chapters that the spread and the yield stress followed similar patterns of behaviour, as did the V-funnel flow time and the plastic viscosity. Also, concrete properties have shown similar patterns of behaviour to their mortar components.

10.2.1 Relationships between mortar properties

The most likely relationships between rheological properties and the measured flowability by simple test methods are discussed as shown in **table 10-3**. Other relationships such as those between yield stress and V-funnel flow time, which are unlikely, are not included. The data used are given in appendices **tableA7-1, tableA8-1, table A8-4, table A9-1, table A9-2, table A9-3, table, A9-1-4, table A10-1, table A10-2, table A11-5, table A12-2, table A12-3, tableA13-1, tableA13-4, table A13-5,** and **table A13-8**.

Table 10-3 The relationships between the properties of mortar discussed

Mortar properties		Mortar properties				
		Spread D_m	V-funnel T_V	Time to 250 mm spread T_{250}	Yield stress τ_0	Plastic viscosity μ
	Spread, D_m					
	V-funnel, T_V					
	Time to 250 mm spread, T_{250}		x			
	Yield stress, τ_0	x				
	Plastic viscosity, μ		x	x		

10.2.1.1 Yield stress (τ_0) and spread (D_m)

An overall general relationship was examined, as well as the factors which affect it.

Figure 10-7 plots the relationship for all data. Non-linear behaviour is apparent. A logarithmic regression was applied and the correlation coefficient is 0.94. There is some scattering data, particularly at higher yield stress, and the factors that may cause this were examined.

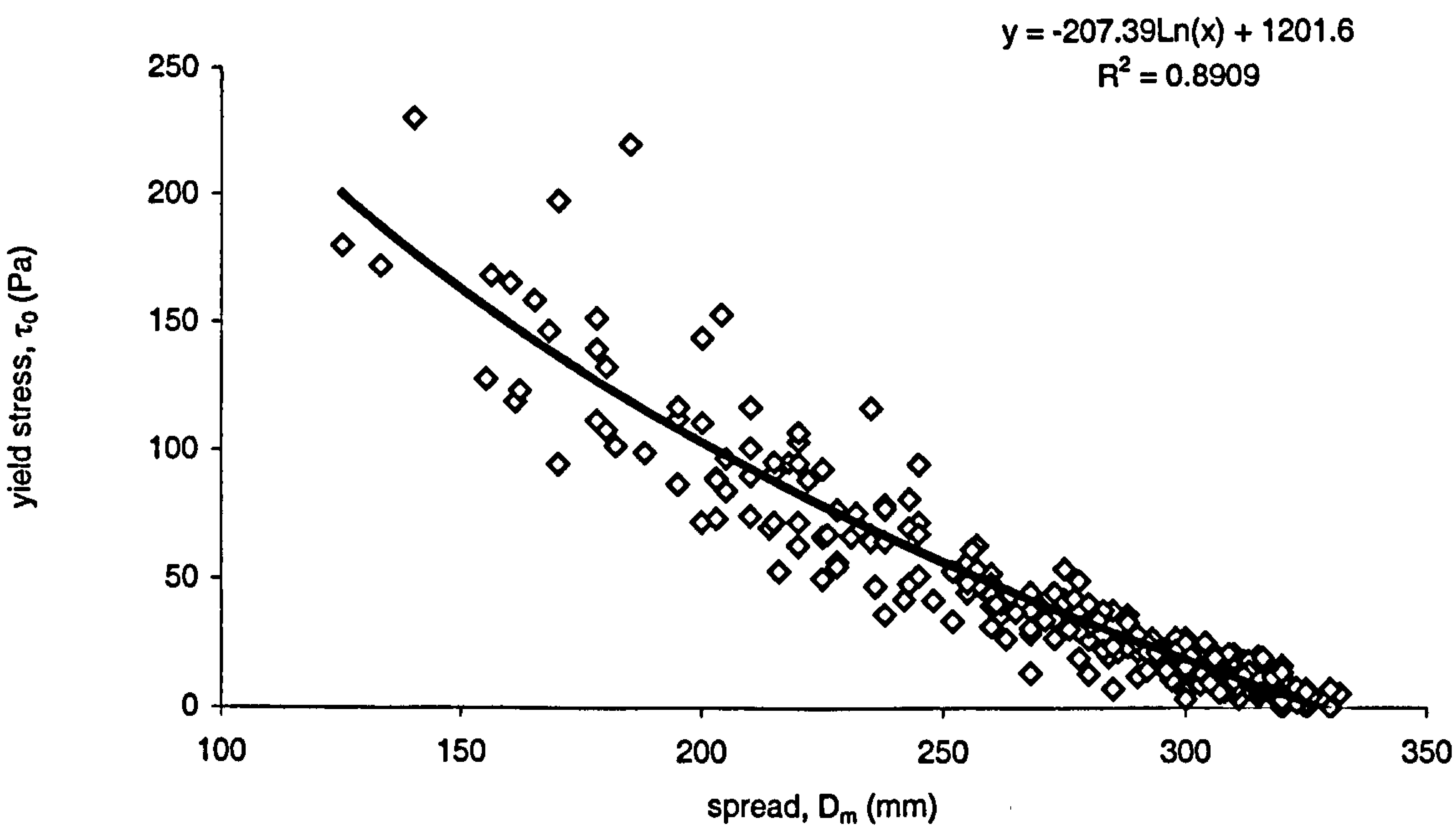


Figure 10-7 The relationship between yield stress and spread for mortar

The data for the 100% PC mixes, PFA binary mixes, LSP100 binary mixes, PC based Welan gum mixes gave a correlation coefficient of 0.96, as shown in **figure 10-8**. These mixes were therefore called "reference mixes". According to the relationship obtained, a mortar for SCC with a spread higher than 300 mm (a requirement according to UCL mix design) has a yield stress less than 20 Pa. This is consistent with Fujiwara's proposal that the yield stress of mortar for SCC should be in the range of 5 to 20 Pa.

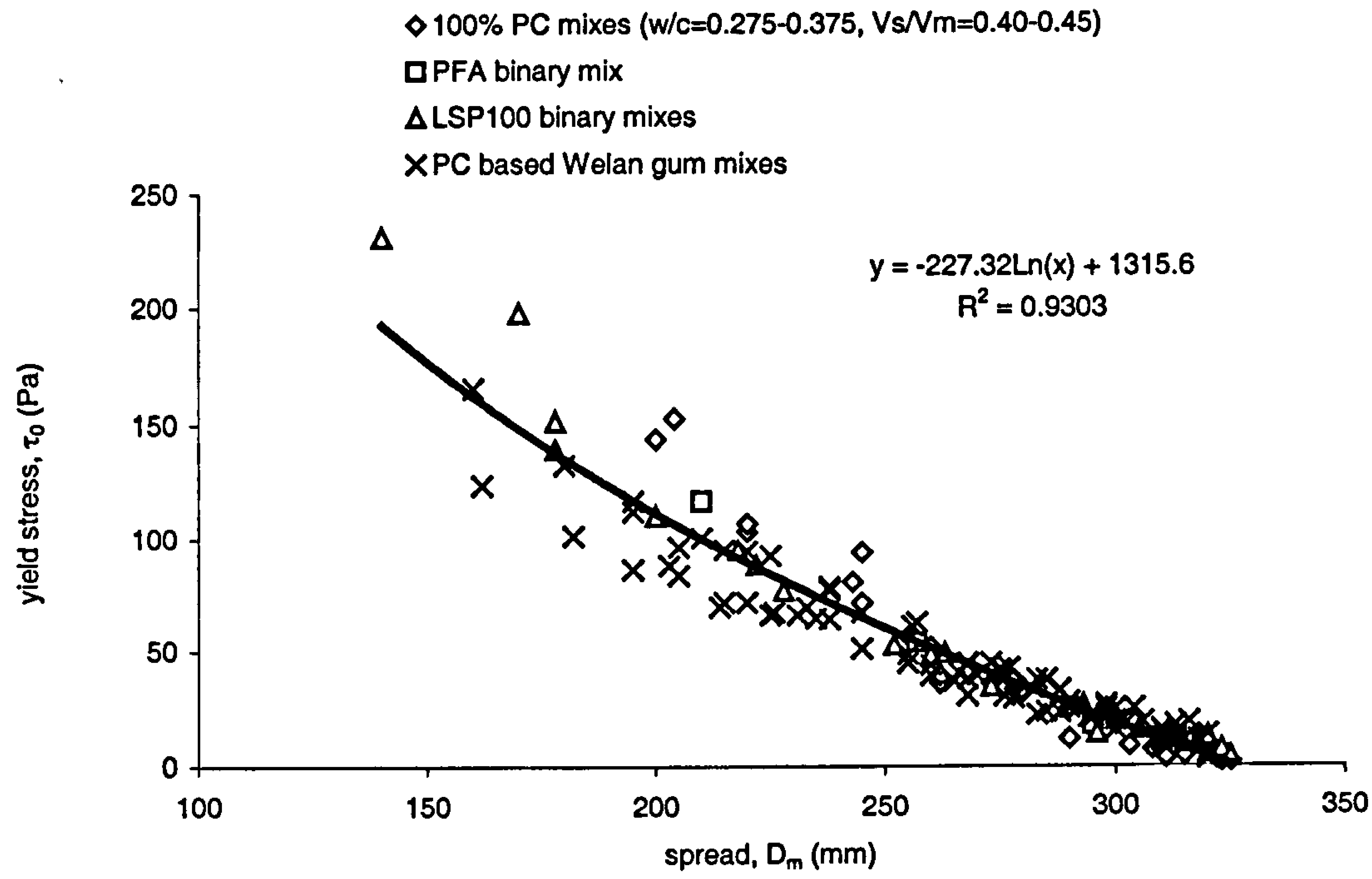
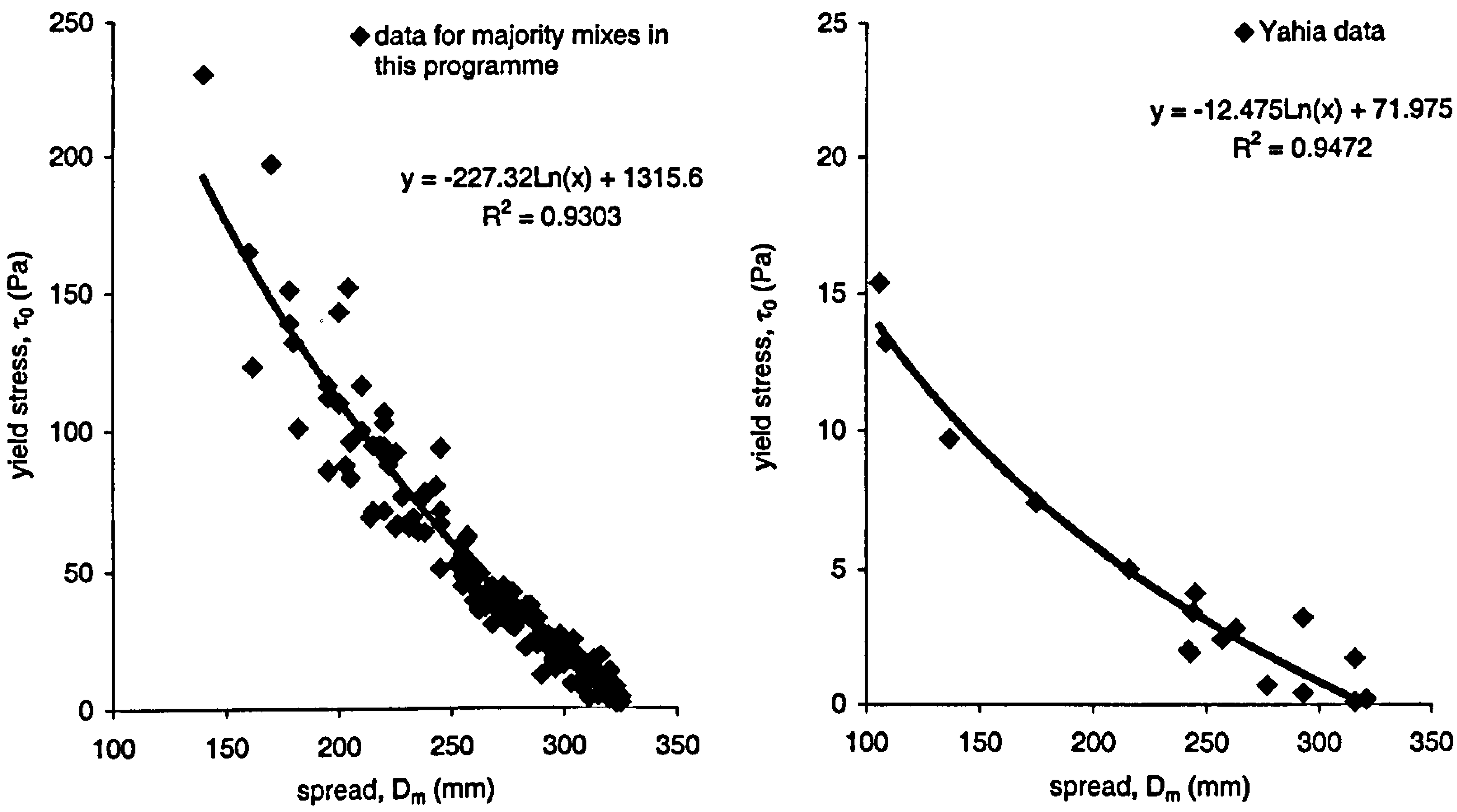


Figure 10-8 The relationship between yield stress and spread



(a) the data in the current programme (b) Yahia's data

Figure 10-9 A comparison of the two relationships between yield stress and spread

Yahia *et al* [98] also tested rheological properties and flowability for SCC mortar with PFA and LSP blends. These data are compared with that for the current programme in **figure 10-9**. They obtained a similar trend but with very different magnitudes of yield stress, which was about 10 times lower than that obtained in this programme. This might be due to different testing conditions and methods. Yahia *et al* used a coaxial cylinder viscometer with a 10 mm gap size, but the surface condition of the wall was not described; there may have been slippage between the wall and sheared mortar. The difference also may be because of using different materials.

It was found that the relationship between the yield stress and the spread was also influenced by several factors, mainly hydration time, sand content and the composition of the powder.

1. Hydration time

Figure 10-10 shows the relationships for two groups of 100% PC mixes with similar mix proportions. The results for group 1 are for mixes in **table A8-1**, which were obtained during the measurement of workability loss; group 2 is for mixes in **table A7-1**, which were obtained from different mixes immediately after mixing. It can be seen that for the same spread, the correspondent yield stress in group 1 is higher than that in group 2. This may be explained by an increased degree of coagulation of cementitious particles with time, which may have different degree of effect on the development of yield stress and spread with time; further investigation on this will be very useful.

2. Sand content

As shown in **figure 10-11**, the effect of sand content was only significant in the mixes where this was very high, i.e. 47.5% by the volume of mortar. In this the yield stress increased more rapidly with the decrease of spread. This may be related to the friction force between sand particles which is controlled by the distance between them, which reduces with increasing sand content, but further work is needed to clarify this.

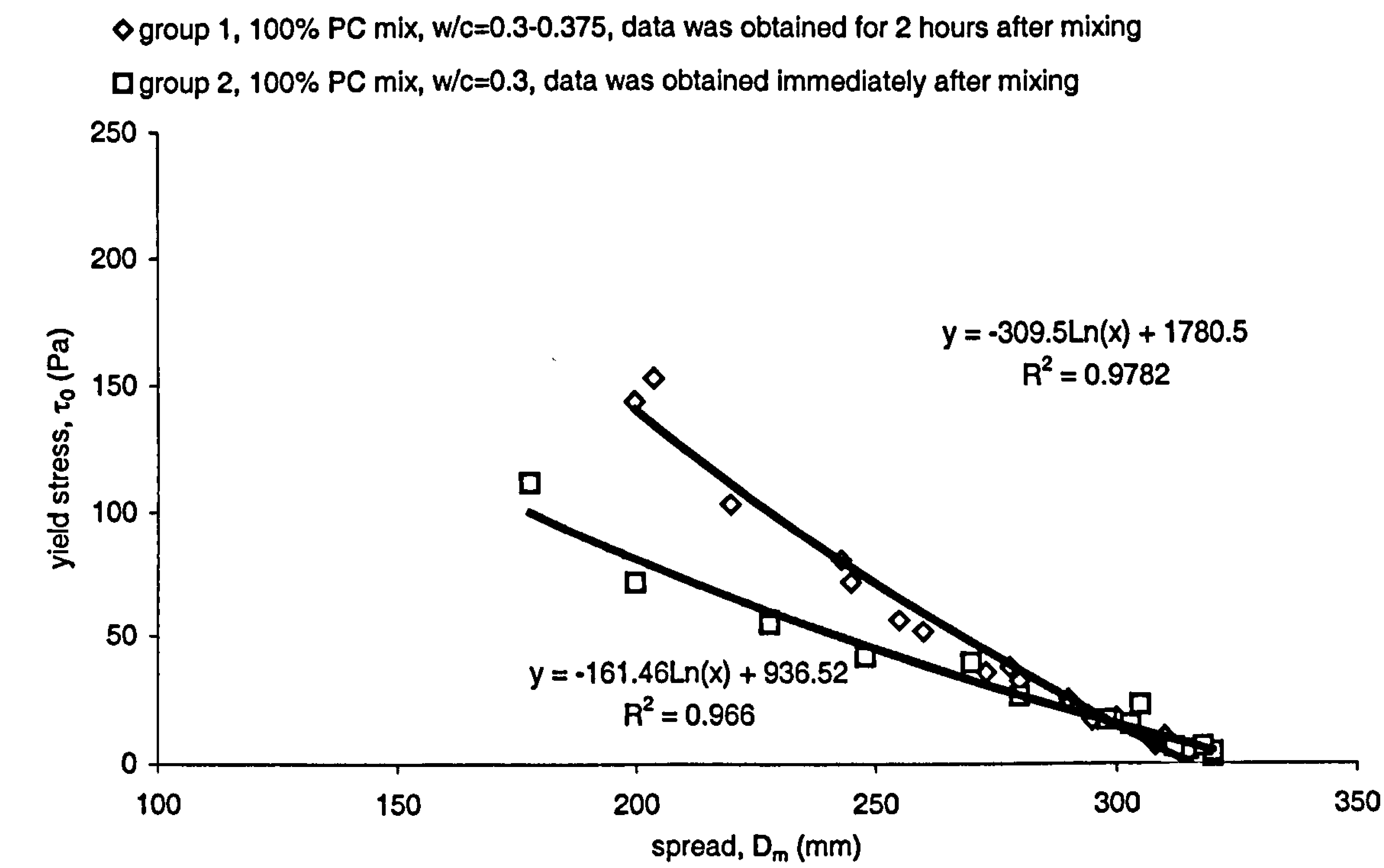


Figure 10-10 Effect of hydration time on the yield stress-spread relationship

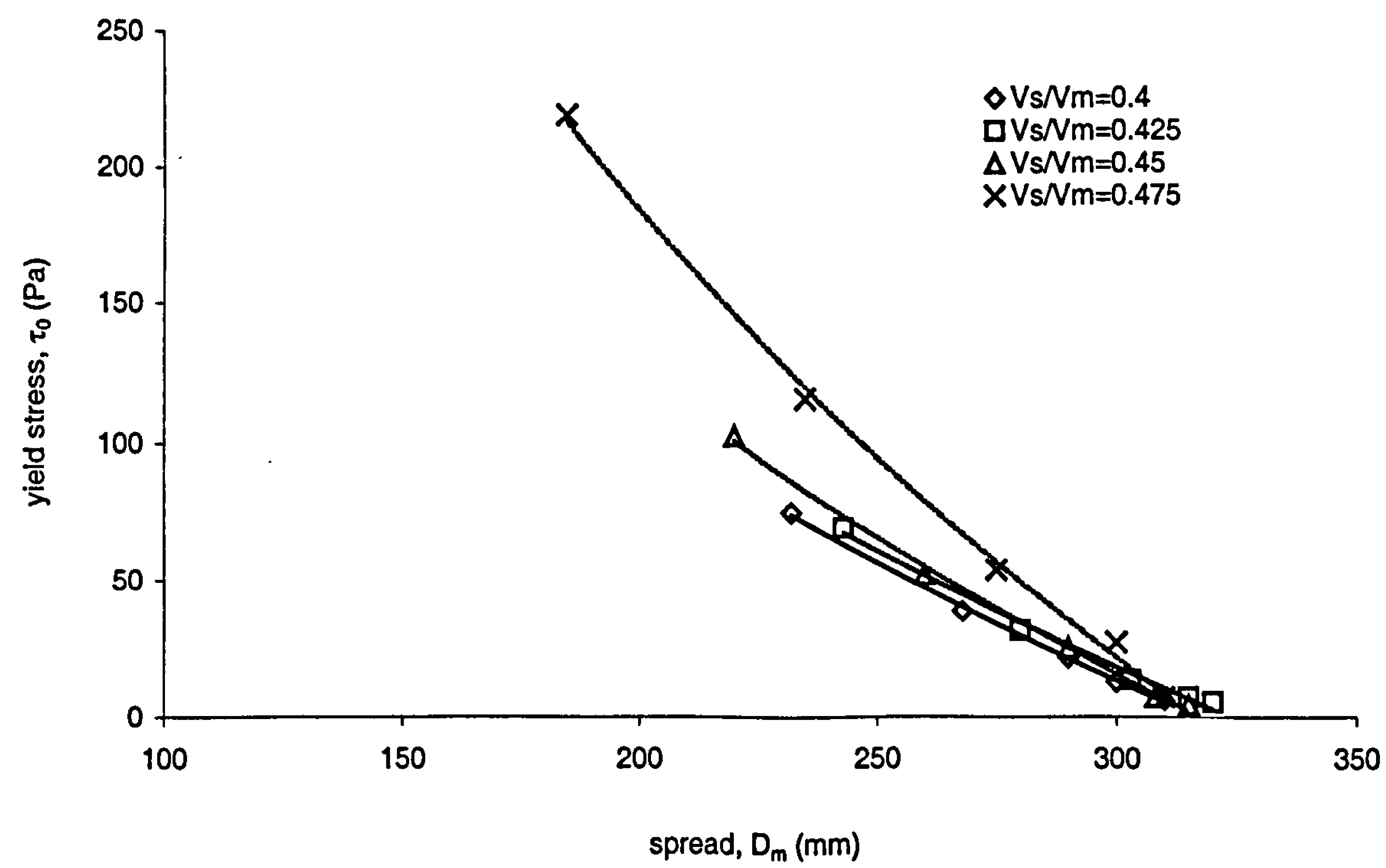


Figure 10-11 Effect of sand content on the yield stress-spread relationship

3. Types of blends of powder

Some types of blends also had an effect on the relationship. **Figure 10-12** shows the effect of GGBS, SRC and CSF. The yield stresses for GGBS and SRC mixes were lower than the reference mixes with same spread, while for CSF mixes they were slightly higher. This seemed to be related to their different rheological behaviour as discussed earlier, i.e. GGBS mix showed a tendency of shear thickening while CSF mix shear thinning. Certainly shear thinning is an advantage for SCC because the segregation resistance will be improved for these mixes.

A significant effect of blends was also found in LSP mixes, as shown in **figure 10-13.** The effect is related to the particle size of the LSP. Only a little difference was found between the trend lines for the LSP100 and PC mixes, where both powders have similar particle sizes; but the difference increased as the particle size of LSP reduced, i.e. with LSP50 and LSP15.

The use of combinations of particles with different shape and size in powder changes their solids packing density, and hence the maximum volume concentration, and consequently the distances between particles. This may have different effects on the yield stress and spread, which consequently results in different relationships for different types of powder mixes; however further evidence is needed.

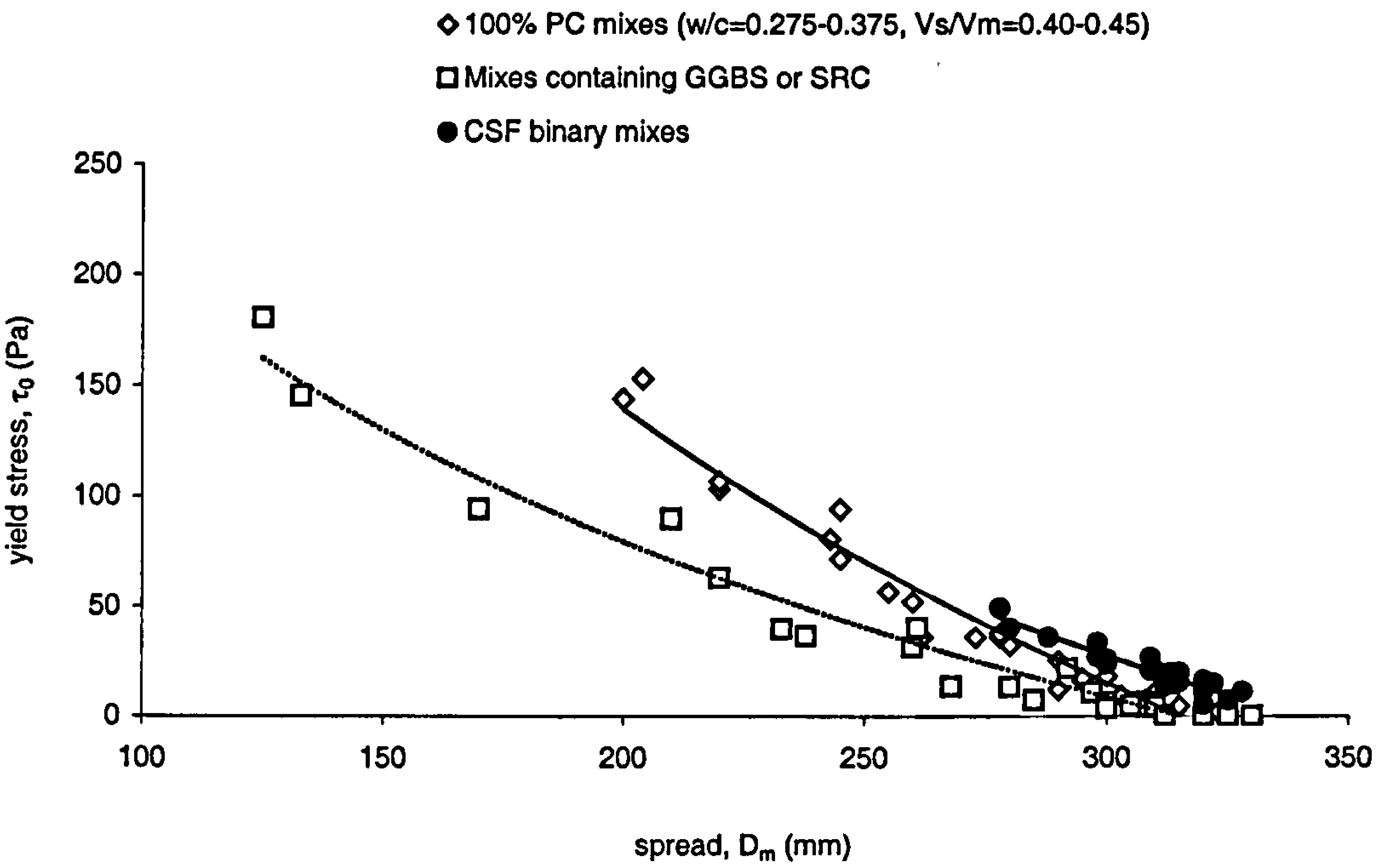


Figure 10-12 Effect of GGBS and CSF on the yield stress *vs* spread relationship

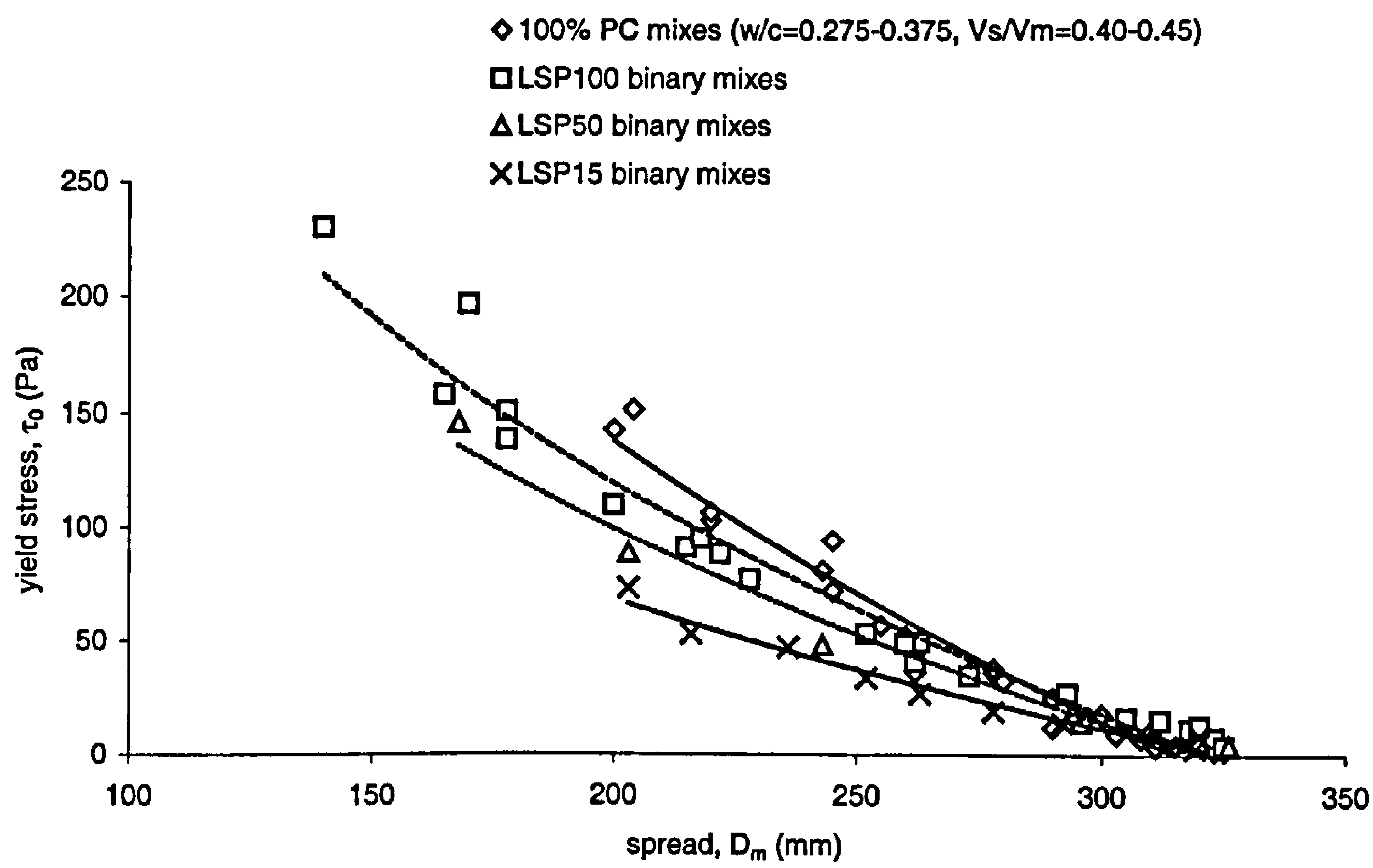


Figure 10-13 Effect LSPs on the yield stress *vs* spread relationship

10.2.1.2 Plastic viscosity (μ) and V-funnel flow time (T_V)

As above both the overall general relationship and factors which affect this are discussed.

Figure 10-14 shows the relationship for all mixes. Clearly, a linear relationship was obtained but this is weaker at higher V-funnel flow times. After eliminating the data with a spread lower than 200 mm, a much stronger relationship was found for the remaining data, shown in **figure 10-15 (a)**, with a correlation coefficient of 0.95, suggesting an effect of spread. Further elimination of some mixes (which will be discussed later) that have differences with the remaining majority of mixes resulted in the relationship shown in **figure 10-15 (b)** which has a correlation coefficient 0.96. These remaining mixes included all 100% PC, GGBS and Welan gum mixes, and are called reference mixes. As reviewed in chapter 2 the required V-funnel flow time for the mortar for SCC is between 4 and 7 seconds according to the UCL mix design method, so the corresponding range of plastic viscosity is of 8-17 Pa.s. This range is only slightly higher than that of 6-12 Pa.s proposed by Fujiwara [65].

A comparison was also made with the data obtained by Yahia's *et al* [98]. Again, this showed similar trends but with a different magnitude, the plastic viscosity being about 4-5 times less than that in this project. This may be because of similar reasons to those discussed earlier. Clearly a comparison of the data obtained under different conditions with different materials is very difficult.

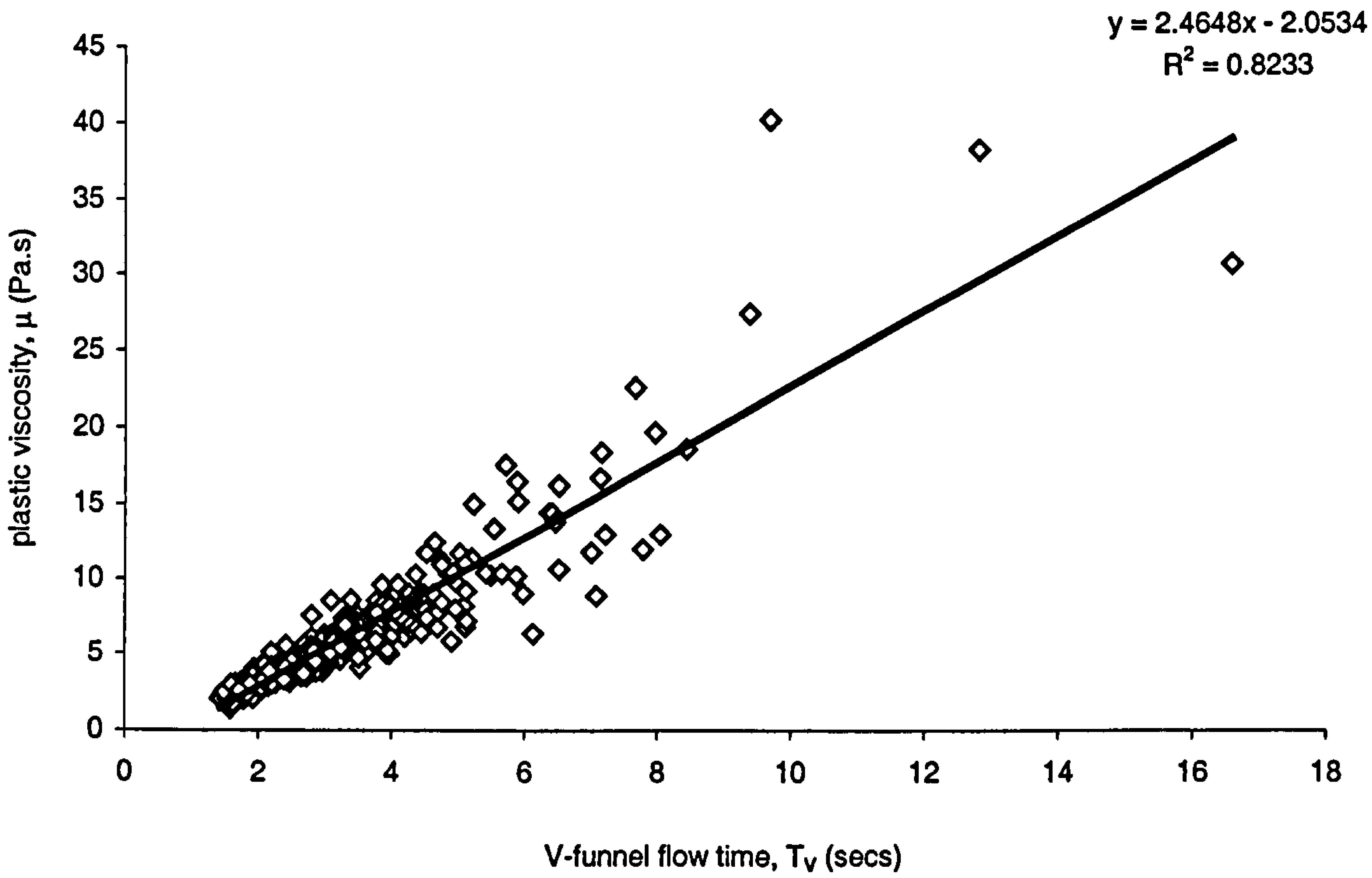
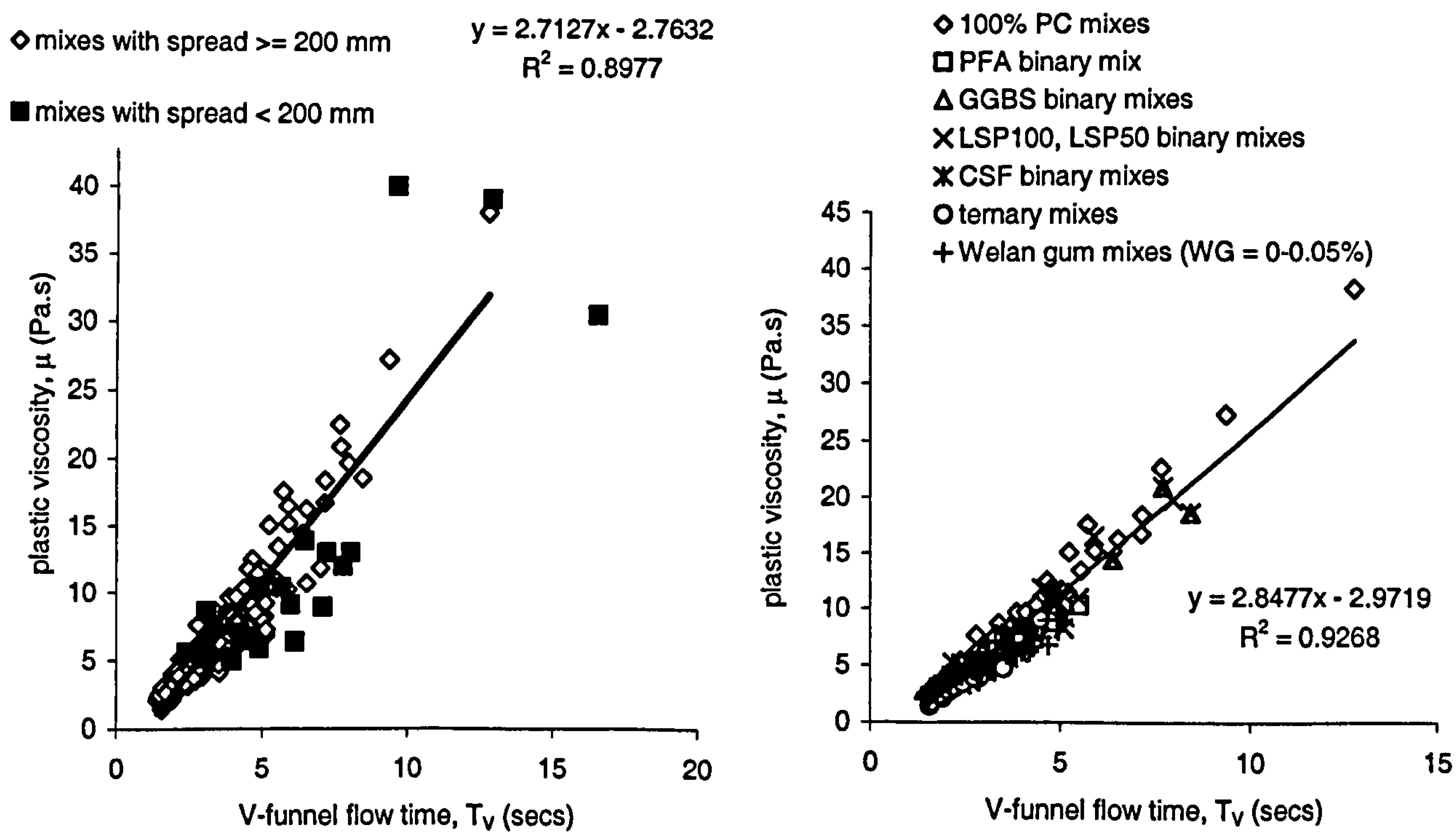
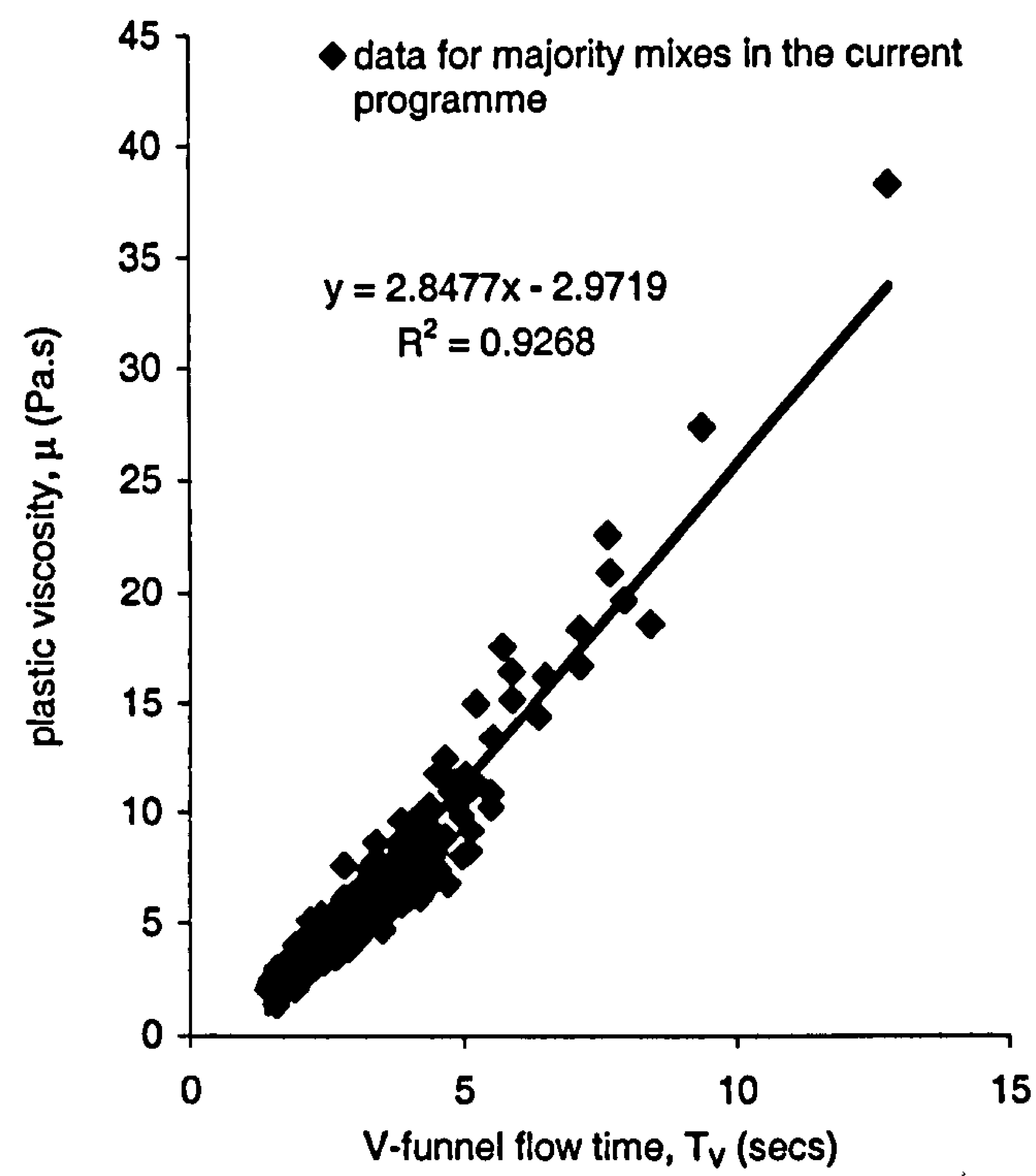


Figure 10-14 The relationship between plastic viscosity and the V-funnel flow time for mortar

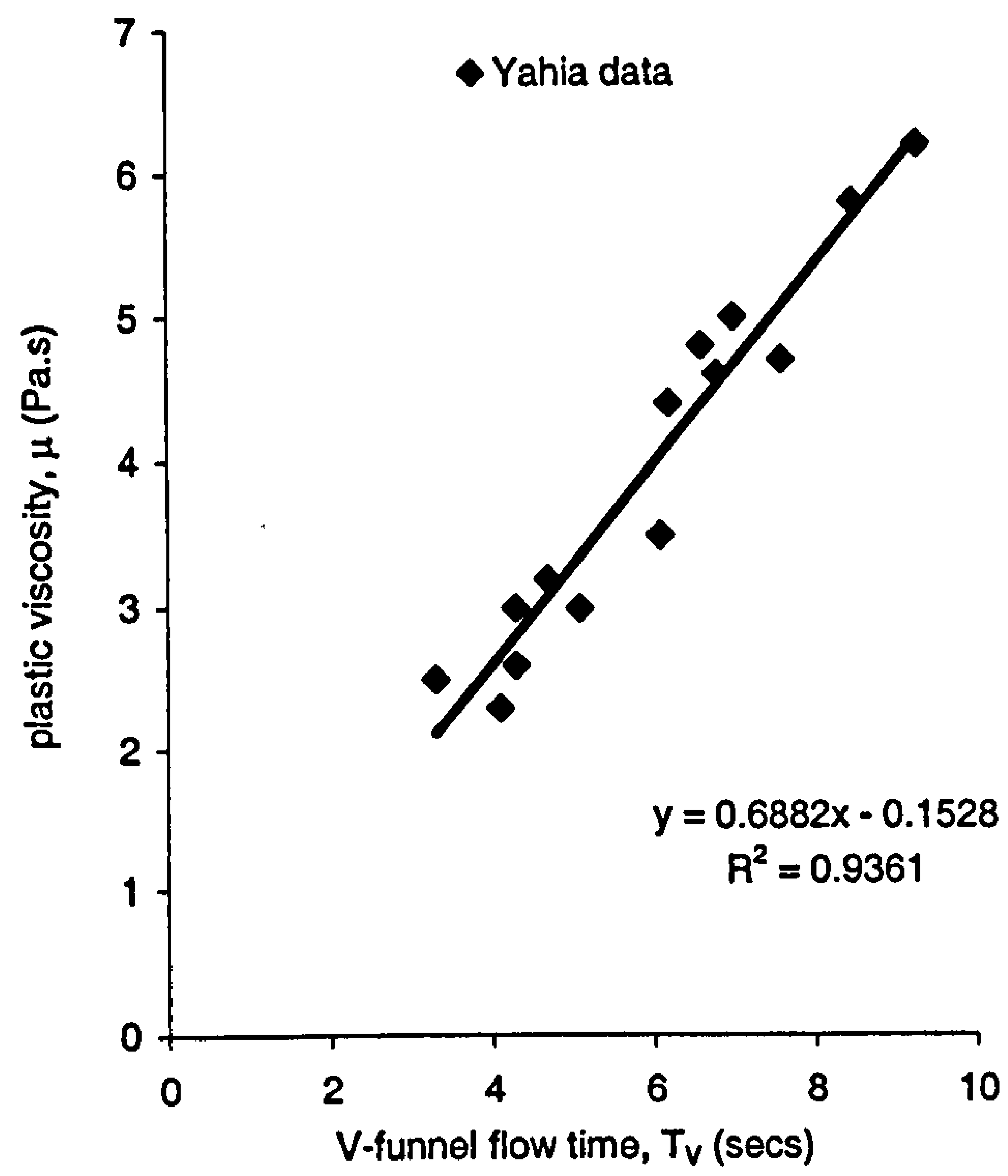


(a) data eliminated with spread < 200 mm (b) data eliminated for some mixes

Figure 10-15 The relationship between plastic viscosity and V-funnel flow time of mortar after elimination of some data



(a) the data in the current programme



(b) Yahia's data

Figure 10-16 Comparison of the relationships between plastic viscosity and V-funnel flow time

The mixes which differed from the reference mixes are LSP15 and SRC mixes and the mixes with high dosage of Welan gum. **Figure 10-17** shows the relationships for these mixes compared to the reference mixes. The trend lines for theses mixes drifted downwards towards the V-funnel flow time axis compared to that for reference mixes. The trend line for the SRC mixes is parallel to the reference mixes line, while the others tend to diverge from this with increased V-funnel flow time.

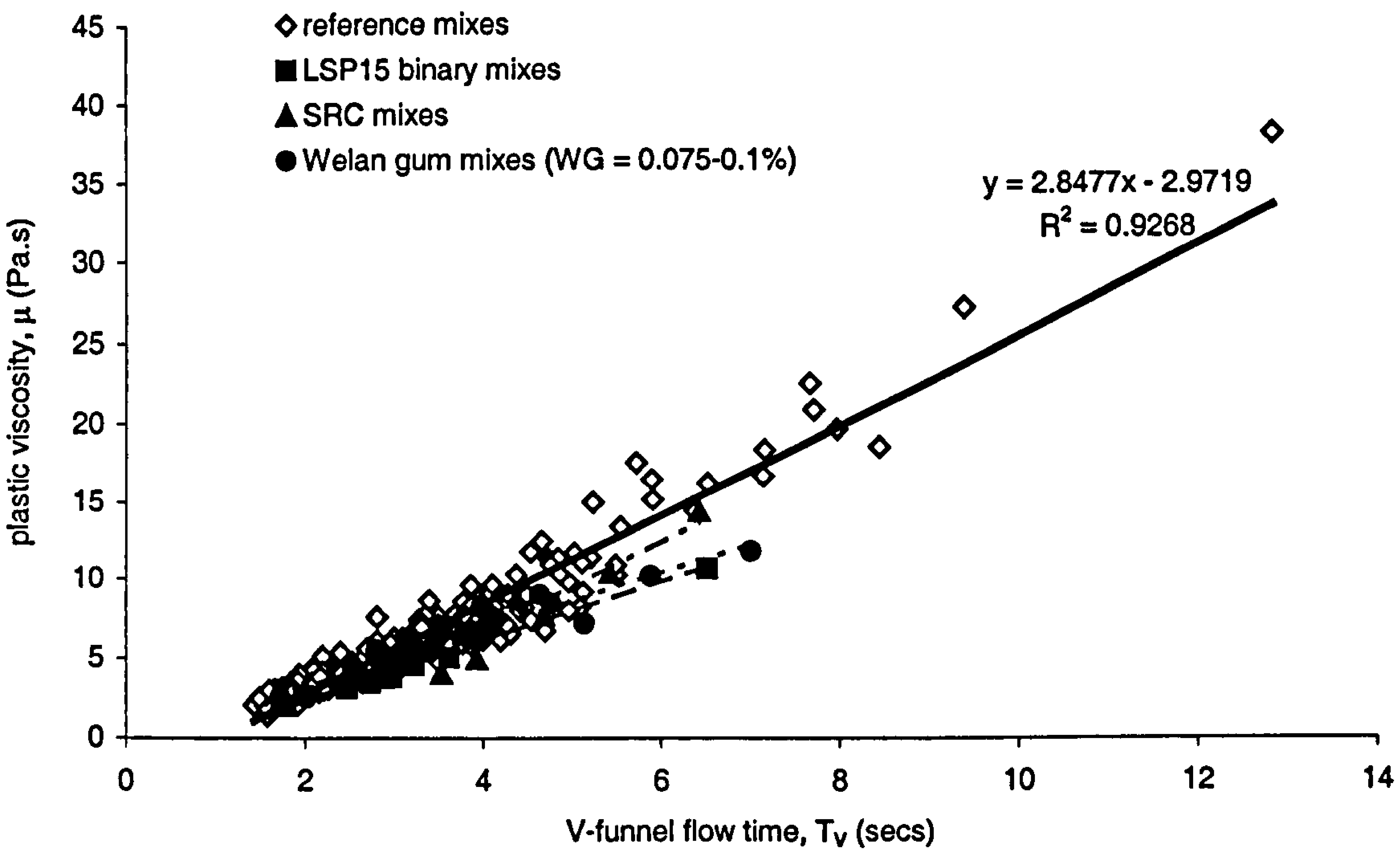


Figure 10-17 Effect of SRC, LSP15 and high dosage of Welan gum on the plastic viscosity-V-funnel flow time relationship

An explanation for the effect of spread on the plastic viscosity – V funnel time relationship can be obtained by considering the nature of flow. It is known that the viscosity of a Newtonian material is related to its flowing time or speed through a tube, therefore methods, such as flow cone, funnel or lateral flow tests, are often used to measure this. However, when applying the same methods to a Bingham material, such as mortar and concrete, the flow is not only controlled by plastic viscosity but also by yield stress. Specially, plug flow occurs, as explained by Tattersall and Banfill [79]. The governing equations are

$$q = \frac{2l\tau_0}{p}\text{, and} \tag{10-1}$$

$$Q = \frac{\pi a^4}{8\mu l}\left(P - \frac{4}{3}p + \frac{p^4}{3P^3}\right) \tag{10-2}$$

where q: the radius of the plug

Q: total volume per second,

a,l: radius and length of tube

P: pressure on flowing object

p: the minimum pressure at which flow begins, which $p = \dfrac{2\pi l \tau_0}{a}$

If yield stress is high enough, then $p = P$ (P is the highest and constant at the start of the V-funnel test), the quantity in the brackets of **equation 10-2** is zero, so $Q = 0$; thus the mortar does not flow. When p is zero, meaning the mortar has zero yield stress, then

$$Q = \frac{\pi a^4}{8\mu l} P \qquad (10\text{-}3)$$

No plug flow occurs, and the mortar flows at highest speed. This suggests that for two mixes with the same plastic viscosity but different yield stress, the V-funnel flow time for the one with lower yield stress is shorter and the result is therefore more representative of plastic viscosity. **Table 10-4** shows an example of this for 100% PC mixes with different dosages of superplasticizer. It can be seen that these have very similar plastic viscosities but different V-funnel flow times due to the different yield stress and spread values.

Table 10-4 A example for the effect of spread on V-funnel flow time

Spread, D_m (mm)	Yield stress (Pa)	V-funnel flow time (secs)	Plastic viscosity (Pa.s)
178	111.5	4.2	8.3
228	54.8	3.9	8.1
270	39.6	3.4	8.6

There is therefore a clear effect of spread on the relationship between the V-funnel flow time and plastic viscosity, but since the correlation was much improved by eliminating data with a spread of less than 200 mm, this effect is small enough to be neglected when spread is higher than 200 mm.

The reason for different relationship between μ and T_V for SRC, LSP15 and high Welan gum dosage mixes is not clear; further investigation on these particular mixes will be very useful.

10.2.1.3 Plastic viscosity (μ) and flow time to 250 mm spread (T_{250})

Figure 10-18 shows the relationship between μ and T_{250} for all data; a very weak relationship was found. **Figure 10-19** shows the data for different types of mixes with a spread higher than 300 mm. It can be seen that each type of mix has its own strong relationship, but each of them is very different from the other, showing a clear effect of factors such as spread, powder types *etc.*

As discussed earlier, the flow time through the V-funnel is affected by both yield stress and plastic viscosity, therefore it in fact represents an apparent viscosity, as shown in **figure 10-20.** Urano [139] *et al* reported that the maximum shear strain rate is nearly 1.0/s for a flow on a slab but nearly 10/s in the V-funnel test, suggesting that the apparent viscosity measured in the V-funnel test is at 10 times higher shear rate than in the spread test. Consequently the V-funnel test results are less affected by yield stress and more related to plastic viscosity, and the shear thinning property of Welan gum has more significant effect on T_{250} than on T_V. This is confirmed in **figure 10-21,** which shows the relationship between μ and T_{250}, μ and T_V respectively for a series of 100% PC mixes. It can be seen that the correlation between μ and T_V is much higher than that for μ and T_{250}. The latter can be significantly improved by limiting the mixes to those only with a spread higher than 300mm. Clearly V-funnel flow time test results indicate the plastic viscosity for the mixes with a broader range of spread and yield stress, but the flow time to 250 mm spread can not.

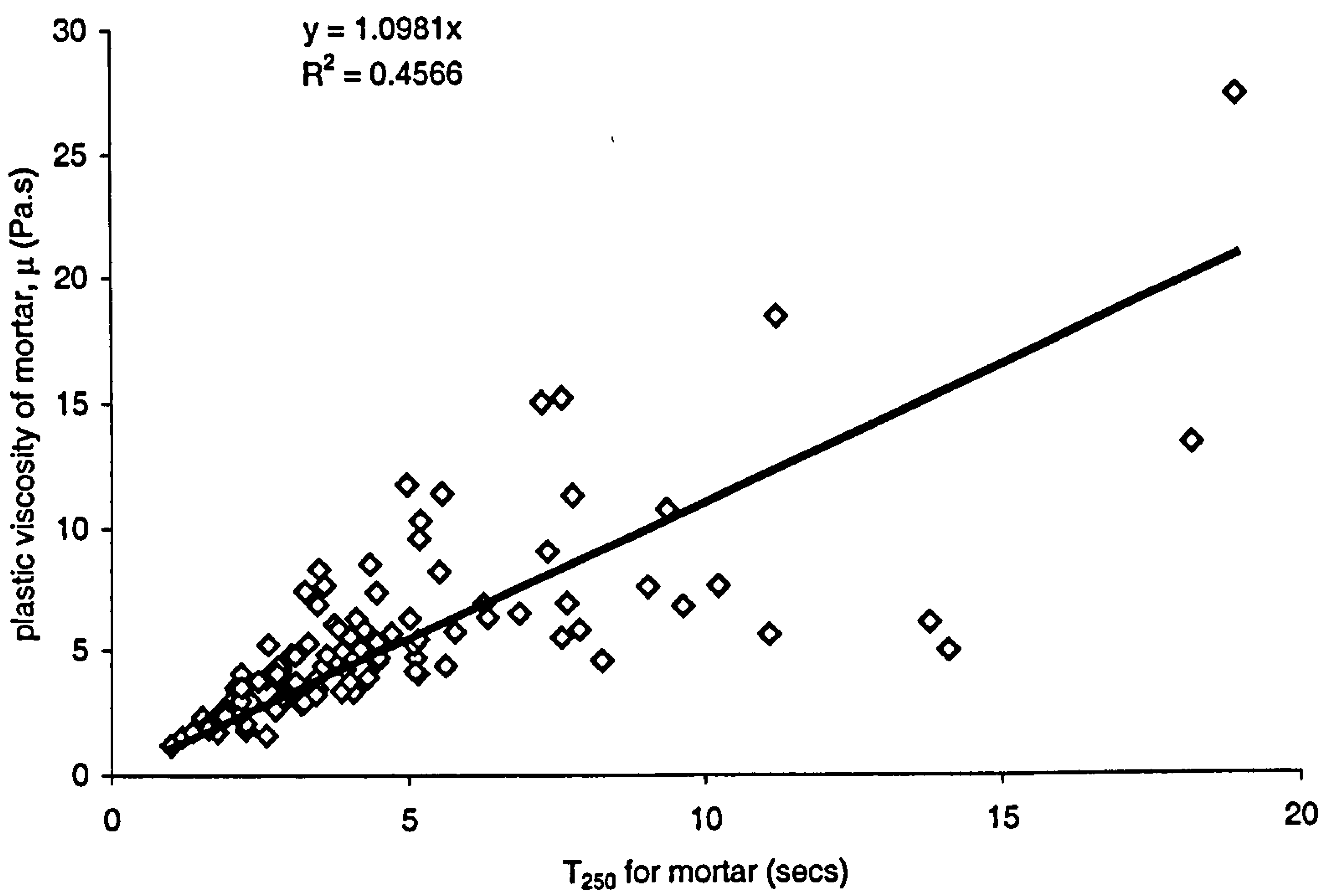


Figure 10-18 The relationship between μ and T_{250}

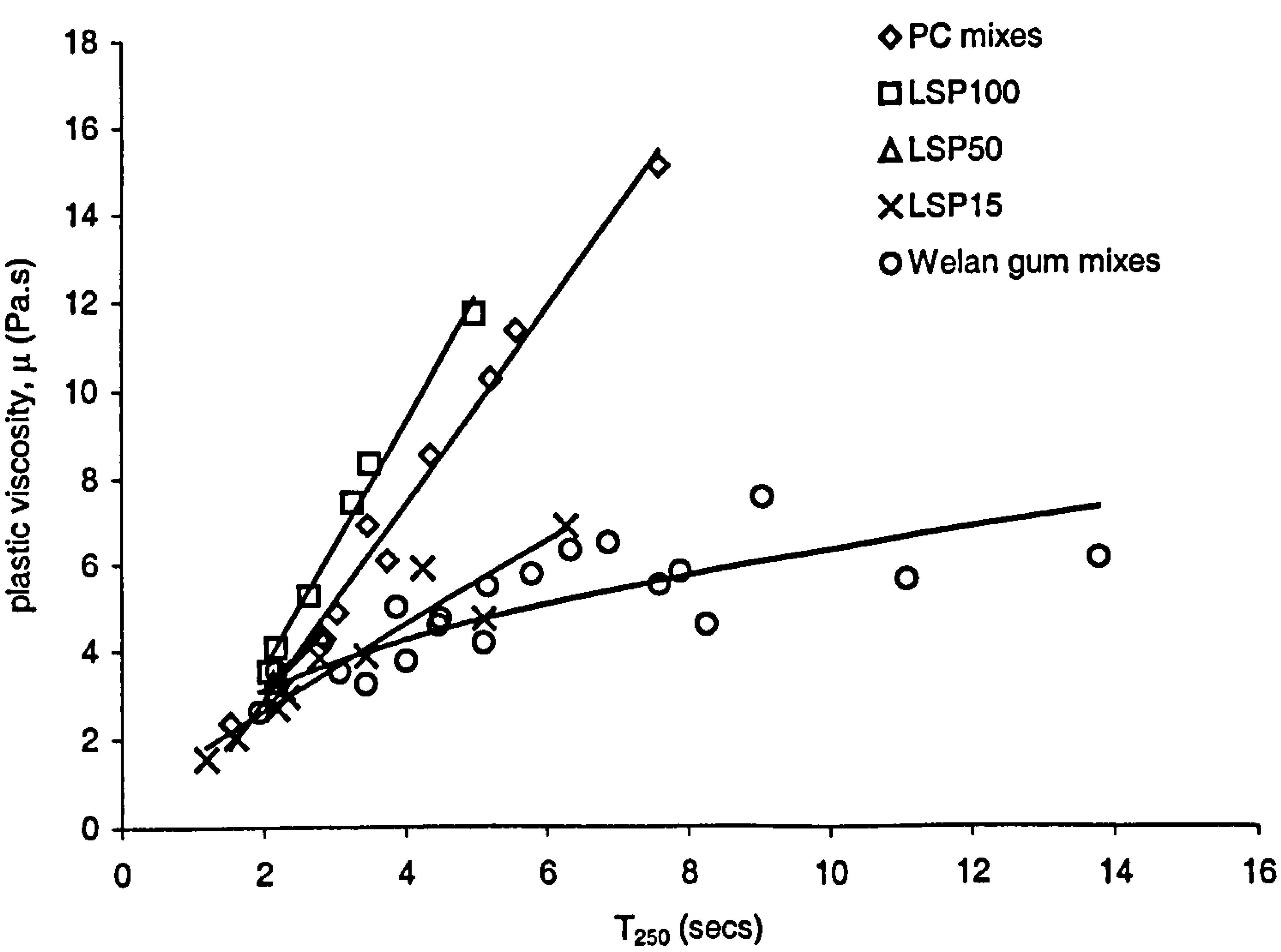


Figure 10-19 The relationship between μ and T_{250} for different types of mixes

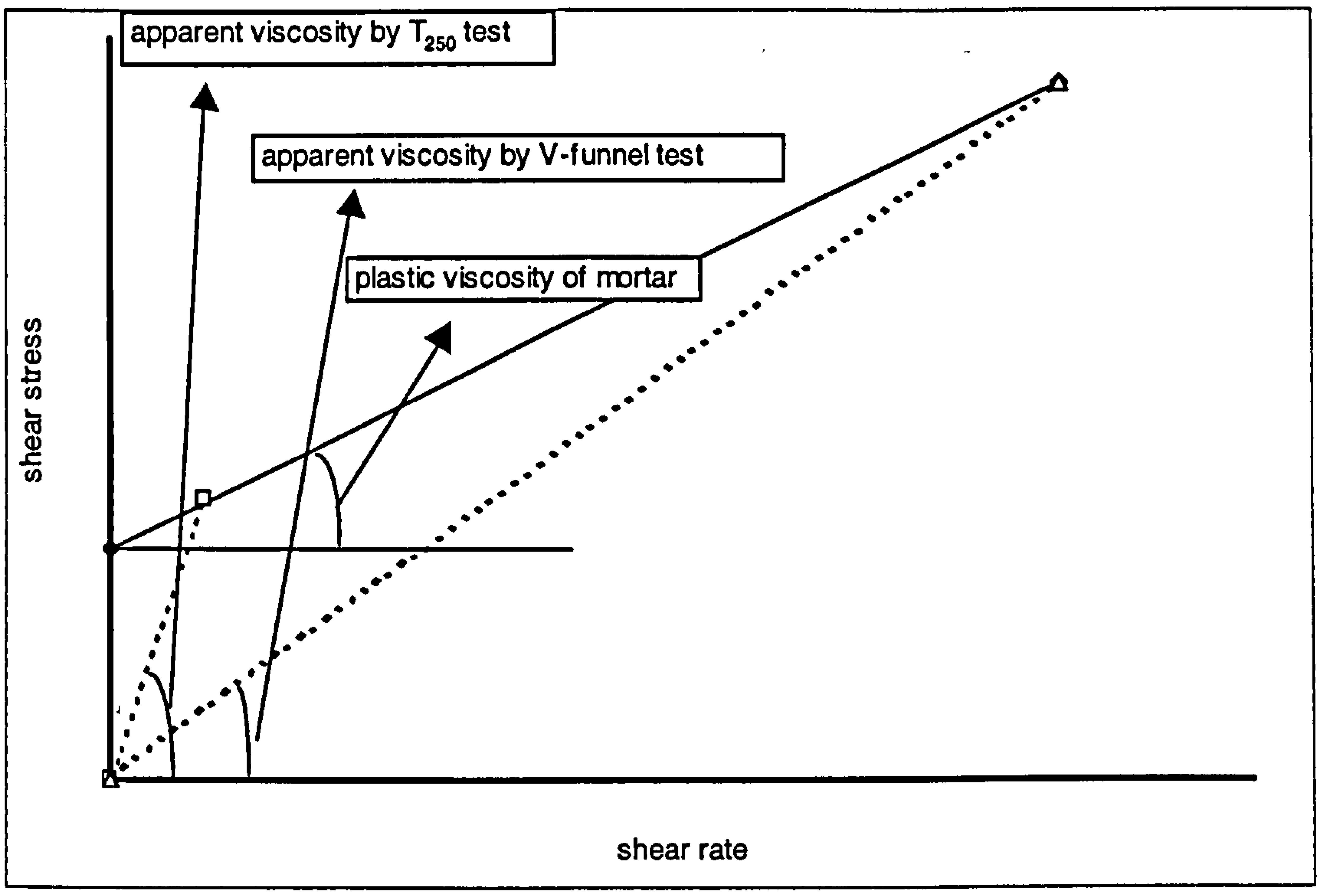
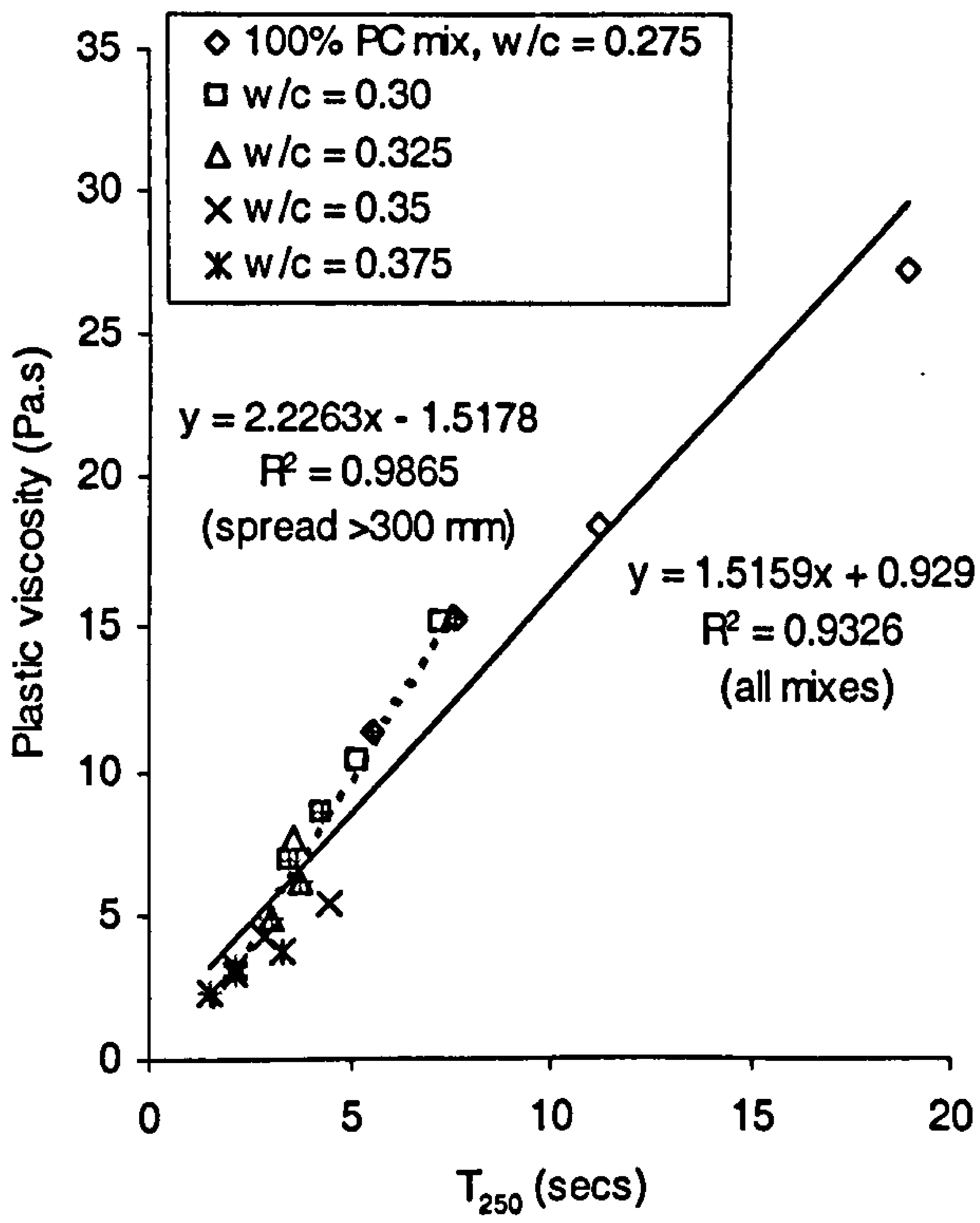
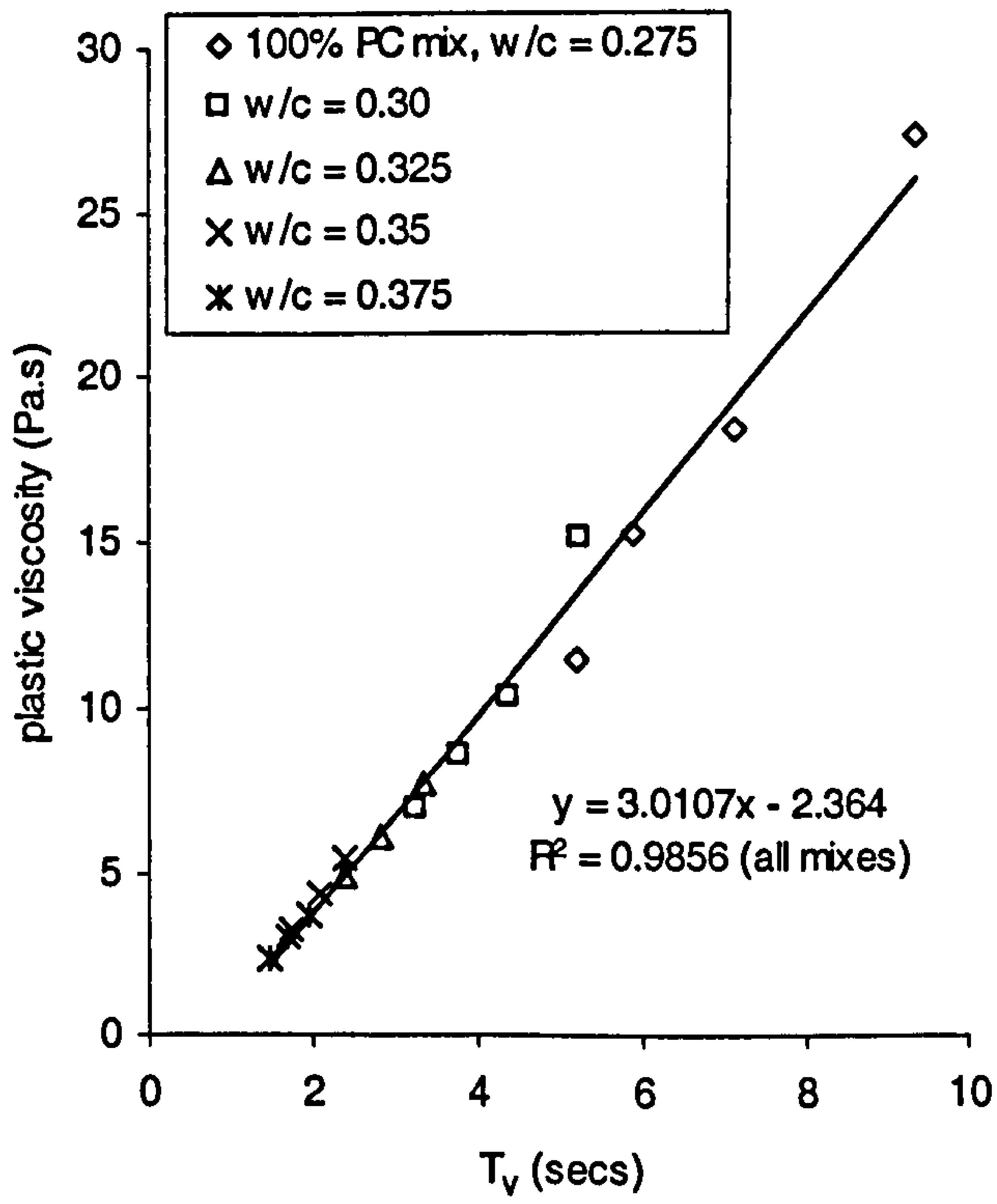


Figure 10-20 The principle for V-funnel test and spread test



(a) The relationship of μ-T_{250}



(b) The relationship of μ-T_V

Figure 10-21 Comparison of the relationships between μ-T_{250} and μ-T_V for some mixes

10.2.1.4 V-funnel flow time (T_V) and flow time to 250 mm spread (T_{250})

Because of weak relationship between μ and T_{250} and strong relationship between μ and T_V, a weak relationship between T_V and T_{250} was expected; this is confirmed in **figure 10-22.** It can be seen that the degree of correlation is similar to that between μ and T_{250}.

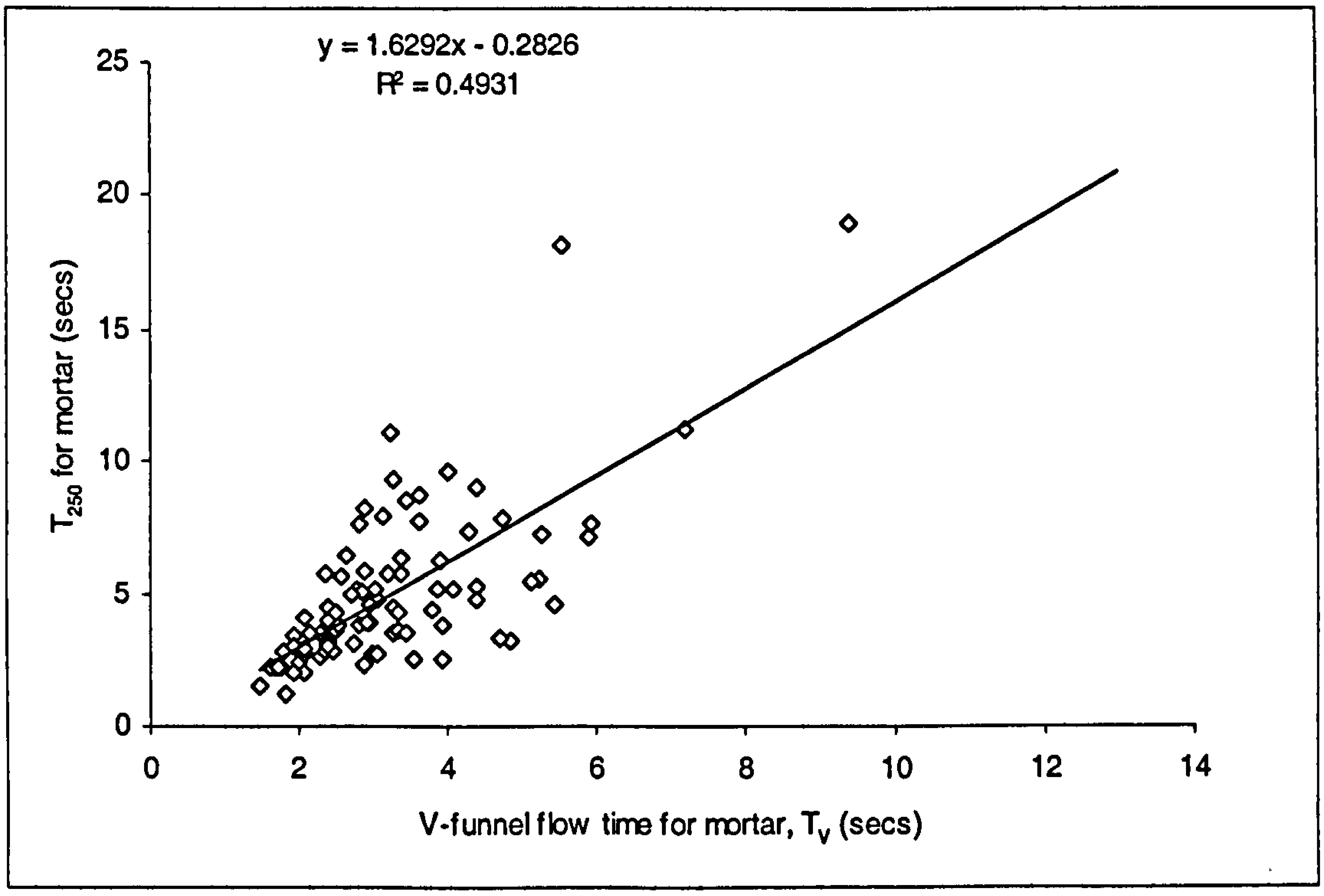


Figure 10-22 Relationship between V-funnel flow time and the time to 250 spread for mortar

10.2.1.5 Discussion

Table 10-5 shows the correlation coefficients for the relationships discussed above for the whole set of data. There are strong relationships between yield stress and spread, and plastic viscosity and V-funnel flow time, all with correlation coefficients higher than 0.95; the other two relationships are very weak. This suggests that rheological properties of mortar can be represented by its spread and V-funnel flow time, but understanding the testing conditions and the factors affecting these relationships are important. For mix design purposes, there is no need to measure both rheology and flowing properties.

Table 10-5 Correlation coefficients for the relationships between the properties of mortar

Mortar properties	R	Spread D_m	V-funnel T_V	Time to 250 mm spread T_{250}	Yield stress τ_0	Plastic viscosity μ
	Spread, D_m					
	V-funnel, T_V					
	Time to 250 mm spread, T_{250}		0.70			
	Yield stress τ_0	**0.95**				
	Plastic viscosity, μ		**0.96**	0.68		

10.2.2 Relationships between concrete properties

It should be noted that in all concrete mixes the coarse aggregate content was constant at 0.317 m^3 per cubic metre, meaning the volume of mortar component is also constant.

As with the mortar test, the most likely relationships are discussed here; these are shown in **table 10-6**. The data used are given in **table A7-5, table A8-3, table A8-6, table A8-7, table A9-5, table A10-3, tableA13-4** and **table A13-8**.

The test methods used for concrete are very similar to for mortar, therefore similar relationships were expected for those properties.

Table 10-6 The relationship discussed between concrete properties

	Concrete properties					
R	Yield stress, τ_0	Plastic viscosity, μ	V-funnel, T_V	Time to 500 slump flow, T_{500}	Time to 250 U-box height, $T_{U\text{-}box}$	Slump flow, SF
Sections	10.2.2.1	10.2.2.2	10.2.2.3			
Concrete properties						
Yield stress, τ_0						
Plastic viscosity, μ						
V-funnel, T_V		x				
Time to 500 slump flow, T_{500}		x	x			
Time to 250 U-box height, $T_{U\text{-}box}$		x	x	x		
Slump flow, SF	x					

10.2.2.1 Yield stress (τ_0) and slump flow (SF)

Figure 10-23 shows the relationship for all mixes. It can be seen that it is much weaker than the relationship between the yield stress and the spread for mortar. This may be partially because of the error occurring during the yield stress measurement, for example, some measured yield stresses are below zero because of the poor repeatability as discussed in chapter 4.

As reviewed in chapter 2 several equations for this relationship have been proposed, some including the parameter of concrete density. Assuming a SCC density of about 2350 kg/m^3 the relationships from the **equations 2-8** and **2-10** proposed by Furokawa [32] and Sedran [116] respectively, were plotted together with that for the current project in **figure 10-23**. It can be seen that there are significant differences between these relationships, which may be due to reasons such as the use of different testing equipments, conditions and mix proportions *etc*. The NIST report [43] on the comparative tests between rheometers suggested the relationship between the yield stress values measured by the two-point test and the BTRHEOM as used by Sedran *et al* is:

$$\tau_{0(2-ponit)} = 0.54\tau_{0(BTRHEOM)} - 153.9 \qquad (10\text{-}4)$$

Using this to convert Sedran's equation to that for the 2-point test, given as shown in **figure 10-23**, a trend line very close to that for the current project. This therefore suggests a significant effect of different testing equipment on the results.

For an SCC with slump flow higher than 650 mm the yield stress can be roughly estimated to be lower than 30 Pa from the trend line for the current programme. This is higher than CBI's proposal for satisfactory SCC (τ_0 < 12 Pa) but lower than Wallevik and Nielsson's suggestion (τ_0 is between 50 and 70 Pa) as measured by the BML viscometer [2]. Again many reasons may cause these differences, the main one may be the different test methods and criteria for a successful SCC proposed by different countries.

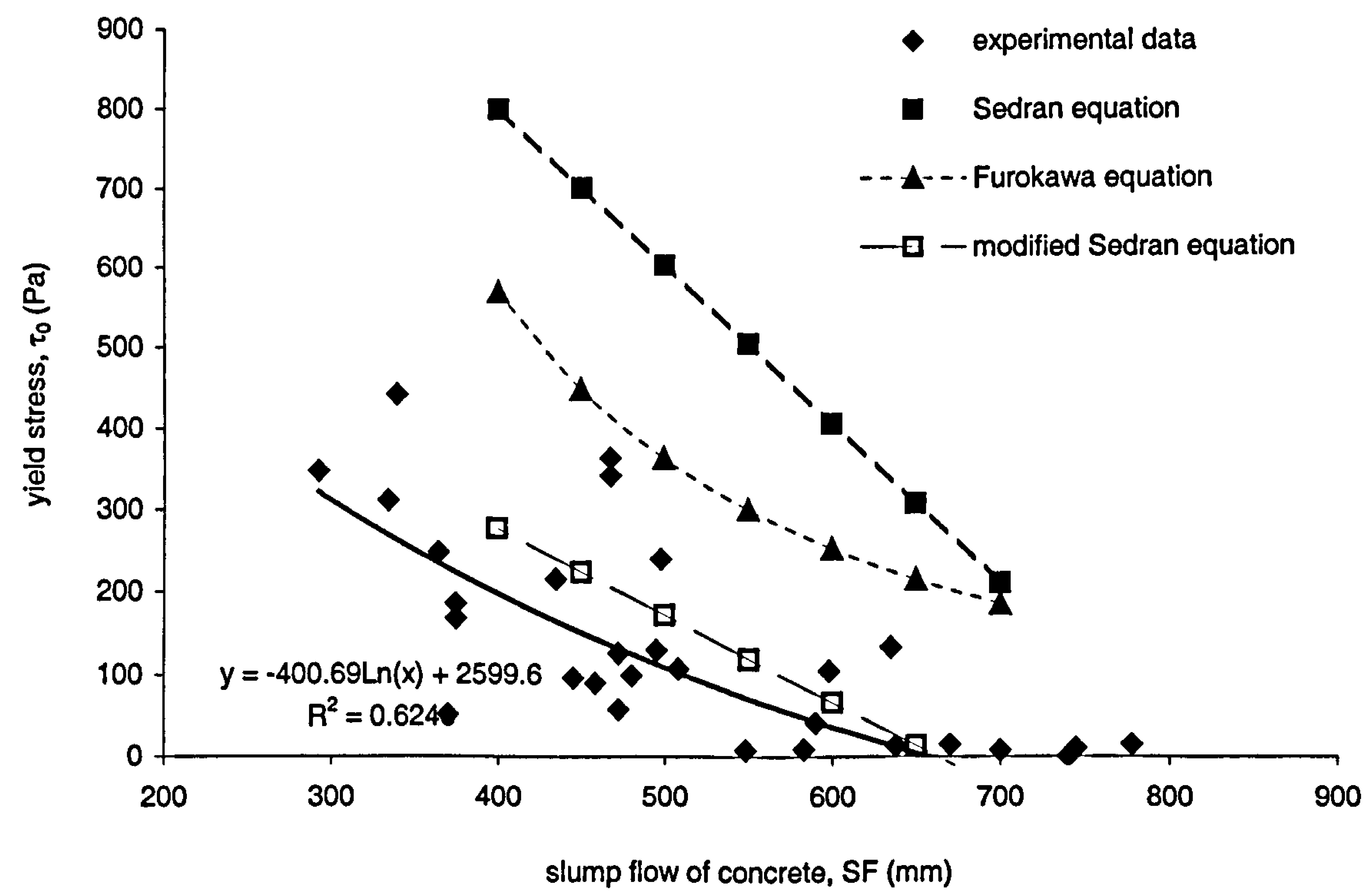


Figure 10-23 Comparison of the relationships between yield stress-slump flow obtained by different workers

10.2.2.2 Plastic viscosity (μ) relationships

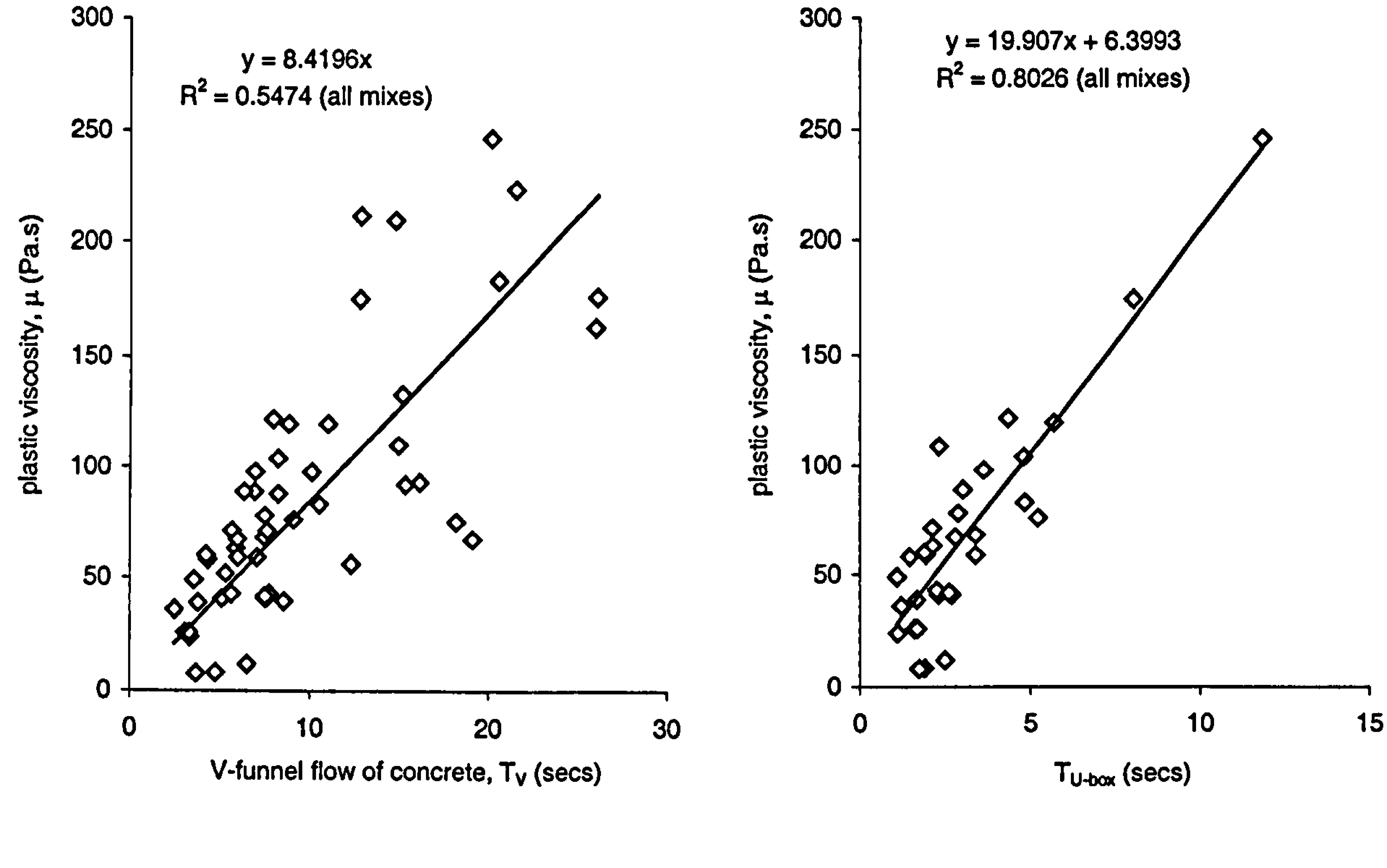
Figures 10-24 & 10-25 show the relationships between μ and T_V, μ and $T_{U\text{-box}}$ and μ and T_{500} for all data. Surprisingly the best relationship was obtained between μ and $T_{U\text{-box}}$, with a correlation coefficient of 0.92; the reasons will be discussed later.

A comparison was made for the relationship between μ and T_{500} with the data from Kurakawa's and Sedran's equations (**equation 2-9 & 2-11**), as shown in **figure 10-25.** The trend line for Sedran equation is relatively close to the line for the data in the current programme. The equivalent relationship to yield stress from the NIST report is: $\mu_{(2-ponit)} = 0.36\mu_{(BTRHEOM)} + 7.20$ (10-4)

The resulting modified trend line is parallel to but consistently lower than that for the current project, suggesting the possibility of predicting the plastic viscosity for SCC with UK materials after further modification.

According to the relationship between μ and T_V (**figure 10-24(a)**) an SCC with V-funnel flow time between 4 and10 seconds may have a plastic viscosity of 30-100 Pa.s. This is lower than the requirement proposed by CBI (150-250 Pa.s) but higher than by Wallevik *et al* (20-30 Pa.s) [43]. Again this may be because of many reasons mentioned as above, and highlights the great difficulty when comparing SCC properties between different countries.

The relationships between the properties for concrete may also be affected by many factors such as slump flow, mix proportions, the composition of mixtures, but the number of concrete tests were not sufficient for such detailed analysis.



(a) (b)

Figure 10-24 Relationships between the plastic viscosity (μ) and (a) the V-funnel flow time (T_V), (b) the time to 250 mm height in U-box test ($T_{U\text{-}box}$)

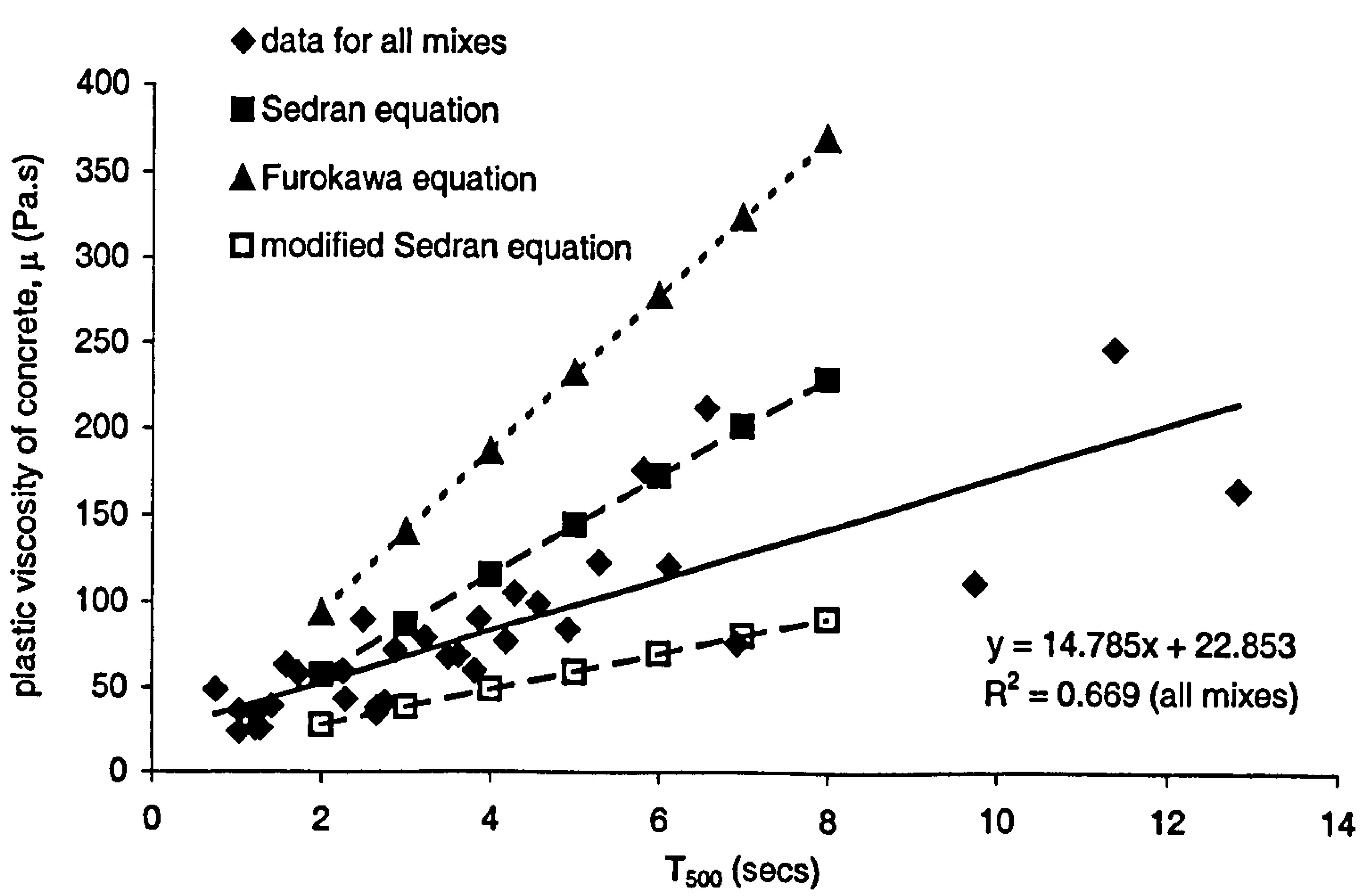


Figure 10-25 A comparison of the relationships between plastic viscosity (μ) and time to 500 mm slump flow (T_{500}) proposed by different workers

10.2.2.3 Flow time relationships

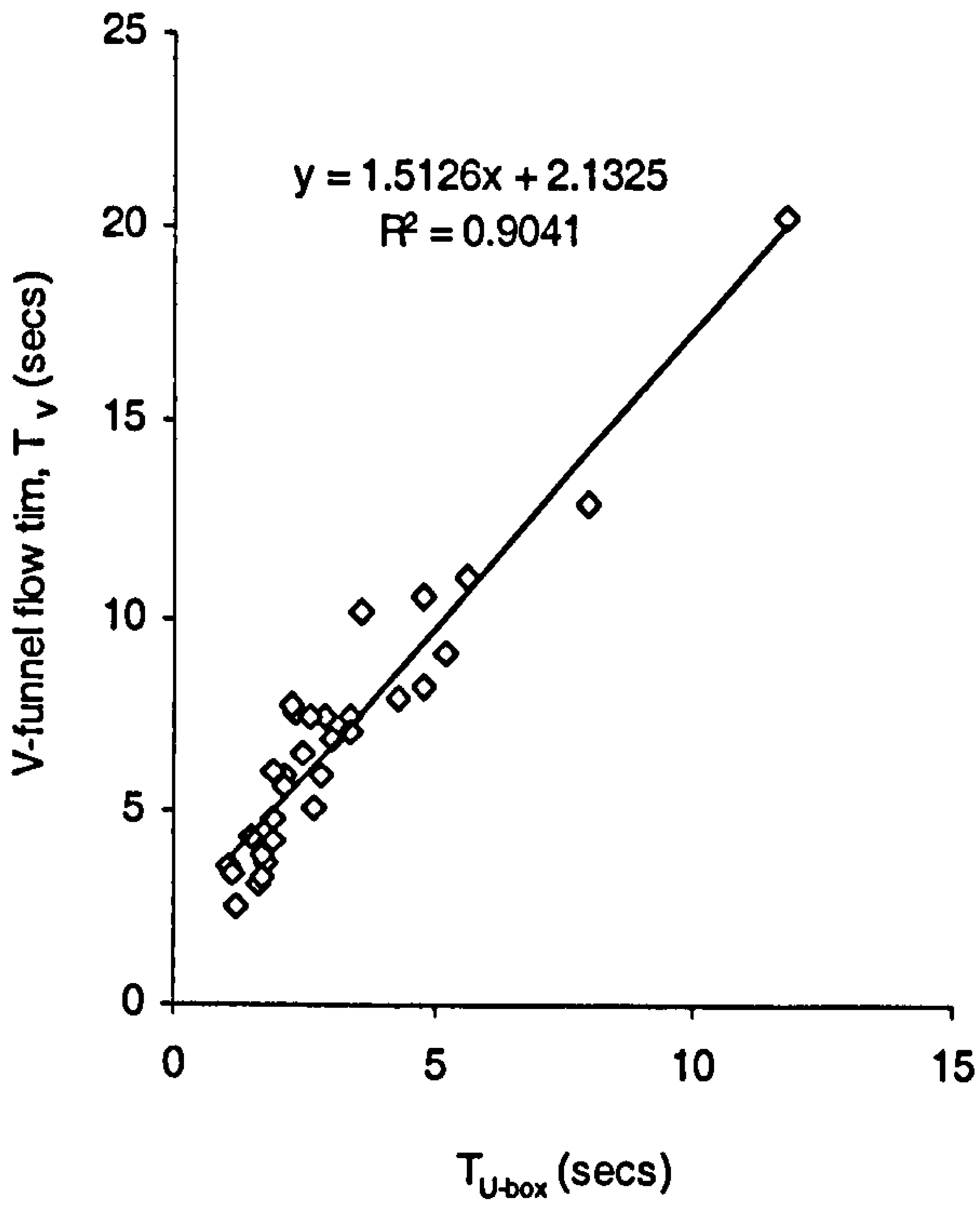
Figure 10-26 shows the relationships between T_V and $T_{U\text{-box}}$, T_V and T_{500}, and T_{500} and $T_{U\text{-box}}$. Very good relationships were obtained between T_V and $T_{U\text{-box}}$, and T_{500} and $T_{U\text{-box}}$ with correlation coefficients of 0.95. The relationship between T_V-T_{500} was slightly weaker but the correlation coefficient is still higher than 0.9. All these relationships are much stronger than those with plastic viscosity discussed in section 10.2.2.2; the reasons will be discussed later. No effect of mix constituents and proportions on these relationships was found, which might be because of the small number of results. It can be predicted that for an SCC with a V-funnel flow time between 4 and10 seconds, the flow time to 500 mm is between1 and 5 seconds, and time to 250 mm filling height in U-box test is also 1 to 5 seconds. No comparison has been made with other worker's results because different testing conditions were used.

10.2.2.4 Discussion

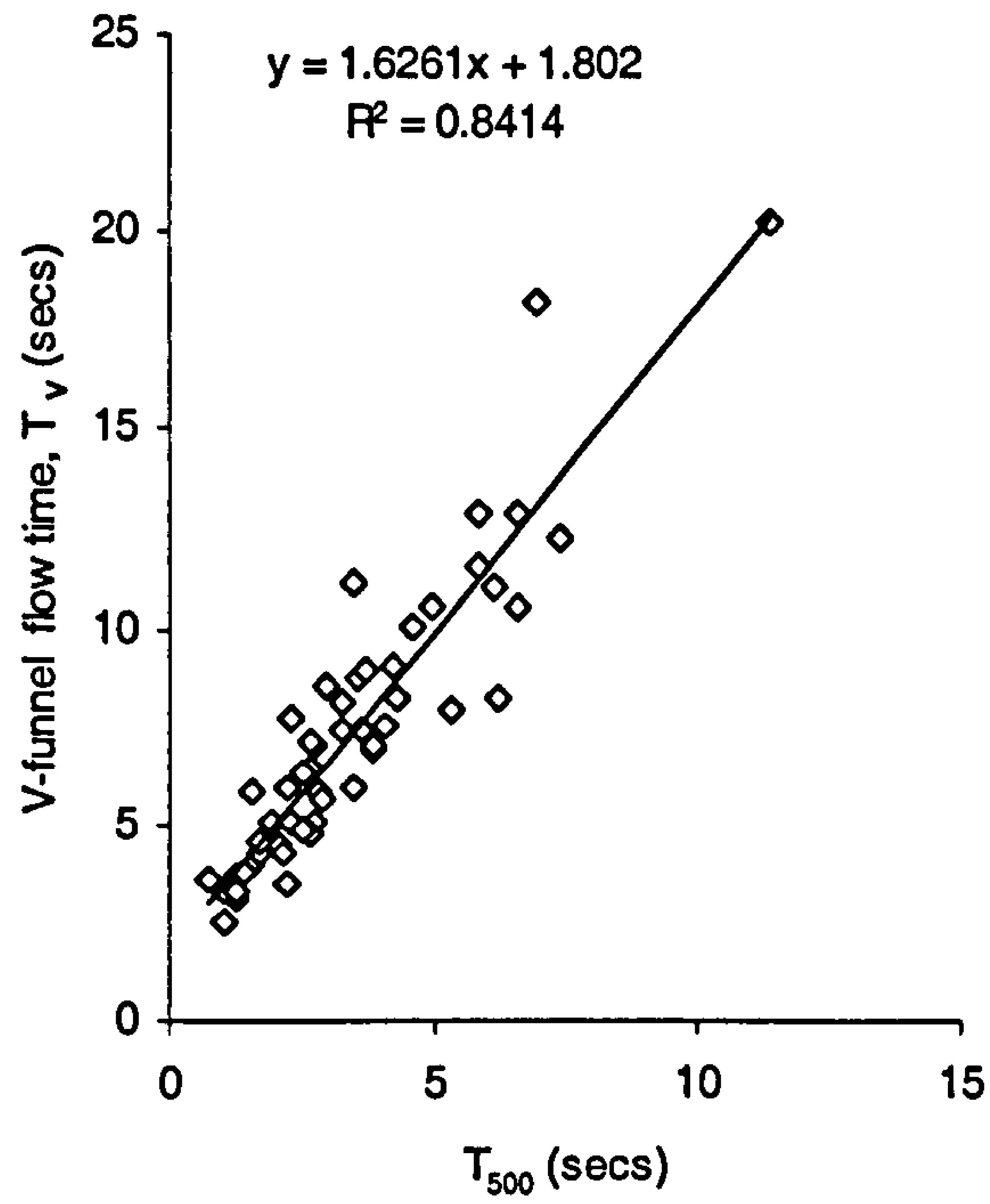
Table 10-7 shows the correlation coefficients for the relationships discussed above.

Table 10-7 Correlation coefficient for the relationship between the properties for concrete

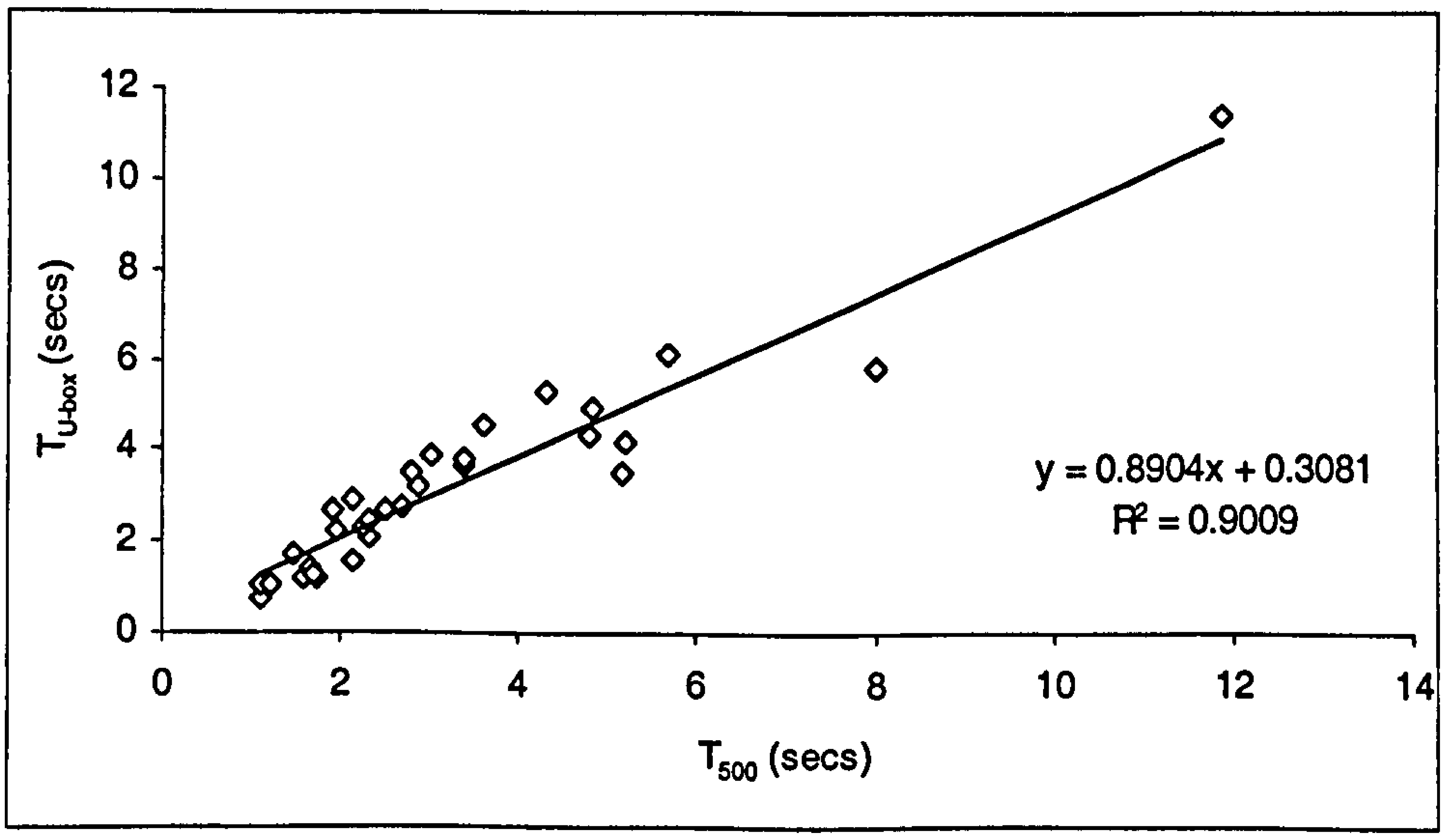
		Concrete properties					
	R	Yield stress, τ_0	Plastic viscosity, μ	V-funnel, T_V	Time to 500 slump flow, T_{500}	Time to 250 U-box height, $T_{U\text{-box}}$	Slump flow, SF
	Sections	10.2.2.1	10.2.2.2	10.2.2.3			
Concrete properties	Yield stress, τ_0						
	Plastic viscosity, μ						
	V-funnel, T_V		0.88/0.74				
	Time to 500 slump flow, T_{500}		0.83	0.92			
	Time to 250 U-box height, $T_{U\text{-box}}$		**0.92**	**0.95**	**0.95**		
	Slump flow, SF	0.79					



(a)



(b)



(c)

Figure 10-26 Relationship between (a) T_V -T_{Ubox} (b) T_V-T_{500}, (c) $T_{U\text{-}box}$-T_{500}

The slump flow-yield stress relationship is not as strong as expected from the mortar tests, which may be due to many factors such as the accuracy of test results, segregation of some concretes *etc.*

$T_{U\text{-box}}$ has the best relationships with plastic viscosity, V-funnel flow time and the time to 500 mm slump flow. $T_{U\text{-box}}$ is the filling time to 250 mm height in the U-box test, and the concrete has to pass through the obstacles before to reach this. This suggests only those concretes nearly satisfying SCC requirements (i.e. good passing ability and segregation resistance and high flowability) can obtain $T_{U\text{-box}}$ values, meaning the properties of the concrete are confined to a narrow range. However, the range for μ, T_V and T_{500} is much larger, i.e. concrete with low slump flow or high segregation can still produce results, therefore many factors can affect these. For example, if only the test results of T_V for those concretes with slump flow higher than 550 mm were used to plot the relationship for μ-T_V, as shown in **figure 10-27**, this is much stronger than the one for all data (**figure 2-26(a)**), suggesting an effect of slump flow on V-funnel flow time. This is in agreement with the suggestion in the recent RILEM report [2] that the T_V and the T_{500} can not be used as a representation of plastic viscosity of a mixture independently of flowing capacity, such as slump flow.

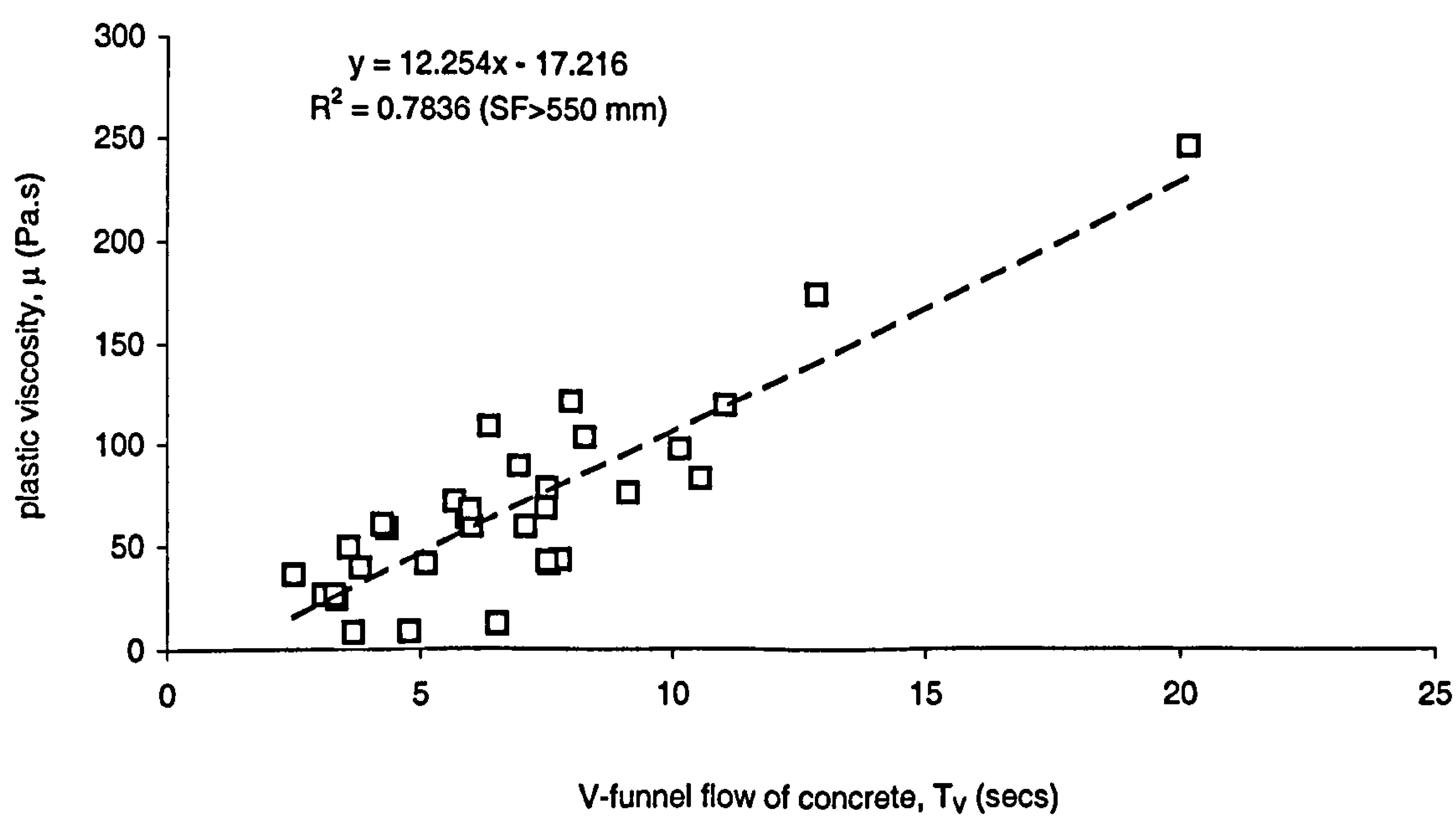


Figure 10-27 The plastic viscosity vs V-funnel flow time relationship for concrete with slump flow higher than 550 mm

In general, it can be concluded that good relationships can be established between the properties of plastic viscosity and flow times, if the factors affecting those relationships are taken into account. Further study is needed on the relationship between yield stress and slump flow.

10.2.3 Relationships between the fresh properties of concrete and its mortar component

As discussed in chapter 3 there are many advantages of testing mortar when studying the properties of SCC. This was confirmed in chapters 5 to 9 by finding that there are similar trends for the same property measured on mortar and concrete.

This section discusses the relationships between the fresh properties of concrete and its mortar component. There are a great number of relationships that could be discussed, but only those most important have been analysed; these are shown in **table 10-8**. The relationships between the yield stress of concrete and the yield stress and spread of mortar, which may also be strong, are not analysed, because as discussed earlier the data for concrete are not reliable.

Table 10-8 The discussed relationships between the properties of concrete and its mortar component

	sections	Concrete properties				
		10.2.3.1	10.2.3.2	10.2.3.3	10.2.3.4	10.2.3.5
		Slump flow, SF	V-funnel flow, T_V	Time to 500 mm slump flow, T_{500}	Time to 250 mm filling height, $T_{U\text{-box}}$	Plastic viscosity, μ
Mortar properties	Spread, Dm	x				
	Yield stress, τ_0	x				
	V-funnel flow, T_V		x	x	x	x
	Time to 250 mm spread, T_{250}		x	x	x	x
	Plastic viscosity, μ		x	x	x	x

The data used include those test results for mortar and concrete shown in appendix 7-13 (**table A7-5, table A8-3, table A8-6, table A8-7, table A9-5, table A10-3, tableA13-4** and **table A13-8**), excluding those results for yield stress and plastic viscosity for mortar obtained by manual recording.

As mentioned earlier in all concrete mixes 20 mm maximum size gravel was used and the content was constant at 0.317 m^3/m^3.

10.2.3.1 Slump flow

Figure 10-28 shows the slump flow of concrete plotted against the spread and the yield stress of mortar. It can be seen that there is a strong linear relationship between the slump flow and the spread with a correlation coefficient of about 0.93. For an SCC with a slump flow higher than 650 mm the correspondent mortar spread is 302 ± 10 mm, which is consistent with the criterion in the UCL mix design method for the mortar, i.e. a spread higher than 310 mm [29]. The relationship of the slump flow of concrete with the yield stress of mortar is not as strong as with the spread; this may be because the slump flow test is similar to the spread test in terms of flowing mechanism.

As reviewed in chapter 2 several workers have found a strong correlation between the slump flow of concrete and the spread of mortar, as shown in **figure 2-52 (a).** Yahia's and Chai's data are compared with the results in the current programme (**figure 10-28 (a)**) in **figure 10-29,** because both have similar mixes or testing condition. It can be seen that Chai's data are consistent with those of the current programme, while Yahia's data only agree for mortar spread values between 310 and 330 mm, but diverge with a decrease of spread. Chai, who also worked in UCL, used the same materials and testing conditions, and the coarse aggregate content was between 0.3-0.32 m^3/m^3, Yahia also used coarse aggregate with a 20 mm maximum particle size with a content of 0.3 m^3/m^3, but the type of aggregate was not mentioned. This may be the main reason for the differences.

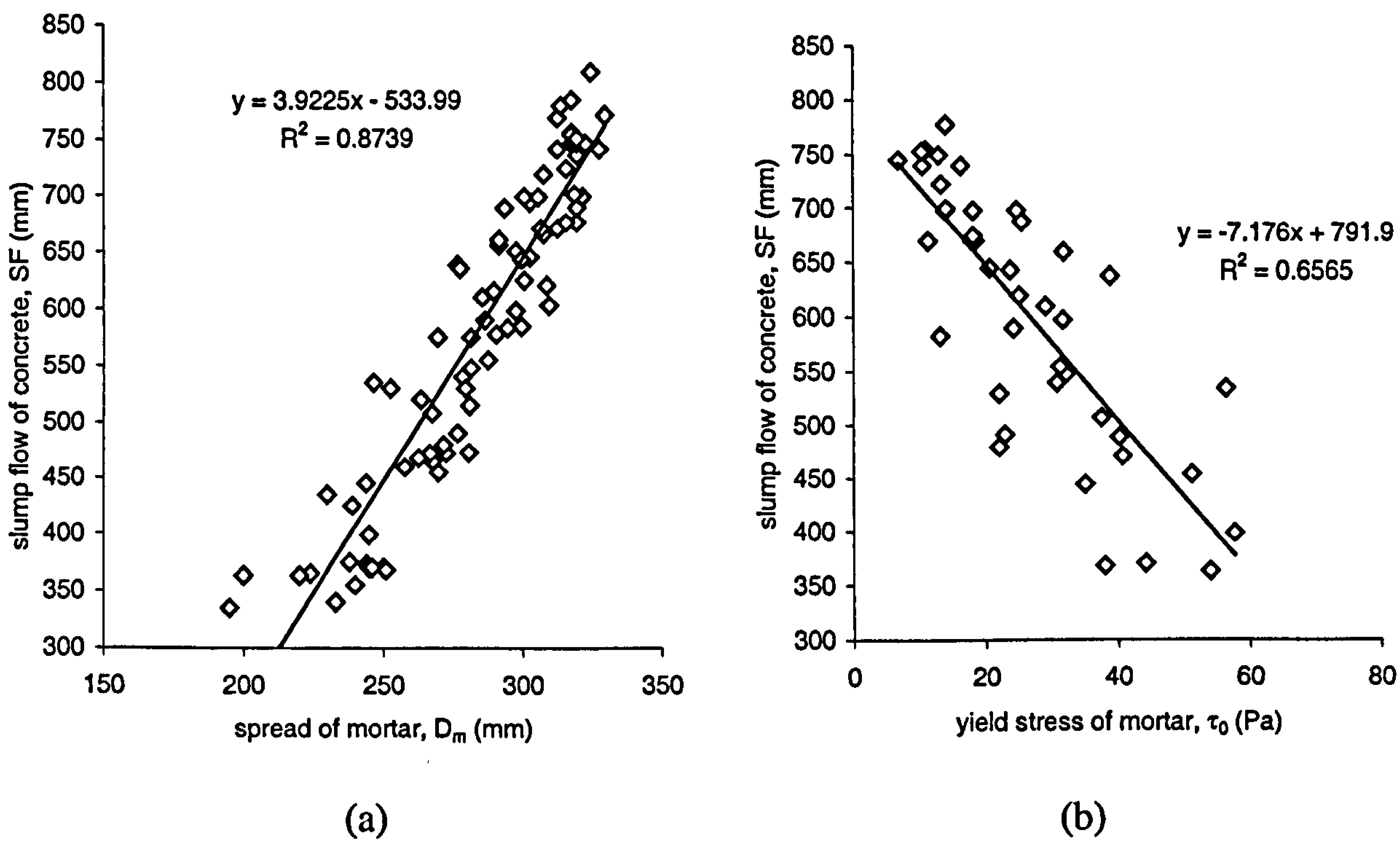


Figure 10-28 The relationship between the slump flow of concrete and (a) the spread of mortar, (b) the yield stress of mortar

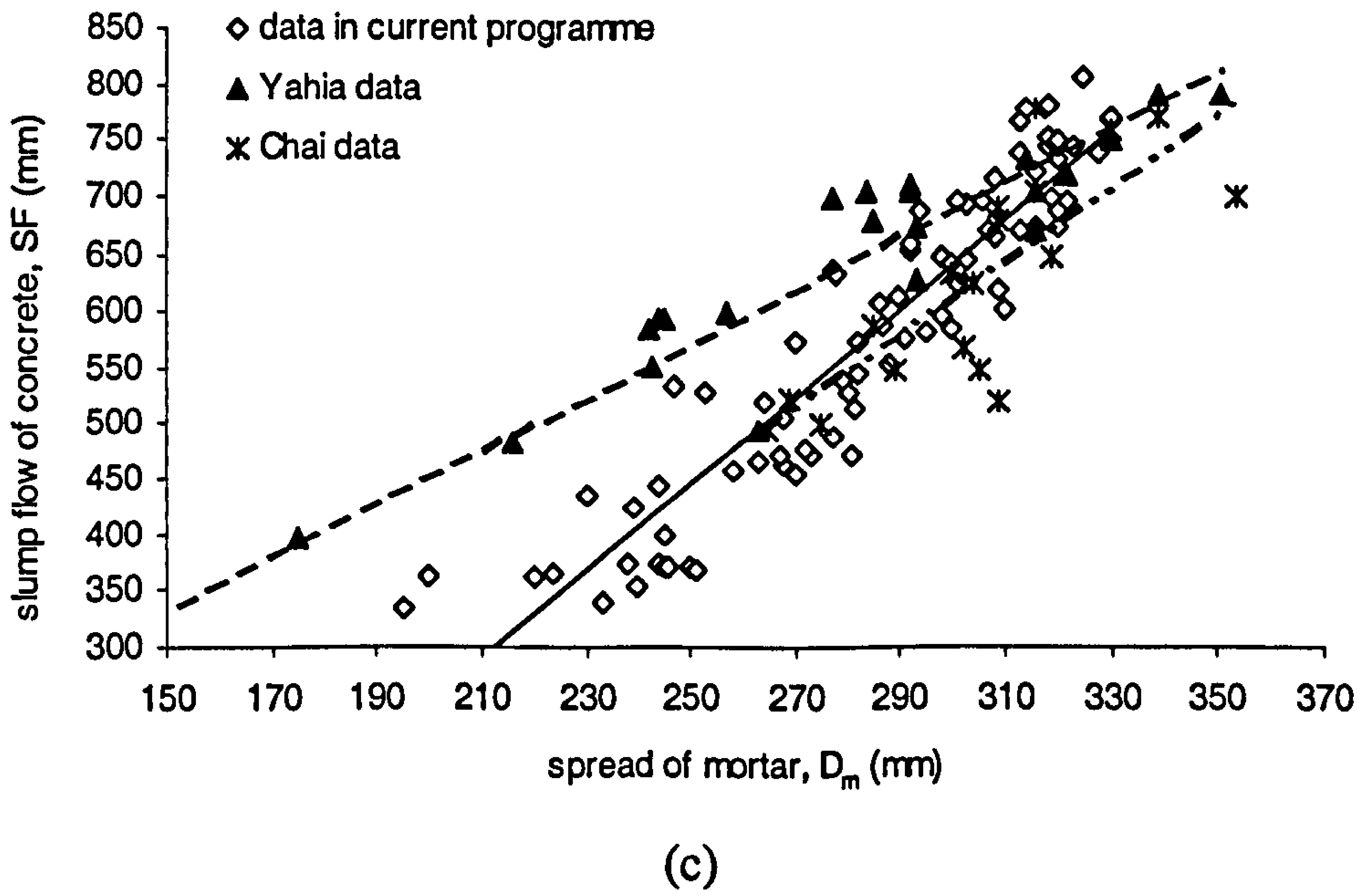


Figure 10-29 Comparison of the relationships between the slump flow and spread obtained by different workers

10.2.3.2 V-funnel flow time

Figure 10-30 shows the relationships between the T_V for concrete and the T_V, μ and T_{250} for mortar respectively. The best relationship was obtained between the V-funnel flow times for concrete and mortar, but the relationships for the others are improved when mixes with Welan gum are separated, in this case the strongest relationship is between T_V (concrete) and μ (mortar). Two near parallel linear relationships were obtained for the mixes with and without Welan gum as shown in **figures 10-30 (b) & (c),** which might be due to their different rheological behaviour. This effect was not found in the relationship between the V-funnel flow times of concrete and mortar, and the reason for this is not clear.

Again a comparison was made with both Chai's and Yahia's results, as shown **in figure 10-31.** Surprisingly Yahia's data are very consistent with the relationship for the current project but Chai's data are consistently lower. The V-funnel used by Yahia *et al* for concrete is slightly different from the one used in UCL, it had an opening size of 65 × 75 mm instead of 75 × 75 mm at UCL, and it is not clear how much this difference effects the relationship. Chai used same size of V-funnel made of wood, which was also used in the current programme for a few initial tests. It was found that the opening had widened due to deterioration, so a new steel V-funnel was made for the formal study. This may be the main reason causing the difference between Chai's data and the current programme.

According to the UCL mix design method the V-funnel flow time for SCC with 20 mm maximum size coarse aggregate should be in the range of 4 and 10 seconds, and the corresponding V-funnel flow time for mortar is 4 and 7 seconds according to Chai's relationship, but is 3 and 6 seconds according to the current programme.

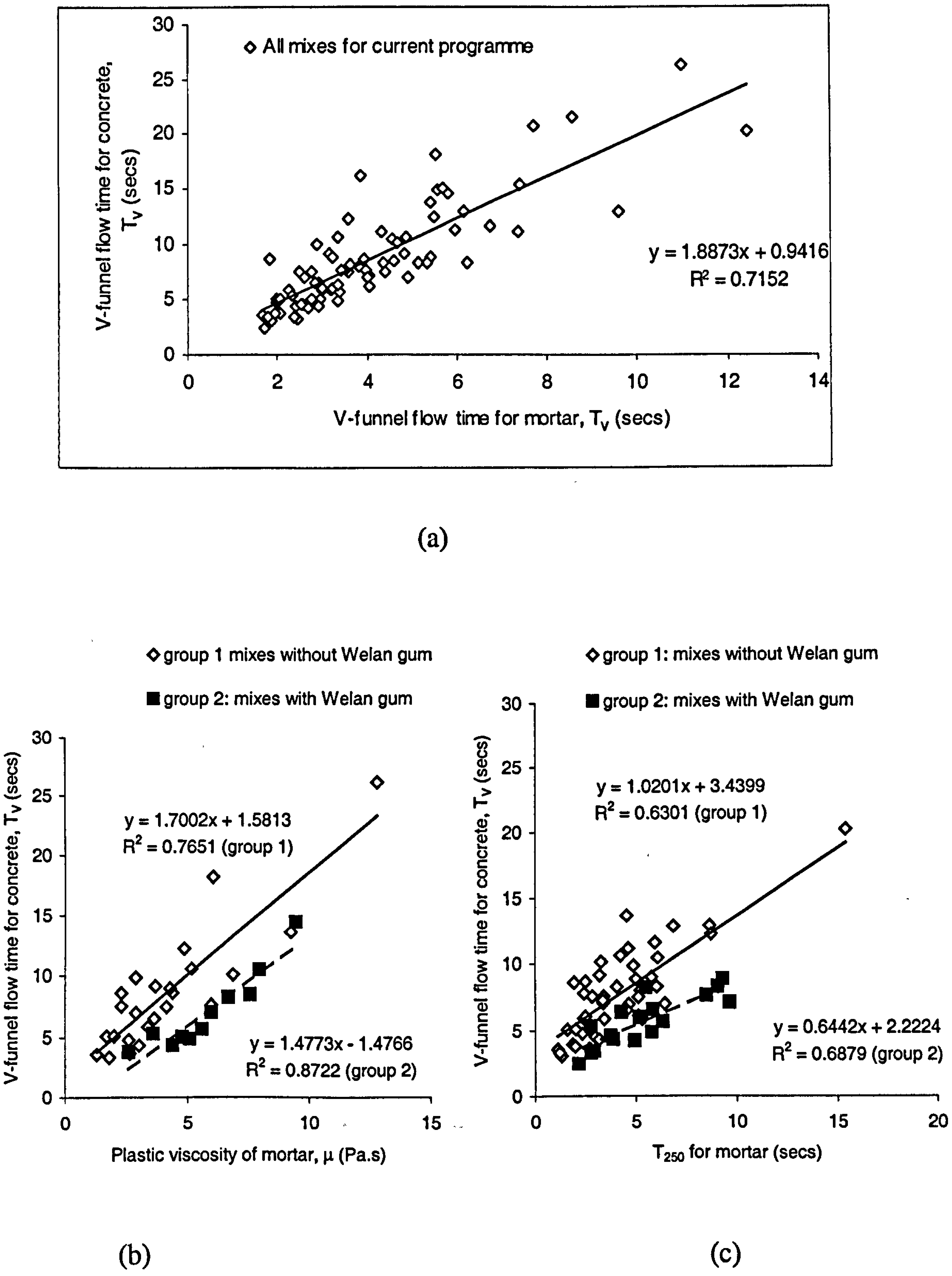


Figure 10-30 The relationship between T_V for concrete with (a) T_V, (b) μ and (c) T_{250} for mortar.

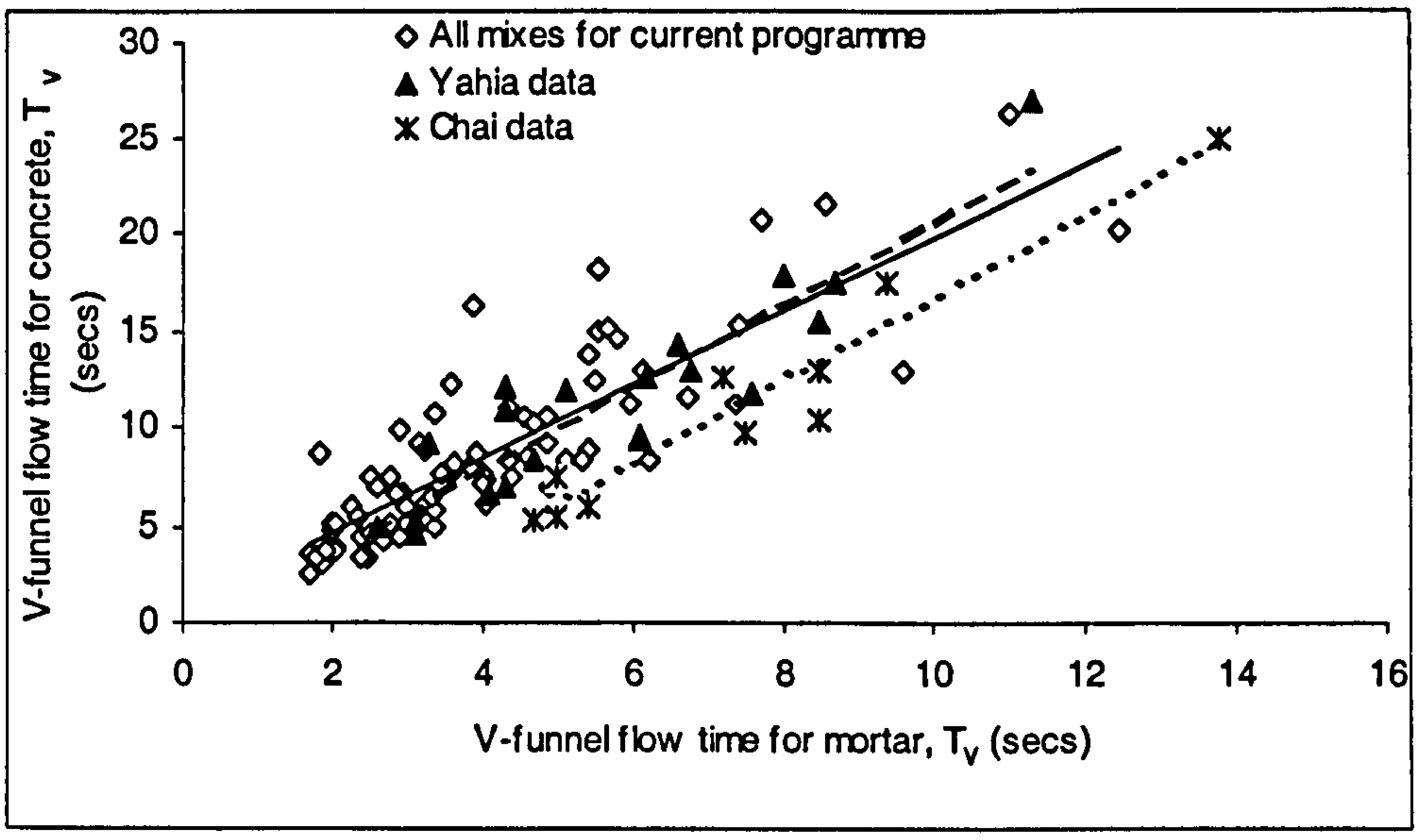


Figure 10-31 Comparison of the relationships between the V-funnel flow times for mortar and concrete proposed by different workers

10.2.3.3 The time to 500 mm slump flow

Figure 10-32 shows the relationships between T_{500} for concrete with T_V, μ and T_{250} for mortar. The best relationship was obtained between the T_{500} and the T_{250} when the effect of Welan gum was isolated, with the correlation coefficients higher than 0.9, while the other relationships are much weaker. Again the effect of Welan gum might be related to its rheological properties, however, this needs further work to confirm this.

10.2.3.4 The time to 250 mm filling height

Figure 10-33 shows the relationships between $T_{U\text{-}box}$ for concrete with T_V, μ and T_{250} for mortar. The best relationship was obtained between the $T_{U\text{-}box}$ and the T_V with the correlation coefficient of 0.92. There seemed to be no effect of Welan gum on these relationships but further confirmation is needed.

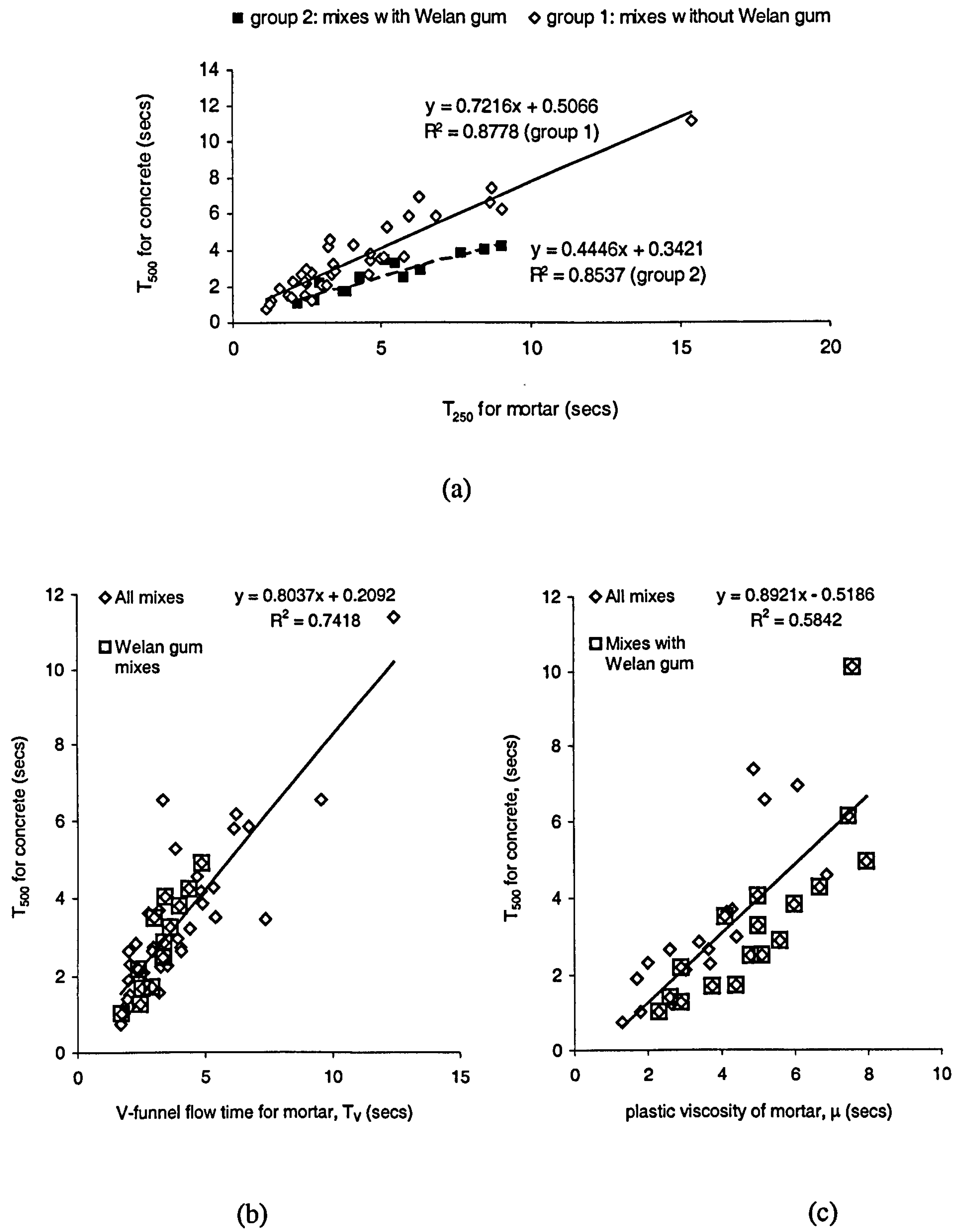


Figure 10-32 The relationship between T_{500} for concrete and (a) T_{250}, (b) T_V, (c) μ for mortar

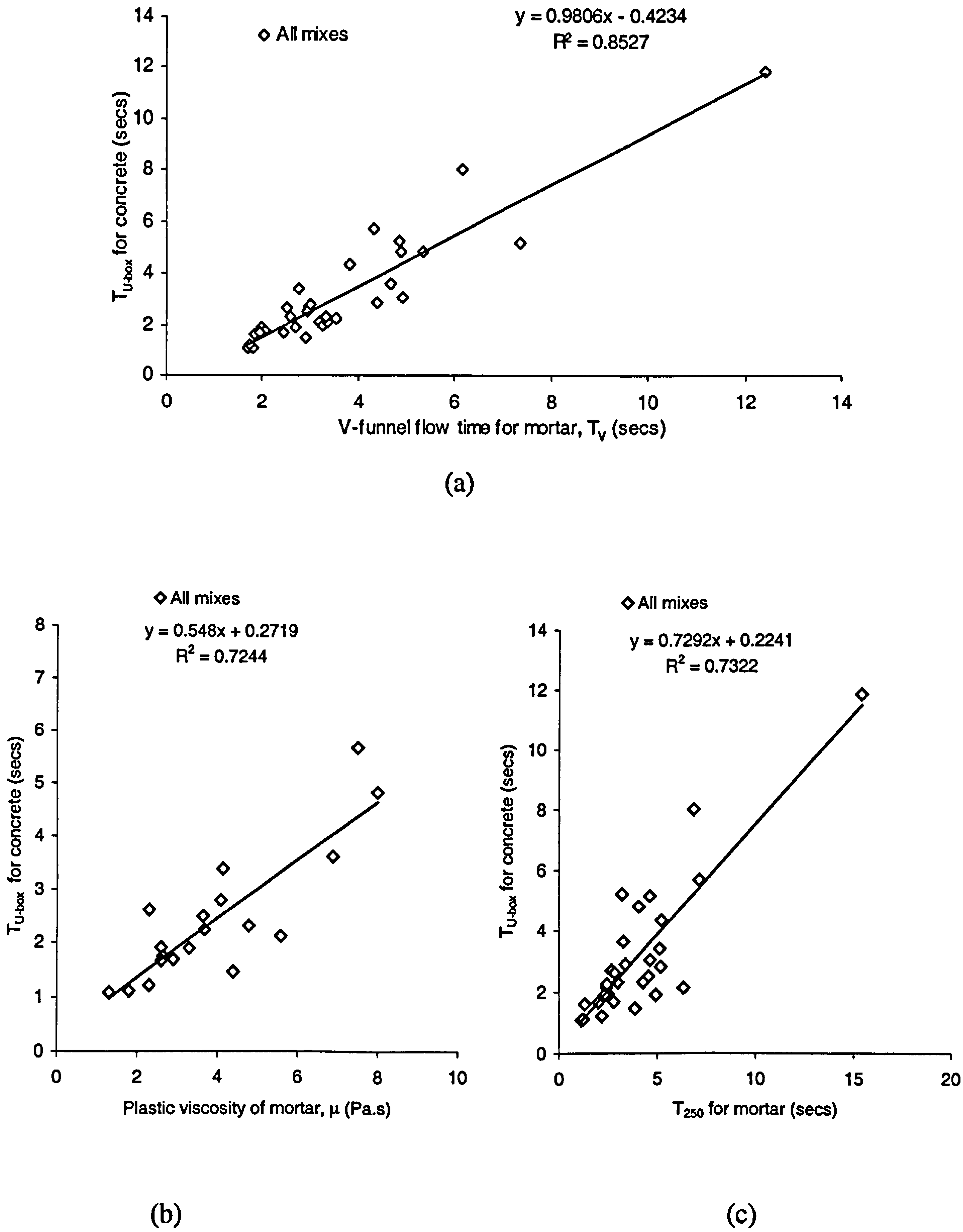


Figure 10-33 The relationship between $T_{U\text{-box}}$ for concrete and (a) T_V, (b) μ, (c) T_{250} for mortar

10.2.3.5 Plastic viscosity

Figure 10-34 presents the relationships between the plastic viscosity for concrete (μ) and the μ, T_V and T_{250} for the mortar. Strong linear relationships between the plastic viscosity of the concrete and mortar, and the plastic viscosity of concrete and the V-funnel flow times of mortar are apparent with correlation coefficients higher than 0.9. This suggests that the plastic viscosity of concrete can be efficiently predicted from the same property or V-funnel flow time for its mortar component. The relationship between the plastic viscosity of the concrete and the flow time to 250 mm spread for mortar seems to be dependent on the types of powder of the mixes. The flow time for Welan gum mixes and the mixes containing CSF seem to be longer than those expected from other mortars, which might be due to their rheological behaviour, but further confirmation is needed.

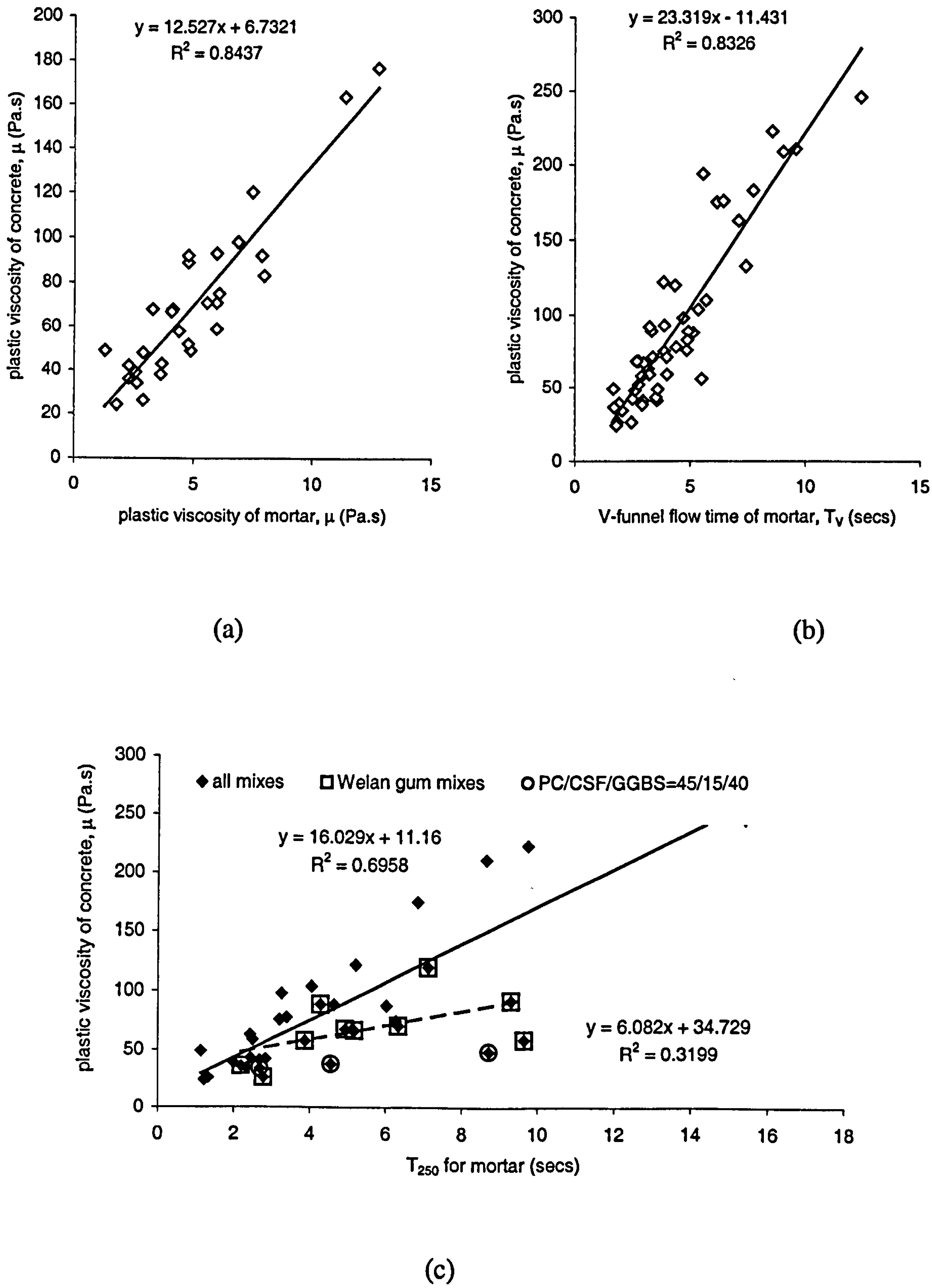


Figure 10-34 The relationship between μ for concrete and (a) μ, (b) T_V, (c) T_{250} for mortar

10.2.3.6 Discussion

Table 10-9 shows the correlation coefficients for the relationships discussed above.

Table 10-9 The discussed relationships between properties of concrete and mortar

	sections R	Concrete properties				
		10.2.3.1	10.2.3.2	10.2.3.3	10.2.3.4	10.2.3.5
		Slump flow, SF	V-funnel flow, T_V	Time to 500 mm slump flow, T_{500}	Time to 250 mm filling height, $T_{U\text{-box}}$	Plastic viscosity, μ
Mortar properties	Spread, Dm	0.93				
	Yield stress, τ_0	0.81				
	V-funnel flow, T_V		0.85	0.86	0.92	0.91
	Time to 250 mm spread, T_{250}		0.79*/0.83**	0.94*/0.92**	0.85	0.83*/0.57**
	Plastic viscosity, μ		0.87*/0.93**	0.76	0.85	0.92

*: without Welan gum, **: with Welan gum

There is a strong relationship between the slump flow concrete and the spread of its mortar component, while that between the slump flow and the yield stress is not as strong as expected.

For plastic viscosity and flow times, the relationships between T_V(concrete) and μ(mortar), T_{500}(concrete) and T_{250}(mortar), $T_{U\text{-box}}$(concrete) and T_V(mortar), and μ(concrete) and μ(mortar) are the strongest in each section, and all have correlation coefficients higher than 0.9. The T_{500}(concrete) and the T_{250}(mortar) tests are similar, both properties being measured during the flowing capacity test. Although the T_V(concrete) and the T_V(mortar) tests are also similar their relationship was not as strong as that between T_V(concrete) and the μ(mortar) because of the difference between the relative size of the openings between the two V-funnels; the V-funnel opening for mortar is about 6 times of maximum size of sand while for concrete is about 3 times of the maximum size of coarse aggregate. Similarly, the $T_{U\text{-box}}$(concrete) *vs* T_V(mortar) relationship is stronger than the $T_{U\text{-box}}$(concrete) vs T_{250}(mortar) and $T_{U\text{-box}}$(concrete) *vs* μ(mortar) because there is more similarity between $T_{U\text{-box}}$(concrete) and T_V(mortar) tests, both measure flow times at high shear rate. Undoubtedly there is a strong relationship between μ(concrete) and μ(mortar) but the correlation between the μ (concrete) and the T_V (mortar) is also strong because of the strong relationship between the μ and the T_V for mortar.

Generally, it can be concluded there are strong relationships between the fresh properties of concrete and mortar if the test methods used are similar. There is effect of types of mix on the relationship, especially when T_{250} is concerned, therefore attention should be paid to the details of the mixture when discussing these.

SCC properties can be evaluated by slump flow and U box tests, which gives value of SF, U_H and $T_{U\text{-box}}$; these can be predicted from mortar tests on spread and V-funnel flow time. This establishment of the correlation may simplify concrete mix design methods for SCC.

10.3 Relationship between concrete strength and powder composition—a discussion of Feret's rule

Although strength property was not a main property investigated in this project, it was measured and the results analysed.

As reviewed in chapter 2 most SCC uses two or three powders, therefore Abram's rule is not suitable for predicting 28 days strength. Chai [29] reported that the strength of SCC follows Feret's rule as modified by de. Larrard [54], as shown in **equation 2-12.**

$$f_c = \frac{K_g \bullet R_c}{\left(1+3.1\dfrac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} \qquad (2\text{-}12)$$

where

f_c	:cylinder compressive strength,
K_g	:an aggregate coefficient;
R_c	:the cement strength (45.0 MPa at 7 days and 57.3 MPa at 28 days for that as supplied to UCL;
W	:free water content;
A	:entrapped air volume;
K_1	:a pozzolanic activity coefficient = 0.4PFA/C + 3CSF/C ($K_1 \leq 0.5$)

K_2 :a limestone activity coefficient = 0.2 LSP/C ($K_2 \leq 0.07$)

C, PFA, CSF, LP and GGBS :content of cement, fly ash, microsilica, limestone powder and blast furnace slag.

It can be seen that this equation includes all the important factors including types and content of powder, water content and cement strength that control concrete strength.

Chai converted the equation to give cube strengths by using the CEB-FIP recommendation [138] for the relationship between cube and cylinder strength. The resulting equations are:

$$f_c = \frac{K_g \cdot R_c}{\left(1+3.1\dfrac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} + 10, \qquad (10\text{-}1)$$

$$\text{if } f_c \; \frac{K_g \cdot R_c}{\left(1+3.1\dfrac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} \geq 40 \text{ Mpa}$$

and

$$f_c = \frac{K_g \cdot R_c}{\left(1+3.1\dfrac{W+A}{C(1+K_1+K_2)+GGBS}\right)^2} + 1.25, \qquad (10\text{-}2)$$

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

These equations were used to evaluate the 7 days and 28 days strength results given in appendix 8-13. The outcome is shown in **figures 10-35**. The coefficient K_g was altered until the calculated values have a minimum difference from the test results; this gives 4.75 for 28 days and 4.81 for 7 days strength results. It can be seen in **figure 10-35** that the modified Feret's rule is more suitable to predict later age strength but in general both ages showed a good correlation. The aggregate coefficient was slightly higher than that obtained by Chai which is 4.6

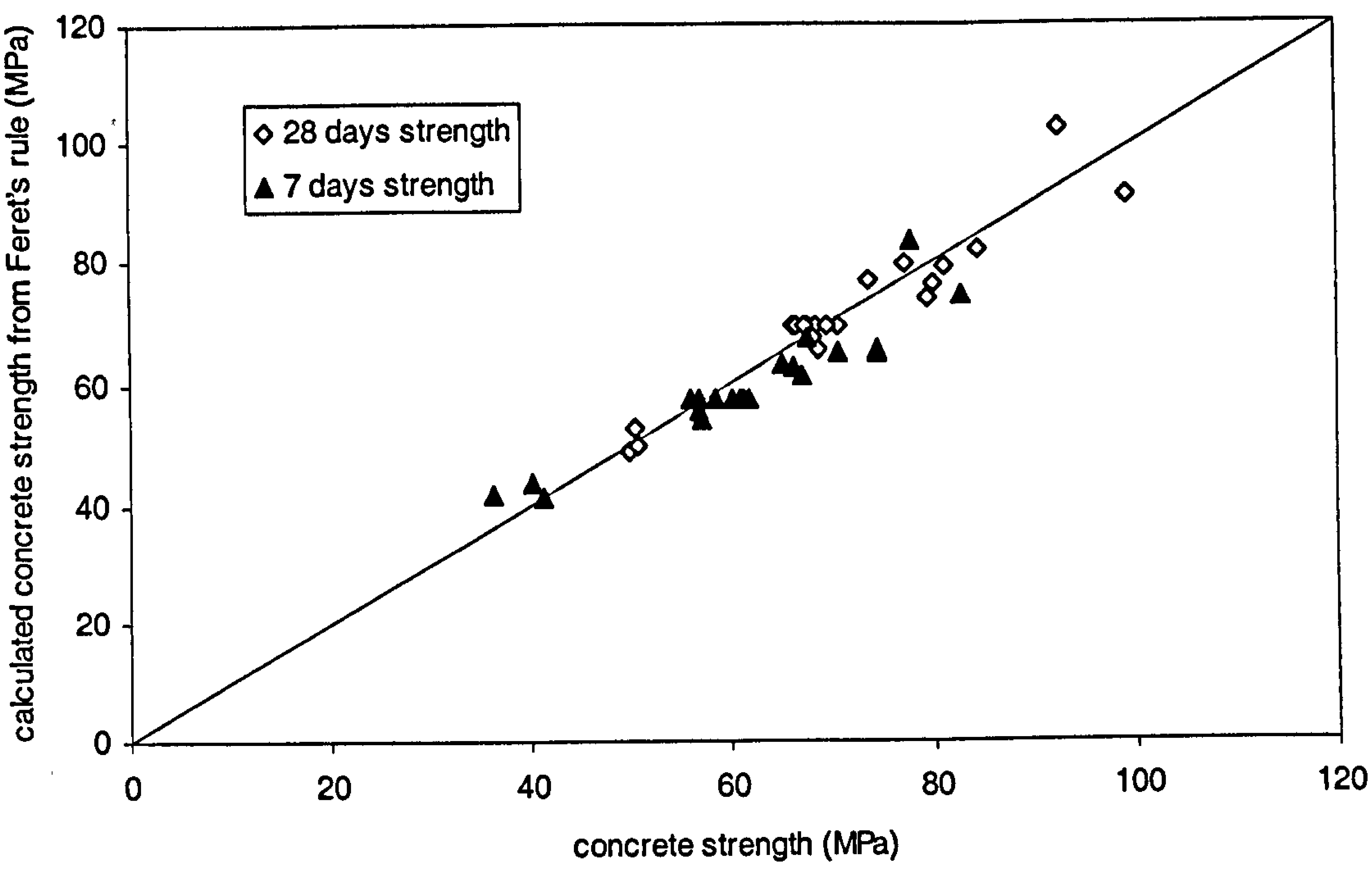


Figure 10-35 Comparison of the 28 days strength with those calculated with modified Feret's rule

The 1 day strength was found to be only controlled by cement and water/cement ratio, not by water/powder ratio, as shown in **figure 10-36**. The mixes with Glenium51 had about 10% higher early strength than that with Conplast 430, while Welan gum slightly reduced the early strength, this is consistent with these admixtures' properties as described in chapter 2.

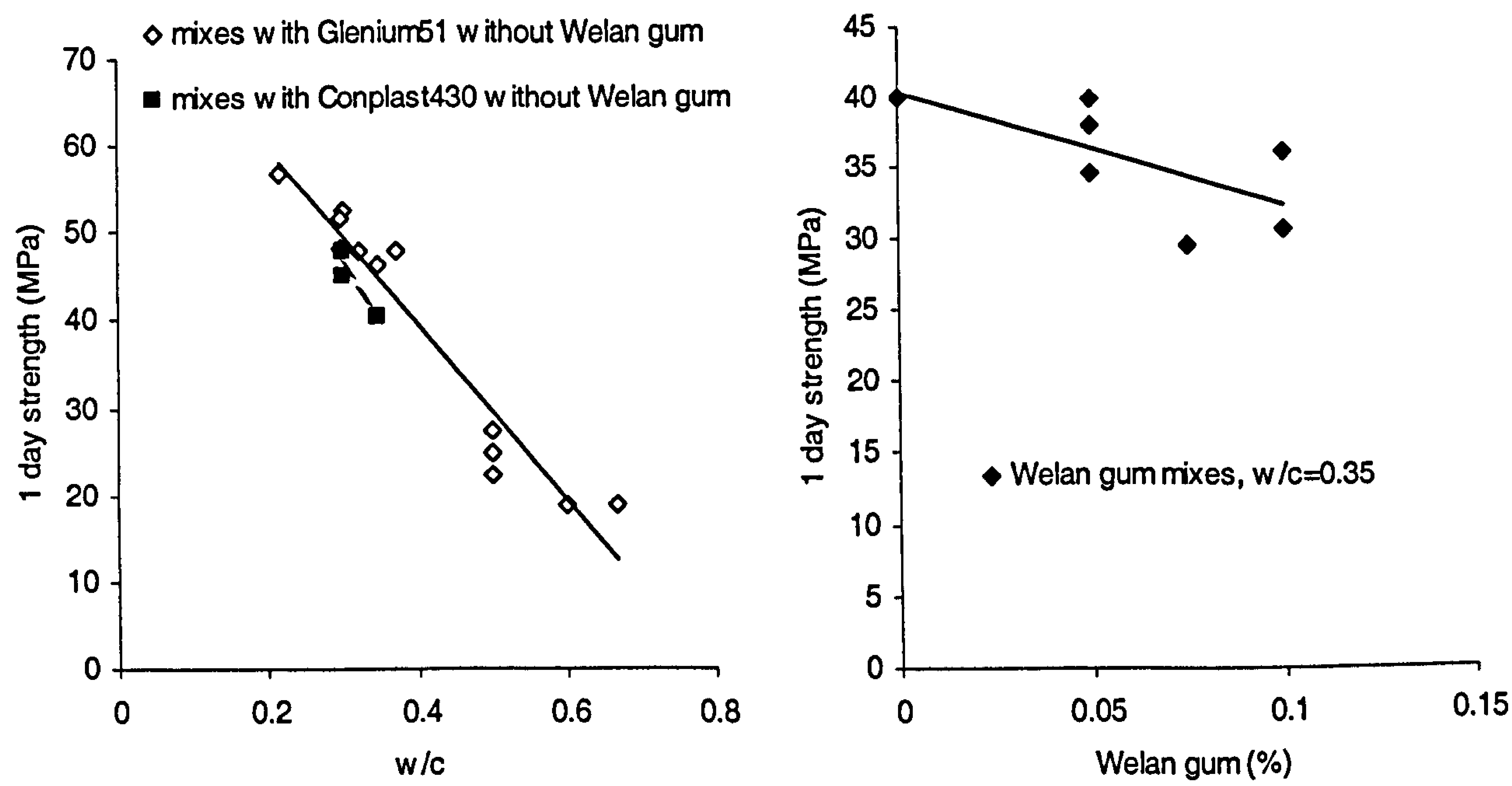


Figure 10-36 The relationships between the 1 day strength of concrete and (a) water/cement ratio (b) Welan gum dosage

10.4 Conclusion

Rheological models, the relationships between the fresh properties of mortar and concrete, and Feret's rule have been investigated. The conclusions are:

- There are two situations when the rheological model of a mortar appears to be shear thickening; one is when the mortar has a overdose of superplasticizer and tends to segregate, the other is when the mortar has a high content of GGBS. High shear thickening makes the concrete sticky during flow, and increases the possibility of bleeding or segregation at rest. On the other hand CSF, Viscocrete and a high dosage of Welan gum increase the tendency to shear thinning, which is beneficial to concrete segregation resistance. The Herschel-Bulkley model can be applied to these mortars and the parameter "n" can give an indication for the magnitude of the significance of shear thickening or shear thinning.

- There are strong relationships between the yield stress and the spread, the plastic viscosity and the V-funnel measurements for mortar. The yield stress and plastic viscosity can therefore be estimated from the simpler tests. However these relationships are affected by some factors such as the composition of the powder, admixtures and the range of spread. These should be taken into account when using these relationships.

- The relationships between the properties measured for concrete are not as strong as mortar. This may be because of lack of accuracy of some test methods and combined with the small number of concrete tests carried out. These relationship could be improved with more precise measurement of yield stress and a better understanding affecting the factors. $T_{U\text{-}box}$ results showed the best relationship with plastic viscosity and other flow times, suggesting only slump and U box tests may be sufficient to examine SCC properties. Further study will be needed.

- There are strong relationships between the fresh properties of concrete and its mortar fraction, with correlation coefficients higher than 0.9 when similar test methods are used and types of mixes separated. This suggests that there is a high possibility of predicting concrete properties from the related mortar test results, and reducing the amount of concrete tests during SCC mix design.

- Both T_{250} and T_{500} methods measure flow time at low shear rate, meaning significant effect of yield stress, therefore are not good to be used to indicate plastic viscosity compared to other methods.

- According to the UCL mix design method the criteria for SCC properties are a slump flow higher than 650 mm, a V-funnel flow time between 4 and 10 seconds and the U-box filling height higher than 300 mm. According to the relationships found in the current programme the corresponding other properties for concrete and mortar are as shown in **table 10-10.**

Table 10-10 Properties of satisfying SCC according to UCL mix design

Criteria for SCC			Corresponding concrete properties				Corresponding mortar properties			
SF (mm)	T_V (secs)	U_H (mm)	T_{500} * (secs)	$T_{U\text{-}box}$ * (secs)	τ_0 ** (Pa)	μ* (Pa.s)	D_m** (mm)	T_V * (secs)	τ_0 *** (Pa)	μ*** (Pa.s)
> 650	4-10	> 300	1-5	1-5	< 30 Pa	30-100	>300	3-6	20	6-14

* corresponding to concrete V-funnel flow time, ** corresponding to concrete slump flow, *** corresponding to mortar spread and V-funnel flow time respectively.

- It has been confirmed that the 7 days and 28 days strength for SCC can be predicted by modified Feret's rule. The 1 day strength was still controlled by cement and water/cement ratio only.

Chapter 11

Conclusions and recommendations for future work

11.1 Conclusions

An investigation was carried out on the effect of types and amount of powder materials, admixtures, sand content and water content on the fresh properties of SCC. This was primarily by using tests on mortar, with a lesser number of tests on concrete for comparison and confirmation of the most important effects. The properties were measured immediately after mixing and for the following two hours (to assess the workability retention). The relationships between the fresh property measurements, including the Bingham constants, for and between mortar and concrete were investigated. Rheological models for the mortar were examined; some compressive strength tests were also carried out and the prediction of strength by the modified Feret's law assessed.

Detailed conclusions have been given at the end of chapters 4 to 10. The most important of these can be summarised as follows:

1. Two-point test for mortar

   A small version of the two-point test for concrete with a helical impeller (with a diameter of 42 mm) for measuring the Bingham constants of mortar was developed and calibrated. The possibility of trapping of aggregates, slippage between mortar and the wall, and the influence of the wall-effect were avoided by selection of an appropriate cup size. A cup of 92 mm diameter, with a roughened surface and a gap between the impeller and the wall of 24 mm was chosen.

2. Superplasticizer efficiency and addition time

The efficiency of all six of the superplasticizers tested varied greatly, and in each case was significantly affected by their time of addition during mixing. There is an addition time 'window' where the maximum efficiency was obtained, and this was typically between 2 to 4 minutes after the start of mixing of the other components. However, with the Glenium51 superplasticizer, a polycarboxylic ether based product, maximum efficiency was obtained with only a half-minute delayed addition. Also, of all the superplasticizers tested, the Glenium51 had the highest flow and the lowest flow losses during the two-hour assessment period, and consequently was used for the most of the programme.

3. Superplasticizer dosage

In most of the tests, the dosage of superplasticizers was adjusted to achieve a constant mortar spread of 300-320 mm. Slightly less superplasticizer was required for PFA binary mixes than 100% PC mix but significantly less (about 2/3) for mixes with PC/GGBS and PC/LSP binary blends of powder. In contrast CSF binary mixes required significantly higher dosage. The required dosage in ternary mixes depended on the types and content of CRMs and fillers e.g. a PC/CSF/GGBS mix required less dosage than the PC/CSF mix with same CSF content but a higher dosage than the PC/GGBS mix.

4. Workability retention

In mixes with a single powder, SRC mixes showed excellent workability retention; this may be due to the low C_3A content of the cement. In mixes with binary blends of powders, mixes containing CSF were much superior to other mixes, possibly due to the high superplasticizer content required to achieve the initial spread. However, ternary mixes with CSF have equally good workability retention but required lower superplasticizer dosages.

5. Yield stress and plastic viscosity

The tests on mixes without a viscosity agent showed that yield stress and plastic viscosity are two distinct properties which are affected in different ways by different factors.

The development of yield stress during the initial two-hour period was closely related to:

- the type of superplasticizer; Glenium51 improved the retention (probably because of steric hindrance obstructing particle coagulation),
- the superplasticizer dosage, with higher dosages producing smaller changes,
- the water content,
- the sand content, with decreased retention with increased content (probably due to the decreased distance between sand particles and increased friction between them. This effect was very significant when the sand content was near to the high limit for SCC (such as 47.5% by volume of mortar).

The initial value of the plastic viscosity and its development seemed to be mainly affected by the particle content and the inter-particle distance. Increasing water content and reducing sand content decreased the initial plastic viscosity and its change with time after mixing. Combinations of powders with different particle sizes, such as PC/LSP15 mixes, improved the workability retention, due to the increase in the particle volume concentration (and hence the inter-particle distance). The effect of superplasticizer on workability retention was found to be insignificant, as it has no impact on the distance between particles.

6. Mixes with Welan gum

The Welan gum viscosity agent was found to have better compatibility with the conventional melamine or naphthalene superplasticizers than with the 'new generation' products such as Glenium51. The maximum spread of mortar achieved at the superplasticizer saturation dosage decreased with increasing dosage of Welan gum, which therefore limits the dose if a mortar spread of 300 mm is to be achieved.

Welan gum improved workability retention in terms of yield stress, which may be a result of the delayed hydration and high dosage of superplasticizer. However, there is a maximum dosage (e.g. 0.05-0.075% for a mix with water/cement ratio of 0.35), beyond which no further improvement was obtained.

The development of plastic viscosity was not significantly affected, which, as with the superplasticizer effects, may be due to the Welan gum not changing the inter-particle distance.

The setting time was delayed by the addition of Welan gum, and early and 28 days strength were decreased.

7. Rheological models

The rheological behaviour of most of the mortars followed the Bingham model fairly closely, but analysis of the flow curves in terms of the Herschel-Bulkley model gave two cases in which the parameter 'n' was significantly different to 1. Shear thickening (i.e. $n > 1$) was obtained when the mortar had a high GGBS content, and shear thinning ($n < 1$) was obtained in some mixes containing CSF, Viscocrete and a high dosage of Welan gum. Apparent shear thickening was also obtained in mixes which tended to segregate during the two-point test. No departure from Bingham behaviour was apparent in tests on concrete, possibly due to the lack of resolution in the two-point test.

8. Relationships between measured properties

There are strong relationships between yield stress and spread, and plastic viscosity and V-funnel time for mortar. However these relationships are slightly affected by factors such as the composition of powder, the type of admixture and the range of properties measured. There are similar relationships between the properties measured on concrete, but these are not as strong as those for mortar.

9. Relationships between properties of mortar and concrete

There are strong relationships between the fresh properties of concrete and its mortar fraction, with correlation coefficients higher than 0.9 for similar test methods and types of mixes. This suggests that there is a high possibility of predicting concrete properties from the related mortar test results, and of reducing the amount of concrete tests required during SCC mix design.

10. Applicability of modified Feret's rule

It was confirmed that the 7 days and 28 days strength for SCC can be predicted by modified Feret's rule. The 1 day strength was still controlled by cement and water/cement ratio only.

11.2 Recommendations for future work

The following areas are recommended for future work:

- As discussed in chapter 6 and 7, ion solution parameters such as ionic strength and ion concentrations which are influenced by several factors such as type and dosage of superplasticizer, type and content of powder and water content in the mix, may be the fundamental factor controlling the development of yield stress. It will be useful to investigate the relationships between these parameters, particularly in mixes containing Glenium51, and the development of yield stress.

- It was also discussed that particle concentration and inter-particle distance have significant effects on plastic viscosity development; these could be quantified by measuring physical properties of each component such as particle distribution, particle shape and maximum volume concentration by using rigorous technique and equipment. This will be helpful in understanding the development of plastic viscosity.

- The effect of sand content on workability and workability retention was investigated, but broader study is needed of other factors such as the effect of shape and size of sand, which could vary widely, e.g. between river sand, sea sand and crushed sand, fineness modulus could be as low as 2.0 or as high as 3.0. This would be very useful to help give the whole picture of fresh properties and their development.

- Properties of Welan gum and its effect on SCC was studied, which will be similar to the behaviour with several other viscosity agents. A similar study is needed for non-adsorptive viscosity agents such as Glycol-based water-soluble polymers since these may be major types of viscosity agents in the future.

- The relationship between the fresh properties of concrete and mortar has been proven to be good; further confirmation is needed using SCC with other types of coarse aggregate, such as crushed granite, of various size and content (normally between 30-35% by volume of concrete) in order to obtain a more complete understanding.

- Herschel-Bulkley behaviour was found in some mortars but not in their respective concretes. Further experiments are needed on concrete, involving more sensitive rheology equipment to give precise measurement of the rheological properties.

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Appendix 1 Mix design methods

Mix design methods in Japan

Two mix design methods have been proposed, one is a simple step by step method, and the other is in the form of general guidelines.

1. Okamura and Ozawa's Method

FigureA1.1 shows the mix design flow chart [46].

The method is based on the assumption that moderate-heat Portland cement or Belite-rich Portland are the only available powder materials. It is considered that [8]:

a) It is difficult to control self-compactability at a specific level, and in fact, it is more difficult to control than the quality of normal concrete.

b) It is safer to set a high level of self-compactability, even when a lower level is adequate, for adapting to various conditions of the structure and construction by permitting a wider variability of production, thereby widening control limits.

After having set the volume of air for durability requirements, the coarse aggregate volume is fixed to 50% of its dry-rodded bulk density and the fine aggregate (minimum size 90 μm) to 40% of the mortar by volume. The water/powder ratio and the superplasticizer dosage are determined by spread and V-funnel tests on mortar to achieve a mortar property: $\Gamma_m = 5$ (D_m=245 mm), and $R_m = 1$ (T_V=10 seconds), as shown in **figure A1-2** [47]. Clearly for each type of mixture only one combination of water/powder ratio and superplasticizer dosage can satisfy the requirement.

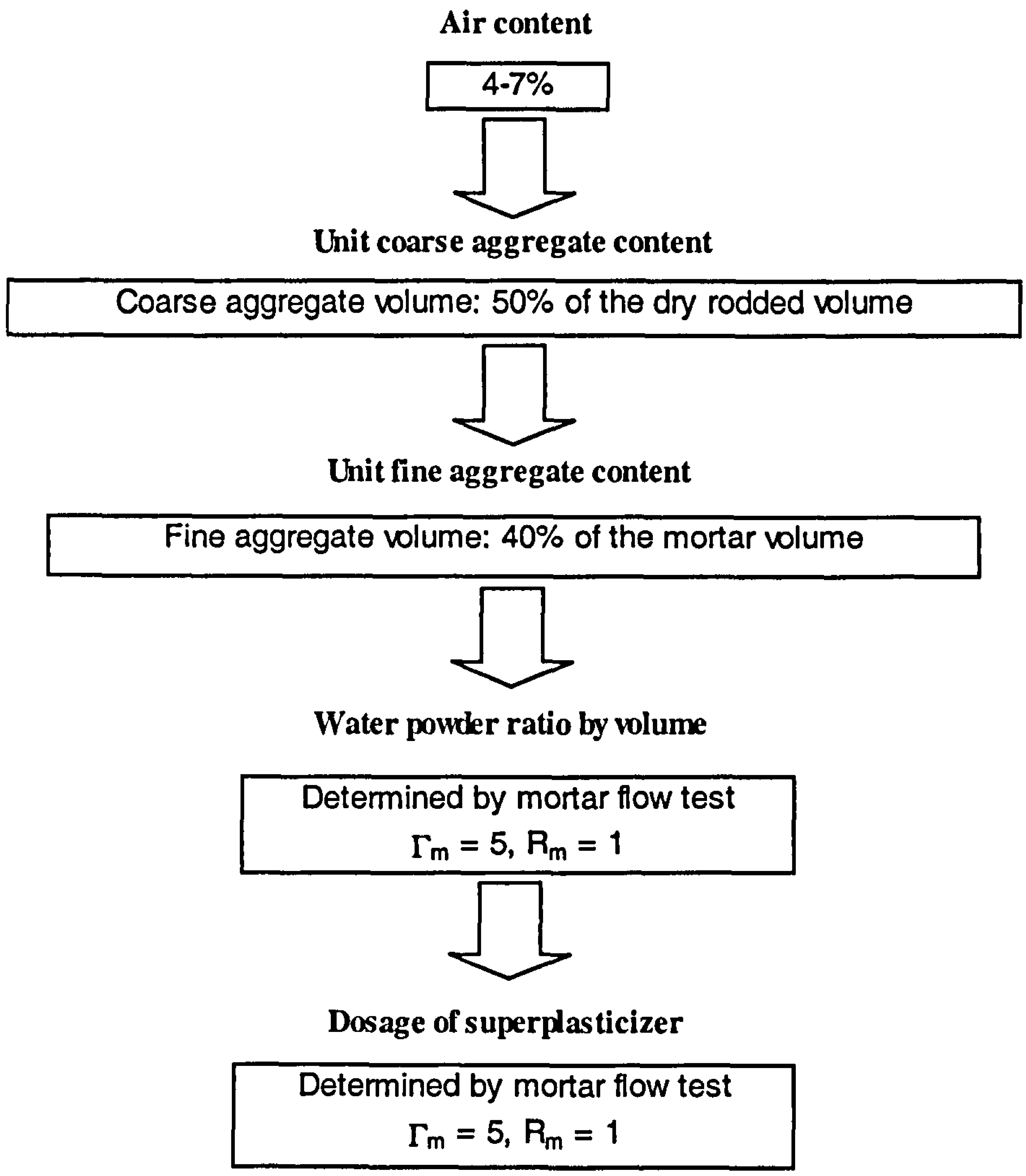


Figure A1-1 Mix design flow chart (adapted from [46])

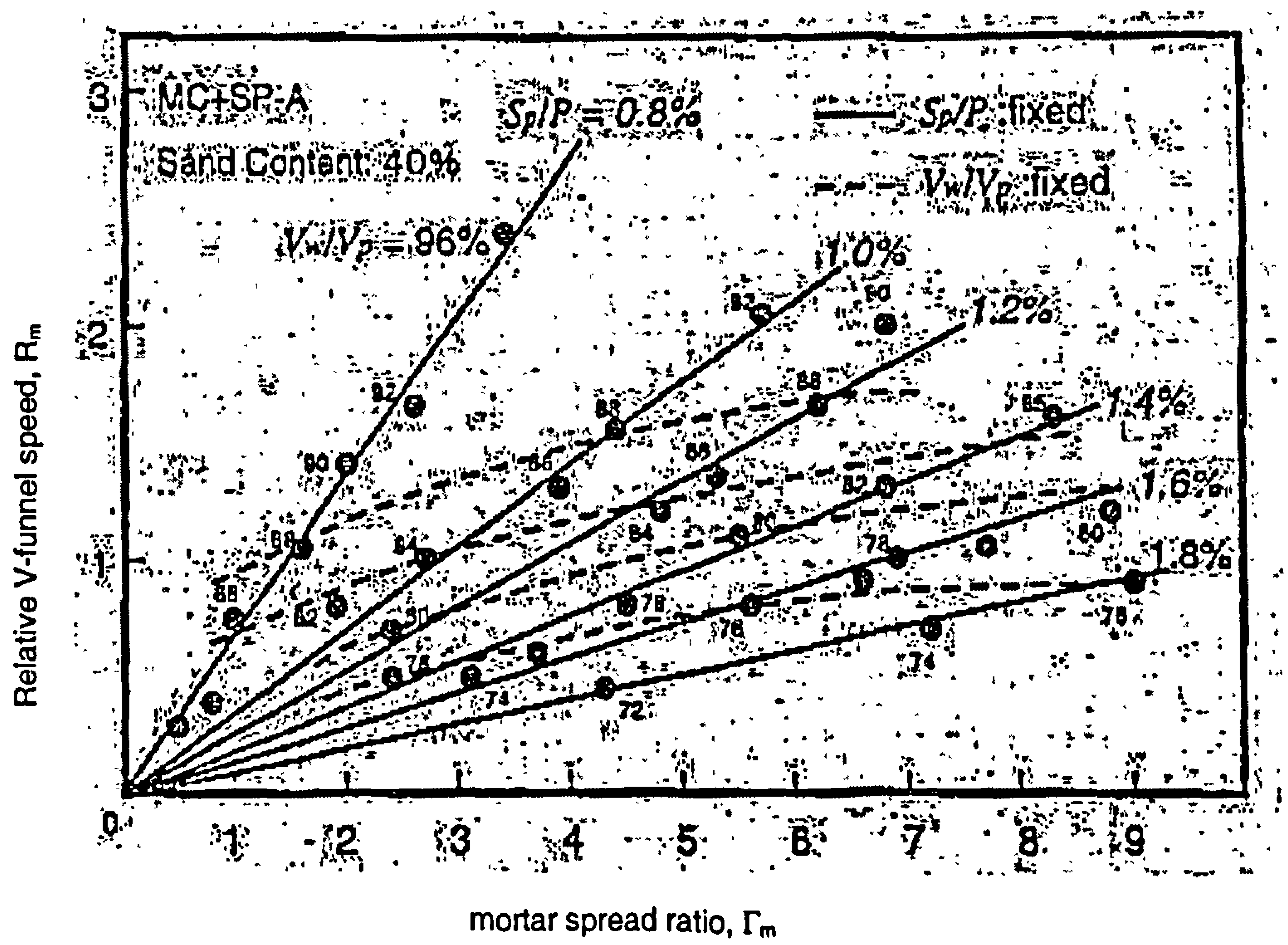


Figure A1-2 Effect of superplasticizer dosage and water/powder ratio by volume on mortar properties (adapted from [47])

2. JSCE Method

This mix proportioning procedure is based on past research as well as experience with actual construction work [8]. **Figure A1-3** shows the flow chart, which is divided into mixes with and without a viscosity agent. The guidelines for mixes with a viscosity agent mix are subdivided according to the types of the agent, as shown in **table A1-1.**

The designed mix should satisfy the criteria shown in **table A1-2,** otherwise an adjustment in the mix proportion should be made.

Table A1-1 Guidelines for JSCE mix design method for SCC with viscosity agent [43]

	Type of viscosity agent			
	Cellulose	Acrylic	Glycol	Polysaccharide
Water (kg/m^3)*	170-180			155-170
Powder (kg/m^3)**	300-450	400-450	400-480	>0.13 m^3/m^3
Viscosity agent dosage (% by wt of water)	0.15-0.3	3-5	2-3	0.05

*: if durability is not a concern, this can be up to 190kg/m3,

Table A1-2 Ranks for self-compactability and corresponding target values [31]

RANK OF SELF COMPACTABILITY		1	2	3
Structural conditions	Minimum clearance of bar, mm	35 ~ 60	60 ~ 200	No less than 200
	Mass of reinforcement, kg/m^3	Not less than 350	100 ~ 350	Not more than 100
Filling height by U-Box test; mm		Not less than 300 (Obstacle R1)	Not less than 300 (Obstacle R2)	Not less than 300 (Obstacle R3)
Unit coarse aggregate content by absolute volume, m^3/m^3		0.28 ~ 0.3	0.30 ~ 0.33	0.32 ~ 0.35
Flowability	Slump-flow value, mm	600 ~ 700	600 ~ 700	500 ~ 650
Segregation resistance	Funnel flow time (V-funnel with 65x75 mm opening), sec	9 ~ 20	7 ~ 13	4 ~ 11
	Time to 500 mm slump flow	5 ~ 20	3 ~ 15	3 ~ 15

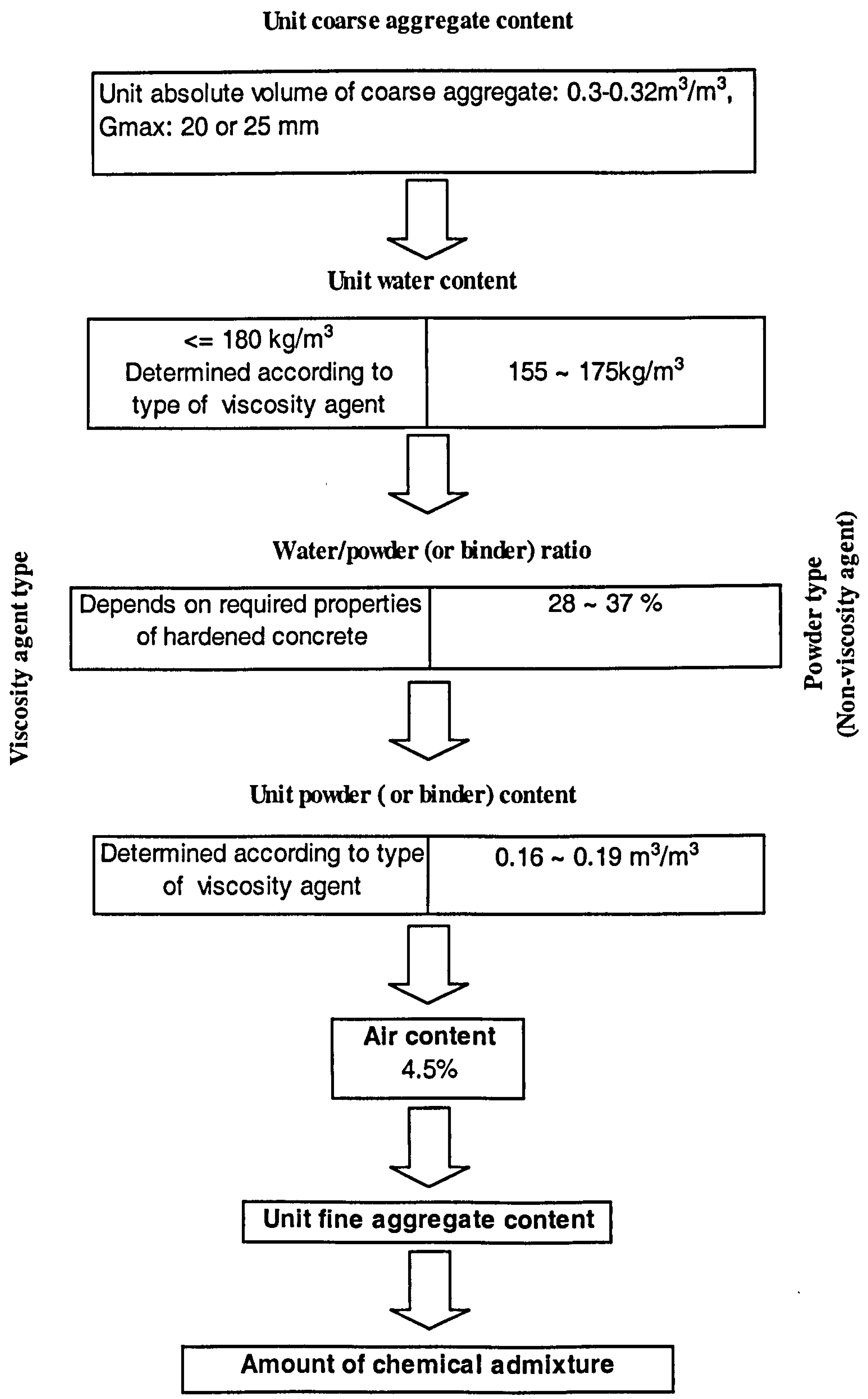


Figure A1-3 JSCE mix design method (adapted from [8])

Thailand & CBI mix design method

The Swedish Cement and Concrete Research Institute (CBI) and a research group in Thailand have developed a SCC design method based on the following considerations [48,49,50]:

- to obtain the smallest paste volume as possible;
- to obtain the largest aggregate separation distance possible;
- no risk of blocking.

The **figure A1-4** shows the flow chart. The key part is to obtain the minimum paste content based on two equations. One is to obtain the minimum paste volume to fill all voids in the aggregate phase and to envelop all the surfaces of the particles. The other is blocking criterion, which is that the sum of the separate contributions of individual particle size ranges of the aggregate to concrete blocking when it tries to pass through the gaps in reinforcement should be no more than 1.0,
i.e. risk of blocking = $\sum(n_{ai}/n_{bi}) \leq 1.0$
where n_{ai} is the volume ratio of the single size group i of aggregate, and n_{abi} is the blocking volume ratio of this group, which is a function of aggregate volume, aggregate size, bar spacing and bar size.

The paste volume should be higher than the both of the above minimum volumes, with a consideration for air content.

Then the fine mortar rheology is then tested to select the powder type, superplasticizer dosage and water/powder ratio, and the water/cement ratio is determined by the required hardened properties of concrete. No specific range for the properties were proposed.

Trial mixes are also needed, and if the concrete properties are not satisfied, then adjustment of the paste volume are made.

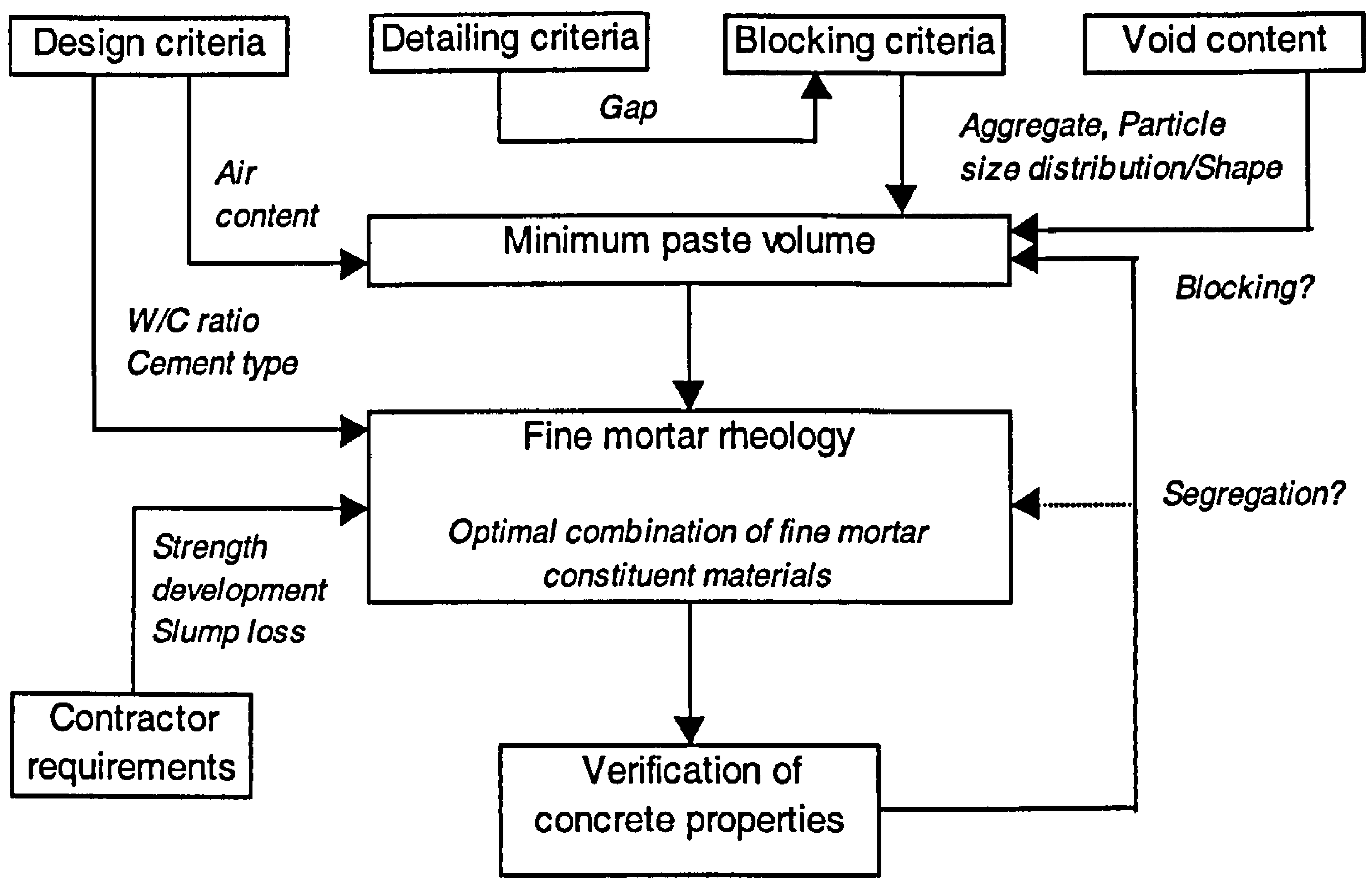


Figure A1-4 Thailand & CBI mix design method (adapted from [52])

LCPC's mix design method (France)

This mix design method is based on two developments: one is the BTRHEOM rheometer for concrete; and the other is the Solid Suspension Model software (RENE_LCPC™) [53,54]. The software is based on a mathematical model aiming at optimising the granular skeleton, while taking into account the degree of confinement in which the concrete has to be placed.

The general criteria are as follows:

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

The materials required are well-graded aggregate, cement with a compatible superplasticizer, a retarder and CRMs. The stages of the method are shown in **figure A1-5.**

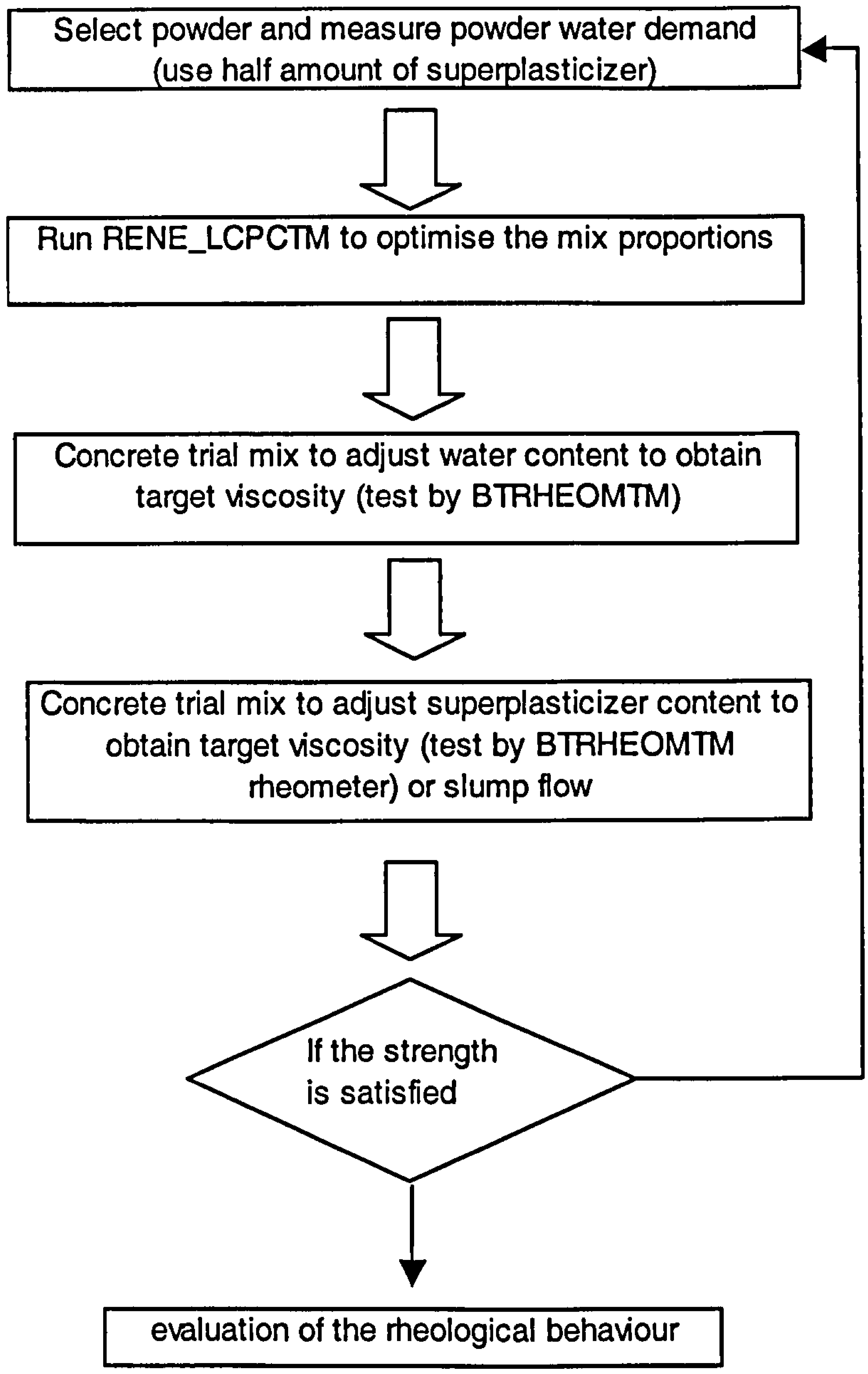


Figure A1-5 LCPC's mix design method

UCL Mix Design Method

The method developed is based on the general method of others, notably that of Ozawa and Okamura in Japan, but was extended to be able to handle a combination of more materials [25]. **Figure A1-6** shows the mix design flow chart.

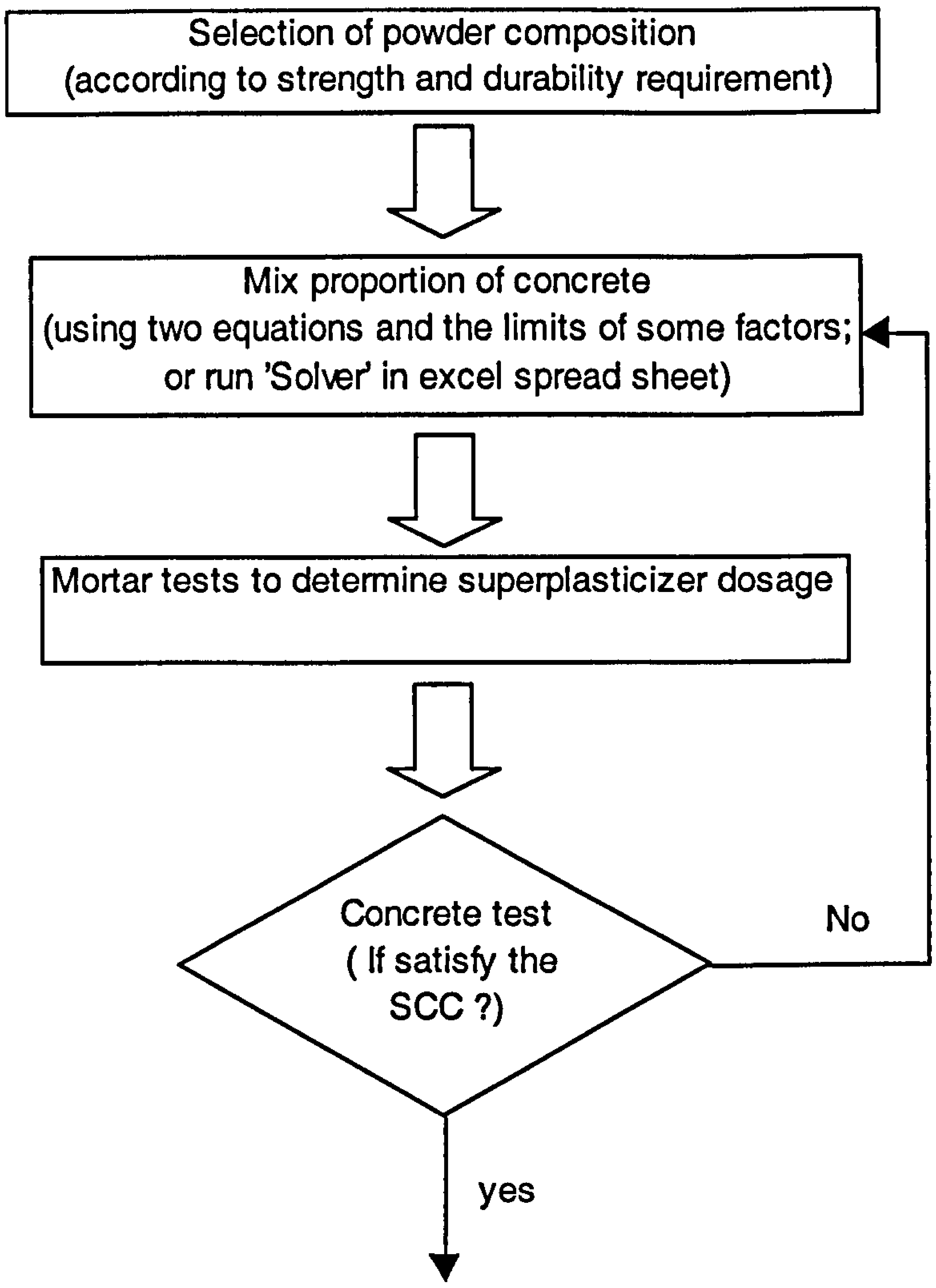


Figure A1-6 UCL mix design

There are two important equations used in this mix design. One is for obtaining the water/powder ratio to ensure stability of concrete and segregation resistance. It was obtained from extensive tests on paste rheology, and makes use of the powder characteristic of retained water powder ratio and deformation coefficient [55].

$$\eta = \frac{a}{E_p}\left(\frac{V_w / V_p}{\beta_p}\right)^{-k} \qquad \text{(A-1)}$$

where a, k are empirical constants obtained by experiment.

The second equation is that for strength. This is the modified Feret's law, developed by LCPC in France [56].

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

where

f_c :cylinder compressive strength,

K_g :an aggregate coefficient;

R_c :the cement strength;

W :free water content;

A :entrapped air volume;

K_1 :a pozzolanic activity coefficient = 0.4PFA + 3CSF/C

K_2 :a limestone activity coefficient = 0.2 LP/C

C, PFA, CSF, LP and GGBS :content of cement, fly ash, microsilica, limestone powder and blast furnace slag.

Clearly, this equation recognises that the strength is not only controlled by water/cement but also powder composition.

A number of limits for important factors ensuring successful SCC have also been suggested, as shown in **table A1-3**.

Table A1-3 Limiting mix proportions for successful self-compacting concrete [25]

	max. aggregate size 20 mm		max. agg. Size 10 mm	
Coarse agg. Content (kg/m^3)	50% of dry rodded bulk density		50-54% of dry rodded bulk density	
Max. water content (Kg/m^3)	200			
Water /powder ratio by wt (w/p)	0.28-0.4		0.28-0.5	
Water/(powder + fine aggregate) ratio by wt.	0.12-0.14		0.12-0.17	
Paste volume (m^3/m^3 concrete)	0.38-0.42			
	w/p	$V_{F.A.}$	w/p	$V_{F.A.}/V_m$
Volume sand /volume mortar	<0.3	0.4	<0.3	0.4
	0.3-0.34	0.4-0.45	0.3-0.34	0.4-0.45
	0.34-0.4	0.45-0.47	0.34-0.4	0.45-0.47
			0.4-0.5	>0.47

The mix design process can also be helped by use of 'Solver' function within the Excel spreadsheet package. The procedure is:

1. A spread sheet is first set up with all of the calculations required to calculate the mix proportions, the properties of materials and requirements of the concrete.
2. The limits to the quantities are the entered as 'Solver' constraints.
3. A 'target' is then chosen, normally the minimum binder content, and the variables that 'Solver' is allowed to change to achieve the target selected, normally the water content, the water/powder ratio and the proportions of the cement replacement materials.
4. Running 'Solver' then produces an optimum mix, and gives useful information about which parameters have been limited by the imposed restraints.

This is only a first 'guess' at the mix proportions, and it is followed by tests on the mortar to give the required superplasticizer dosage and then on concrete. The use of mortar tests reduces the number of tests required on the concrete.

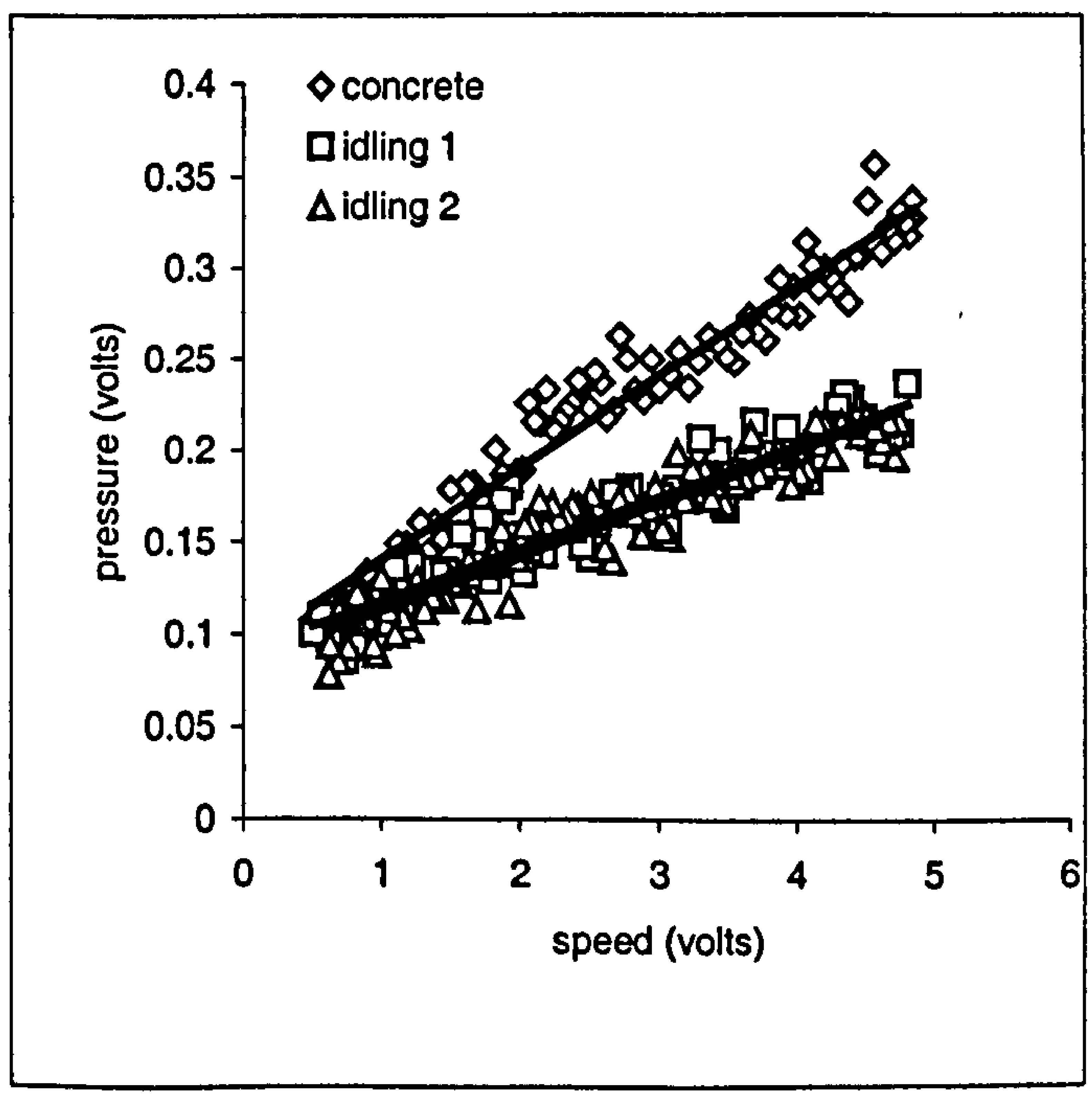
Appendix 2 A typical output of the programme of two-point test for concrete

SCC12b(1 hour after mixing) helical impeller

$Vp = a + bVs$; $T=g + h N$; $g=(a_1-a_0)*725*0.053$; $h= (b_1-b_0)*0.053*725/0.208$; $\tau_0=122*g$; $\mu=17.24*h$

$b_1 =$	0.050	$b_{01} =$	0.028	$b_{02} =$	0.029	$b_0 =$	0.028	$h=$	3.963	$\mu=$	68
$a_1 =$	0.090	$a_{01} =$	0.090	$a_{02} =$	0.083	$a_0 =$	0.087	$g=$	0.120	$\tau_0=$	15
$R_1^2 =$	0.956	$R_0^2 =$	0.895	$R_0^2 =$	0.894						

mix test		idling test(1)		idling test(2)	
speed (volts)	Pres. (volts)	speed (volts)	Pres. (volts)	speed (volts)	Pres. (volts)
2.798	0.230	2.700	0.166	2.536	0.157
Vs	Vp	Vs	Vp	Vs	Vp
4.861	0.328	4.817	0.236	4.753	0.216
4.859	0.338	4.763	0.209	4.720	0.197
4.849	0.327	4.708	0.208	4.679	0.216
4.829	0.318	4.652	0.214	4.629	0.205
4.803	0.325	4.596	0.198	4.575	0.211
......	......	......	......	......	......
2.78625	0.2493	2.51404	0.1413	2.5238	0.1752
2.73376	0.2618	2.45728	0.1474	2.47772	0.1672
2.6828	0.2213	2.40021	0.1563	2.43195	0.1688
2.63611	0.217	2.34283	0.1584	2.38586	0.1697
2.59491	0.2365	2.2879	0.1569	2.33765	0.1645
......	......	......	......	......	......
1.449	0.151	0.981	0.098	1.038	0.106
1.394	0.160	0.924	0.118	0.970	0.089
1.339	0.144	0.861	0.108	0.902	0.108
1.287	0.160	0.802	0.112	0.833	0.106



Appendix 3 Results for tests on effect of cup size

Series 1:

Mix proportion: 100% PFA, $V_w/V_p = 0.945$, $V_s/V_m = 0.45$, ConplastR was used as retarder. **Fresh property**: spread = 250 mm, V-funnel time = 2.17 seconds.

Table A3-1 g and h values measured with different cups in series 1

g value (N.mm)				h value (N.mm.s)			
Cup No.	g	g for No.5	Diff. Between	Cup No.	h	h for No.5	Diff. between
No.6	4.0	4.5	-0.5	No.6	4.6	4.7	-0.1
No.4	4.4	4.4	0	No.4	4.6	4.6	0
No.3	5.1	5.1	0	No.3	5.2	5.1	0.1
No.2	4.4	4.8	-0.4	No.2	5.7	4.8	0.9
No.1	4.5	5.0	-0.5	No.1	5.5	4.8	0.7
Average g value for cup No.5: **4.8**				Average h value for cup No.5: **4.8**			
Calculated g values for different cups *				Calculated h values for different cups *			
No.6	4.3			No.6	4.7		
No.5	4.8			No.5	4.8		
No.4	4.8			No.4	4.8		
No.3	4.8			No.3	4.9		
No.2	4.4			No.2	5.7		
No.1	4.3			No.1	5.5		

* : using average g value for cup No. 5 and the difference between its with each other cup.

Series 2:

Mix proportion: 100% PFA, $V_w/V_p = 0.8$, $V_s/V_m = 0.45$, ConplastR was used as retarder. **Fresh property**: spread = 240 mm, V-funnel time = 4.39 seconds.

Table A3-2 g and h values measured with different cups in series 2

g value (N.mm)				h value (N.mm.s)			
Cup No.	g	g for No.4	Diff. between	Cup No.	h	h for No.4	Diff. between
No.7	5.8	6.0	-0.2	No.7	7.7	8.4	-0.7
No.6	4.6	5.2	-0.6	No.6	7.3	7.2	0.1
No.5	4.5	4.5	0	No.5	7.2	7.9	-0.7
No.3	4.5	4.5	0	No.3	6.5	6.3	0.2
No.2	4.3	4.3	0	No.2	7.1	6.9	0.2
No.1	4.8	4.9	-0.1	No.1	8.8	7.9	0.9
Average g value measured with cup No.4: **4.9**				Average h value measured with cup No.4: **7.4**			
Calculated g values for different cups *				Calculated g values for different cups *			
No.7	4.7			No.7	6.7		
No.6	4.3			No.6	7.5		
No.5	4.9			No.5	6.7		
No.4	4.9			No.4	7.4		
No.3	4.9			No.3	7.6		
No.2	4.9			No.2	7.6		
No.1	4.8			No.1	8.3		

* : using average g value for cup No. 5 and the difference between its with each other cup.

Series 3:

Mix proportion: 100% PFA, V_w/V_p = 0..72, V_s/V_m = 0.45, ConplastR was used as retarder. **Fresh property**: spread = 230 mm, V-funnel time = 4.82 seconds.

Table A3-3 g and h values measured with different cups in series 2

g value (N.mm)				h viscosity (N.mm.s)			
Cup No.		No.5	Diff. between	Cup No.		No.5	Diff. between
No.7	7.0	7.0	0	No.7	8.3	8.6	-0.3
No.6	6.9	7.3	-0.5	No.6	7.7	7.6	0.1
No.4	8.8	9.0	-0.2	No.4	8.4	8.4	0
No.3	10.3	9.0	1.3	No.3	9.6	9.2	0.4
No.2	10.2	9.2	1.0	No.2	10.1	8.7	1.4
No.1	8.3	8.5	-0.2	No.1	10.0	8.4	1.6
Average g value measured with cup No.5: **8.1**				Average h value with cup No.5: **8.5**			
Calculated g values for different cups *				Calculated h values for different cups *			
No.7	8.1			No.7	8.2		
No.6	7.6			No.6	8.6		
No.5	8.1			No.5	8.5		
No.4	7.9			No.4	8.5		
No.3	9.4			No.3	8.9		
No.2	9.1			No.2	9.9		
No.1	7.9			No.1	10.1		

* : using average g value for cup No. 5 and the difference between its with each other cup.

Series4

Mix proportion: Same as series2 but tested after 4 hours of mixing

Table A3-4 g and h values measured with different cups in series 4

g value (N.mm)				h (N.mm.s)			
Cup No.		No.5	Diff. between	Cup No.		No.5	Diff. between
No.7	5.3	5.3	0	No.7	8.3	8.3	0
No.6	8.0	9.0	-0.1	No.6	12.3	12.3	0
No.4	8.3	7.5	0.8	No.4	11.7	11.5	0.2
No.3	9.0	7.8	2.2	No.3	13.4	12.2	0.2
No.2	8.8	8.0	0.8	No.2	14.2	11.9	1.3
No.1	8.0	8.0	0	No.1	13.1	12.6	0.5
Average g value measured with cup No.5: **7.6**				Average h value measured with cup No.5: **11.5**			
Calculated g values for different cups *				Calculated g values for different cups *			
No.7	7.6			No.7	11.5		
No.6	7.5			No.6	11.5		
No.5	7.6			No.5	11.5		
No.4	8.4			No.4	11.7		
No.3	8.8			No.3	12.7		
No.2	8.3			No.2	13.7		
No.1	7.6			No.1	12.0		

* : using average g value for cup No. 5 and the difference between its with each other cup.

Appendix 4 Two examples of the programme for calibration to obtain K value.

Example 1.

Solution: 1.0% welan gum. Equipment: cup No. 3, helical impeller; chart recorder

For rheomat viscometer with cylinder D145, μ(app) = $\mu\%_0$ × reading/1000

For two-point test with helical impeller, μ(app) = (T/N)/G

μ% apparent viscosity represented for 1 unit

$G = 1.1*10^{-3,} m^3$

Table A4-1 Test results for calibration using 1.0% Welan gum solution

	Rheomat 115 with D145 cylinder				Rheomat 115 with helical impeller			
	shear rate	apparent viscosity			Rotating speed	apparent viscosity		
		μ%	reading	μ(app)	N	reading	T	μ(app)
	(1/s)	(mPa.s)	unit	(Pa.s)	(rev/secs)	unit	(Nm)	(Pa.s)
1	**0.945**	205	98	**20.09**	0.012317	32	0.0016	118.0957
2	**1.366**	143.1	102	**14.5962**	0.017633	33	0.00165	85.06616
3	**1.955**	100	108	**10.8**	0.025233	35	0.00175	63.04792
4	**2.8**	69.8	112	**7.8176**	0.036167	36.5	0.001825	45.87348
5	**4**	48.9	118	**5.7702**	0.051667	38	0.0019	33.43109
6	**5.73**	34.1	124	**4.2284**	0.074	40	0.002	24.57002
7	**8.2**	23.8	130	**3.094**	**0.10583**	42	0.0021	**18.0387**
8	**11.75**	16.62	136	**2.26032**	**0.15167**	44.5	0.002225	**13.3367**
9	**16.81**	11.67	140	**1.6338**	**0.217**	47	0.00235	**9.84499**
10	**24.1**	8.11	146	**1.18406**	**0.31067**	49	0.00245	**7.16933**
11	**34.5**	5.67	152	**0.86184**	**0.445**	51.5	0.002575	**5.26047**
12	**49.3**	3.97	159	**0.63123**	**0.63667**	53.8	0.00269	**3.84103**
13	**70.6**	2.77	165	**0.45705**	**0.91167**	56	0.0028	**2.79209**
14	**101**	1.936	177	**0.34267**	**1.30333**	58	0.0029	**2.02279**
15	**144.6**	1.352	187	**0.25282**	**1.86667**	59	0.00295	**1.43669**

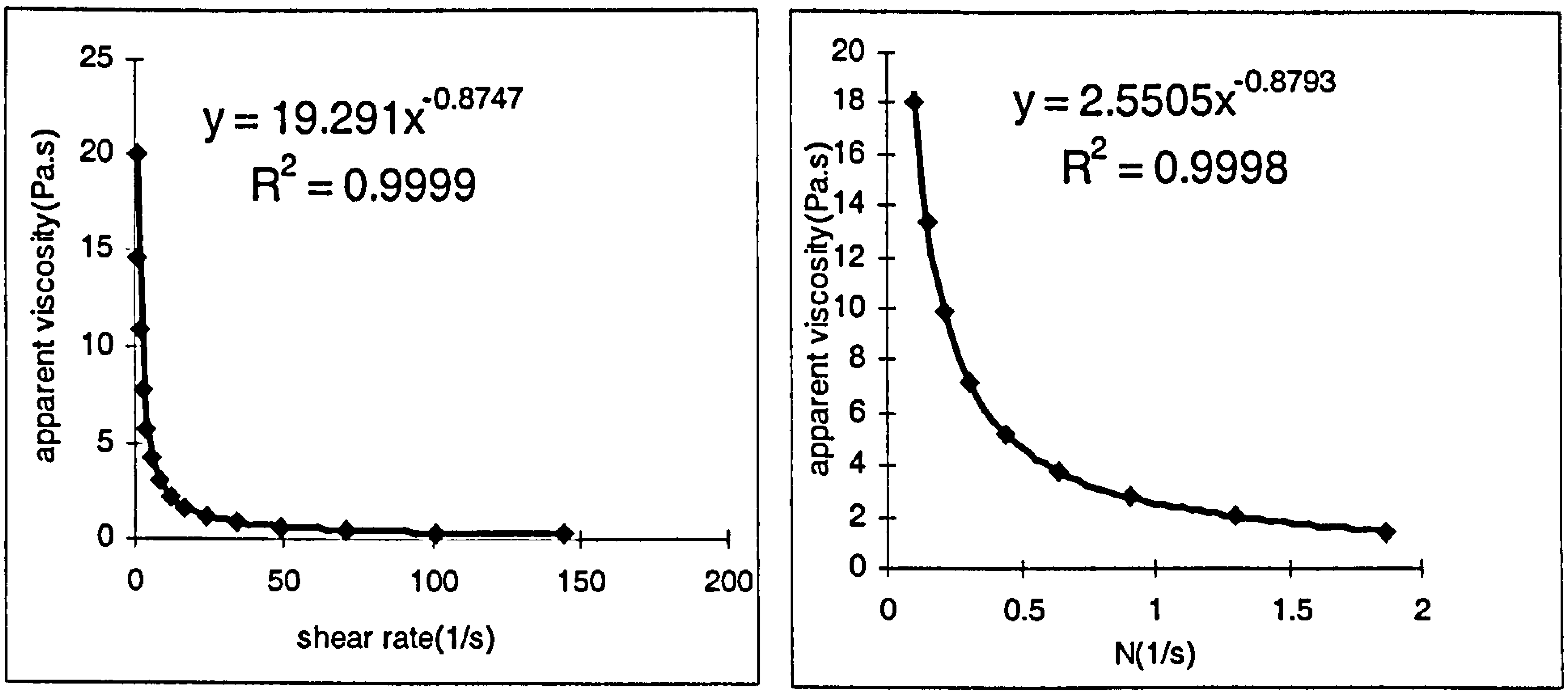
The data in bold in the table were used to plot figure as below, and constants were obtained by power law regression, as shown in **table A3.2.**

Table A4-2 Constants obtained from the regression equation

s-1	s	r	q-1	q	p/G	q/s
-0.8747	0.1253	19.291	-0.8793	0.1207	2.5505	1.038

Therefore,

$$K = \left(\frac{p}{rG}\right)^{1/(s-1)} = \mathbf{10.11}$$



(a) (b)

Figure A4-1 Relationship between shear rate and apparent viscosity for Welan gum solution measured with (a) viscometer with D145 cylinder (b) helical impeller (example 1)

Example 2.

Solution: 1.0% welan gum. Equipment: Rheomat 115, cylinder impeller, helical impeller, cup No. 5; computer was used to the out put data.

$G = 0.98*10^{-3,}\ m^3$

Table A4-3 Test results for rheological property of Welan gum solution measured using rheomat 115 with D145 cylinder impeller*

test 1					test 2					test 3				
shear rate		apparent viscosity			shear rate		apparent viscosity			shear rate		apparent viscosity		
		Torque	τ	μ(app)			Torque	τ	μ(app)			Torque	τ	μ(app)
volts	1/s	volts	(Pa)	(Pa.s)	volts	1/s	volts	(Pa)	(Pa.s)	volts	1/s	volts	(Pa)	(Pa.s)
1.44	143.95	1.86	36.42	0.25	1.44	144.04	1.87	36.47	0.25	1.44	143.89	1.88	36.70	0.26
1.44	143.77	1.87	36.51	0.25	1.43	142.79	1.86	36.29	0.25	1.43	143.37	1.89	36.87	0.26
1.43	143.31	1.86	36.33	0.25	1.43	142.79	1.87	36.56	0.26	1.43	143.13	1.87	36.63	0.26
1.43	142.58	1.86	36.28	0.25	1.42	142.18	1.84	36.04	0.25	1.42	142.46	1.88	36.75	0.26
1.42	142.03	1.87	36.52	0.26	1.42	141.75	1.87	36.50	0.26	1.42	142.12	1.87	36.60	0.26
1.41	141.39	1.85	36.11	0.26	1.41	141.08	1.85	36.24	0.26	1.41	141.33	1.87	36.58	0.26
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
0.25	24.63	1.60	31.27	1.27	0.25	24.54	1.60	31.29	1.28	0.25	24.60	1.60	31.35	1.27
0.24	24.08	1.59	31.12	1.29	0.23	23.13	1.60	31.23	1.35	0.24	24.08	1.60	31.37	1.30
0.23	23.32	1.59	31.03	1.33	0.23	23.07	1.59	31.17	1.35	0.23	23.50	1.61	31.52	1.34
0.23	23.16	1.59	31.14	1.34	0.23	22.55	1.59	31.10	1.38	0.23	23.38	1.59	31.17	1.33
0.22	22.40	1.57	30.77	1.37	0.22	22.16	1.59	31.08	1.40	0.22	22.31	1.60	31.22	1.40
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
0.12	12.05	1.50	29.33	2.43	0.12	11.78	1.48	29.03	2.46	0.12	12.18	1.50	29.40	2.41
0.11	11.44	1.49	29.22	2.55	0.11	11.02	1.49	29.11	2.64	0.12	11.51	1.50	29.26	2.54
0.11	11.08	1.48	28.97	2.62	0.11	10.89	1.47	28.77	2.64	0.11	11.08	1.49	29.08	2.62
0.11	10.59	1.48	28.88	2.73	0.10	9.77	1.47	28.69	2.94	0.10	10.25	1.48	28.92	2.82
0.10	10.22	1.47	28.76	2.81	0.10	9.77	1.46	28.48	2.92	0.10	9.70	1.48	28.95	2.98

* : For rheomat viscometer with cylinder D145, for shear rate 1 volt = 100 1/s; shear stress; 1 volt = 1.955 Pa

Table A4-4 Test results for rheological property of Welan gum solution measured using rheomat 115 with helical impeller*

test 1					test 2					test 3				
shear rate		apparent viscosity			shear rate		apparent viscosity			shear rate		apparent viscosity		
		Torque		μ(app)			Torque		μ(app)			Torque		μ(app)
volts	rev/sec	volts	(Nm)	(Pa.s)	volts	rev/sec	volts	(Nm)	(Pa.s)	volts	rev/sec	volts	(Nm)	(Pa.s)
1.44	**1.86**	0.58	0.00291	**1.60**	1.44	**1.86**	0.59	0.00295	**1.62**	1.44	**1.86**	0.58	0.00291	**1.60**
1.43	**1.85**	0.59	0.00293	**1.61**	1.43	**1.85**	0.59	0.00296	**1.63**	1.43	**1.85**	0.59	0.00295	**1.63**
1.43	**1.85**	0.58	0.00292	**1.61**	1.43	**1.85**	0.60	0.00298	**1.65**	1.43	**1.85**	0.59	0.00293	**1.62**
1.42	**1.84**	0.59	0.00293	**1.63**	1.43	**1.84**	0.59	0.00293	**1.62**	1.42	**1.84**	0.59	0.00296	**1.64**
1.42	**1.84**	0.58	0.00291	**1.62**	1.42	**1.83**	0.59	0.00295	**1.65**	1.42	**1.83**	0.59	0.00293	**1.63**
1.41	**1.82**	0.58	0.00291	**1.63**	1.42	**1.83**	0.59	0.00295	**1.65**	1.41	**1.83**	0.59	0.00295	**1.65**
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
1.08	**1.39**	0.58	0.00289	**2.12**	1.08	**1.39**	0.59	0.00293	**2.15**	1.08	**1.39**	0.59	0.00294	**2.16**
1.07	**1.38**	0.58	0.00289	**2.14**	1.07	**1.38**	0.59	0.00293	**2.17**	1.07	**1.39**	0.59	0.00293	**2.16**
1.07	**1.38**	0.58	0.00288	**2.14**	1.07	**1.37**	0.58	0.00292	**2.17**	1.06	**1.37**	0.59	0.00293	**2.18**
1.06	**1.37**	0.58	0.00289	**2.16**	1.06	**1.37**	0.59	0.00293	**2.18**	1.06	**1.37**	0.59	0.00294	**2.19**
1.06	**1.36**	0.58	0.00290	**2.17**	1.05	**1.36**	0.59	0.00293	**2.20**	1.05	**1.36**	0.59	0.00296	**2.22**
......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
0.81	**1.04**	0.57	0.00284	**2.78**	0.81	**1.04**	0.58	0.00288	**2.82**	0.81	**1.04**	0.58	0.00288	**2.82**
0.80	**1.04**	0.57	0.00285	**2.81**	0.80	**1.04**	0.57	0.00287	**2.82**	0.80	**1.04**	0.58	0.00288	**2.83**
0.79	**1.03**	0.57	0.00285	**2.84**	0.80	**1.03**	0.58	0.00290	**2.88**	0.80	**1.03**	0.58	0.00291	**2.88**
0.79	**1.02**	0.57	0.00286	**2.86**	0.79	**1.02**	0.58	0.00292	**2.91**	0.79	**1.03**	0.57	0.00285	**2.83**
0.78	**1.01**	0.57	0.00285	**2.87**	0.79	**1.01**	0.57	0.00285	**2.87**	0.79	**1.02**	0.58	0.00288	**2.89**

*: For two-point test with helical impeller, for rotating speed: 1 volt = 1.2909 rev/secs, for torque 1 volt = 0.005 Nm

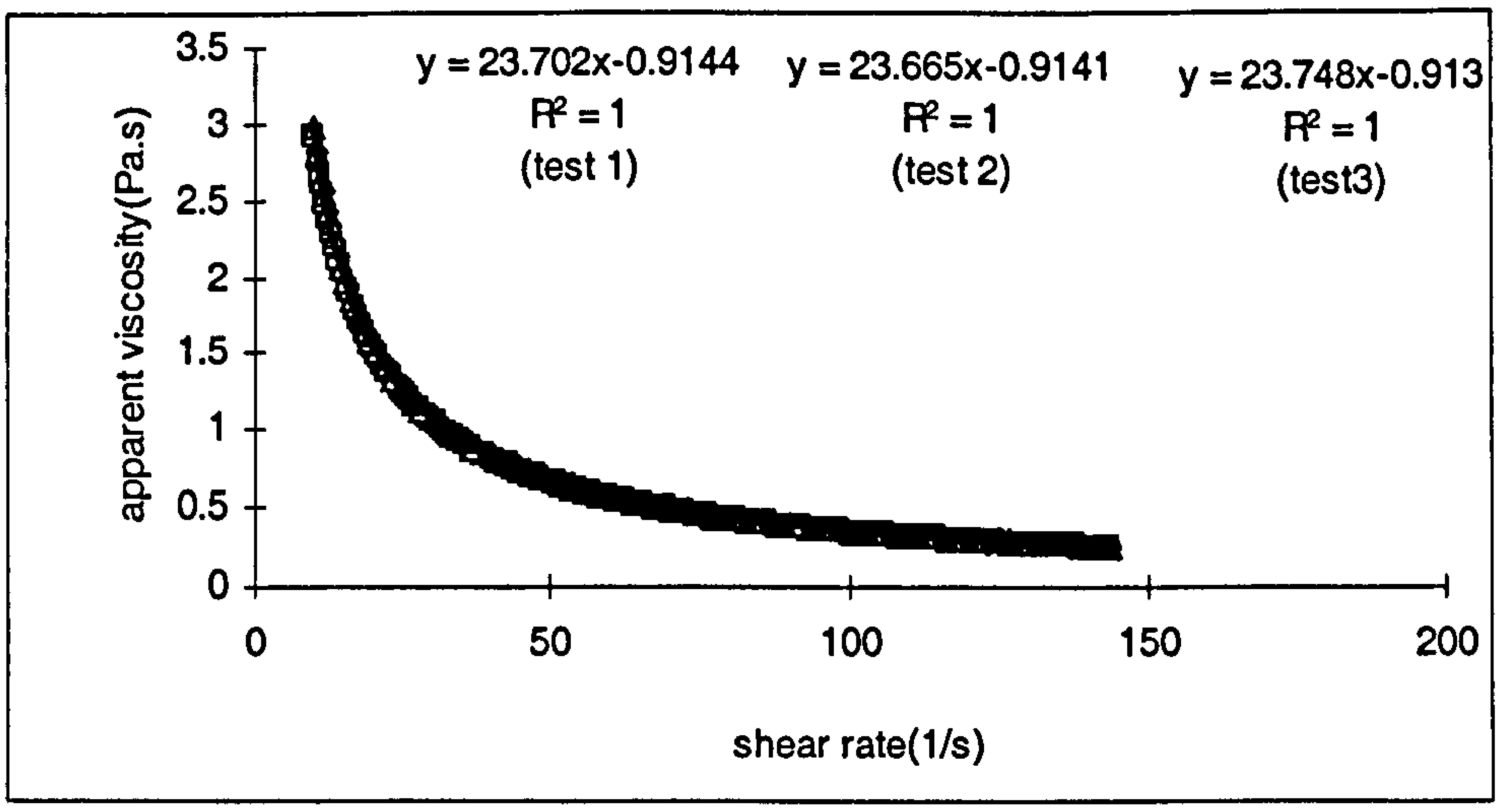
The data in bold in the **table A3.3 & A3.4** were used to plot figure as below, and constants (average of three tests) were obtained by power law regression, as shown in **table A3.5.**

Table A4-5 Constants obtained from the regression equation

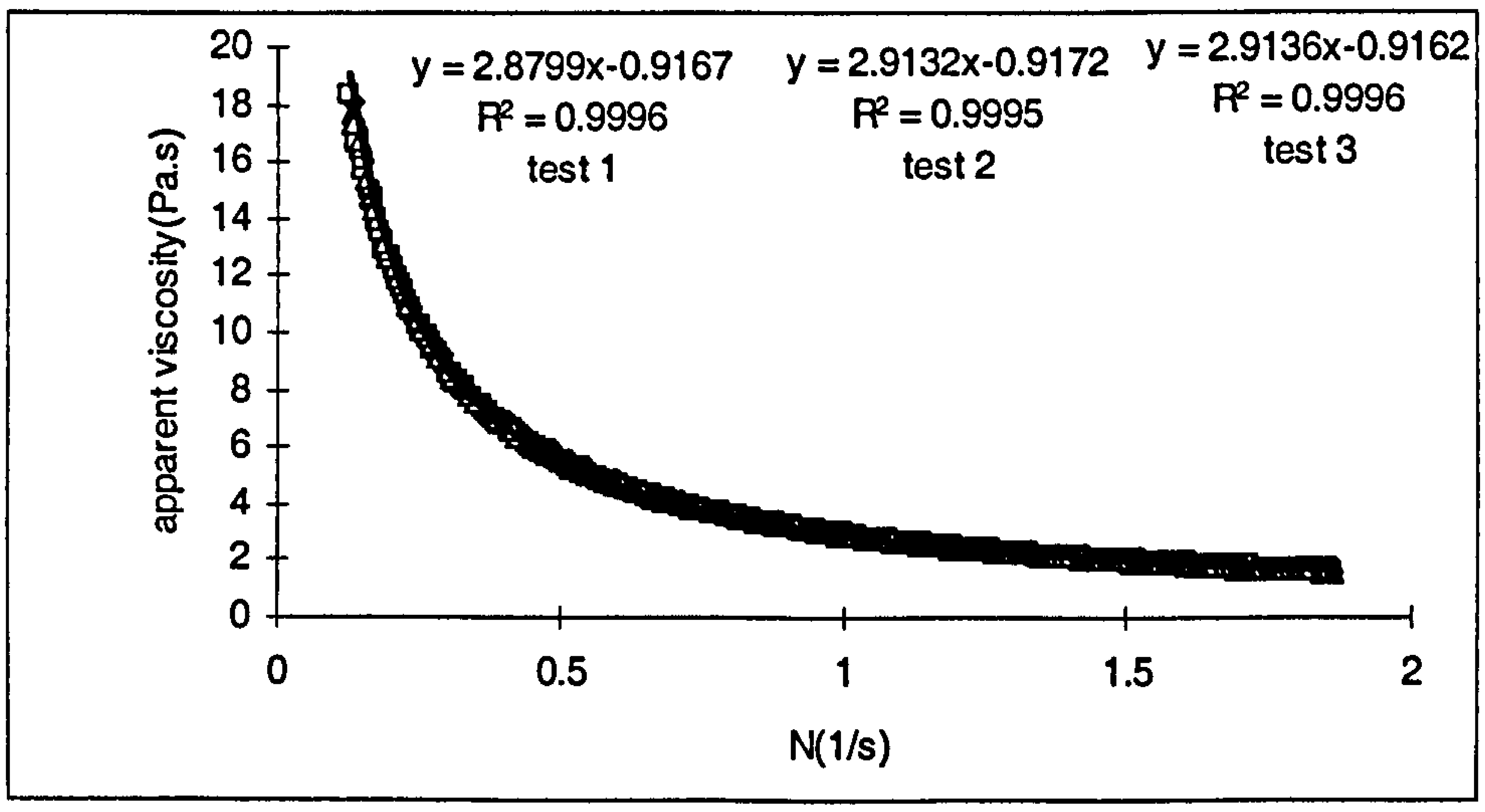
s-1	s	r	q-1	q	p/G	q/s
-0.913833	0.0862	23.705	-0.9167	0.083	2.902233	1.04

Therefore,

$$K = \left(\frac{p}{rG}\right)^{1/(s-1)} = \mathbf{9.96}$$



(a)



(b)

Figure A4-2 Relationship between shear rate and apparent viscosity for Welan gum solution measured with (a) viscometer with D145 cylinder (b) helical impeller (example 2)

Appendix 5 Results for tests on effect of cup size, further study

Table A5-1 Proportions of the mix for cup size further study.

Mix No.	V_w/V_p	Vs/Vm	Composition of powder	Welan gum (%)
Mix 4-1	0.945	0.45	100 % PC	0
Mix 4-2	0.945	0.45	PC/LSP = 60/40	0
Mix 4-3	1.103	0.45	100 % PC	0.075

Table A5-2 Test results for Mix 4-1: 100% PC

Test1						Test2					
Cup No.3			Cup No.5			Cup No.3			Cup No.5		
Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)
20	0	8.6	15	0	8.3	30	0	9.5	35	0.9	9.6
40	0	10.2	35	1.3	10.8	41	0	8.5	46	10.1	11.1
51	9.7	10.4	46	12.6	11	52	5.4	9.6	57	18.8	11.3
62	21.1	11.6	57	23	12.3	63	18.3	10.7	68	31.4	12.5
73	36.4	13	68	39.1	13.2	74	30.4	11.6	79	45.4	13.7
84	58.2	13.5	80	60.7	14.2	85	44.7	13.1	90	70.1	14.8
95	80.5	15.4	91	80.2	15.8	96	69.2	14.2	101	98.3	16.6
106	108.1	17.3	102	105	17.1	107	97.5	16.1	112	118.6	17.5

Table A5-3 Test results for Mix 4-2: PC/LSP100 = 60/40

Test1						Test2					
Cup No.3			Cup No.5			Cup No.3			Cup No.5		
Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)
17	2.3	5.3	11	0	5.2	11	19.2	4.8	16	26.6	5.7
27	16.3	6.9	22	16.1	6.4	21	40.9	6.3	26	58.4	6.8
38	46.1	7.7	32	39.5	7.8	32	84.1	7.9	36	85.8	8.6
49	66.7	9.8	44	69.6	8.8	42	111	9.2	47	121.2	10.42
59	99.7	11.8	55	103	10.6	52	145.6	10.7	57	161.6	11.5
71	132.7	14	65	139.2	12.4	63	191.1	11.1	68	212.3	13.1
83	189.8	16.6	76	188.6	14.5	74	224.2	12.5	79	259.1	15.5

Table A5-4 Test results for Mix 4-2 WG = 0.075%, sp = 0.1%

Test1						Test2					
Cup No.3			Cup No.5			Cup No.3			Cup No.5		
Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)	Time (mins)	τ_0 (Pa)	μ (Pa.s)
16	14.2	4.04	11	18.4	4.7	11	14.5	4.2	16	22.3	5.2
28	16.8	4.45	21	21.8	4.9	30	19.8	4.75	35	25.7	5.5
38	18.1	4.47	33	22.4	4.97	50	24.5	5.3	54	32.3	5.71
48	20.2	4.6	43	24.7	5.25	70	32.1	5.4	75	37.9	5.93
59	24.2	4.9	53	30.9	5.3	90	40.8	5.6	94	45.3	6.3
75	30.7	5.1	70	34.6	5.6	110	49.2	6.1	114	56.1	6.7
94	35.8	5.7	90	42.1	6.2	130	59.8	6.4	134	65.7	7
116	48.2	6.1	111	53.9	6.6	150	67.4	6.7	154	76.5	7.3
134	57.1	6.4	130	66.8	7.2	170	81.1	7.2	174	94.1	7.9
156	67.4	6.8	151	73.2	7.4						

Appendix 6 Repeatability and reproducibility of the test results for mortar and concrete

Mortar

Table A6-1 Reproducibility of the fresh properties for mortar (table 4-11)

Mix proportions: w/c=0.3, Vs/Vm=0.45, Glenium51=0.09%

Test No..	Spread (mm)	V-funnel (secs)	Yield stress (Pa)	Plastic viscosity (Pa.s)
1	226	7.23	45.4	15.2
2	229	6.9	43.4	15.0
3	220	7.29	50.9	16.0
average	**225.0**	**7.1**	**46.6**	**15.4**
Standard Deviation	**4.6**	**0.2**	**3.9**	**0.5**
Reproducibility (R)*	**12.8**	**0.6**	**10.9**	**1.5**

* at 95% probability level: R = 2.8 x Standard Deviation

Concrete

Table A6-2 Test results for repeatability and reproducibility of concrete (figure 4-9)

Mix proportions: 100% SRC, w/c = 0.3, V_s/V_m = 0.45, C.A = 0.317 m^3 per cube meter concrete

Mix1						Mix2				
Time (t) (mins)	SF (mm)	T_{500} (secs)	Time (t) (mins)	T_V (secs)	note	Time (t) (mins)	SF (mm)	T_{500} (secs)	Time (t) (mins)	T_V (secs)
12	605.4	3.44	10	5.6	After mixing	9	618	2.76	8	7.37
19	645	2.78	18	7.15		25	698	2.75	24	5.232
27	640	3.5	23	8.37		34	675	2.56	31	6.25
37	**669.2**	**2.28**	**36**	**6.25***	remixed	41	675	2.63	39	6.09
45	657.5	3.06	41	8.03		**48**	**675**	2.18	46	6.81
51	650	4.37	48	9.06		**55**	**640**	2.5	**54**	**5.50**
59	**603**	**3.1**	**57**	**7.37**	remixed	**63**	**625**	3.55	**61**	**6.38**
65	593	3.82	62	9.4		**72**	**588**	4.16	**70**	**7.22**
71	565	4.06	68	15.8		84			**79**	**7.76**
By linear regression: SF = 782.68 – 3.0455 × t T_V = 4.33 + 0.0533 × t						By linear regression: SF = 836.82-3.4424 × t T_V = 4.2979 + 0.0412 × t				

* only the bold data were used for linear regression and repeatability/ reproducibility analyses, the test results are shown in figures 4-9, 10, 11 & 12.

Table A6-3 Repeatability and reproducibility analyses for slump flow and V-funnel of concrete (table 4-12)

Time start mixing (mins)	slump flow (mm) Original data	Data on the trend line	error (e_i)	Time start mixing (mins)	V-funnel (secs) Original data	Data on the trend line	error (e_i)
48	**675**	671.60	3.396	**54**	**5.50**	5.9047	0.1853
55	**640**	647.51	-7.51	**61**	**6.38**	6.8111	-0.4311
63	**625**	619.97	5.026	**70**	**7.22**	7.1819	0.0381
72	**588**	589.0	-0.996	**79**	**7.76**	7.5527	0.2073
Repeatability variance, var(e)= $\frac{1}{n-1}\sum_{i=1}^{n} e_i^2$, (n=4)			*31.4*	Repeatability variance, var(e)= $\frac{1}{n-1}\sum_{i=1}^{n} e_i^2$, (n=4)			*0.09*
Repeatability standard deviation = $S_r = \sqrt{\text{var}(e)}$			*5.60*	Repeatability standard deviation = $S_r = \sqrt{\text{var}(e)}$			*0.30*
Repeatability at 95% probability level $r = 2.8 \times S_r$			***16***	Repeatability at 95% probability level $r = 2.8 \times S_r$			***0.84***
variance between Mix1 and Mix2 (obtained from average absolute difference between two trend lines) var (B)= $S_L^2 = 33.5^2$			*1122.3*	variance between Mix1 and Mix2 (obtained from average absolute difference between two trend lines) var (B)= $S_L^2 = 33.5^2$			*0.36*
Reproducibility standard deviation = $\sqrt{S_r^2 + S_L^2}$			*34*	Reproducibility standard deviation = $\sqrt{S_r^2 + S_L^2}$			*0.7*
Reproducibility at 95% probability level = $2.8\sqrt{S_r^2 + S_L^2}$			***95***	Reproducibility at 95% probability level = $2.8\sqrt{S_r^2 + S_L^2}$			***2.0***

Table A6-4 Repeatability of the results for two-point test for concrete (table 4-13)

Mix No.	Slump (mm)	Yield stress(Pa) τ_0 (Pa)	Standard deviation (Pa), S_r*	Repeatability at 95% probability level $r = 2.8\times S_r$	Plastic viscosity (Pa.s) μ (Pa.s)	Standard deviation (Pa), S_r*	Repeatability at 95% probability level $r = 2.8\times S_r$
Mix1	220	83	3.5	10.0	13	2.12	6.0
		88			10		
Mix2	185	405	27.6	77.2	61	1.4	4.0
		366			59		
Mix3	230	103	17.0	47.5	39	8.48	24
		79			51		
Mix4	230	161	7.1	19.8	22	2.83	7.9
		171			18		
Mix5	222	252	29.0	81.2	23	10.6	29.7
		211			38		
		Average of repeatability at 95% probability (r)		47**	Average of repeatability at 95% probability (r)		14**

*For n = 2, $S_r^2 = \frac{1}{2p}\sum_{i=1}^{p} 2S_i^2$, where S_i is standard deviation of each series test result. Because p = 1 in this test, $S_r = S_i$. ** It was examined that the repeatability r is independent to the property measured.

Appendix 7 Results for tests on mixing procedure and selection of superplasticizer

Table A7-1 Effect of mixing methods on Conplast430 saturation dosage and maximum workability* (mortar tests) (figure 5-1)

Mortar proportion: 100% PC1, w/c = 0.3, V_s/V_m = 0.45

mixing method	sp dosage %	Test results			
		Spread, (mm)	V-funnel, (s)	τ_0, (Pa)	μ, (Pa.s)
Direct addition	0.8150	178	4.2	111.5	8.3
	0.8828	200	3.9	71.5	7.7
	1.0186	248	3.4	41.8	6.6
	1.1545	280	3	26.5	6.3
	1.2903	**305**	2.9	22.9	5.4
	1.4261	310	2.9	18.4	5.2
	1.5620	312	2.7	16.6	5.1
2 mins delayed addition	0.5	228	4.2	56.6	9.1
	0.6	270	3.4	39.6	8.6
	0.65	298	4	17.1	9.0
	0.68	**315**	**3.3**	5.4	7.1
	0.75	320	3.5	2.7	7.6
4 mins delayed addition	0.5	228	3.9	54.8	8.1
	0.6	303	3.5	15.3	7.1
	0.65	**312**	**3.5**	6.3	6.8
	0.7	320	3.1	4.5	6.3
	0.8	318	3.1	6.7	5.7

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A7-2 Determination of Saturation dosage for each type of superplasticizer (mortar test) (figure 5-2)

Mix proportion: 100% PC1, w/c = 0.3, V_s/V_m = 0.45

Sp type	Sp dosage (%)	Spread, D_m (mm)	V-funnel, T_V (secs)
Conplast430	0.5	228	4.2
	0.6	270	3.4
	0.65	298	3.5
	0.68	315	3.3
	0.75	320	3.5
Darcem2001	0.5	285	2.53
	0.7	313	2.4
	0.8	305	3.07
Sika10	0.2	280	7.8
	0.247	320	6.3
	0.35	326	6
Glenium51	0.1	200	6.9
	0.15	338	4.3
	0.2	343	4.1
Viscocrete	0.25	265	2.78
	0.33	310	3.22
	0.36	315	3.01

Table A7-3 The effect of addition time of superplasticizers on their efficiency (mortar tests) (figure 5-3)

Mix proportion: 100% PC1, w/c = 0.3, Vs/Vm = 0.45

Sp type	Delay time (mins)	Spread, D_m (mm)	V-funnel time, T_V (secs)
Conplast430	0	115	
	1	275	3.34
	2	295	2.8
	3	295	2.72
	4	275	2.47
Darcem2001	1	230	3.94
	2	285	2.53
	3	285	2.63
	4	280	3.03
	6	238	3.68
Sika10	0	150	
	1	265	4.87
	2	298	4.37
	3	292	4.42
	4	270	4.67
Glenium51	0	204	4.35
	0.5	280	3.5
	1	280	3.54
	2	272	3.45
	4	193	4.88
Viscocrete	0	150	3.56
	1	285	3.34
	2	305	3.45
	3	292	3.78
	4	270	3.56

Table A7-4 The workability retention of mixes with different types of superplasticizer (mortar tests) (figure 5-4)

Mix proportion: 100% PC1, w/c = 0.3, V_s/V_m = 0.45

Sp type	Sp dosage (%)	Sp addition delay time	Elapsed time (mins)	Spread, D_m (mm)	V-funnel time, Tv (secs)
Conplast430	0.65	2 minutes	10	300	2.72
			30	285	3.5
			60	260	5.83
			90	210	9.7
			120	155	
Darcem2001	0.6	2 minutes	10	312.5	2.4
			30	295	3.1
			60	255	5.5
			90	180	10.2
			120	150	
Sika10	0.3	2 minutes	10	300	4.3
			30	292	5.1
			60	282	6.3
			90	240	9.7
			120	170	
Glenium51	0.15	1 minute	10	311	3.92
			30	300	4.71
			60	282	5.83
			90	244	7.24
			120	200	11.10
Viscocrete	0.33	2 minutes	10	310	3.22
			30	295	4.02
			60	263	4.91
			90	220	6.09
			120	183	10.03

Table A7-5 Comparison of the properties of concrete and mortar mixes with different types of superplasticizer and different mixing methods (tables5-1 & 2, figures5-5, 6 & 7)

Mix proportion: 100% PC4, w/c = 0.3, V_a/V_m = 0.45 C.A. = 0.317 m^3 per cube meter concrete

	Properties*	Slump flow		V-funnel		Two-point test			U-box test		Compressive strength		Mortar test				
Mix No.	Mixes	Time^ (mins)	SF (mm)	time (mins)	T_V (secs)	time (mins)	τ_0 (Pa)	μ (Pa.s)	time (mins)	H (mm)	age	Strength (Mpa)	time (mins)	D_m (mm)	T_V (secs)	τ_0 ! (Pa)	μ ! (Pa.s)
C5-1	Glenium51	11	735	10	7.53	8	-25	78	16	340	1	52.4	10	320	4.4	1	5.7
	with 1 mins	32	665	31	8.84						7	70.7	30	308	5.41	1.3	11.7
	delayed	64	578	63	12.87	61	-72	175	69	302	28	81.2	60	291	6.16	9.2	11.4
	addition	92	455	91	24.85								90	270	7.16	13.2	15.4
		124	355	126	87.69	121	334	209					120	240	9.04	40.5	21.4
C5-2	Conplast430	11	625	9	8	9	281	122	19	325	1	47.5	10	301	3.84	13.2	8.7
	with 2 mins	32	515	30	10.46						7	67.6	30	281.5	4.56	22.6	10.4
	delayed	64	425	64	14.84	62	82	209	71	220	28	68.1	60	239	5.56	38.5	13.9
	addition	94	255	92	56								90	205	6.63	70	16.6
C5-3	Conplast430	9	568	22	10.6				10	320	1	44.8					
	with direct	33	400	35	10.06						7	67.2					
	addition	66	330	68	19.04				70	0	28	69.7					

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete, but not the relationship between the properties for mortar

!: The τ_0 μ values were obtained by manual recording

^: Time after mixing

Appendix 8 Test results for fresh properties of the mixes with a single types of powder

Table A8-1 Workability retention of mortar with various water/cement ratios* (table 6-1, figure 6-1&2)

Mix proportion: 100% PC2, $V_w/V_m = 0.45$, Glenium51 was used and the dosage was adjusted to achieve 310-320mm spread for mortar.

Mix No.	W/c	Sp dosage (%)	Time after mixing (mins)	Spread, D_m (mm)	time to 250 mm, T_{250} (secs)	V-funnel, T_V (secs)	τ_0 (Pa)	μ (Pa.s)
M6-1	0.275	0.18	10	311	5.59	5.22	3.6	11.4
			30	303	7.62	5.92	9.0	15.2
			60	295	11.25	7.18	15.7	18.4
			90	278	18.97	9.41	35.9	27.3
			120	245		12.85	94.2	38.2
M6-2	0.30	0.145	10	315	3.5	3.26	4.5	6.9
			30	308	4.4	3.78	7.2	8.5
			60	290	5.2	4.38	25.1	10.3
			90	260	7.3	5.25	52.0	15.0
			120	220		6.54	103.2	16.2
M6-3	0.325	0.125	10	310	3.03	2.38	9.9	4.9
			30	300	3.75	2.81	17.9	6.1
			60	278	3.59	3.35	37.7	7.7
			90	243		4.09	80.8	9.1
			120	204		4.97	152.5	9.8
M6-4	0.35	0.11	10	310	2.2	1.75	10.8	3.2
			30	295	2.9	2.07	17.0	4.2
			60	273	4.5	2.4	35.9	5.4
			90	245		3.27	71.8	6.8
			120	200		4.42	143.6	8.0
M6-5	0.375	0.105	10	310	1.5	1.47	10.8	2.3
			30	300	2.2	1.69	17.9	2.9
			60	280	3.4	1.94	32.3	3.7
			90	255	5.8	2.34	56.5	4.5
			120	220		2.81	106.8	7.6

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A8-2 Effect of superplasticizer dosage on workability retention of mortar (table 6-2, figures 6-3 & 4)

Mix proportion: 100% PC, w/c=0.45, Vs/Vm=0.35, Glenium51 was used and the dosage was adjusted to achieve 310-320mm spread.

Mix No	Sp type	Sp dosage (%)	Time after mixing (mins)	Spread, D_m (mm)	V-funnel, T_V (secs)	τ_0 (Pa)	μ (Pa.s)
M6-6			10	178	1.67	84.9	1.8
			30	167	1.79	94.8	2.1
			60	156		114.9	2.0
			90	150		137.2	2.2
M6-7	Conplast430	0.1	10	194	1.36	63.2	1.3
			30	177	1.43	83.0	1.4
			60	165	1.67	95.6	1.7
			90	157		117.1	1.8
M6-8	Conplast430	0.3	10	300	0.97	8.3	0.7
			30	288	1.03	15.9	0.8
			60	254	1.22	28.3	0.9
			90	219	1.23	44.8	1.1
M6-9	Glenium51	0.015	10	217	1.21	46.6	1.2
			30	198	1.37	56.6	1.5
			60	185	1.49	73.7	1.7
			90	174	1.58	83.2	1.8
M6-10	Glenium51	0.03	10	275	1.17	20.0	0.9
			30	251	1.15	29.1	1.0
			60	228	1.35	39.0	1.2
			90	217	1.43	47.4	1.6

Table A8-3 Workability retention of concrete and mortar with various water/cement ratios (table 6-3, figures 6-5~9)

Mix proportion: 100% PC, w/c=0.3, C.A. = 0.317 m^3 per cube meter concrete, Glenium51 was used and the dosage was obtained by repeating the spread test on mortar component

Properties*			Slump flow			V-funnel		Two-point test			U-box test			Compressive strength		Mortar test					
	W/c	Sp (%)	Time^ (mins)	SF (mm)	T_{500} (secs)	time (mins)	T_V (secs)	time (mins)	τ_0 (Pa)	μ (Pa.s)	time (mins)	$T_{U\text{-box}}$ (secs)	H (mm)	age	f_C (MPa)	time (mins)	D_m (mm)	T_{250} (secs)	T_V (secs)	τ_0! (Pa)	μ ! (Pa.s)
C6-1	0.275	0.16	8	783	3.47	15	11.16				11	5.16	330	1	56.5	10	318	4.62	7.38	0.7	13.1
			65	575	11.4	64	20.22	33	-202	229	69	11.84	280	7	77.8	30	292	8.66	9.59	9.0	36.1
			37	655	6.57	35	12.91							28	92.6	60	270	15.43	12.44	24.8	57.9
			96	370		93	36.81	61	-47	246						90	250		17		
						119		118	313	298						120	195		23.56	*74.2*	*33.7*
C5-1	0.3	0.13	11	735	3.22	10	7.53	8	-25	78	16	2.88	340	1	52.4	10	320	3.4	4.4	1	5.7
			32	665	3.52	31	8.84							7	70.7	30	308	5	5.41	1.3	11.7
			64	578	5.82	63	12.87	61	-72	175	69	8.03	302	28	81.2	60	291	6.86	6.16	9.2	11.4
			92	455		91	24.85									90	270	8.34	7.16	13.2	15.4
			124	355				121	334	209						120	240		9.04	40.5	21.4
C6-2	0.325	0.11	11	768	1.58	9	5.92	7	-162	73	15	2.14	332	1	47.7	10	313	2.43	3.19	3.5	4.3
			32	650	2.75	32	7.06							7	67.2	30	298	3.38	4.03	6.9	6.2
			69	472		67	8.28	70	127	88	70		250	28	79.6	60	273	6.03	5.13	16	8.9
			93	373		92	11.24									90	244		5.97	29.7	13.3
																120	200		8.09	65.3	19.9
C6-3	0.375	0.087	10	745	1.22	8	3.09	9	10	26	17	1.6	332	1	47.7	10	318	1.32	1.86	3.2	2.2
			32	693	1.53	31	3.97							7	57.2	30	303	1.87	2.04	6.2	3
			65	575	2.1	64	4.53				70	2.31	305	28	68.7	60	282	3	2.59	10.1	4.4
			93	460		91	5.88									90	258	5.31	3	25.6	5.5
			124	365		121	7.56	120	249	41						120	224		3.57	52.9	8.7

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete, but not the relationship between the properties for mortar

!: The τ_0 μ values were obtained by manual recording

^: Time after mixing

Table A8-4 Workability retention of mortar with various sand contents* (table 6-4, figures 6-10 & 11)

Mix proportion: 100% PC, w/c=0.3, Glenium51 was used and the dosage was adjusted for mortar to achieve 310-320mm spread.

	V_s/V_m	Sp dosage (%)	Time after mixing (mins)	Spread, D_m (mm)	time to 250 mm spread, T_{250} (secs)	V-funnel, T_V (secs)	τ_0 (Pa)	μ (Pa.s)
M6-11	0.4	0.115	10	310	2.6	2.28	6.3	3.9
			30	300	3.6	2.5	12.6	4.4
			60	290	4.7	3.07	21.5	5.7
			90	268	7.7	3.63	38.6	6.9
			120	232		4.47	75.4	8.2
M6-12	0.425	0.135	10	320	3.1	2.72	5.4	4.8
			30	315	3.8	2.96	7.2	5.9
			60	303	4.5	3.28	13.5	7.4
			90	280	7.4	4.28	31.4	9.0
			120	243		5.04	69.5	11.7
M6-2	0.45	0.145	10	315	3.5	3.26	4.5	6.9
			30	308	4.4	3.78	7.2	8.5
			60	290	5.2	4.38	25.1	10.3
			90	260	7.3	5.25	52.0	15.0
			120	220		6.54	103.2	16.2
M6-13	0.475	0.15	10	310	5.2	3.87	7.2	9.6
			30	300	7.8	4.75	26.9	11.3
			60	275	18.2	5.56	53.8	13.4
			90	235		7.16	116.6	16.7
			120	185		9.72	219.8	40.1

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A8-5 Workability retention of mortar with different types of cement* (table 6-6, figure 6-17)

Mix proportion: w/c=0.3, V_s/V_m=0.45, Glenium51 was used and the dosage was adjusted for mortar to achieve 310-320mm spread.

Mix No.	Cement type	Sp dosage (%)	Tested time (mins)	Spread, D_m (mm)	V-funnel, T_V (secs)	τ_0 (Pa)	μ (Pa.s)
M6-14	SRC	0.145	10	310	3.8	5.4	5.8
			30	310	3.98	4.5	6.3
			60	308	4.16	6.7	6.9
			90	310	4.4	4.5	7.6
			120	305	4.7	4.5	8.3
M6-15	PC	0.15	10	311	3.92	9.0	8.1
			30	300	4.71	13.5	10.7
			60	282	5.83	29.2	13.6
			90	244	7.24	60.6	18.4
			120	200	11.1	125.6	24.0

* The test results were **not** used for analysing the relationships between the fresh properties for mortar because the SRC mix properties have not changed much for 2 hours and the PC mix is a repeating test of the same mix in tableA8.1.

Table A8-6 Workability retention of concrete and mortar with various sand contents (table 6-5, figures 6-12~6-16)

Mix proportion: 100% PC, w/c=0.3, C.A. = 0.317 m^3 per cube meter concrete, Glenium51 was used and the dosage was obtained by repeating the spread test on mortar component

Properties*			Slump flow			V-funnel		Two-point test			U-box test			Compression strength		Mortar test					
Mix No.	V_s/V_m	Sp (%)	time^ (mins)	SF (mm)	T_{500} (secs)	time (mins)	T_V (secs)	time (mins)	τ_0 (Pa)	μ (Pa.s)	time (mins)	$T_{U\text{-}box}$ (secs)	H (mm)	age	f_C (Mpa)	Time (mins)	D_m (mm)	T_{250} (secs)	T_V (secs)	τ_0! (Pa)	μ! (Pa.s)
			12	808	2.25	10	6.03	8	-63	59	19	1.94	340	1	47.9	10	325	2.5	3.25	3.1	3.3
			32	718	2.65	31	7.25							7	74.6	30	308	3.36	4.06	5.2	4.6
C6-4	0.4	0.115	65	615	3.87	63	6.97	60	-39	89	69	3.03	322	28	77.4	60	290	4.65	4.91	8.7	7.1
			93	520	6.19	91	8.27									90	264	9.07	6.25	20.1	10.1
			123	435		122	15.26	121	158	159	125		212			120	230		7.41	38	13.6
			11	735	3.22	10	7.53	8	-25	78	16	2.88	340	1	52.4	10	320	3.4	4.4	1	5.7
			32	665	3.52	31	8.84							7	70.7	30	308	5	5.41	1.3	11.7
C5-1	0.45	0.13	64	578	5.82	63	12.87	61	-72	175	69	8.03	302	28	81.2	60	291	6.86	6.16	9.2	11.4
			92	455		91	24.85									90	270	8.34	7.16	13.2	15.4
			124	355				121	334	209						120	240		9.04	40.5	21.4
			10	745	4.29	8	8.27	7	-70	104	16	4.81	335	1	51.4	10	320	4.06	5.34	0.5	8.7
			32	603	5.87	31	11.6							7	74.6	30	310	5.94	6.74	1.1	13.1
C6-5	0.475	0.145	65	473		63	21.59	61	-20	223	70		250	28	81.1	60	281	9.75	8.56	9.4	18.8
			92	370		92	26.21									90	245		11	29.7	27
				-217												120	193		16.69	78.1	45.3

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete, but not the relationship between the properties for mortar

!: The τ_0 μ values were obtained by manual recording

^: Time after mixing

Table A8-7 Workability retention of concrete and mortar with different type of cement (table 6-7, figures 6-18~20)

Mix proportion: 100% PC, w/c=0.3, C.A. = 0.317 m^3 per cube meter concrete, Glenium51 was used and the dosage was obtained by repeating the spread test on mortar component

Properties*			Slump flow			V-funnel		Two-point test			U-box test			Compressive strength		Mortar test					
Mix No.	Cement type	Sp (%)	Time^ (mins)	SF (mm)	T_{500} (secs)	time (mins)	T_V secs)	time (mins)	τ_0 (Pa)	μ (Pa.s)	time (mins)	$T_{U\text{-}box}$ (secs)	H (mm)	age	f_c (MPa)	Time (mins)	D_m (mm)	T_{250} (secs)	T_V (secs)	τ_0 ! (Pa)	μ ! (Pa.s)
C5-1	PC	0.13	11	735	3.22	10	7.53	8	-25	78	16	2.88	340	1	52.4	10	320	3.4	4.4	1	5.7
			32	665	3.52	31	8.84							7	70.7	30	308	5	5.41	1.3	11.7
			64	578	5.82	63	12.87	61	-72	175	69	8.03	302	28	81.2	60	291	6.86	6.16	9.2	11.4
			92	455		91	24.85									90	270	8.34	7.16	13.2	15.4
			124	355				121	334	209						120	240		9.04	40.5	21.4
C6-6	SRC1	0.145	11	653		8	5.95				16		337	1	33.7	10	310		3.8	5.4	5.8
														7	76.9	30	310		3.98	4.5	6.4
			61	638		65	8.73				69		340	28		60	308		4.16	6.8	7.0
																90	310		4.4	4.5	7.6
			124	621		123	10.81				125		340			120	305		4.7	4.5	8.4
C6-7	SRC2	0.13	9	618		9	7.37				14		340	1		10	285	2.28	2.87	7.3	3.8
			34	675		33	10.57							7		30	308	2.69	3.07	6.3	4.6
			63	625		63	11.27				64		330	28		60	307	3.47	3.43	6.0	5.7
			92	560		91	13				90		310			90	297	3.78	3.94	10.6	6.6
			123	495		123	16.5				125		275			120	280	4.72	4.38	13.1	8.8

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete, but not the relationship between the properties for mortar.

!: The τ_0 μ values were obtained by recording manually.

^: Time after mixing.

Appendix 9 Test results for fresh properties of mixes with binary blends of powder

Table A9-1 Binary powder mortar* (table 7-1, figures 7-1~3)

Mix proportion: V_w/V_p=0.945, V_s/V_m = 0.45, Glenium51 was used and the dosage was adjusted to achieve 310-320mm spread for mortar.

Mix No.	Types of blends	Sp (%)	Time,(mins)	D_m, (mm)	T_V, (secs)	τ_0, (Pa)	μ, (Pa.s)
M7-1	100% PC	0.15	10	311	3.92	9	8.1
			30	300	4.71	13.5	10.7
			60	282	5.83	29.2	13.6
			90	244	7.24	60.6	18.4
			120	200	11.1	126	24
M7-2	PFA/PC=40/60	0.125	10	323	3.08	4.5	4.4
			30	315	3.47	9.9	6.2
			60	295	3.9	17.9	7.2
			90	257	4.46	53.8	9
			120	210	5.51	117	10.3
M7-3	GGBS/PC=40/60	0.10	10	325	3.82	0	7.3
			30	300	4.87	6.3	10.3
			60	260	6.39	31.4	14.4
			90	210	8.46	89.7	18.6
			120	125	16.62	180	30.7
M7-4	LSP100/PC=40/60	0.09	10	325	2.54	4	4.2
			30	305	3.18	16.2	6.1
			60	260	3.97	48.5	8.3
			90	218	5.12	95.1	11.1
			120	170	7.8	197	12
M7-5	PC/CSF=95/5	0.35	10	320	2.49	5.4	4.3
			30	320	3.1	10.8	5.1
			60	312	3.39	13.5	5.9
			90	300	3.81	23.3	6.9
			120	280	4.41	40.4	8.6
M7-6	SRC2	0.13	10	285	2.87	7.3	3.8
			30	308	3.07	6.3	4.6
			60	307	3.43	6	5.7
			90	297	3.94	10.6	6.6
			120	280	4.38	13.1	8.8
M7-7	SRC2/GGBS	0.098	10	330	3.53	0	4.1
			30	320	3.93	0	5
			60	300	4.69	3.5	7.7
			90	268	5.43	13.4	10.4
			120	238	6.44	36.4	14.4

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A9-2 LSP binary mixes with different particle sizes of LSP powder* (table 7-2, figure 7-4)

Mix proportion: V_w/V_p=0.945, V_s/V_m = 0.45, Glenium51 was used and the dosage was adjusted to achieve 310-320 mm spread for mortar.

Mix No	Types of blends	Sp dosage (%)	Time after mixing (mins)	D_m (mm)	Tv (secs)	τ_0 (Pa)	μ (Pa.s)
M7-8	100%PC3	0.165	10	325	4.11	1.9	9.6
			30	323	4.7	1.9	12.5
			60	290	5.74	12	17.5
			90	262	7.69	36	22.5
			120	220	9.17		
M7-9	LSP15/PC3=40/60	0.1	10	320	1.78	8.6	2
			30	292	2	14.4	2.7
			60	263	2.73	26.9	3.5
			90	236	3.23	47.1	4.6
			120	203	3.89	73	6.2
M7-10	LSP50/PC3=40/60	0.095	10	326	2.43	4.3	3.3
			30	294	3.1	19.2	4.4
			60	243	3.92	48	6.1
			90	203	5.1	88.8	8.2
			120	168	7.23	146	13
M7-11	LSP100/PC3=40/60	0.085	10	323	3.01	7.7	5.2
			30	293	3.6	26.9	7.4
			60	228	4.77	76.8	10.9
			90	178	6.48	151	13.9
			120	133			

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A9-3 CSF binary powder mixes (table 7-3, figure 7-5)

Mix proportion: V_w/V_p=0.945, V_s/V_m = 0.45, Glenium51 was used and the dosage was adjusted to achieve 310-320 mm spread for mortar.

Mix No.	Types of blends	Sp dosage (%)	Time after mixing (mins)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
M7-1	100% PC	0.15	10	311	3.92	9	8.1
			30	300	4.71	13.5	10.7
			60	282	5.83	29.2	13.6
			90	244	7.24	60.6	18.4
			120	200	11.1	126	24
M7-5	CSF/PC=5/95	0.2	10	320	2.49	5.4	4.3
			30	320	3.1	10.8	5.1
			60	312	3.39	13.5	5.9
			90	300	3.81	23.3	6.9
			120	280	4.41	40.4	8.6
M7-12	CSF/PC=10/90	0.25	10	325	2.19	7.2	3.3
			30	320	2.6	11.7	4.1
			60	315	3	15.3	5
			90	310	3.3	20.6	5.7
			120	300	3.8	26	7
M7-13	CSF/PC=15/85	0.35	10	320	2.17	10.8	3.2
			30	320	2.45	11.7	3.8
			60	320	2.7	13.5	4.2
			90	320	2.97	16.2	4.9
			120	315	3.33	19.7	5.9

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A9-4 LSP100 binary powder mixes with various content* (table 7-4, figure7-6)

Mix proportion: V_w/V_p=0.945, V_s/V_m = 0.45, Glenium51 was used and the dosage was adjusted to achieve 310-320 mm spread for mortar.

Mix No	Types of blends	Sp dosage (%)	Time after mixing (mins)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
M7-10	100% PC	0.165	10	325	4.11	1.9	9.6
			30	323	4.7	1.9	12.5
			60	290	5.74	12	17.5
			90	262	7.69	36	22.5
			120	220	9.17		
M7-13	LSP100/PC3=20/80	0.115	10	320	3.88	5.8	8.3
			30	296	4.5	14.4	11.8
			60	252	5.91	52.8	16.5
			90	200	7.99	110	19.7
			120	160			
M7-14	LSP100/PC3=40/60	0.085	10	323	3.01	7.7	5.2
			30	293	3.6	26.9	7.4
			60	228	4.77	76.8	10.9
			90	178	6.48	151	13.9
			120	133			
M7-15	LSP100/PC3=60/40	0.072	10	318	2.65	11.5	3.5
			30	262	3.7	40.3	5.6
			60	215	4.13	91.2	8.2
			90	165	5.67	158	10.4
			120	135		216	15.3

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A9-5 Binary powder concrete and mortar mixes (table 7-5, figures 7-9~14)

Mix proportion: V_w/V_p=0.945, V_s/V_m=0.45, C.A. = 0.317 m^3 per cube meter concrete, Glenium51 was used and the dosage was obtained by repeating the spread test on mortar component

Properties*			Slump flow			V-funnel		Two-point test			U-box test			Compressive strength		Mortar test					
Mix No.	Types of powder	Sp (%)	Time^ (mins)	SF (mm)	T_{500} (secs)	time (mins)	T_{Vf} (secs)	time (mins)	τ_0 (Pa)	μ (Pa.s)	time (mins)	$T_{U\text{-}box}$ (secs)	H (mm)	age	f_C (MPa)	Time (mins)	D_m (mm)	T_{250} (secs)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
C5-1	PC4	0.1	11	735	3.22	10	7.53	8	-25	78	16	2.88	340	1	52.4	10	320	3.4	4.4	1.1	6.4
			32	665	3.52	31	8.84							7	70.7	30	308	5	5.41	1.4	13.1
			64	578	5.82	63	12.87	61	-72	175	69	8.03	302	28	81.2	60	291	6.86	6.16	9.8	12.8
			92	455		91	24.85									90	270	8.34	7.16	14	17.3
			124	355				121	334	209						120	240		9.04	42.9	24
C7-1	PC/ GGBS =40/60	0.9	11	583	4.19	10	9.13	8	9	76	16	5.22	291	1	27.2	10	312	3.21	4.85	0.2	11.4
			32	340		31	20.66	35	444	183				7	65.2	30	233		7.73	39.6	20.9
														28	73.6	60	133		12.97	145	39.2
																90					
																120					
C7-2	PC/LSP100=40/60	0.8	12	675	2.75	10	5.12	8	-9.3	41	16	2.69	303	1	22.1	10	320	2.68	2.97	13.1	4.6
			33	468		32	6.12							7	40.2	30	263	5.13	4.06	49.3	7.5
			65	363		63	12.35	62	365	56				28	50.4	60	200		5.5	110	10.9
																90					
																120					

(Table 11-5, continued)

Properties*			Slump flow			V-funnel		Two-point test			U-box test			Compressive strength		Mortar test					
Mix No.	Types of powder	Sp (%)	Time^ (mins)	SF (mm)	T_{500} (secs)	time (mins)	$T_{V\text{-funnel}}$ (secs)	time (mins)	τ_0 (Pa)	μ (Pa.s)	time (mins)	$T_{U\text{-box}}$ (secs)	H (mm)	age	f_C (MPa)	Time (mins)	D_m (mm)	T_{250} (secs)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
			10	740	2.65	9	4.78	8	68	8.3	16	1.91	333	1	45.9	10	328	2.34	2	11.1	2.9
			33	698	2.84	32	5.88							7	82.8	30	322	3.44	2.28	14.7	3.8
C7-3	CSF/PC=15/85	0.3	64	670	3.62	63	7.5	61	15	68	70	3.4	327	28	99.2	60	313	5.12	2.78	19.5	4.7
			92	620	6.56	91	10.62									90	309	4.25	3.35	26.5	5.8
			125	598	6.93	124	18.25	120	106	75	128	10.25	270			120	298	6.28	3.88	33.5	6.8
			9	618		9	7.37				14		340	1		10	285	2.28	2.87	7.3	3.8
			34	675		33	10.57							7		30	308	2.69	3.07	6.3	4.6
C6-7	SRC2	0.13	63	625		63	11.27				64		330	28		60	307	3.47	3.43	6	5.7
			92	560		91	13				90		310			90	297	3.78	3.94	10.6	6.6
			123	495		123	16.5				125		275			120	280	4.72	4.38	13.1	8.8
			10	770	2.28	9	7.78	8	-37	43	16	2.25	340	1	31.2	10	330	2.44	3.53	-3.2	4.1
			32	688	2.97	31	8.65							7	69.6	30	320	2.5	3.93	-0.4	5
C7-4	SRC/GGBS=40/60	0.098	93	585	4.57	63	10.15	61	-13	98	98	3.63	315	28	83.6	60	300	3.27	4.69	3.5	7.7
			92	465		91	13.69									90	268	4.54	5.43	13.4	10.4
			122	375		121	26.16	120	169	176						120	238		6.44	36.4	14.4

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete, but not the relationship between the properties for mortar

^: Time after mixing

Appendix 10 Test results for properties of CSF ternary blends of powder mixes

Table A10-1 CSF ternary blends of powder mortar mixes and reference mixes* (table 8-1, figure 8-1)

Mix proportion: V_w/V_p=0.945, V_s/V_m = 0.45, Glenium51 was used and the dosage was adjusted to achieve 310-320 mm spread for mortar.

Mix No.	Types of blends	Sp dosage (%)	time (mins)	D_m (mm)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
M8-1	100%PC	0.16%	10	315	4.11	4.0	8.5
			30	300	4.7	5.4	11.0
			60	280	5.74	13.5	15.5
			90	252	7.69	35.9	19.9
			120	210	9.17		
M8-2	PC/PFA/LSP15=50/25/25	0.09	10	313	1.93	10.8	2.2
			30	284	2.41	19.7	3.8
			60	242	2.89	42.2	3.9
			90	210	3.51	74.0	4.7
			120	180	4.24	107.7	7.0
M8-3	PC/PFA/CSF=50/40/10	0.20	10	315	1.91	14.4	2.4
			30	306	2.16	16.2	2.9
			60	292	2.44	25.1	3.4
			90	271	2.61	34.1	4.1
			120	258	2.91	46.7	4.7
M8-4	PC/LSP15/CSF=50/40/10	0.18	10	320	1.58	10.8	1.4
			30	318	1.62	12.6	1.7
			60	303	1.92	16.2	2.1
			90	286	2.05	21.5	2.6
			120	273	2.26	26.9	3.1
M8-5	PC/GGBS/CSF=50/40/10	0.18	10	311	2.4	12.6	3.6
			30	303	2.8	14.4	4.8
			60	285	3.3	24.2	6.3
			90	260	3.9	44.9	7.6
			120	235	4.5	67.3	9.0
M8-6	PC/CSF=90/10	0.25	10	312	2.64	17.9	3.8
			30	309	2.2	20.6	5.1
			60	298	3.62	26.9	6.0
			90	288	4.13	35.9	7.4
			120	278	5.13	49.4	9.2

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A10-2 PC/CSF/GGBS ternary blends of powder and PC/GGBS binary mortar mixes* (table 8-2, figure 8-3)

Mix proportion: V_w/V_p=0.945, V_s/V_m = 0.45, Glenium51 was used and the dosage was adjusted to achieve 310-320 mm spread for mortar.

Mix No.	Types of blends	Sp dosage (%)	Time after mixing (mins)	D_m (mm)	T_{vi} (secs)	τ_0 (Pa)	μ (Pa.s)
M8-5	PC/GGBS/CSF=50/40/10	0.18	10	311	2.62	12.6	3.6
			30	303	3.3	14.4	4.8
			60	285	4.03	24.2	6.3
			90	260	4.93	44.9	7.6
			120	235	5.85	67.3	9.0
M8-7	PC/GGBS/CSF=45/40/15	0.25	10	325	1.84	6.3	2.4
			30	332	2.05	5.4	2.8
			60	330	2.21	7.2	3.0
			90	320	2.46	9.9	3.4
			120	310	2.74	12.6	3.9
M8-8	PC/GGBS=60/40	0.1	10	325	3.82	0.0	7.3
			30	300	4.87	6.3	10.3
			60	260	6.39	31.4	14.4
			90	210	8.46	89.7	18.6
			120	125	16.62	179.5	30.7

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A10-3 Ternary blends of powder mixes and the reference mix of concrete and mortar (table 8-3, figure 8-4~8-7)

Mix proportion: V_w/V_p=0.945, V_s/V_m=0.45, C.A. = 0.317 m^3 per cube meter concrete, Glenium51 was used and the dosage was obtained by repeating the spread test on mortar component

Properties*			Slump flow			V-funnel		Two-point test			U-box test			Compressive strength		Mortar test					
Mix No.	Types of blends	Sp (%)	time (mins)	SF (mm)	T_{500} (secs)	time (mins)	T_V (secs)	time (mins)	τ_0 (Pa)	μ (Pa.s)	time (mins)	$T_{U\text{-}box}$ (secs)	H (mm)	age	f_c (MPa)	Time (mins)	D_m (mm)	T_{250} (secs)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
C5-1	100%PC	0.13	11	735	3.22	10	7.53	8	-25	78	16	2.88	340	1	52.4	10	320	3.4	4.4	1	5.7
			32	665	3.52	31	8.84							7	70.7	30	308	5	5.41	1.3	11.7
			64	578	5.82	63	12.87	61	-72	175	69	8.03	302	28	81.2	60	291	6.86	6.16	9.2	11.4
			92	455		91	24.85									90	270	8.34	7.16	13.2	15.4
			124	355				121	334	209						120	240		9.04	40.5	21.4
C8-1	PC/GGBS/CSF =45/40/15	0.225	10	778	1.22	9	3.68	8	50	8	17	1.75	335	1	18.7	10	314	2.69	2.06	14	2.64
			33	670	2.12	32	4.34							7	67.6	30	307	3.18	2.4	18	3.03
			64	590	2.65	63	6.53	61	80	12	69	2.5	315	28	84.4	60	287	4.56	2.93	24.2	3.65
			92	540	3.69	91	9									90	279	5.78	3.19	30.7	4.3
			124	508	7.37	122	12.28	120	222	10	129	8.72	253			120	268	8.72	3.6	37.5	4.9
C8-2	PC/PFA/LSP15 =50/25/25	0.08	9	700	1.03	8	3.35	8	7.7	24	15	1.12	326	1	18.6	10	319	1.22	1.81	14	1.8
			34	530	2.31	32	5.1							7	36.2	30	280	2.03	2.06	22	2
			63	445		62	7	61	48	98	68		230	28	50.7	60	244	6.43	2.62	35	2.9
			92	363		91	9.16									90	220		3.16	54	3.7
																120	198		3.71	78	4.8

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete, but not the relationship between the properties for mortar

Appendix 11 Results of preliminary study on Welan gum solutions and mortar containing Welan gum

Table A11-1 Rheological properties of Welan gum and cellulose solutions in water (figure 9-1)

	1.0% WG	2.0% WG	1.5% cellulose
shear rate (1/s)	μ_{app} (mPa.s)	μ_{app} (mPa.s)	μ_{app} (mPa.s)
0.945	20.09		4.1
1.366	14.5962		3.1482
1.955	10.8	37.5	2.8
2.8	7.8176	27.1522	2.40112
4	5.7702	19.3644	2.1516
5.73	4.2284	13.981	1.8414
8.2	3.094	10.115	1.6184
11.75	2.26032	7.24632	1.42932
16.81	1.6338	5.2515	1.2837
24.1	1.18406	3.74682	1.08674
34.5	0.86184	2.67624	0.93555
49.3	0.63123	1.88575	0.794
70.6	0.45705	1.37115	0.6648
101	0.342672	0.98736	0.549824
144.6	0.252824	0.719264	0.454272

Table A11-2 Rheological properties of Welan gum and cellulose solutions in deionized and filtered cement water (figure 9-2)

solutions	apparent viscosity*(mPa.s)	
	WG(1.0%)	MC(1.5%)
Deionized water	0.95698	0.94076
filtered cement water	1.2165	0.190585

* measured at 24.1(1/s) shear rate

Table A11-3 Welan gum efficiency with different mixing conditions and mixing times in terms of spread (figure 9-3)

Mix proportion: 100% PC mix, w/c = 0.5, V_s/V_m = 0.45, Glenium51 = 0.4% by weight of PC, WG = 0.1% by weight of water.

mixing time (mins)	mixing at low speed		mixing at high speed	
	spread (mm)	V-funnel (secs)	spread (mm)	V-funnel (secs)
3			190	2.2
4	232	1.6	232	1.6
5	233	1.5	225	1.55
6	253	1.4	259	1.35
8	265	1.4	276	1.2
10	269	1.4	273	1.2

Table A11-4 Welan gum and superplasticizer compatibility in terms of spread (figure 9-4)

The mix proportion: w/c=0.4 V_s/V_m=0.45

WG (%)	sp(solid) dosage to achieve 280 (mm)+-5 spread, (%)			
	conplast430	darcem2001	sika10	glenium51
0.00	0.3	0.3	0.1	0.08
0.05	0.4	0.4	0.2	0.2
0.10	0.6	0.6	0.6	2

Table A11-5 Effect of Welan gum content on superplasticizer saturation dosage and maximum workability * (figure 9-5)

The mix proportion: w/c=0.4 V_s/V_m=0.45

WG dosage (%)	splast (%)	spread (mm)	V-funnel (s)	τ_0 (Pa)	μ (Pa.s)
0.05	0.3	175	1.93	94.2	3.3
	0.4	283	1.47	22.4	2.3
	0.5	310	1.45	12.1	2.2
	0.6	320	1.43	5.4	2.1
	0.8	320	1.55	3.1	2.0
0.1	0.4	220	2.94	71.8	4.4
	0.6	288	2.32	23.3	4.0
	0.8	300	2.28	19.7	3.8
	1	310	2.13	16.2	3.5
	1.2	310	1.98	15.3	3.4
0.15	0.4	195	3.97	112.2	5.0
	0.5	235	3.3	64.6	5.1
	1.0	270	3.08	39.5	4.8
	2.0	278	2.8	29.6	4.8
	3.0	290	2.81	25.1	4.3
	5	295	2.76	21.5	3.9

* The test results were used for analysing the relationship between the fresh properties for mortar

Appendix 12 Test results for Welan gum and superplasticizer compatibility

Table A12-1 Welan gum/superplasticzer compatibility in terms of initial fresh properties* (table 9-1, figure 9-6 & 7)

The mix proportion: w/c=0.35 V_s/V_m=0.45, WG=0.05%

types of superplasticizer	sp dosage (%)	welan gum (%)	D_m (mm)	T_v (secs)	τ_0 (Pa)	μ (Pa.s)
conplast430	0.47	0	309	1.56	12.8	2.7
		0.025	295	2.1	22.9	3.6
		0.05	266	2.78	40.5	4.4
		0.075	231	3.61	66.1	5.8
		0.1	215	4.7	95.2	6.7
conplastM1	0.65	0	313	1.71	11.5	3.0
		0.025	295	2.08	21.2	3.9
		0.05	268	2.67	44.1	4.9
		0.075	225	4.2	92.5	6.1
		0.1	220	4.31	94.8	6.5
darcem2001	0.52	0	310	1.64	11.5	3.0
		0.025	290	2.44	28.2	4.0
		0.05	268	2.97	37.9	5.0
		0.075	225	4	66.1	6.1
		0.1	203	5.12	88.1	6.8
sika 10	0.19	0	313	1.85	12.3	3.5
		0.025	290	2.2	28.2	4.2
		0.05	238	2.44	64.3	4.0
		0.075	115		277.6	6.1
		0.1			0.0	0.0
glenium51	0.11	0	313	1.9	10.6	3.4
		0.025	265	2.71	37.0	4.5
		0.05	214	3.86	69.6	5.8
		0.075	182	4.91	101.4	5.8
		0.1	155	6.14	127.8	6.3

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A12-2 Welan gum/superplasticzer compatibility in terms of workability retention*
(table 9-2, figure 9-9)

The mix proportion: w/c=0.35 V_s/V_m=0.45, WG=0.05%

types of superplasticizer	sp dosage (%)	time (mins)	D_m (mm)	T_v (secs)	τ_0 (Pa s)	μ (Pa)
		10	315	2.08	11.7	3.5
		30	313	2.5	14.4	4.6
conplast430	0.7	60	298	2.87	22.4	5.5
		90	275	3.31	42.2	7.1
		120	238	4.07	78.5	8.0
		10	311	2.34	12.6	4.1
		30	302	2.7	17.9	5.1
conplastM1	1.1	60	276	3.13	30.5	6.1
		90	255	3.79	44.9	7.7
		120	233	4.67	69.5	8.9
		10	313	2.53	17.9	4.8
		30	260	3.3	44.0	6.0
darcem2001	0.7	60	226	4.27	67.3	7.1
		90	205	4.97	96.5	8.0
		120	195	5.99	116.6	9.0

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A12-3 Welan gum/superplasticzer compatibility in terms of strength development
(figure 9-11)

The mix proportion: w/c=0.35 V_s/V_m=0.45, WG=0.05%

conplast430, sp=0.7%			conplastM1, sp=1.1%			dracem2001,sp= 0.7%		
ages (days)	strength (MPa)	load (kN)	ages (days)	strength (MPa)	load (kN)	ages (days)	strength (MPa)	load (kN)
1	**24.6**	61.5	**1**	**19.4**	48.6	**1**	**0.0**	0
3	**47.8**	119.4	**3**	**43.4**	108.6	**3**	**41.8**	104.5
7	**59.2**	148.1	**7**	**51.3**	128.2	**7**	**50.6**	126.6
14	**67.3**	168.3	**14**	**57.8**	144.6	**14**	**54.7**	136.8
28	**72.4**	181.1	**28**	**62.3**	155.7	**28**	**67.3**	168.2

Table A12-4 Welan gum/superplasticzer compatibility in terms of setting time (figure 9-10)

The mix proportion: w/c=0.35 V_s/V_m=0.45, WG=0.05%

setting time	conplast430	conplastM1	darcem2001
initial	7.7	9.2	23.0
final	9.7	11.3	26.4

Appendix 13 Test results of the effect of Welan gum on the properties of the mixes with single type of powder

Table A13-1 Workability retention of Welan gum mortars with single type of powder*

(table 9-4, figure 9-12 & 13)

The mix proportion: w/c=0.35 V_s/V_m=0.45, Conplast430 was used and the dosage was adjusted to achieve 300-310 mm spread for mortar

types of cement	Welan gum dose. (%)*	sp dose. (%)**	time (mins)	D_m (mm)	T_V (secs)	T_{250} (secs)	τ_0 (Pa)	μ (Pa.s)
PC2	0	0.45	10	300	1.49		13.9	2.5
			30	268	1.7		28.7	3.0
			60	225	1.94		50.2	4.0
			90	188	2.42		98.7	5.6
			120	156	3.1		168.2	8.6
	0.025	0.5	10	309	1.6	2.17	11.7	3.0
			30	298	1.9	3.02	25.1	3.6
			60	260	2.1		39.5	4.3
			90	215	2.7		71.8	5.6
			120	180	3.34		132.4	7.3
	0.05	0.7	10	315	2.08		11.7	3.5
			30	313	2.5		14.4	4.6
			60	298	2.87		22.4	5.5
			90	275	3.31		42.2	7.1
			120	238	4.07		78.5	8.0
	0.075	1	10	301	2.8	7.6	19.7	5.5
			30	300	3.1	7.9	25.1	5.8
			60	285	3.54		37.7	6.8
			90	268	3.98		44.9	8.2
			120	245	4.64		67.3	9.0
	0.1	1.6	10	304	2.88	8.27	25.1	4.6
			30	298	3.2	11.1	26.9	5.6
			60	283	3.78		37.7	6.4
			90	273	4.15		44.9	7.5
			120	257	4.77		62.8	8.4
SRC1	0.05	0.6	10	313	2.14	3.46	14.4	3.5
			30	292	2.6	5.63	21.5	4.4
			60	261	3.1		40.4	4.9
			90	220	3.77		62.8	5.9
			120	170	4.39		94.2	6.7

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A13-2 Strength development of Welan gum mortar with single types of powder (figure 9-15)

The mix proportion: w/c=0.35 V_s/V_m=0.45

types of cement	Welan gum dosage (%)					
	PC2					SRC1
	0	0.025	0.05	0.075	0.01	0.05
ages (days)	compressive strength (MPa)					
1	28.3	27.68	24.6	19	11.6	20
3	51.2	52.8	47.8	43	40.9	43.4
7	61.2	63.92	59.2	55	49.2	53.16
14	71.4	70.96	67.3	60	55.2	67.32
28	76.6	76.04	72.4	68	60.9	67.88

Table A13-3 Setting times of Welan gum mortar with single types of powder (figure 9-14)

The mix proportion: w/c=0.35 V_s/V_m=0.45

setting time	welan gum dosage (%)					
types of cement	PC2					SRC1
(hours)	0	0.025	0.05	0.075	0.1	0.05
sp (%)	0.45	0.50	0.70	1.00	1.60	0.60
initial	5.5	5.8	7.7	9.6	12.5	8.0
final	6.8	6.9	9.7	11.3	14.6	9.4

Table A13-4 The effect of Welan gum dosage on the properties of concrete and mortar mixes with single type of powder (table 9-5, figures 9-16~20)

Mix proportion: 100% PC4, w/c =0.35 by weight, V_s/V_m = 0.45, C.A. = 0.317 m^3 per cubic meter

Properties*				Slump flow			V-funnel		Two-point test			U-box test			Compres. strength		mortar test					
types of cement	Mix No.	WG	Sp (%)	Time^ (mins)	SF (mm)	T_{500} (s)	time (mins)	T_V (s)	time (mins)	τ_0 (Pa)	η (Pa.s)	time (mins)	$T_{U\text{-}box}$ (s)	H (mm)	age	(MPa)	time (secs)	D_m (mm)	T_{250} (secs)	T_V (s)	τ_0 (Pa)	η (Pa.s)
PC4	C9-5	0	0.5	9	670	1.41	8	3.81	8	-40	39	17	1.67	316	1	40.1	10	313	2	1.94	12.0	2.9
				34	492		32	5.34							7	61.3	30	290	2.78	2.35	24.2	4.0
				63	370		62	5.06	61	52	52				28	74.4	60	246		2.78	46.9	5.4
																	90	203		3.4	74.2	6.6
	C9-6	0.05	0.75	12	740	1.72	11	4.35	10	-26	58	17	1.47	334	1	34.5	10	313	3.88	2.91	17.3	4.9
				32	688	2.5	31	4.91							7	58.4	30	294	5.79	3.37	27.0	5.7
				62	638	3.81	61	7.09	60	13.1	59	68	3.4	322	28	67.7	60	277	9.65	4	41.1	6.7
				92	535	10.09	91	8.53									90	247		4.62	59.9	8.5
				122	495	9.75	121	15.03	120	130	110						120	217		5.68		
	C9-7	0.075	1.2	13	698	2.87	12	5.69	11	-17	71	20	2.13	328	1	29.3	10	301	6.34	3.38	26.2	6.3
				32	660	4.25	31	8.29							7	61.8	30	292	9.06	4.37	33.7	7.5
				63	635	4.92	62	10.56	61	134	83	70	4.84	312	28	65	60	278		4.88	48.5	9.0
				92	530	20.44	91	14.53									90	253		5.81	61.2	10.7
				121	498	12.85	121	26.09	121	241	163						120	231		7.1	87.4	12.8
SRC2	C9-8	0.075	1.0	14	753	1.28	13	3.31	11	-12	26	20	1.69	336	1	30.1	10	318	2.78	2.46	11.0	3.3
				33	723	1.69	32	4.63							7	52.1	30	316	3.75	2.53	14.1	4.2
				63	645	3.5	62	6	61	-30	67	73	2.81	320	28	67.3	60	303	5.18	3	21.8	4.6
				95	610	4.04	93	7.62									90	286	8.5	3.44	30.8	5.6
				123	472		122	16.19	120	58	93						120	267		3.88	43.2	6.7

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete and mortar

^: Time after mixingTest results for the effect of Welan gum on the properties of mixes with binary blends of powder

Table A13-5 Workability retention of Welan gum binary mortar mixes* (table 9-6, figure 9-21)

The mix proportion: V_w/V_p=1.10 V_s/V_m=0.45, WG = 0.05% by weight of water

types of powder	sp (%)	time (mins)	D_m (mm)	T_{250} (secs)	T_V (secs)	τ_0 (Pa)	μ (Pa.s)
100%PC	0.7	10	315	2.84	2.08	11.5	3.4
		30	313	4.31	2.5	14.1	4.5
		60	298		2.87	22.0	5.4
		90	275		3.31	41.4	6.9
		120	238		4.07	77.1	7.8
pc/ggbs=60/40	0.55	10	310	3.94	2.38	10.6	4.2
		30	294	5.1	2.8	21.2	5.1
		60	255		3.52	48.5	6.3
		90	210		4.54	100.5	7.4
		120	160		7.09	165.3	8.9
pc/pfa=60/40	0.46	10	312	2.82	1.78	12.3	2.7
		30	285	4.07	2.1	23.8	3.3
		60	245		2.41	51.1	4.1
		90	195		3.09	86.4	5.1
		120	161		3.92	119.0	5.2
pc/lsp=60/40	0.42	10	300		1.88	15.9	3.0
		30	268		2.2	30.8	3.8
		60	205		2.84	83.7	4.3
		90	162		3.95	123.4	5.2
		120	133		4.46	171.9	6.4
pc/csf=90/10	0.8	10	308		1.24	13.2	1.4
		30	295		1.3	17.6	1.8
		60	264		1.4	29.1	2.2
		90	233		1.74	44.1	2.8
		120	208		2.01	59.1	3.2

* The test results were used for analysing the relationship between the fresh properties for mortar

Table A13-6 Strength development of Welan gum binary mortar mixes (figure 9-22)

The mix proportion: w/c=0.35 V_s/V_m=0.45, WG = 0.05% by weight of water

types of powder	100%PC	pc/ggbs=60/40	pc/pfa=60/40	pc/lsp=60/40	pc/csf=90/10
sp dosage (%)	0.7	0.55	0.46	0.42	0.8
ages (days)			strength development (MPa)		
1	24.6	11.08	9.6	10.2	25.36
3	47.8	36.96	24.2	24.1	44.04
7	59.2	53.88	29.0	29.1	61.76
14	67.3	68.64	37.6	36.0	64.68
28	72.4	76.2	50.2	37.8	74.72

Table A13-7 Setting time of Welan gum binary mortar mixes (figure 9-22)

The mix proportion: w/c=0.35 V_s/V_m=0.45, WG = 0.05% by weight of water

	types of powder	100%PC	PC/GGBS=60/40	PC/PFA=60/40	PC/LSP100=60/40	PC/CSF=90/10
	sp dosage (%)	0.7	0.55	0.46	0.42	0.8
setting time (hours)	initial	7.7	7.3	8.0	6.8	6.4
	final	9.7	9.3	10.0	8.8	7.9

Table A13-8 Properties of Welan gum binary concrete and mortar mixes (table 9-7, figures 9-23~26)

Mix proportion: Vw/Vp=1.10, V_s/V_m = 0.45, C.A. = 0.317 m^3 per cubic meter, Conplast430 was used and the dosage was obtained by repeating the spread test on mortar component

Properties*				Slump flow			V-funnel		Two-point test			U-box test			compres. strength		mortar test					
Mix No.	types of powder	WG (%)	Sp (%)	Time^ (mins)	SF (mm)	T_{500} (s)	time (mins)	T_V (s)	time (mins)	τ_0 (Pa)	η (Pa.s)	time (mins)	$T_{U\text{-}box}$ (s)	H (mm)	age	(MPa)	time (secs)	D_m (mm)	T_{250} (secs)	T_V (s)	τ_0 (Pa)	η (Pa.s)
C9-9	PC/GGBS=60/40			14	755	2.49	12	6.95	11	-155	121	20	2.32	325	1	13.2	10	318	4.29	3.34	11.7	5.4
				33	698	3.26	32	8.81							7	54.3	30	306	5.5	5.14	19.2	7.2
		0.075	0.9	65	560	6.12	64	11.75	62	7.7	146	71	5.69	302	28	65.2	60	282	7.13	5.89	34.0	10.2
				93	425		92	19.2									90	256		7.02	61.2	11.8
C9-10	PC/CSF=90/10			13	750	1.03	12	2.5	11	-40	36	24	1.22	327	1	30.7	10	320	2.19	1.72	13.7	2.6
				34	675	2.19	32	3.47							7	66.3	30	316	2.94	2.39	19.2	3.3
		0.075	1.3	63	643		62	4.25	61	-26	60	68	1.9	320	28	90.3	60	300	4.94	2.69	25.1	3.7
				93	555		91	6.59									90	288	5.84	2.86	33.1	4.5
				122	490		121	8.87	120	-60	120						120	277	9.31	3.25	42.6	5.4

*: The fresh property test results were used for analysing the relationship between properties of concrete and mortar, between the properties for concrete and mortar

^: Time after mixing

Appendix 14 Test results for rheological models for mortar

Table A14-1 Effect of segregation (figure 10-1)

Mix proportion: 100% PC, w/c = 0.3, V_s/V_m = 0.45, Viscocrete = 0.6% of PC

shear rate (1/s)	shear stress (Pa)
0.5146	1.79
0.73704	2.69
1.0541	3.59
1.5106	4.94
2.16132	7.18
3.09424	10.77
4.4322	16.15
6.3412	23.33
9.0802	34.10
12.9812	52.49
18.592	78.96

Table A14-2 Effect of GGBS content (table 10-1, figure 10-2)

average shear rate (1/s) \ sp (%)	shear stress (Pa)				
	opc 100	opc/ggbs 80/20	opc/ggbs 60/40	opc/ggbs 40/60	opc/ggbs 20/80
	0.145	0.115	0.1	0.09	0.08
2.16132	14.95	18.84	16.15	30.06	
3.09424	22.12	26.47	21.54	39.48	71.78
4.4322	31.10	36.79	30.51	49.35	91.97
6.3412	43.66	51.15	42.17	68.19	121.14
9.0802	62.50	69.99	61.02	95.11	166.00
12.9812	88.52	97.81	89.73	136.39	246.76
18.592	129.80	141.77	136.84	217.15	399.30

Mix proportions: Vw/Vp = 0.945, Vs/Vm = 0.45, Glenium51 was used.

Table A14-3 Shear thinning property of CSF binary mix (figure 10-4)

Mix proportion: mix: M7-1 and M7-13

average shear rate (1/s)	shear stress (Pa) opc 100%	opc/csf 85/15
2.16132	25.12	14.36
3.09424	32.30	18.84
4.4322	44.42	25.12
6.3412	59.22	31.41
9.0802	80.76	41.28
12.9812	111.71	53.39
18.592	157.03	70.44

Table A14-4 Effect of viscocrete (figure 10-5)

Mix proportion: 100% PC, w/c = 0.3, V_s/V_m = 0.45

sp (%) / average shear rate (1/s)	shear stress (Pa)		
	glenium51 0.15	conplast430 0.6	viscocorete 0.33
2.16132	25.12	24.68	26.02
3.09424	32.30	30.51	34.10
4.43220	44.42	39.93	44.86
6.34120	59.22	52.04	59.22
9.08020	80.76	69.99	78.06
12.98120	111.71	96.46	102.29
18.59200	157.03	132.35	139.08

Table A14-5 Effect of Welan gum (figure 10-6)

Mix proportion: 100% PC, w/c = 0.35, V_s/V_m = 0.45, Conplast430 was used and the dosage was adjusted to achieve 305 mm spread

average shear rate (1/s)	shear stress (Pa)		
	welan gum (%)		
	0	0.05	0.1
2.16132	16.60	19.74	25.12
3.09424	19.74	26.02	33.20
4.4322	24.45	33.65	41.28
6.3412	30.51	43.07	52.04
9.0802	38.14	57.43	68.19
12.9812	48.90	75.82	86.14
18.592	63.71	102.29	110.37