UNIVERSITÉ DE
SHERBROOKE

Faculté de génie
Département de génie civil

EFFECT OF VARIOUS CHEMICAL ADMIXTURES AND BINDER COMBINATIONS ON WORKABILITY OF HIGH-PERFORMANCE, SELF-CONSOLIDATING CONCRETE USED IN REPAIR

Mémoire de maîtrise ès ciences appliqués
Spécialité: genie civil

Daniel MAYEN

Sherbrooke (Québec), Canada **January 2005**

ACKNOWLEDGEMENT

I would like to thank Prof. Kamal H. Khayat for his support and guidance throughout this research. His trust, knowledge, and friendship are highly appreciated. Special thanks to the professors in the Cement and Concrete Group: Profs. Pierre Claude Aïtcin, Richard Gagné, and Arezki Tagnit-Hamou. I would like to thank Olivier Bonneau and Soo-Duck Hwang for their technical advice and friendship. To my fellow students Arsenio Gonzales, Alejandro Alvarez, Alma Reyes, and Joseph Assaad thanks for their time and help. To Mrs. Christine Couture for her corrections. Special thanks to the technicians in the Cement and Concrete group: Ghislaine, Sylvain, Denis, Claude, Rajko, and Jean Yve.

L'effet des différentes combinaisons d'adjuvants chimiques et liants sur la maniabilité des bétons autoplaçants à haute performance destinés aux réparations

RÉSUMÉ

Il est bien connu que l'hiver québécois est particulièrement agressif pour les ouvrages en béton. Les organismes publics doivent de plus en plus compter avec des travaux de réfection afin de réparer les structures existantes pour en prolonger la durée de vie. Le but de cette recherche est de développer un béton autoplaçant destiné aux travaux de réparation qui puisse faciliter la construction d'ouvrages minces et fortement renforcés. Cinq différents adjuvants et quatre différents liants hydrauliques ont eté utilisés pour la fabrication d'un tel béton autoplaçant. Deux différentes approches ont eté utilisées : l'une avec un faible rapport eau/liant sans agent colloïdal et l'autre avec un rapport eau/liant moderé avec agent colloïdal. La stabilité dynamique, la stabilité statique et les paramètres rhéologiques ont eté mesurés lors des différents essais. Les propriétés du béton autoplaçant incluaient un étalement de 660 ± 20 mm et une stabilité statique limitée à une valeur maximale de 0,5%, mesurée avec une colonne de tassement de 700 mm. Des fibres ont été incorporées au béton auto-plaçant et ses propriétés ont été améliorées jusqu'à un étalement de 700 ± 20 mm.

Effect of various chemical admixture and binder combinations on workability of high-performance self-consolidating concrete used in repair applications

SUMMARY

It is well known that the winter in Quebec is particularly harsh and poses high demand on concrete performance, especially that used in infrastructure applications. Government agencies, in charge of repair and rehabilitation of such infrastructure, must work to restore the concrete and to extend the lifetime of structures. The objective of this research is to develop high-performance, self-consolidating concrete intended for repair applications that will facilitate the casting of slim and highly reinforced sections while ensuring adequate durability and service life. The performance of fresh concrete made with several chemical admixture and hydraulic binder combinations has been evaluated. In total, five different brands of admixtures along with four binder types were used in this investigation. Two different approaches were used in proportioning the concrete to ensure proper stability: the use of low water-cementitious ratio, or the use of a moderate water-cementitious ratio (w/cm) with a Viscosity-Enhancing Agent (VEA) to enhance cohesiveness. Optimized mixtures were assessed for key workability characteristics, including: static stability, dynamic stability, and rheological parameters. The mixtures had initial slump flow of 660 ± 20 mm and maximum surface settlement of 0.5%. Some mixtures were made with synthetic fibres and initial slump flow of 700 ± 20 mm.

TABLE OF CONTENTS

LIST OF FIGURES

INDEX OF TABLES

Chapter 1

INTRODUCTION

Since the prototype of self-consolidating concrete (SCC) was achieved at the University of Tokyo in 1989, the interest of different research centres and private companies has grown. Countries like Japan, Sweden, Iceland, France, USA, and Canada are using this new technology in several types of construction and pre-cast applications.

Different specifications have been written to regulate the use of this new material, including: provisional recommendations of the French Association of Civil Engineering, recommendations for use of self-consolidating concrete of the Swedish Concrete Association, state-of-the-art report of the technical committee 174-SCC of RILEM, recommendations for the construction with SCC of the Japan Society of Civil Engineering and the Japanese Society of Architecture, recommendations of the Quebec Transport Minister, recommendations of the American Concrete Institute (ACI) technical committee 237, Precast/Prestressed Concrete Institute (PCI), the American Standard of Testing Materials (ASTM), the European Federation of Chemicals in Construction (EFNARC), etc.

SCC has been used in different applications for various reasons. In the pre-cast industry, SCC has been used because it improves the working environment by reducing significantly noise from vibration and placement time and effort. SCC has also been used in the construction of cast-in-place structural elements, including those presenting high density of reinforcement and elements with complex sections.

However, one of the most important and promising fields for use of SCC in Canada remains the repair and rehabilitation of the infrastructure. High density of reinforcement, difficult access to vibration of relatively slim sections, as well as requirements for good aesthetic finish necessitate the use of high-performance material capable of filling all the voids in the formwork, encapsulate the reinforcement, facilitate casting operations, and ensure the desired performance characteristics.

Since 1997, the Ministère des Transport du Quebec has used SCC on some projects to repair the bridge and highway infrastructure. In 2000, the City of Montreal started to use SCC in repair. In order to produce a material that will enhance and extend the service life of damaged structures, full knowledge of the components of this material and its performance is required. This includes knowledge of the influence of binder and admixture type and combination on fresh and hardened properties, that are the main focus of this thesis.

Different binders and chemical admixtures used in SCC that are commercially available in Quebec were employed in this research to produce high-performance repair materials. The fresh properties of these concretes were investigated and compared to better understand the effect of each compound on the self-consolidating properties, including static and dynamic stability, workability characteristics, and rheological parameters.

Chapter 1 addresses some of the recommendations for using SCC around the world. Perspective of using SCC in repair applications is also discussed.

In Chapter 2, literature review is undertaken. Properties of SCC at the fresh state are discussed along with some classifications. The rheological behavior of SCC is one of the most important parameters governing workability and stability. The effect of different parameters on the rheological properties of SCC is discussed.

Chapter 3 reviews some of the advantages of SCC. It presents some repair case studies and discusses some of the specifications employed when using SCC in repair.

In Chapter 4, the outline of the research project is presented with description of the methodology employed, materials, mixing procedure, and adopted test methods. The results of a preliminary research are discussed in Chapter 5. In general, the study aimed at developing two reference SCC mixtures for comparing the influence of various binder and admixture materials on SCC performance. Two classes of SCC mixtures were developed to ensure proper stability; the first with a low water-to-cementitious material ratio (w/cm) of 0.35 to reduce free water content and enhance cohesiveness provide stability, while the second had moderate w/cm of 0.42 and included the use of viscosity-enhancing admixture (VEA) to increase stability.

The main body of the research is presented in Chapter 6. The project is divided in two Phases. In Phase I, the main objective was to compare the approaches adopted to achieve self-consolidating properties using different brands of commercially available admixtures. The performance of several mixtures made with either 0.35 w/cm and no VEA were compared to that of similar mixtures with 0.42 w/cm and VEA. In Phase II, a parametric study was carried out in which the influence of different binder and admixture combinations was investigated.

In Chapter 7, a study undertaken to develop a fibre-SCC mixture is presented. Two main factors are varied: the fibre dosage and the sand-to-total aggregate ratio. Fresh state properties are assessed and compared to better understand the performance of these fibers in repair SCC. Finally in Chapter 8 conclusions are presented, and future studies are suggested.

Trial batches carried out to optimize the SCC mixtures in Phase I are presented in Appendix I. The rheological data from the IBB rheometer used to determine the apparent yield value and torque plastic viscosity are presented in Appendix II. The settlement results and the procedure employed to calibrate the concrete rheometer are given in Appendix III and IV, respectively.

Chapter 2

LITERATURE REVIEW ON SCC

2.1 Properties and Characteristics of SCC

Self-consolidating concrete (SCC) is a new category of high-performance concrete that has the ability to flow readily into place and fill a given formwork without any mechanical consolidation. An important characteristic of SCC is the non-segregation of the coarse aggregate and the lack of bleed water. These two characteristics are essential and contribute to the overall stability of the mixture.

The three main functional requirements of fresh SCC are good filling ability, proper resistance to segregation, and high passing ability (Skarendahl and Petersson, 2001). These requirements are needed to ensure that the concrete can readily flow around various obstacles, completely fill formwork, and properly encapsulate the reinforcement.

SCC is a product of technological advancements in the area of underwater concrete technology where the mixture is proportioned to ensure high fluidity and yet high resistance to water dilution and segregation (Khayat, 1999). SCC was first conceived to produce high-performance concrete that can be cast into place without the need for consolidation. This was due to the lack of skilled Japanese workers and the concern of structural durability when concrete was not properly consolidated.

An obvious advantage of SCC over conventional concrete is the reduction in the number of workers necessary for placing concrete. Given the fact that there is no vibration, better work environment can result when using SCC. Also, the so-called "white finger" effect caused by manipulating the vibrator can be avoided when using SCC. Another advantage to the use of SCC is the reduction in cost and construction time. With no vibration requirement the work of casting concrete is considerably facilitated, and new casting techniques can be developed and optimized given the high fluidity of the concrete. Since one of the most important characteristics of SCC is its high stability despite the high flowability, casting deep sections can be accelerated by decreasing the number of lifts (Khayat, 1999, Skarendahl and Petersson, 2001).

Casting hard-to-reach areas or densely reinforced members is difficult with conventional concrete; the use of SCC facilitates such construction processes and allows for proper quality assurance. The casting of concrete for repair and rehabilitation applications, involving relatively thin structural sections, is also facilitated when using SCC (Khayat, 1999).

2.1.1 Required Fresh Properties of SCC

Three parameters are essential to describe the workability of SCC (Khayat, 1999; Skarendahl and Petersson, 2001):

A) Filling ability: This means the complete filling of the formwork and encapsulation of reinforcement with a homogeneous concrete. Substantial horizontal and vertical movements of the concrete within the formwork are allowed using the inherent flow properties of the material.

SCC must be able to deform or change its shape readily under its self-weight. As mentioned, the meaning of the filling ability includes high deformability in terms of how far from the discharge point the concrete can spread, and high rate of deformability that describes the speed by which concrete could flow.

In order to achieve good filling ability, the concrete must attain the following properties:

- *Small inter-particle friction*: To make the concrete deform well, it is beneficial to reduce friction between the various solid particles, which includes coarse aggregate, sand and powder materials. Such solid-to-solid friction increases the internal resistance to flow, thus limiting the deformability and the speed of deformability of the fresh concrete.

In order to reduce aggregate-aggregate friction, it is necessary to reduce the possibility of aggregate inter-particle contact. One way to achieve this is to increase the inter-particle distance by reducing the coarse aggregate and sand volume, and increase the paste volume to enhance deformability. The incorporation of continuously graded cementitious materials and fillers can also reduce inter-particle friction. It is important to note that the selection of proper combinations of binary or ternary binders should take into account the effect of the powder material on the adsorption of water and admixtures, workability loss and temperature rise, as well as the development of engineering properties and durability.

- *Paste with excellent deformability*: to secure proper self-consolidating characteristics, the cement paste has to deform well to achieve low yield value and moderate viscosity. A highly deformable cement paste will give the SCC the ability to flow readily around various obstacles and achieve good filling capacity (Skarendahl and Petersson, 2001).

The reduction of the water-to-powder ratio (w/p) can limit the deformability of the cement paste. The deformability of concrete is closely related to the deformability of the paste and can be increased by incorporating High Range Water Reducer Admixtures (HRWRA). The use of HRWRA reduces mostly the yield value and causes a limited decrease in viscosity. Unlike the addition of water that reduces both the yield value and plastic viscosity, the incorporation of a HRWRA lowers mostly the yield value of the concrete (better flowability). Such addition results in limited drop in viscosity, until a certain dosage. Therefore, highly flowable concrete can be obtained without significant reduction in viscosity and cohesiveness.

B) Resistance to segregation: this characteristic refers to the ability of fresh concrete to maintain homogeneity during all steps before its final placement and thereafter until the onset of hardening. Segregation of fresh concrete is characterized by inhomogeneity in the distribution of constituent materials, which in turn causes a distribution of properties within the structure.

In a highly stable concrete, none of the following behaviours should be observed (Skarendahl and Petersson, 2001):

- bleeding of water at the surface;
- paste and aggregate segregation;
- coarse aggregate segregation leading to blockage, or
- non-uniformity in air-pore distribution.

It is important to note that adequate stability must be attained in stationary and flowing states; static and dynamic stability respectively. A highly flowable concrete exhibiting adequate stability may undergo some segregation during the pumping or spread into place. This is because the apparent viscosity at such shear rates can be significantly lower than that at rest because of the pseudo-plastic behaviour of the concrete (Skarendahl et al., 2001).

In order to reduce segregation, coarse aggregate content should be reduced, and the maximum size aggregate (MSA) should be small. It is also important to increase cohesion of the mixture to enhance bond between the mortar and coarse aggregate, hence providing enough cohesion to ensure uniform flow of both phases (Khayat, 1999).

In order to avoid segregation between the water and solid phases, it is essential to reduce the amount of movable free water in the mixture. Movable free water is defined as the water, which is not adhered with solid particles and can move independently from the solid phase of the mixture. The method to reduce the amount of movable water can be using low water content. It is also possible to use powder materials with high surface area in order to retain additional water onto the solid particle surface. The segregation resistance between water and solid can also be improved by increasing the viscosity of the water through the use of a viscosity-enhancing agent (VEA) (Khayat, 1999).

C) Passing ability: this is define as the ability of the concrete to pass through narrow sections in the formwork and closely spaced reinforcing bars without blockage due to the interlocking of aggregate particles (Skarendahl and Petersson, 2001). The mechanism of blocking can be explained by using a two-dimensionally illustrative model of concrete flowing through an opening, as shown in Fig. 2.1.

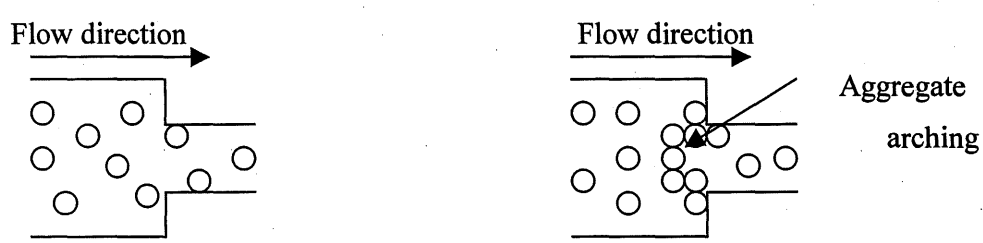


Fig. 2.1 Mechanism of blocking (Skarendahl and Petersson, 2001)

In order to flow readily through an opening, aggregate particles around the opening have to change their flow path. As a result, collision among aggregate particle arises creating many instantaneous contacts among the aggregate particles at the vicinity of the opening. By theses aggregate contacts, there is a possibility that some aggregate particles form a stable arch, which block the rest of the flow of the concrete. The arching is developed easier when the size of aggregate is large and also the content is high. For smaller aggregates, arching occurs at the higher content of aggregate, however, arching cannot occur if the solid particles are too small when compared to the dimension of the opening (Skarendahl and Petersson, 2001).

In order to prevent blockage when concrete flows among closely spaced obstacles, the mortar should have adequate cohesiveness. This is achieved by reducing the water to powder ratio and/or incorporating an adequate dosage of a VEA. As the clear spacing between the obstacles in the congested section decreases, the coarse aggregate volume and MSA should be reduced to limit the inter-particle collision in the vicinity of reinforcement and hence the risk of blockage (Skarendahl and Petersson, 2001).

It is important to note that the three workability properties of SCC (filling ability, segregation resistance and passing ability) are not independent but rather interrelated and must be satisfied consequently to achieve self-consolidation.

2.1.2 Classification of SCC Mixtures

According to the Japan Society of Civil Engineers, there are three different types of SCC depending on the method used to obtain self-consolidating properties (JSCE, 1996):

Powder-type SCC in this case, it is proportioned to provide the required self-consolidating properties not by using a VEA, but primarily by reducing the water-powder ratio (in effect increasing the powder content) to impart adequate segregation resistance and using an air-entraining and HRWRA to develop high deformability.

Viscosity agent-type SCC it is proportioned to provide the required self-consolidating properties by the use of a VEA to impart segregation resistance, also to incorporate HRWRA to provide high deformability of the fresh concrete.

Combination-type SCC it is proportioned to provide the required self-compactibility primarily by reducing the water-powder ratio (in effect increasing the powder content) to enhance segregation resistance and HRWRA to ensure high deformability. VEA is incorporated, typically at low dosage rate in this case, to enhance the robustness of the mixture.

2.1.3 Stability of SCC

The stability of fresh concrete describes its ability to resist **bleeding, surface settlement** and **segregation**; and depends on the cohesiveness and viscosity of the mixture (Khayat et al., 2000).

A lack of stability can cause anisotropy in the direction of casting and weaken the interface between the aggregate and cement paste, hence increasing the tendency to develop micro-cracking in such regions (Khayat and Guizani, 1997). Also, the quality of the interface between the cement paste and the reinforcing steel can be deteriorated. All this can affect the durability of concrete and decrease its strength and impermeability.

As summarized by Khayat (1999) **stability** can be divided in two parts: **dynamic** stability that occurs when the concrete is being cast into the formwork and spreading through the reinforcement, and **static** stability which is important once concrete has already being cast into the formwork and still in a plastic state.

Dynamic stability can be assessed by observing the passing ability, blocking resistance and filling capacity of the concrete. Instability occurs when highly flowable concrete undergoes some segregation while casting given high shear rates at the vicinity of various obstacles, such as reinforcing bars. As stated earlier, appropriate viscosity is necessary to avoid separation of the various constituent materials of fresh concrete to ensure high stability. Proper achievement of dynamic stability requires the reduction of the volume of coarse aggregate and decrease of MSA. Also, cohesion of the mixture should be enhanced to improve cohesion between the aggregate and mortar, hence ensuring uniform and homogeneous flow of both phases (Khayat, 1999).

The **static stability** refers to the resistance to segregation, bleeding, and surface settlement of fresh concrete after the casting in the formwork and before setting. Well proportioned SCC can maintain homogeneous distribution of the various phases while in a plastic state, which is important to ensure uniform in-place mechanical and transport properties of the hardened concrete.

Segregation occurs when the constituents of the mixture are separated at the fresh state. In dry mixtures, the mortar is separated from coarse aggregate; this occurs especially when the concrete is over-vibrated.

In wet mixtures, **bleeding** occurs, which is a form of segregation in which some of the free water separated from the mixture tends to rise to the top surface. Bleeding is caused by the inability of solid constituents and various polymeric admixtures in the mixture to hold all of the mixing water (Neville 1996). When the bleed water reaches the surface, it is referred to as **external bleeding**. However, in some cases water is trapped at the bottom of coarse aggregate, in bleed channels, under horizontal reinforcement, or even under the ribs of vertical reinforcement, and is then referred to as **internal bleeding** (Mehta and Monteiro, 1993). Both types of bleedings are represented in Fig. 2.2.

If all bleed water rises to the surface in a uniform way and it is collected from the surface, bleeding could reduce the water-to-cementitious materials ratio (w/cm) (Mehta and Monteiro, 1993). Unfortunately, this does not occur in practice, and bleeding should be minimized.

Water rising to the surface can carry with it fine particles, such as cementitious materials, sand, and clay particles found as impurity in the aggregate. This forms an outer layer at the concrete surface that is very porous and is referred to as **laitance**. **Laitance** will decrease the durability and wear resistance of the concrete surface and bond between two successively cast concrete lifts. If the concrete surface is the top of an intermediate layer and will receive another layer, it is necessary to remove laitance, to enhance bonding between the two layers. Some of the factors affecting bleeding are (Neville 1996):

Fineness of cement if the cement is fine, bleeding can decrease. Since fine cement grains can hydrate faster, hence reducing the free water content.

C_3A content of cement when a cement with high C_3A is used, concrete is less prone to bleed.

Fine aggregate adequate proportion of very fine aggregate particles (smaller than 150 μm) can significantly reduce bleeding.

Use of pozzolans and fillers depending of the use of these materials (as supplementary or replacement cementitious materials) bleeding could be decreased.

Entrained air it can effectively reduce bleeding.

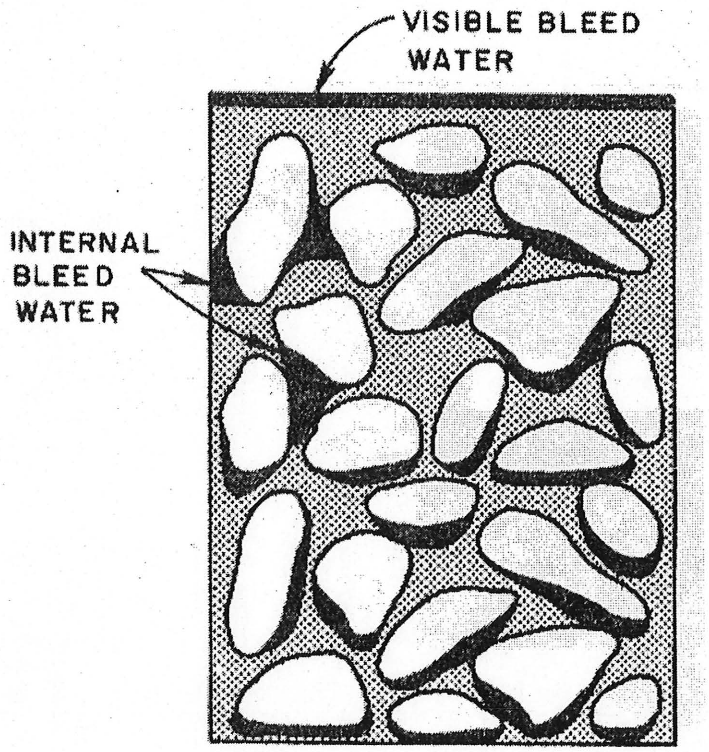


Fig. 2.2 Internal and external bleeding of concrete (Mehta and Monteiro, 1993)

Surface settlement occurs in fresh concrete when heavy particles sink towards the bottom of the cast section due to difference in unit weight from the rest of the matrix (consolidation). Likewise, the lightest materials (air and water in normal weight concrete) have the tendency to rise towards the surface.When hydration products are formed, they take less space than cement and water causing a chemical contraction (Le Chatelier). In reinforced concrete, steel and formwork walls are obstacles that can cause difference in settlement, therefore originating cracks. Settlement cracking can also occur over the top reinforcement when the concrete cover is limited. Settlement induced cracking is represented in Fig. 2.3.

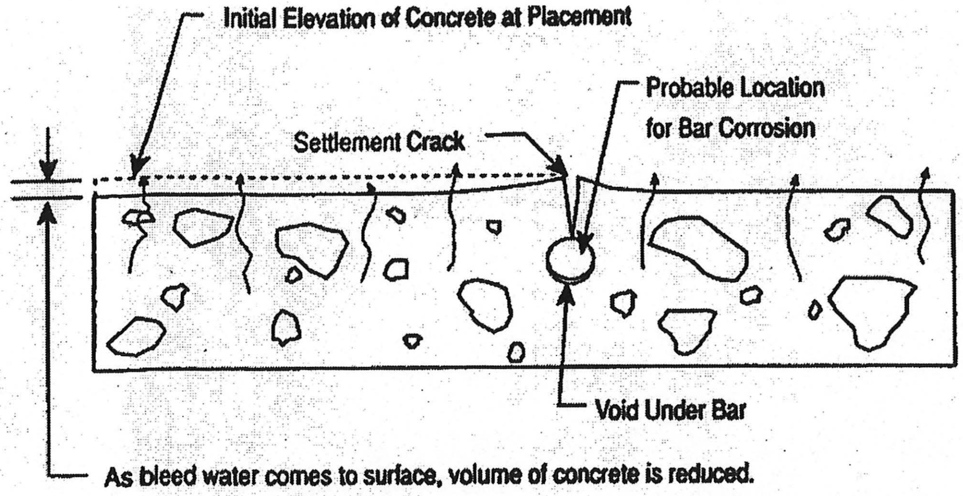


Fig. 2.3 Schematic representation of settlement in a slab. Settlement crack can be seen over the reinforcement bar (Gagné, 2003)

2.2 Rheology of SCC

2.2.1 General Rheological Definitions

The definition of **rheology**, adopted by the American Society of Rheology in 1929, is the study of the deformation and flow of matter (Scott, 1969). Prof. E.C. Bingham of Lafayette College, Easton Pa. USA, proposed this definition. He studied the flow of oil paint and found that there exists a class of fluid or fluid-like substances that have non-linear behaviour. Such substance does not follow the classical behaviour proposed for fluids nor for solids. These substances change their properties when an applied stress changes, regardless of the amount of stress. These changes can occur instantaneously or over a period of time and can either decrease or increase the parameters that define the rheological behaviour of the material.

Parameters used to describe rheological behaviour of fluid materials include shear stress (τ), force per unit area needed to cause shearing of the fluid, and shear rate (γ) which refers to the speed gradient as a measure of the variation of speed between two layers of a fluid. The ratio of shear stress to shear rate is defined as viscosity (η), which is the measure of internal resistance to flow.

According to the definition of rheology, liquids should be included in this field of study. On the other hand, since solids flow after a given application of a sustained stress, they could also be included in the study of rheology. However, these two are the extreme flow behaviours and, therefore, they are not included in the scoop of this field (Barnes et al., 1989).

2.2.2 Different Flow Behaviours

Several types of flow behaviours are recognized; the most common are shown in Fig. 2.4.

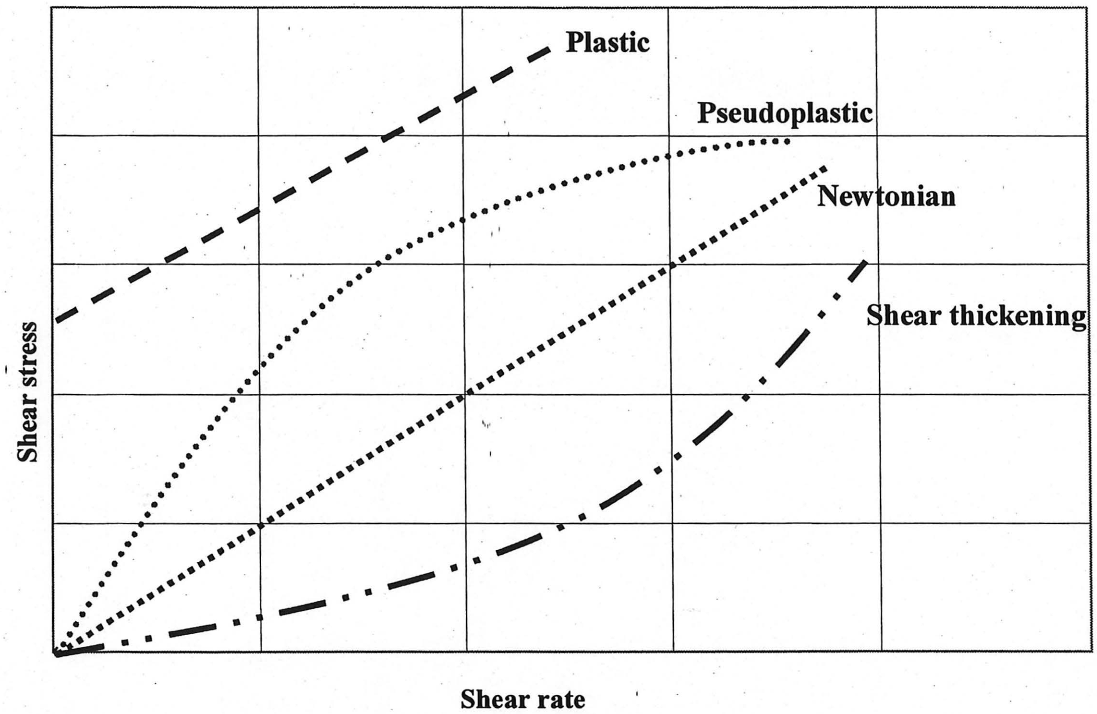


Fig. 2.4 Different flow behaviours (Struble and Ji, 1995)

The simplest is Newtonian behaviour, with a linear relationship between shear stress and shear rate, and zero shear stress at zero shear rate. This is the ideal fluid behaviour, analogous to Hookean behaviour in a solid (Struble and Ji, 1995).

Concrete is a pseudo-plastic material. As in the case of other plastic materials, it can be considered as a Bingham fluid, where the material flow properties are characterized by two parameters, the yield value (τ_0) and the plastic viscosity (μ) (Tattersall et al., 1983).

A material whose flow curve is concave towards the shear stress axis is said to be shear thickening because the shear stress is increasing more rapidly than the shear rate. At higher shear rates, a shear thickening material exhibits greater resistance to flow. On the other hand, a material whose flow curve is concave towards the shear rate axis is said to be shear thinning because the stress is increasing less rapidly than the shear rate, and it becomes easier and easier to increase the flow rate (Tattersall and Banfill, 1983).

2.2.3 Bingham Model

Characteristics of the Bingham model

An important characteristic of the Bingham model is that the fluid requires a minimum stress to start flowing. The material flow properties are characterized by two parameters, the yield value (τ_0) and the plastic viscosity (μ). If the applied stress is lower than the yield value the material could not flow and will behave as an elastic solid. If the yield stress is surpassed, the material would then flow like a viscous liquid. A Bingham fluid can be described as:

$$\tau = \tau_0 + \mu \gamma \qquad \textbf{Eq. 2.1}$$

where:

τ = shear stress (Pa)

τ_0 = yield stress (Pa)

μ = plastic viscosity (Pa.s)

γ = rate of shear

Due to its inherent resistance to flow, fresh concrete requires the application of a given stress to flow. **Concrete flow behaviour** can then be approximated as a **Bingham behaviour**.

Yield stress can be interpreted as the internal friction between solid particles, and plastic viscosity can refer to the viscous dissipation due to the movement of water in the sheared material (Ferraris et al., 1998).

The reason for concrete to be only an approximation to the Bingham's behaviour is due to the fact that it is a composite material made of suspension of aggregate, cement and water as main components. It is possible to consider coarse aggregate as solids in suspension into mortar, and sand as a suspension in the cement paste, and finally the cement as a suspension in water (Billberg, 1999).

Usually, flow equations describing concentrated suspensions (like concrete or mortar) try to relate the suspension concentration to the viscosity (or shear stress to shear rate), thus assuming that there is only one value for the viscosity of the whole system (Ferraris, 1999).

A low yield stress (approaching to that of a Newtonian fluid: zero) and a moderate plastic viscosity are defining rheological characteristics of SCC. **Stability** is directly related to the rheological parameters of the concrete, especially the plastic viscosity. A moderate viscosity will ensure proper suspension of particles in the matrix when the concrete is at rest, in the absence of any shear rate (static stability).

When comparing the rheological properties of conventional concrete, high-strength concrete, and SCC in Fig. 2.5.a, the yield stress of the SCC is close to zero, whereas in conventional concrete it would be much higher. High-strength concrete would develop a medium yield stress given its high fluidity when using a HRWRA. Observing the different slopes of shear stress-shear rate linear regressions can compare the plastic viscosity of the mixtures. The plastic viscosity of the SCC can be somewhere between these of the other two concretes. The highest plastic viscosity could be that of the high-strength concrete, and the lowest one corresponds to that of the conventional concrete.

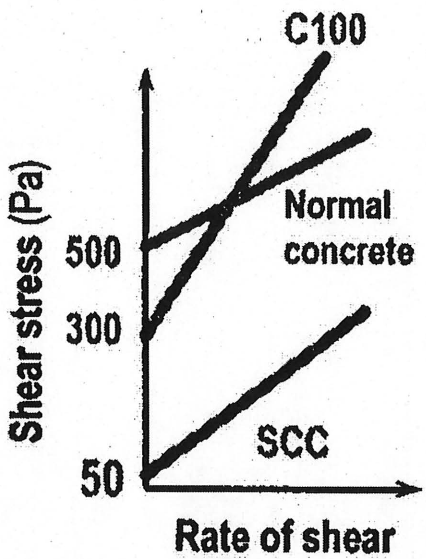


Fig. 2.5.a Comparison of rheologial properties of conventional concrete, high-strength concrete (C100) and SCC (Wallevik, 2003)

If the plastic viscosity is too high, the flowability and deformability of SCC would be hindered, thus affecting the passing ability and filling capacity characteristics. If the plastic viscosity is too low, mortar could not suspend coarse aggregate particles, hence leading to segregation. Therefore, a balance is necessary between achieving proper flowability and segregation resistance to achieve self-consolidation.

When torque viscosity versus apparent yield stress data obtained from different concrete types are compared (Fig. 2.5.b), the apparent yield stress is shown to decrease with the increase in slump consistency of the conventional concrete with slump values under 140 mm. The apparent yield stress of underwater concrete is greater than that of SCC and its viscosity is higher than that of SCC. Comparing among different types of SCC, the use of VEA to achieve self-consolidating properties increases the torque viscosity compared to the powder type SCC. Similar situation occurs when incorporating fibres in the SCC.

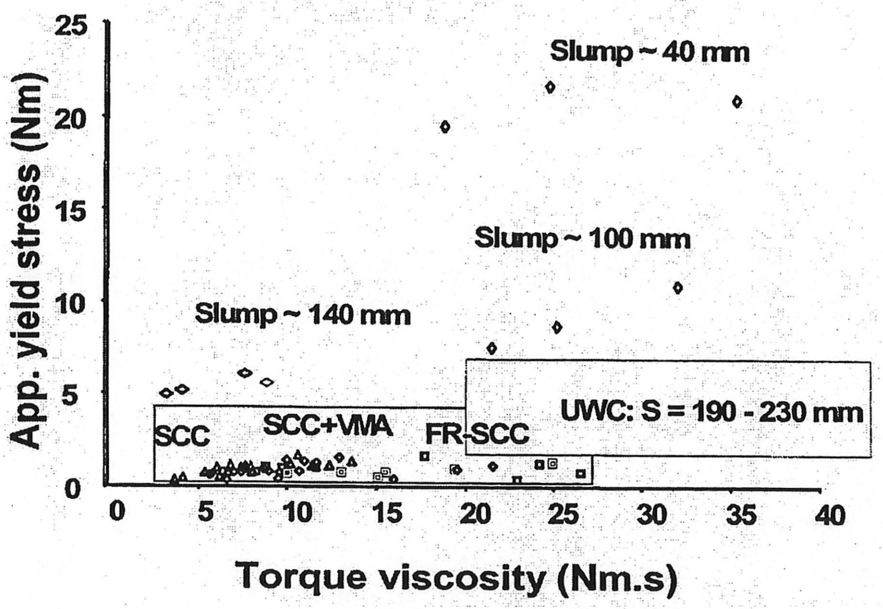


Fig. 2.5.b Workability boxes of various types of concrete with 40-140 mm slump, SCC, SCC with VEA, fibre-reinforced SCC and underwater concrete with 190 to 230 mm slumps (Khayat, 2003)

Hershell-Bulkley model

De Larrard et al. (1998) studied the rheological behaviour of fresh concrete using a BTRHEOM (De Larrard et al., 1994) to characterize the rheology of a series of mixtures. The BTHHEOM measures rheological parameters in fundamental units, yield stress in Pa and plastic viscosity in Pa.s. The study included four normal-strength concretes, three high-performance concretes, and three SCC. The authors found that highly flowable concrete could not best be described as Bingham fluids. In the case of concrete with high powder content and when using SCC, the rotation speed (RPS) versus torque (N.m) data did not yield a straight line. Bingham model would then result in negative yield values. Therefore, the Hershel-Bulckley model was proposed to characterize the non-linear behaviour of highly flowable mixtures. This model is based on the hypothesis that SCC exhibits an apparent shear thickening behaviour.

In Fig. 2.6, the rheological curves of three different SCCs are plotted. The differences between them are as follows: BHP8C has a w/cm of 0.26 and cement content of 619 kg/m^3, BHP8B and BHP8A with a w/cm of 0.27 and cement content of 616 and 609 kg/m^3, respectively. The cement used was an ordinary Portland cement ASTM type I/II.

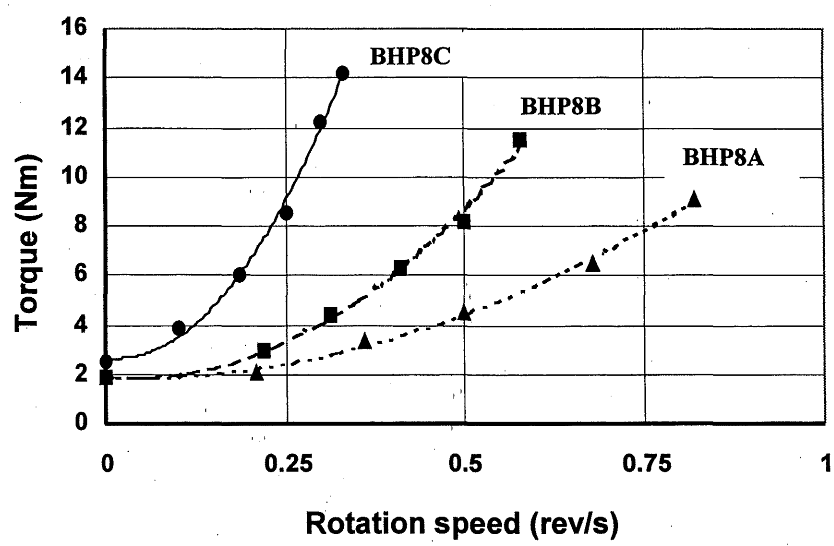


Fig. 2.6 Non-linear behaviour of SCC, internal units using the BTRHEOM (Ferraris and de Larrard, 1998)

The Hershel-Bulkley model is deducted from the work done by Coussot and Piau (1995) on coarse aggregate-mud suspensions; and is represented by the following equation:

$$\tau = \tau'_0 + a\,\gamma^b \qquad \textbf{Eq. 2.2}$$

where:

τ is the shear stress,

τ'_0 is the Hershel-Bulkley (H-B) shear stress,

γ is the shear rate strain imposed to the sample,

and **a** and **b** are the characteristic parameters describing the rheological behaviour of the suspension.

This model presents three parameters: the H-B yield stress and two variables: **a** and **b**. When **b** is equal to one, the Herschel-Bulkley's equation can be transformed into a Bingham fluid equation with **a** as the plastic viscosity.

In order to correlate the H-B equation to the results from the BTRHEOM, the relationship between the torque and the angular velocity of the rheometer is calculated by integration of the function relating the velocity field and the torsional motion imposed by the geometry of the test, as follows:

$$\Gamma = \Gamma_0 + A\,N^b \qquad \textbf{Eq. 2.3}$$

where:

Γ is the torque,

Γ_0 is the minimum torque necessary to shear the sample;

N is the angular velocity in revolutions per second;

and **A** and **b** are the parameters that depend on the concrete and the dimensions of the apparatus.

From the given relationship and the integration of the contribution of each surface element to the torque, the formulas to characterize the H-B parameters can be deducted, as follows:

$$\tau'_0 = \{3/[2\Pi(R_2^3 - R_1^3)]\}\ \Gamma_0 \qquad \textbf{Eq. 2.4}$$

and

$$\mathbf{a} = \{0.9[(b + 3)h^b / (2\Pi^{b+1}\ (R2^{b+3} - R1^{b+3}))]\}A \qquad \textbf{Eq. 2.5}$$

where:

$\mathbf{R_1}$ and $\mathbf{R_2}$ are the inner and outer radii of the rheometer,

and **h** is the height of the sheared concrete specimen.

Better correspondance of the Hershel-Bulkley model with fresh SCC behaviour is reinforced because it never results in meaningless negative yield stresses, as it is in some cases for SCC with the Bingham model. It is important to note that whenever a negative yield value is obtained (which is impossible physically), it could be due to segregation of the SCC during testing, lack of precision of the testing instrument, or lack of calibration. The **b** value is almost never close to 1, showing the limitation of the Bingham model. Also slump flow measurements are fairly well correlated with H-B yield stress, as shown in Fig. 2.7.

The main disadvantage of the Hershel-Bulkley model is the use of three parameters to describe the behaviour of fresh concrete. This could generate a difficulty to handle their optimization. However, there is the possibility that a relationship exists between the **a** and **b** parameters, as shown in Fig. 2.8. Using this relationship the model is reduced to only two independent parameters. Further research in this sense is necessary (de Larrard et al., 1998).

Another solution to the three parameter model might be the use of the Bingham model with the parameters deducted from the Hershel-Bulkley model as shown in Fig. 2.8.. The yield stress would be referred to as τ'_0. An equivalent plastic viscosity, μ', could be calculated from Bingham's straight line that is adjusted to the best possible approximation of the Hershel-Bulkley's curve under maximum limits of strain gradient between (0 and γ max). If this approach is used, μ' could be used to characterize the secondary aspects of SCC found by the Hershel-Bulkley method (de Larrard et al, 1998).

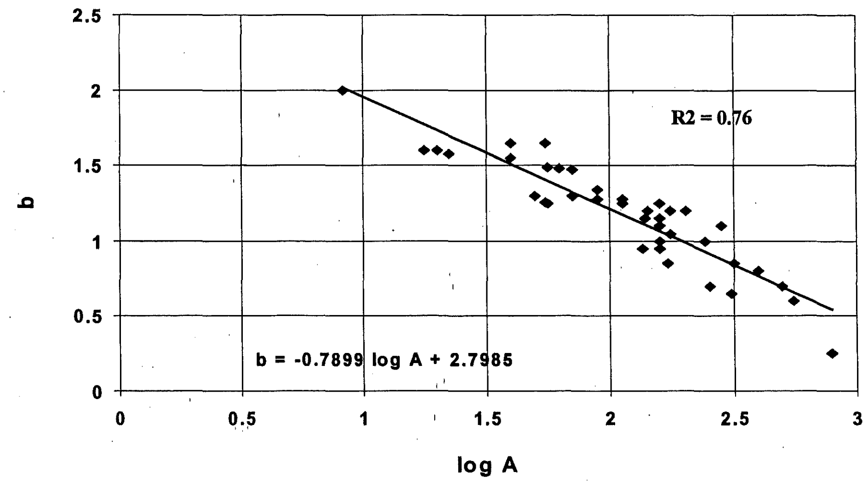


Fig. 2.7 Correlation between the yield stress determined with the Hershel-Bulkley model and the slump flow spread of SCC (de Larrard et al., 1998)

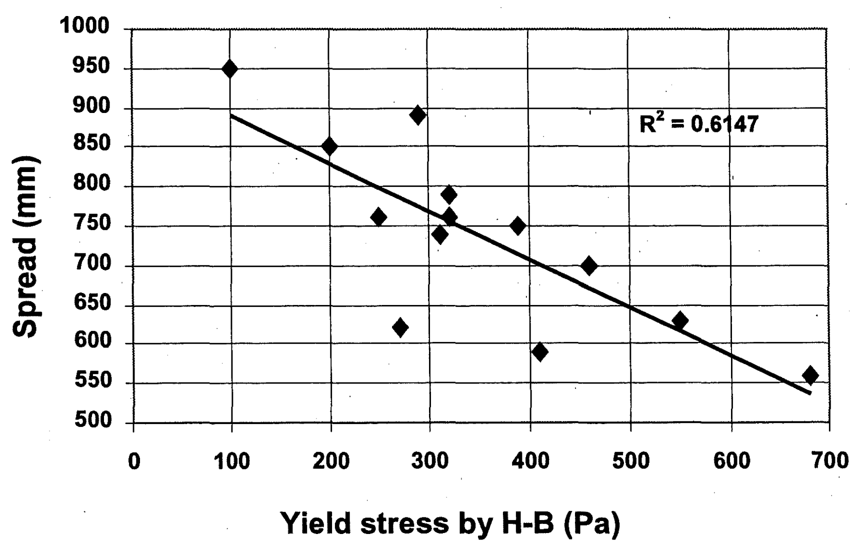


Fig. 2.8. Correlation between a and b variables of Hershel-Bulkley model for SCC (Ferraris and de Larrard, 1998)

2.2.4 Measurement of Rheological Parameters

Since Abrams introduced the slump method to evaluate the consistency of fresh concrete in 1918, it has been widely used due to its ease of. Slump consistency can be correlated to yield value. Other tests that can be used to assess yield stress of concrete include: penetrating rod (e.g. Kelly ball, Vicat, Wigmore test); K-slump test. On the other hand, tests that only can assess viscosity include: Ve-Be time or remolding test (Powers apparatus), LCL apparatus, vibration testing apparatus or settling curve, flow cone, turning tube viscometer, filling ability and Orimet apparatus (Brower and Ferraris, 2003).

However, a Bingham fluid is defined by two parameters, and testing procedures that only measure one parameter could not define completely the concrete flow behaviour. Consequently, a testing procedure or apparatus capable of measuring both parameters is required. In 1941, Powers and Willer (Wallevik, 1999) introduced a plastometer to describe workability of fresh concrete from a rheological point of view. Tattersall introduced in 1973 his two-point test apparatus for measuring concrete workability.

Nowadays, measurements of rheological parameters of concrete are obtained using a number of commercially available rheometers. A rheometer is an apparatus that applies different shear rates to a plastic material and then measures the necessary force to maintain the same shear rate. It measures the torque at different rotation speeds of an impeller submerged in a bowl of fresh concrete. These torque and rotation speed data can be related to the shear stress and shear rate, respectively. The relationship between rotational speed and torque can enable the extrapolation of the torque at which flow would start to determine the yield value. Also the slope of the resulting linear graphic can be related to the plastic viscosity (Fig. 2.9).

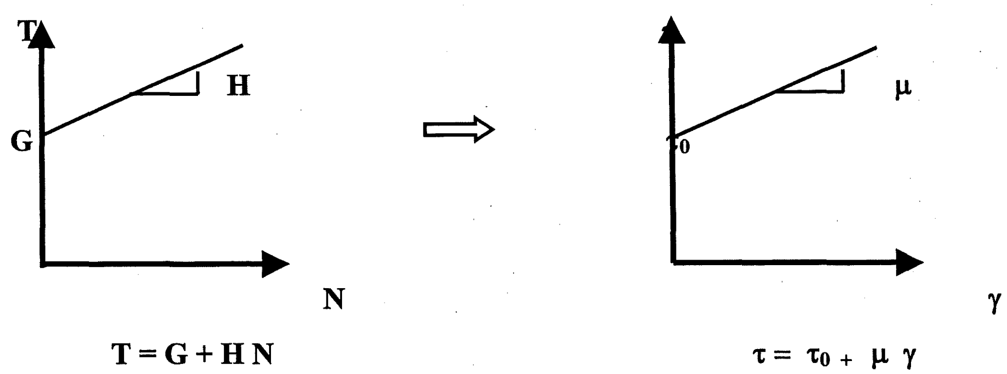


Fig. 2.9 Rheometer results of Bingham model using a torque-rotational speed machine units that are then converted into shear stress-shear rate data (Wallevik and Nielsen, 1998)

Today, several rheometers are available for use in laboratory conditions or at the jobsite. Some of the most important are described below:

BML rheometer developed by Wallevik and Gjorv at the Norwegian Institute of Technology, Trondheim, 1990. This is a coaxial cylinder rheometer in which the outer cylinder rotates at varying speeds, with the inner cylinder being sheared by the concrete poured in the gap between outer and inner cylinders. The torque at the inner cylinder is then measured. The approximated sample required for this test is 12 L. The outer cylinder speed variates from 0.001 to 0.9 rev/s (RPS) with a maximum torque of 100 Nm. Average torque is between 0.5 to 25 Nm when the speed varies between 0.1 and 0.5 RPS. Usually a slump over 50 mm is required to obtain reliable measurements (Brit EuRam, 2000).

BTRheom rheometer developed in France at LCPC Paris by de Larrard et al. in 1993. It is a parallel plate unit rheometer in which concrete is placed in a cylindrical container with a fixed bottom plate. The top plate rotates around a vertical axis. The concrete is poured in the hollow axis, and the torque required to shear it is measured. A sample of 7 L is required for concrete with 25 mm MSA (Brit EuRam, 2000).

CEMAGREF-IMG rheometer this is a coaxial cylinder rheometer in which the inner cylinder rotates at varying speeds. It was originally developed by Coussot in 1993 to study mud flow rheology. The use of this rheometer is limited to the laboratory due to the high amount of concrete required (500 L) (Bower and Ferraris, 2003).

IBB rheometer developed in Canada at the University of British Columbia by Beaupré in 1994. It has an H-impeller that rotates in planetary motion when inserted into fresh concrete placed in a cylindrical bowl. The apparent yield value (g) measured in Newtons meters (N.m), and the torque plastic viscosity (h) in Newtons meters seconds (N.m.s) (Brower and Ferraris, 2003). This rheometer is based in the MK-III two-point workability apparatus developed by Tattersal.

Two-point rheometer modified by Domone et al. in the UK, 1999. It uses a rotating impeller with a helical pattern that rotates at the centre of the sample chamber. The torque is then measured as a function of rotation rate (Brower and Ferraris, 2003).

2.2.5 Effect of Measuring Procedures on Rheological Parameters of SCC

Geicker et al. (2002) carried out a study on the effect of different shear rates and shearing times on the apparent rheological properties of SCC. They found that when the colloidal particles were suspended, a structural breakdown or a rebuilding of flocks of particles occured, depending on whether the suspension was subjected to an increasing or decreasing of shear rate during testing. The amounts of flocks broken down by shearing were proportionally direct to the increase in the shear rate and the time to reach equilibrium shear stress. However, when the shear rate decreased or stopped coagulation occurred, and the suspension returned to its original structure.

A BML viscometer was used to test the SCC mixtures at shear rates of 0.57, 0.5, 0.4, 0.3, 0.2, 0.1, and 0.01 rev/s, starting at the highest and finishing at the lowest. Five separate SCC batches were made to test five different shearing times at each shear rate. The five shearing time were 5, 8, 10, 15, and 25 sec. In Fig. 2.10 the plastic viscosity versus yield value for each shearing time are shown. Rheological parameters were measured after SCC was subjected to each shear rate for the specific shearing time. The measurement was always undertaken during the final two seconds. It is clear that the rheological parameters are affected by the different shearing times. When the shearing time is increased plastic viscosity is decreased and yield stress is increased.

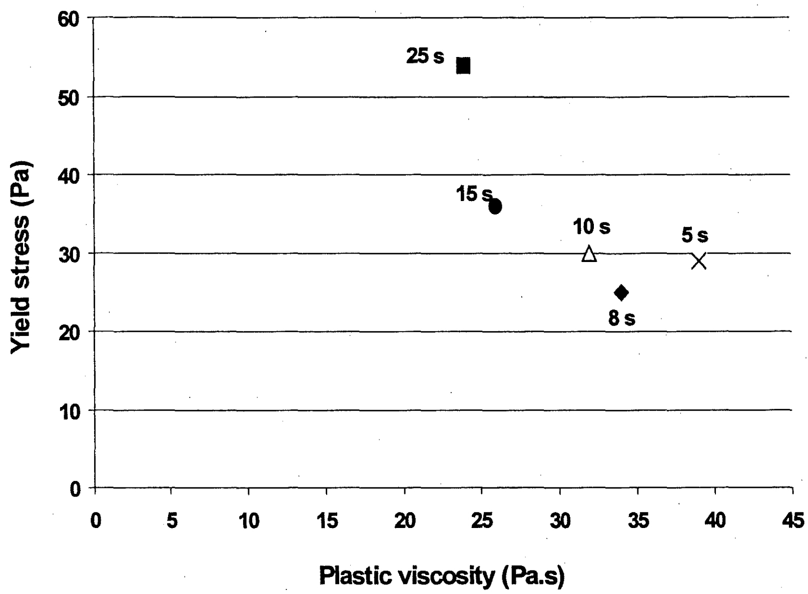


Fig. 2.10 Effect of different shearing times on the calculation of rheological parameters (Geiker et al, 2002)

When the shearing time was extended, and the equilibrium was reached, the yield stress increased and the plastic viscosity decreased. This demonstrates that the shearing time should be long enough to reach equilibrium. The problem is that long shearing times can lead to segregation when testing SCC. Segregation may occur either vertically (aggregate disappearing from the top and sinking towards the bottom) or horizontally (aggregate flowing towards the walls of the container, on the shearing zone of the rheometer).

2.3 Effect of Material Properties on Workability and Rheology of SCC

In order to obtain the three basic plastic characteristics of SCC, the concrete-making materials should be carefully chosen, and the mixture composition should include a sound mix design. In this section, materials used in the production of SCC are presented, and their effect on fresh properties and rheology is highlighted.

2.3.1 Portland Cement

Proper type of Portland cement should be used to fulfill the requirements for specific purposes. Achieving good compatibility between cement and admixtures is essential. Cements with low contents of C_3A and C_4AF, or belite-rich cements are designed specially for applications in which a large amount of cement is used (e.g., high-strength concrete and SCC).

Chemical factors that affect the flowability include the influence of interaction of interaction of mineral compound composition of cement on the dispersion of chemical admixtures (Nawa, et al., 1998). The substantial amount of chemical admixture molecules is firstly adsorbed onto the surface of C_3A and C_4AF in cement within a few minutes immediately after contact with water due to their initial rapid hydration. Then the remaining one is adsorbed on C_3S and C_2S, which are mainly composing compounds of cement. The amount of adsorption on C_3S and C_2S is dependent on the amount of adsorption of C_3A ad C_4AF. For cement with rich C_3A and C_4AF the adsorption of chemical admixtures is not uniform over the surface of cement, and the dispersion action of chemical admixtures is reduced. Moreover, ettringite can become bound onto cement particles, hence reducing flowability.

Low yield stress and appropriate plastic viscosity values can be obtained in mixtures containing belite-rich cement, even at low w/cm (Nawa et al., 1998). In Fig. 2.11 different types of concrete made with the same w/cm (0.30), same sand to cement ratio (1:1), and same dosage of HRWRA of 1.5% by cement weight, are compared. Plastic viscosities and yield values of four different cements are shown being the belite rich cement the one with the lowest values.

Two physical characteristics of cement influence plastic properties and rheology: the particle-size distribution and the particle shape. These characteristics affect also early age strength development. The specific surface of cement has a direct influence on plastic viscosity: the higher the specific surface, the higher the plastic viscosity can be (Nawa et al., 1998). This relationship is due to the adsorption of free water onto cement grains. When the specific surface area is higher, more water is adsorbed, hence reducing the fluidity of the mixture. On the other hand, the yield stress value is affected by the spread of particle-size distribution and the **n** value of the Rosin-Rammler curve. The smaller the **n** values the smaller the yield value (Nawa et al., 1998).

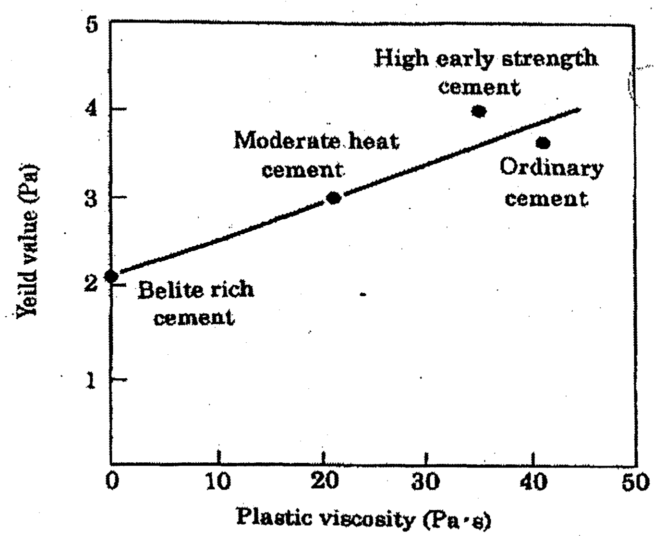


Fig. 2.11 Rheological parameters of concretes made with different cements, 0.30 w/cm, and 1.5% HRWRA, by weight of cement (Nawa et al., 1998)

2.3.2 Supplementary Cementitious Materials and Fillers

Due to the special rheological requirements of SCC, both inert and reactive mineral additions are commonly used to improve and maintain workability. These additions can reduce the cement content, so reducing the heat of hydration and autogenous shrinkage at young age. Inert additions include limestone fillers, ground glass fillers, and stone dust. Reactive additions include supplementary cementing materials, such as fly ash, and silica fume. Ground granulated blast furnace slag (GBFS) can be considered as a hydraulic binder or supplementary cementitious material.

Incorporating inert additions and supplementary cementitious materials enhances the stability of SCC. These fine materials can enhance the grain-size distribution and particle packing of the mixture, thus ensuring greater cohesiveness.

Supplementary cementing materials

According to the Canadian Portland Cement Association (CPCA, 1995), supplementary cementing materials are materials that, when used in conjunction with Portland cement, contribute to the properties of the hardened concrete through hydraulic or pozzolanic activity or both. Commonly used supplementary cementing materials in SCC include fly ash, silica fume, and GBFS.

Fly ash is a finely divided residue that results from the combustion of pulverized coal and is carried from the combustion chamber of a furnace by exhaust gases (CPCA, 1995). Mechanical collectors or electrostatic precipitators remove fly ash as a fine particle residue from the combustion gases before they are discharged into the atmosphere. The particle shape is typically spherical and under the electronic microscope it can be seen that some are hollow. Fly ash is classified in two classes:

- Class F: fly ash normally produced from burning pulverized anthracite or bituminous coal; and
- Class C: fly ash normally produced from burning pulverized lignite or subbituminous coal. This class of fly ash has normally some cementitious properties on its own.

Fly ash has been used in the production of SCC for different applications, including: structural members, vaults, jail cells, septic tanks, steps and various pre-cast architectural pieces. It normally reduces water demand, improves stability, and reduces costs (Shadle et al., 2002).

Silica fume is the finely divided residue resulting from the production of silicon or silicon-containing alloys that are carried from the furnace by exhaust gases. The Canadian Standards Association (CSA) covers Type U silica fume, which results from the production of silicon or ferro-silicon alloys, containing at least 75% silicon (CPCA, 1995).

Silica fume is composed of round spherical shape particles with diameters going from about 0.1 μm and up to 1 or 2 μm. The mean diameter of silica fume is 100 times smaller than the mean diameter of cement (Aïtcin, 2001).

The use of less than 10% of silica fume in concrete has a fluidifying effect on very low w/cm mixtures. The use of silica fume can sharply reduce viscosity given the morphology of silica fume particles (ball-bearing effect). Silica fume particles displace some of the water present among the flocculated cement grains, thus increasing the amount of water available to fluidify concrete (Aïtcin, 2001).

The effect of substituting cement by silica fume on the rheological parameters depends of the silica fume content. It appears to be a limit content under which the plastic viscosity usually decreases by 50% and the yield value remains constant in well dispersed systems. However, when this limit is surpassed, the yield value tends to increase as well as the plastic viscosity (Wallevik, 2003).

This behaviour is explained considering the particle shape of silica fume. Under the limit content the reduction of plastic viscosity is due to the lubricating effect of the spherical shape of silica fume. The yield value is not increased because of the high water demand of silica fume. However, after the limit value is surpassed, the lubricating effect does not increase; on the contrary water demand does, increasing both yield value and plastic viscosity. Apparently this limit value depends on the cement and water content of the concrete, but an average value is 5% of the total cementitious materials content (Wallevik, 2003).

Because of its fineness, silica fume particles can fill the voids between the larger cement particles, when they are well deflocculated in the presence of an adequate dosage of superplasticizer. Therefore, the resulting solid matrix including silica fume is dense even before any chemical bonds between the cement particles have developed (Aïtcin, 2001).

The use of silica fume in concrete results in a very dense microstructure good bond between the hydrated cement paste and aggregates. With this enhanced microstructure of the interstitial transition zone, silica fume increases the compressive strength of concrete, especially between 7 and 28 days. Moreover, as silica fume reduces the porosity of the cement paste at its interface with aggregate, the concrete permeability is greatly reduced (Aïtcin, 2001).

GBFS is a non-metallic product consisting essentially of silicates and aluminosilicates of calcium that is developed in a molten condition simultaneously with iron in a blast furnace (CPCA, 1995). GBFS is classified in two types:

- Type G: this is the glassy granular material formed when molten blast-furnace slag is chilled rapidly. This type, in the absence of an activator, displays little or no cementitious behaviour; and
- Type H: this is a cementitious hydraulic slag obtained by pulverizing granulated iron blast-furnace slag and displays some hydraulic activity when mixed with water alone.

The use of GBFS in concrete usually decreases the water content required to achieve a given consistency, compared to mixtures using only Portland cement (CPCA, 1995).

In general, the strength development of concrete incorporating GBFS is limited between 1 to 7 days of age. Between 7 and 28 days, the strength is similar to concrete with only portland cement. Beyond 28 days, the compressive strength of slag concrete exceeds that of concrete made without any slag (Malhotra and Mehta, 1996).

Limestone filler is used in SCC to improve rheological properties, lower the adiabatic temperature, and reduce cost. Pedersen and Mortsel, (2001) found that the dominant factors that contribute to enhanced rheological characteristics of SCC are the specific surface area and the grain-size distribution of the filler in use.

Usually finer fillers perform better when used in concretes with relatively high water-to-powder ratios, while coarser fillers are more suitable for mixtures with lower water-to-powder ratios. Mixtures with high amount of water need a higher specific surface to adsorb excess water and reduce segregation (Swedish Concrete Association, 2002).

Trudel (1996) investigated the effect of different binder types on SCC. The evaluated mixtures had total binder contents of 585 kg/m^3, w/cm of 0.41, and fixed dosages of HRWRA and VEA (welan gum). A reference mixture was a concrete with 100% Portland cement using Type 10

CSA Portland cement. Different replacement values (by mass) of silica fume, fly ash, slag, and limestone filler were used. When Portland cement was combined with only one supplementary cementitious material or filler, the better performing SCC mixtures, from a workability point of view, included: 3% silica fume, 20% fly ash, 40% slag, and 30% limestone filler. When silica fume and fly ash were used, the slump flow and filling capacity were slightly lower than the reference concrete. When slag and limestone filler were used, the slump flow and filling capacity increased (Trudel, 1996).

When two supplementary materials were used along with Type 10 cement the results cannot be easily related to each cementitious material. Trudel observed an improvement in fresh state properties of SCC mixtures made with 3% silica fume + 20% fly ash, and 3% silica fume + 40% slag. On the other hand, a higher dosage of HRWRA was necessary when 20% fly ash + 40% slag was used to produce SCC. The use of limestone filler up to 30% was shown to greatly enhance the resistance to surface settlement. Increasing 3% silica fume reduced loss of compressive strength due to such replacement of cement by limestone filler.

2.3.3 Aggregate

The frequency of collision and contact between aggregate particles can increase as the relative distance between the particles decreases. Internal stress can also increase when the concrete is deformed particularly near obstacles. Research has found that the energy required for flowing is consumed by the increased internal stress, resulting in blockage of aggregate particles. Limiting the coarse aggregate content, whose energy consumption is particularly intensive, to a level lower than normal is effective in avoiding this kind of blockage (Okamura and Ouchi, 2003). The most important parameters related to aggregate characteristics for the workability of SCC are:

- volume of coarse aggregate;
- maximum-size aggregate;
- particle shape;
- fine portion of the sand;
- sand-to-total aggregate content; and
- volume of water in aggregate.

The **volume of coarse aggregate** is an important factor in the passing ability of SCC. In order to obtain an economic mixture design, this volume should be the maximum possible. However, in order to reduce interparticle collision, the coarse aggregate volume should be decreased, and the paste should be increased. A limit volume of coarse aggregate is typically fixed at 50% of the solid volume of SCC. Fine aggregate content is also fixed at 40% of the mortar volume as a starting point in mixture optimization. These percentages are illustrated in Fig. 2.12 (Okamura, 1997).

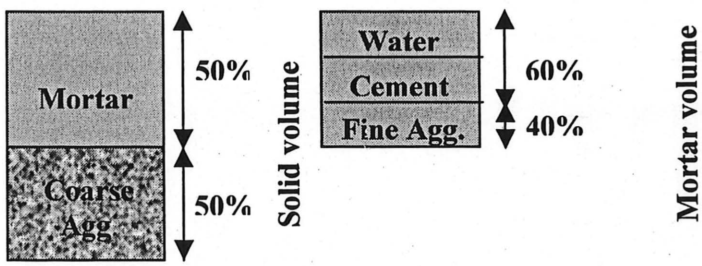


Fig. 2.12 Recommended values for coarse aggregate volume in SCC and fine aggregate in mortar (Okamura, 1997)

The **maximum-size of aggregate (MSA)** is another important factor that affects passing ability. In order to choose a given MSA, the characteristics of the opening dimensions on the actual structure should be carefully considered. Tests results show that the influence of coarse aggregate on the flowability of fresh concrete largely depends on the size of the spacing of the obstacle. Considering options can include reducing the maximum size (e.g. from 18 to 16 mm) since this reduction will have no effect on the proportioning but it will enhance the passing ability (Okamura, 1997).

Particle shape of coarse aggregate does not influence the self-consolidating properties of fresh concrete as long as the ratio of coarse aggregate content to its solid volume in concrete is the same (Okamura and Ouchi, 2003). The very **fine portion of the sand** is also of great interest. All particles in fine aggregate smaller than 90 μm are considered as part of the filler and can play an important role in the rheology of the micro-mortar (Nawa et al., 1998).

Finally, there is evidence of good performance of SCC with both natural and crushed aggregates. When proper selection of aggregate and adequate mixture proportioning are ensured (Swedish Concrete Association, 2002; Domone and Chai, 1996).

2.3.4 Admixtures

A) High Range Water Reducer Admixtures

A high range water reducer admixture (HRWRA), also known as superplasticizer, is used, either to maintain workability of concrete while reducing the water demand, or increase the workability for a given water content. The main difference between a water reducer admixture (WRA) and a HRWRA is the greater water reduction of the latter one and the lower impact on delay in setting time. Compared to the 5% to 10% of water reduction achieved with the use of ordinary WRA, the incorporation of a HRWRA can enable 20% to 25% water reduction without causing considerable loss of cohesiveness. It is important to highlight that all the properties given by the HRWRA must be achieved without undesirable side effects, such as excessive air entrainment or set retardation.

Classification of HRWRA

According to ASTM C 494, HRWRA are classified as:

- Class F: high-range water reducers; and
- Class G: high-range water reducers and retarders.

In the 1960's, Sulfonated Naphtalen Formaldehyde (SNF) and Sulfonated Melamine Formaldehyde (SMF) were developed in Japan and Germany, respectively. At the beginning of 1980's, initially in Germany and then in Japan and United States, polyacrylate-based HRWRA were introduced (Rixom and Mailvaganam, 1999). Chronologically another classification of HRWRA is used: first, second and third generation. Lignin based HRWRA are refered to as first generation as they were the first to appear in the market.

Sulfonated Naphtalen Formaldehyde, also designated as polynaphtalene sulphonate (PNS), and SMF, also designated as polymelamine sulphonates (PMS), are part of the sulphonated synthetic polymers group and they are refered to as second generation HRWRA. The most accepted compound of this group is the poly-β-naphthalene sulphonate as shown in Fig. 2.13.

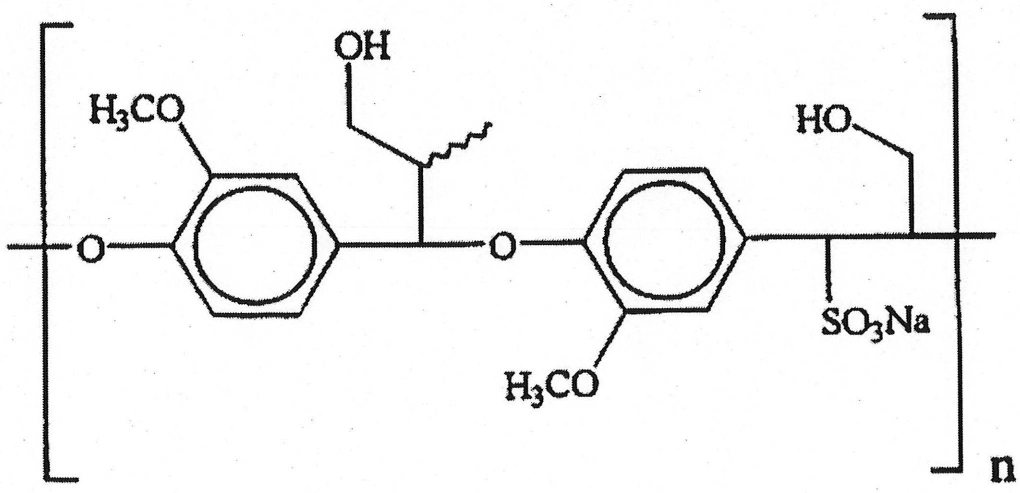


Fig. 2.13 Structure of a molecule of lignosulphonate (Ramachandran, 1998)

In addition to the synthetic polymer group, carboxylated synthetic polymers are used as highly effective dispersants. They include polycarboxylates (e.g. polyacrylates), known as the third generation of HRWRA. The mode of action of HRWRA is different for each group. It is well known that PNS and PMS act in the system by electrostatic repulsion, while PCP acts mainly by steric hinderance.

A generic molecular structure of a polyacrylate copolymer is shown in Fig. 2.14.

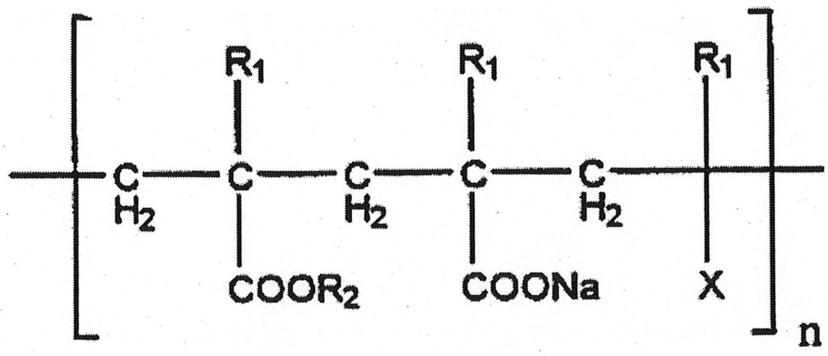


Fig. 2.14 Structure of a molecule of polyacrylate copolymer (Ramachandran, 1998)

Effect of HRWRA on fresh concrete properties

When HRWRA is incorporated in concrete the yield stress is decreased, while the plastic viscosity is not considerably affected at normal dosage rates (Fig. 2.15). This mode of action is completely opposite than increasing the water content of the mixture, that decreases both the yield stress and plastic viscosity.

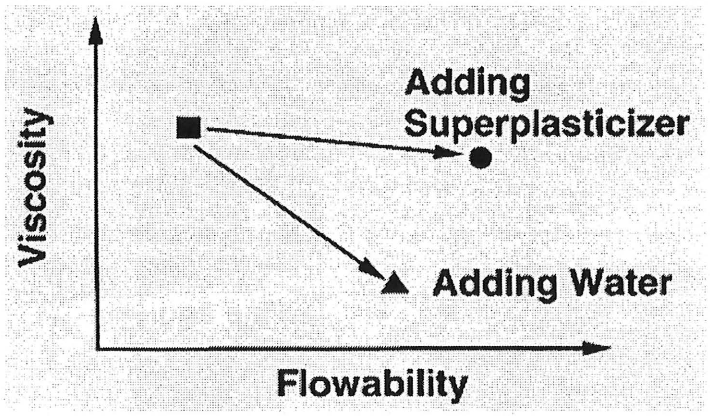


Fig. 2.15 Effect of HRWRA on viscosity and flowability of SCC (Okamura, 1997)

Due to the high dosage of HRWRA used in SCC, there is an undesirable side effect: retardation of setting time in fresh concrete. Another side effect of using a HRWRA in concrete is the relatively high slump loss during the plastic stage. The main causes of slump loss are considered to be chemical coagulation accompanying the hydration reaction of cement particles and physical coagulation due to collisions between cement particles. The phenomenon is a slump loss brought about as a result of consumption of the dispersing agent with time (Nawa et al., 1998).

There are two ways of counteracting this effect: the first one will be a retempering, or the use of repeated dosages of HRWRA to maintain the given consistency. The other way is to incorporate another admixture, such as a setting retarder, or use a HRWRA that already includes such admixture.

B) Viscosity-Enhancing Admixtures

A viscosity-enhancing admixture (VEA) increases the segregation resistance of fresh concrete. The incorporation of VEA enables the control of segregation resistance of SCC when powder content is limited.

Classification

Due to their physical effect on cement-based materials VEA, antiwashout admixtures, and pumping aids can be divided into five classes (Rixom and Mailvaganam, 1999):

Class A - Water-soluble synthetic and natural organic polymers that increase viscosity of the mixing water. Class A materials include cellulose-ethers, polyethylene oxides, pregelatinized starches, poyethylene oxides, alginates, carrageenans, polyacrylamide, carboxyvinil polymers and polyvinyl alcohol. Water-soluble polymers can be divided into three categories (Khayat, 1998):

1. Natural polymers that include starches, guar gum, alginates, agar, gum arabic, welan gum, xanthan gum, rhamsan gum, gellan gum, and plant protein.

2. Semisynthetic polymers that include decomposed starch and its derivatives; cellulose-ether derivatives (Fig. 2.17), such as hydroxypropyl methyl cellulose (HPMC), hydroxyethyl cellulose (HEC), and carboxyl methyl cellulose; as well as electrolytes, such as sodium alginate and propyleneglycol algnate.

3. Synthetic polymers including those based on ethylene, such as polyethylene oxide, acryl type (Fig. 2.16), polyacrylamide, polyacrylate, and those based on vinyl, such as polyvinyl alcohol.

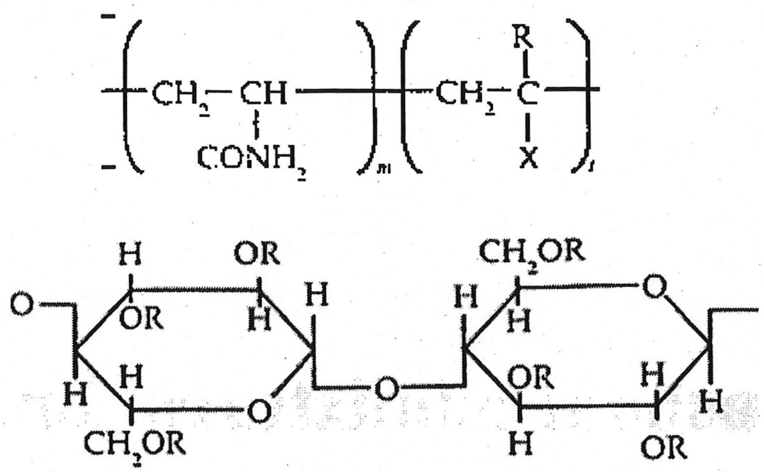


Fig. 2.16 Chemical formulas of water-soluble acryl-type polymers and cellulose ether (RILEM TC 84-AAC, 1995)

Class B - Organic water-soluble flocculants which are adsorbed on the cement particles and increase viscosity by promoting interparticle attraction between cement grains. These materials are styrene copolymers with carboxyl groups, synthetic polyelectrolytes, and natural gums.

Class C - Emulsions of various organic materials which increse interparticle attraction and also supply additional superfine particles in the cement paste. These are materials consisting of acrylic emulsions and aqueous clay dispersions.

Class D - Inorganic materials of high surface area or unusual surface properties, which increase the water-retaining capacity of the mixture. These include very fine clays such as bentonites, pyrogenic silicas, condensed silica fume, milled asbestos and other fibrous materials.

Class E - Inorganic materials, which supply additional fine particles to the mortar paste and thereby increase the thixotropy, such as fly ash, hydrated lime, kaolin, diatomaceous earth, and other raw or calcined pozzolanic materials and various rock dusts.

Effects of VEA on fresh concrete properties

An adequate dosage of VEA enhances cohesiveness and reduces the risk of separation of concrete constituents. Since part of the mixing water is inter-mixed with the VEA, free water is reduced. In consequence, bleeding is reduced because water is fix by the long chains of the polymer. Segregation of coarse aggregate and sedimentation of cement particles are reduced given the higher viscosity of the paste. Also, enhancement of self-consolidating properties is achieved regardless of difference in external factors. Greater robustness can be achieved when using VEA in SCC (Khayat, 1995).

The incorporation of VEA can enhance plastic viscosity and yield stress of the mixture. This is shown in Fig. 2.17 where the plastic viscosity and yield stress are shown to increase with the dosage of VEA for a given concentration polycarboxylate-based HRWRA in the SCC. In order to increase fluidity and enhance self-compactability, increasing the dosage of HRWRA, water to binder ratio, or binder content, must reduce yield stress.

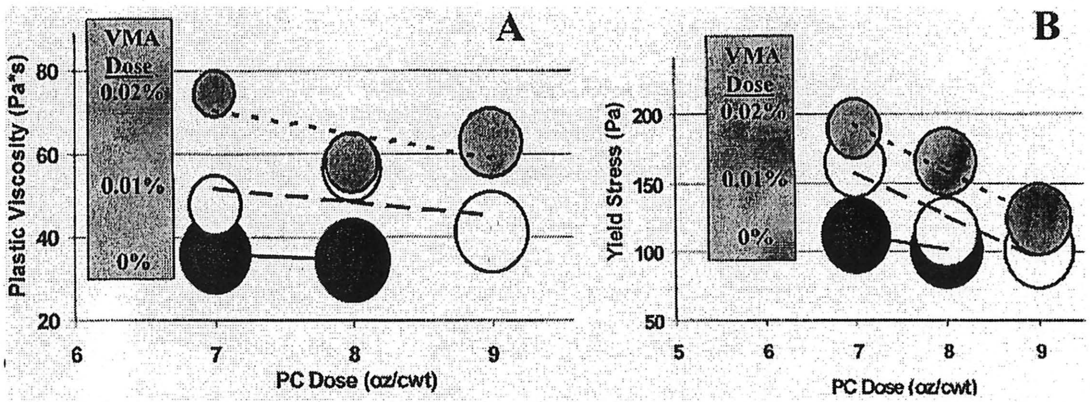


Fig. 2.17 Effect of VEA water-soluble synthetic dosage on plastic viscosity and yield stress of concrete (Berke et al., 2002)

SCC proportioned with VEA can exhibit better robustness and can produce mixes with poorly graded aggregate and can still achieve self-consolidating properties with relatively high w/cm.

For a given slump flow consistency, surface settlement can be reduced by the use of VEA (Khayat, 1999; Petrov, 1998). This is shown in Fig. 2.18 where the maximum settlements of two different SCC are compared. Both concretes have the same cementitious content and w/cm; the HRWRA dosage was adjusted to achieve similar slump flow in the case of the mixture containing greater dosage of VEA (welan gum). The enhanced resistance of consolidation improves homogeneity and enhances bond with embedded reinforcing bars (Petrov et al., 2001). Due to the fluid nature of the SCC, stability of the mixture is especially critical when pouring concrete in deep elements, such as the case in industrial beam, slab, and wall elements (Khayat et al. 1997; Petrov, 1998).

Khayat and Guizani (1997) demonstrated that maximum bleeding is proportional to the VEA content (Fig. 2.19.a). This was confirmed for three different w/cm values. Similar behaviour was observed when the maximum surface settlement was measured (Fig. 2.19.b). The authors compared concrete mixtures made with no VEA, with moderate dosage of welan gum (0.035%) and relatively high dosage of VEA (0.070% by mass of cement). Three consistency levels were tested (140, 180 and 220 mm slump). As shown in Fig. 2.20, the bleeding and settlement of the concrete mixtures increased with slump, regardless of the VEA dosage. However, when a higher dosage of VEA was used there was a significant reduction of these two parameters.

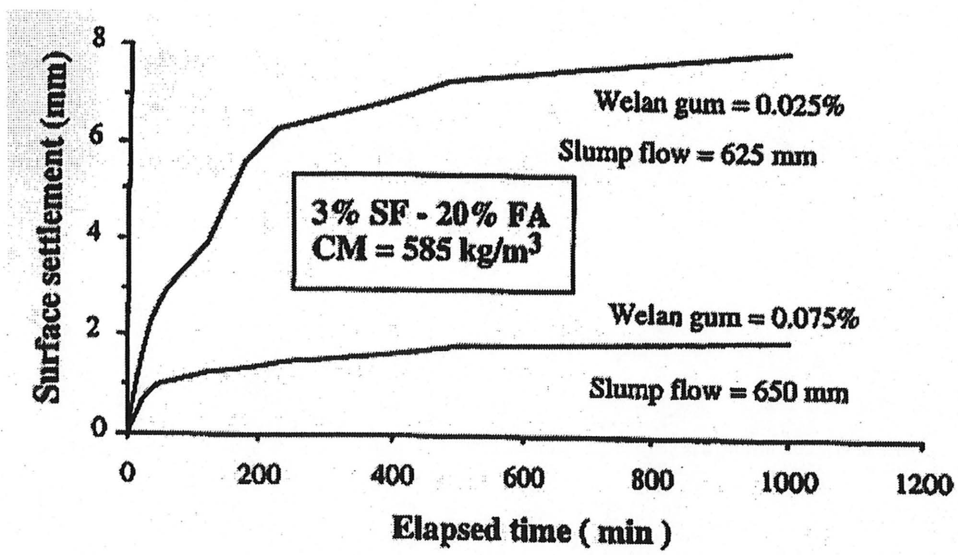


Fig. 2.18 Effect of welan gum content on settlement of SCC (Khayat, 1998)

It was also found that a mixture containing a higher amount of VEA (0.070%) and no silica fume can secure **better stability** than the concrete containing moderate VEA dosage (0.035%) and 8% of silica fume (Khayat and Guizani, 1997).

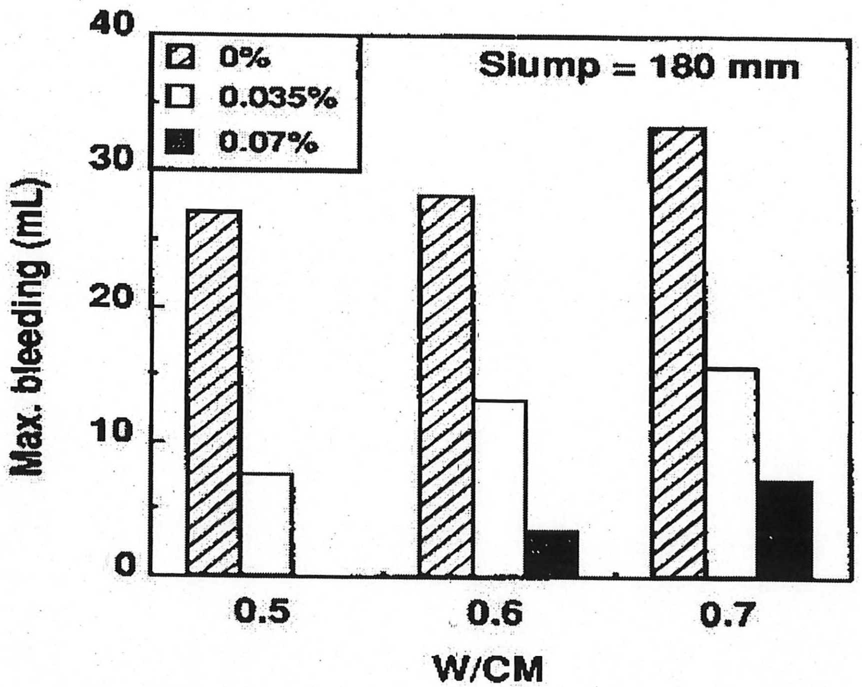


Fig. 2.19.a Effect of VEA on maximum bleeding. Three concretes with different w/cm were tested (Khayat and Guizani, 1997)

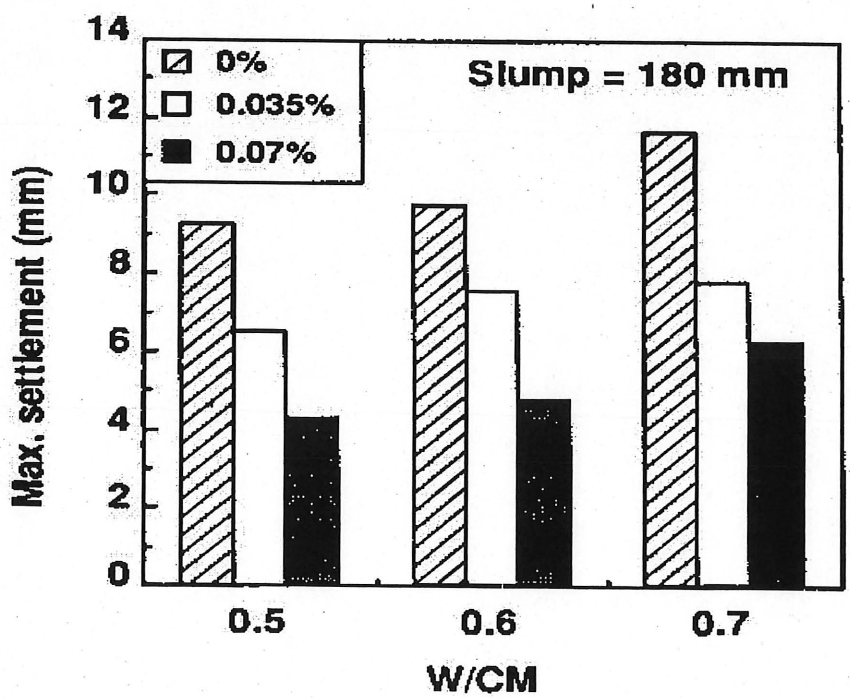


Fig. 2.19.b Effect of VEA on maximum settlement. Three concretes with different w/cm were tested (Khayat and Guizani, 1997)

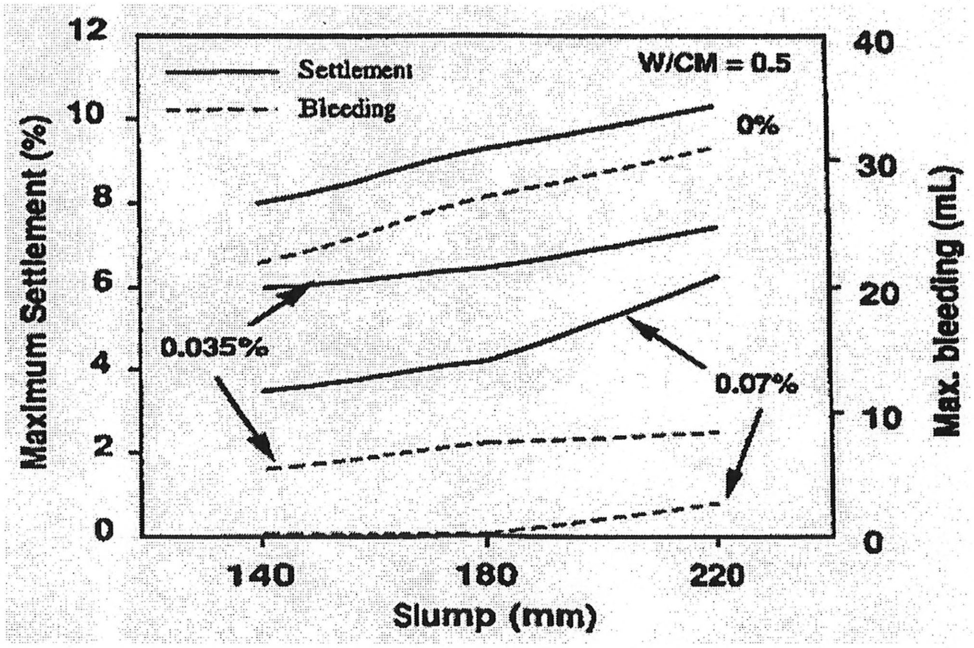


Fig. 2.20 Effect of VEA on maximum bleeding and surface settlement for mixtures at three slump consistency levels (Khayat and Guizani, 1997)

C) Combined effect of HRWRA and VEA

An alternative approach to enhance stability of flowing concrete is to incorporate VEA along with HRWRA in order to ensure high fluidity and adequate stability. Concrete mixtures proportioned using this approach present moderate w/cm (around 0.40), higher demand in HRWRA, and better robustness (JSCE, 1996).

Manai (1995) observed that stability of concrete made with VEA was proportional to the VEA dosage, for the same workability and cementitous materials content. For concrete mixtures containing 0.050% to 0.075% VEA welan gum, the surface settlement was 70% lower when compared with mixtures containing only 0.025% VEA (by mass of cementitious materials). The washout resistance increased 40%, and up to 70% when compared to mixtures made without any VEA. This confirms the idea that the stability and cohesiveness of SCC is enhanced with the use of a VEA. Manai's comparisons are shown in Fig. 2.21.a, Fig. 2.21.b, and Fig. 2.21.c.

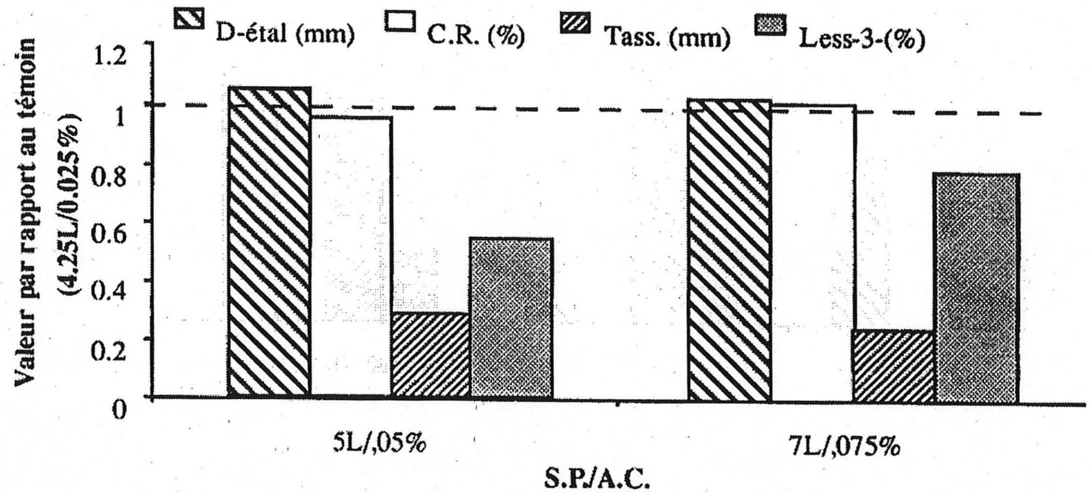


Fig. 2.21.a Effect of VEA dosage on workability of SCC made with 3% silica fume and 20% fly ash. D-étal = slump flow, C.R. = caisson filling capacity, Tass. = surface settlement, Less-3 = washout loss after 3 drops in water (Manai, 1995)

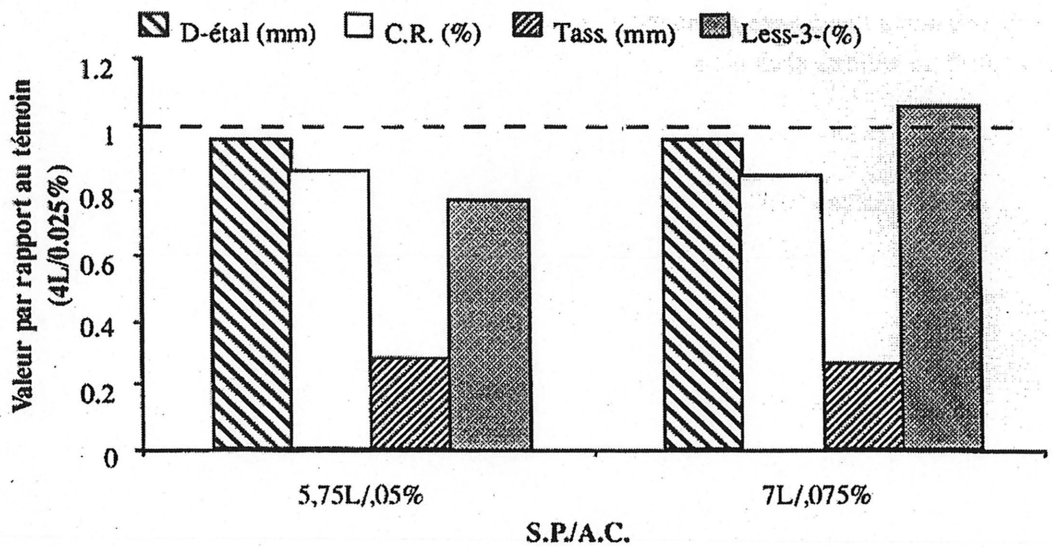


Fig. 2.21.b Effect of VEA dosage on workability of SCC made with 3% silica fume and 40% slag. D-étal = slump flow, C.R. = caisson filling capacity, Tass. = surface settlement, Less-3 = washout loss after 3 drops in water (Manai, 1995)

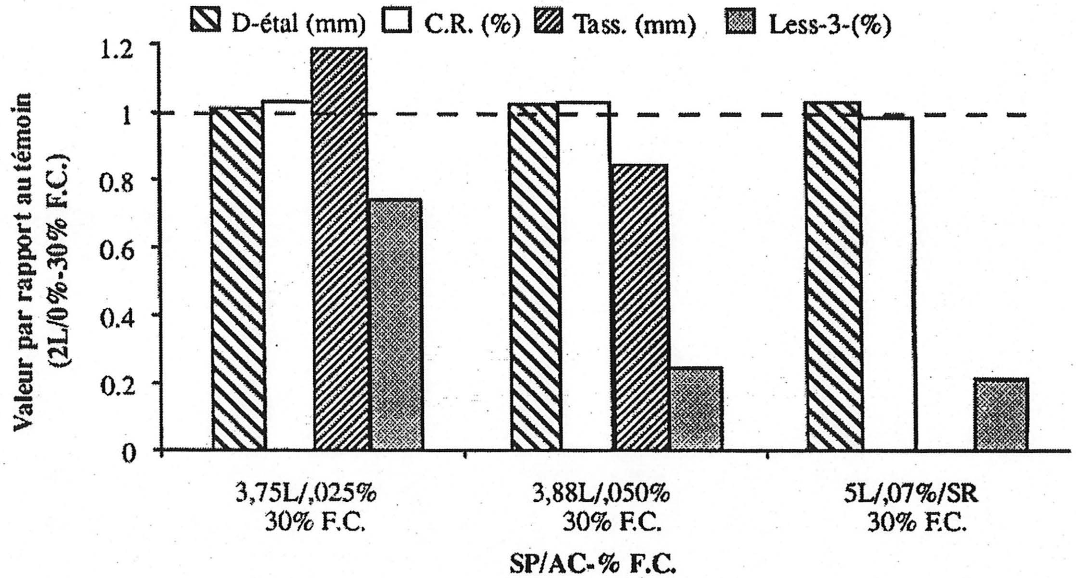


Fig. 2.21.c Effect of VEA dosage on workability of SCC made with 30% Fly Ash. D-étal = slump flow, C.R. = caisson filling capacity, Tass. = surface settlement, Less-3 = washout loss after 3 drops in water (Manai, 1995)

D) Air-Entraining Admixtures

The incorporation of air-entraining admixture (AEA) can lead to the formation of fine and uniformly distributed air bubbles in the plastic mortar that can remain after hardening. The main advantage of entrained air in concrete is to increase its durability to freezing and thawing. The entrainment of air can also increase the resistance to segregation and bleeding (CPCA, 1995).

Some of the materials used as AEA include salts of woods resins (Vinsol resin), some synthetic detergents, salts of sulphonated lignin, salts of petroleum acids, salts of proteinaceous material, as well as fatty and resinous acids (CPCA, 1995).

When using VEA, greater addition of AEA may be necessary to secure a given air volume (Khayat, 1995). When using fly ash the dosage of AEA can also increase; this is dependent of the carbon content of the fly ash. The use of GBFS will also increase the required dosage of AEA but to a smaller amount than most fly ashes. The use of silica fume can cause the largest increase in AEA demand (CPCA, 1995).

The main effect of introducing AEA on the rheology of concrete is the reduction of plastic viscosity. Sometimes, yield value can also decrease, but that has only been reported for stiff mixtures. For a very fluid mixture, the yield value can even increase slightly; however, in a non-significant way (Wallevik, 2003).

E) Set-Retarding Admixture

Set-retarding admixture is used to retard the setting time of concrete. It is used either to increase or to maintain open time, control heat of hydration, and control strength development. Under hot weather, the use of such admixture can be quite helpful. The main problem when using a set-retarding admixture is the increase of bleeding and settlement due to the longer open time (CPCA, 1995). The development of early age strength is also reduced.

2.3.5 Other Parameters

Temperature: changes in concrete temperature can influence workability and the loss of fluidity with time. For repair applications, loss in slump flow can be a problem when ready-mix concrete is used. When using a polycarboxylate HRWRA at low temperature, initial fluidity is usually low and increases with time. When it is used at high temperature, fluidity decreases with time (Yamada et al., 1999). This phenomenon has been explained from different points of view: cement hydration, polycarboxylate adsorption, specific surface area of hydrated cement, and sulphate ions in solution (Okamura et al., 1995; Yamada et al., 1999).

Influence of the mixer and mixing type: in research conducted by Takada et al. (1999), the effect of different mixers and mixing times was evaluated. Using concrete with the same consistency and w/cm, the authors found that concrete viscosity decreased when the mixing intensity is increased. At the same time, HRWRA demand increased proportionally to the mixing intensity. Usually, a forced mixer provides more intensive mixing than a gravity tilting mixer. Two effects have been proposed to explain the decrease of viscosity with the increase in mixing intensity.

- dispersing effect of the mixer on powder particles: when mixing is less intense powder particles have the tendency to agglomerate increasing the viscosity of the concrete;
- the effect on surface procession of powder particles, an intensive mixing breaks the adsorption of HRWRA on the surface of cement grains and early hydration products. This process is repeated continuously resulting in an increase of HRWRA demand for a given slump flow. In addition, the "torn" particles act as lubricants decreasing the viscosity of the mixture;
- the effect of air bubbles: a more intensive mixture generates greater volume of fine air bubbles. A lubricant effect is achieved in concrete decreasing viscosity; and
- the temperature increases when mixing times are longer or when mixing is more efficient.

Chapter 3

USE OF SCC FOR REPAIR APPLICATIONS

3.1 Methodology of Repair

In order to successfully repair a given concrete structure, deterioration of the structure must be stopped, structural integrity must be restored, and acceptable aesthetic finish must be attained (Rizzo et al., 1989). Tracy et al. (1989) proposed a three-step process to achieve successful repair. This is described below.

1. A concrete condition assessment

A visual inspection is performed followed by a revision of proper engineering records, such as design and construction documentation, materials records, etc. A jobsite condition survey is useful to locate the causes or sources of **defects**, **damages** and/or **deteriorations**.

2. An investigation concerning structural aspects

An evaluation of structural, functional and operational constraints imposed to the project is necessary. The repair method will be different depending on several factors, such as the original construction system, the use of the structure, and the constraints imposed by external factors.

3. The repair method

Before selecting any repair method, the cause of the damage must be assessed and the objective of the repair understood. The repair method includes selection of the repair material, preparation of the surface, cleaning of the reinforcement, bonding between new and old materials, and selection of the placement technique. Repair methods can be classified as, repair work not requiring strengthening of the structure, and strengthening of structural members.

The choice of the repair material depends on the volume of the repair material to be replaced, the depth of the repair, the loading effects to be expected, and the conditions of application on site. Proper compatibility between new materials and the original concrete is important. This compatibility includes viscoelastic properties, coefficient of thermal expansion, and drying shrinkage. A lack of compatibility may produce serious internal stresses resulting in tension cracks, loss of load-carrying capability, delamination, corrosion of reinforcement, and poor appearance (Emmons, 1993; Tracy and Fling, 1989). The understanding of the repair material's response to a given service/exposure condition helps in determining the required material properties.

Most commonly used repair materials include: Portland cement concrete, silica fumemodified Portland cement concrete, fibre-reinforced Portland cement concrete, surface sealers, membranes, joint sealants, and anchors.

The objective of the surface preparation is to provide a dry, even, level surface, free of dirt, dust, oil, and grease. The first step for preparing the surface is the removal of damaged concrete. This can be done using one of the following methods:

a) mechanical methods;

- demolitions by means of explosions, splitting and impacting. This method is recommended for demolition of large concrete masses. Several explosive techniques, hydraulic splitting tools, and falling mass techniques are available;
- demolitions by means of drilling and separating. This include saws, core-drilling devices, and grinders;
- chipping off. Recommended for concrete layers of small thickness. Electric hammers, compressed-air hammers, or chisel devices are used. It is important to avoid direct contact between tools and reinforcing bars or prestressing tendons;
- removal of concrete to a flat surface by means of a milling device. Care should be taken to avoid damaging sound concrete or reinforcement;
- sand-blasting. Recommended for thin layers under 5 mm. Especially suitable for roughening of the surface and removal of pollutants, layers of cement, and loose particles;
- the water jet technique. Its efficiency depends on the applied pressure. The pressure goes from 10 MPa (to remove loose particles, scaled concrete, or vegetation coatings) up to 240 MPa (capable of deep penetration or even for cutting grooves on concrete). If quartz sand is added to the water jet even high strength concrete can be cut without dust and vibration;

- grit blasting. Small steel balls are impacted upon the concrete surface through a centrifugal device, thus producing an abrasive action on the concrete surface; and
- steam blasting. Only used to clean concrete surfaces, removal cannot be achieved.

b) ***thermal methods:*** concrete surface is heated up to 1500°C, using an oxy-acetylene flame, to produce a thermal shock leading to scaling of the concrete surface. Because of the high temperature of the flame, it cannot be guaranteed that distress will not occur at greater depths of the concrete; and

c) ***chemical methods:*** acids or alkalines are used for concrete removal. Due to a risk of corrosion, acids should not be used for reinforced and prestressed concrete.

Emmons (1993) reported that the removal of the concrete surrounding the corroded bars is necessary to eliminate chlorides and carbonated concrete present around the rebar. Chloride contaminated layers must be mechanically removed or treated with water, lime milk, or electro-osmosis.

Removal of the surrounding concrete allows the repair material to encapsulate reinforcement, providing a relatively uniform electro-chemical environment. Anchorage between the new and the old material is enhanced (Matt et al., 1991).

In order to properly repair the structure, cleaning of the corroded bars or replacement of damaged ones is necessary.

After damaged concrete cover has been removed, the surface to be repaired must be cleaned before receiving the repair material. Some of the methods use to prepare the surface are: chemical cleaning, mechanical cleaning, blast cleaning, acid etching, and flame cleaning.

The surface to be repaired must be strong enough to achieve proper adhesion with the repair material. Depending on the selected material, surface is required to be dry or saturated.

The quality of the bond between the old and the new material determines the success of the reparation. Repairs, which have bond lines in direct tension, have the greatest dependency on bonding. Repairs that are subject to shear stresses at the bond line are capable of stress resistance not only by bonding mechanisms, but also by aggregate interlocking.

In order to measure bond between old and new materials in the laboratory, several tests are currently used: the slant shear test, the direct shear test, the direct pull-off test, the uniaxial tensile tests, and the flexural testing. Since these methods measure the bonding stress in different ways there is no possible to correlate their results (Emmons, 1993).

In some special cases, bonding agents are used. There are two different types of bond mechanisms: physical bond through adhesion and cohesion, and chemical adhesion through reaction with the surface. Three main types of bonding agents are generally used, cement based slurries, epoxies, and latex emulsions. The bonding agent is chosen depending on the substrate and the repair material.

In certain occasions, the structure's integrity is not compromised, however, a repair is required for aesthetical reasons. In some cases, there might be concern of further development of an already existing weathering of the concrete surface (Matt, et al., 1991). Protection of the concrete surface is then required. The following surface protection measures can be used:

- hydrophobation, achieved by a change of the contact angle between the surface of the material and a water drop. Usually, liquids of a silicone base are used;
- paint coats, systems in which a closed film is produced on the surface;
- impregnation, prevents the penetration of water and solutions into the concrete without hindering the escape of internal moisture from the concrete;
- sealers, provide a heavy barrier against penetrating liquids; however, they hinder the escape of internal moisture. The efficiency of the sealing system is influenced by the type of material and the layer thickness; and
- coatings, they have the same function as the sealers, but they also protect the surface from mechanical effects. Therefore, coatings thickness is larger than those of sealers.

If the deterioration process has reached a level where a shallow surface repair is not feasible, a replacement of the missing concrete section should be considered. Reparation may be required for strengthening the structure or simply to improve the aesthetic or to stop a superficial damage. The repair methods of replacing a substantial depth of concrete include:

shotcrete, suitable for the repair of damaged surfaces, concrete replacement, or strengthening of structural elements. There are two basic shotcrete processes:

a) dry mix process where, mixing water is added at the nozzle and the cement-sand mixture is carried by compressed air through the delivery hose to a special nozzle; and
b) wet mix process where, all the ingredients, including water, are mixed before entering the delivery hose.

low-pressure spraying, this method is similar to the wet mixture shotcrete. It is applied using a small concrete pump or a heavy-duty grout pump. Very little material is rebounded in comparison to shotcrete. Applications of this method include: bridges, bridge and building piers, structural slab undersides, tank walls (interior and exterior), stadiums, tunnels, and retaining walls. The mixture ingredients vary widely, and their selection depends on the specific repair situation;

surface repair using form-and-pour techniques, this technique involves several steps in preparation, formwork construction, and placement of repair materials. The repair materials are placed in the formworks using, buckets, chutes, or buggies. When a conventional concrete is used as the repair material proper consolidation is accomplished by vibration or rodding. The primary consideration to select the materials used in this method is the placeability, mixtures with high flowability will make the placement easier. This method is usually intended for repairing walls, columns, beam sides and bottoms. The advantages of this technique include: different types of repair materials can be used, the repair material can be placed around reinforcing steel relatively easy, and formwork protects against early-age drying that promotes cracking; and

surface repair using form-and-pump techniques, several steps are required in this method, the preparation and construction of the formwork, and the pumping of repair materials into it. Consolidation of the repair material is achieved after the formwork is full, the pump continues to pressurize the material to release the entrapped air. Structural integrity and/or concrete cover requirements are repaired for the damaged elements with this method. The primary consideration to select the materials used in this method is the pumpability. This method is usually intended for repairing walls, columns, and beam sides and bottoms. The formwork must resist the pressure of the material and the pressure after it is full and pressurized. Advantages of this method include, premixed repair materials, formwork supports materials during the placement process; formwork protects the repair material during the curing process, etc.

3.2 Utility of SCC in repair applications

The placement of repair concrete often involves the casting through restricted sections that represent some challenges to ensure successful placement and consolidation. Access for vibrators is often limited due to the small free space inside the formwork and given the densely reinforced sections in some cases. In these circumstances, full encapsulation of the reinforcement is difficult. The use of SCC can indeed facilitate repair operations, secure high quality finish and reduce cracking of the concrete compared to standard repair materials (Campion et al., 2000). SCC can be pumped from the bottom of the formwork or dropped from the top. The recommended maximum free fall height should be less than 2 m, although good surface quality has been reported with drop heights of up to 6 m in restricted sections (Campion et al., 2000).

In addition to its advantages as a highly flowable concrete that can simplify some construction operations, SCC can present some added-value attributes at the hardened state. Experience in Sweden indicates that highly stable SCC used in bridge construction can develop superior microstructural characteristics at the transition zone between cement paste and aggregate than conventional concrete of normal consistency (Billberg, 1999).

Due to its high stability the segregation resistance is secured, resulting in superior surface quality. Aesthetically, the final product is superior as less bug holes and honey-combs can occur (Khayat, 1999). SCC can also be suitable for overhead repair applications. Because mechanical vibration is not needed, placing time is shorter, resulting in shorter construction time. Fewer workers are needed and the working environment is improved (Lacombe et al., 1999).

The proper use of fines in SCC or a correct dosage of VEA decreases bleeding, segregation, and sedimentation, resulting in better bonding between parent concrete and repair material (Lacombe et al., 1999).

3.3. Case Studies for Use of SCC

a) ***Motorway flyover***

The supporting reinforced concrete beams of a motorway flyover in the United Kingdom began experiencing problems due to the penetration of de-icing salts into deteriorated joints used in the upper road deck (McLeish, 1994). Due to difficult access, congested reinforcement, and low cover in some areas, SCC was proposed. Key specifications included:

Binder content	450 kg/m^3
Maximum-aggregate size	8 mm
Water/binder	0.40
Minimum f'c	30 MPa at 3 days at 20°C
Maximum f'c	60 MPa at 7 days at 20°C

Several tests were conducted on fresh and hardened concrete before accepting suitable formulations for use in repairs to the structure. The suitability of each batch was demonstrated by production control tests. Further site tests were carried out on every batch. Quality control and appropriate characteristics were correctly assessed.

b) Repair of a cast-in-place bridge

A bridge built in the early 1960s in the Swiss Alps showed an advanced degree of corrosion due to chloride penetration. Repair of the concrete section along with the reinforcing steel was required because of increased traffic volume (Campion and Jost, 2000).

The repair design included the casting of SCC between two damaged beams. The existing beams and the underside of the bridge deck would form three sides of the newly repaired beams. A form would be fastened to the underside of the existing beams to create the void that would be the new beam.

Concrete was then pumped into the formwork from the bottom. SCC was chosen because consolidation inside the beam was not possible, and the reinforcement density was high. In order to ensure that air could escape from the formwork, holes were drilled through the deck. The mixture proportions included:

Maximum size aggregate	16 mm
Type II Cement	435 kg/m^3
Silica fume	15 kg/m^3
Admixtures	10 mL/kg Sika Viscocrete, by weight of cement
	2.5 mL/kg Sika AER SCC, by weight of cement
Slump flow	680 mm

The use of SCC eliminated the need for vibration. Labor cost was reduced, and in general the work environment was improved. Placement time decreased as well as finishing time, so productivity and profitability increased. Finally, the higher flowability improved the appearance of the finished element.

c) *Repair of parapet wall*

The repair of the upper surface of a 200-m long retaining wall located in a patrimonial area in Montreal was required given extensive corrosion damage and delamination of the concrete (Khayat and Morin, 2002).

The new formwork was complex with special surface definition, return angles and a bell-shaped section at the bottom. Access to vibrators was restricted, and high quality architectural finish was required. The mixture proportioning of the SCC was as follows optimized for this application in 2000:

Type 10 Cement	240 kg/m^3
Blended silica fume cement	240 kg/m^3
w/cm	0.37
Coarse aggregate	297 L/m^3
Maximum-size aggregate	10 mm

The SCC was required to have a slump flow consistency of 650 ± 50 mm, a minimum filling capacity of 70%, a minimum V-funnel flow time of 6 s, a maximum surface settlement of 0.5%, an initial air volume of 4% to 8%, and a 28-d compressive strength of 50 MPa.

From measurements in seven trucks, the slumps flow of the cast concrete varied from 575 to 700 mm (values include measurements of both concretes from start and end of casting from trucks) with an average value of 640 mm. The measured air volume varied from 4.2% up to 7.8% with an average value of 5.9%. The V-funnel flow time values went from 3.1 s to 5.8 s the average time was 4 s. Finally, the filling capacity values varied between 65% up to 100%, with an average value of 88%. Maximum settlement of plastic concrete was 0.5%, measured using a 700 mm high column with a diameter of 200 mm.

Concrete maintained excellent fluidity and stability to ensure adequate flow into place. SCC spread into place readily without any blockage, completely filling the formwork with only minor defects. Hardened properties were also good. SCC showed excellent frost durability and resistance to de-icing salt scaling.

3.4 Performance Specifications for SCC as Repair Material

Rizzo et al. (1989) reported that the characteristics of the materials used in different repairs should include:

- ability to bond adequately to the substrate;
- movement relative to the substrate, which depends on shrinkage, thermal movement, and behaviour when exposed to wetting and drying cycles;
- permeability to water, gases, and aggressive ions, and chemical passivation of reinforcement;
- strength;
- ease of application; and
- durability under freeze-thaw cycling, chemical attack, and weathering.

Compressive strength, shear strength, modulus of elasticity, and coefficient of thermal expansion of repair concrete must be similar to the values of the original concrete. Creep and drying shrinkage must be low in order to minimize high bond line stresses between the patch material and the original concrete (Tracy and Fling, 1989). According to Weyers et al. (1993), usual requirements for concrete can be as follows:

- Portland cement Type I or II according to ASTM C 150,
- maximum w/c of 0.42 (exceeding this value is absolutely prohibited;
- maximum-aggregate size of 13 mm;

- total air content between 6% and 8%; and
- total water content should be kept to a minimum, in order to prevent shrinkage.

Often, engineers are overly concerned with hardened properties and not enough with fresh concrete properties. It is important that the concrete intended for repair applications has good workability and stability to ensure no reduction of strength, stiffness, and proper encapsulation of reinforcing steel bars (Lacombe et al., 1999). Based on early experience with the use of SCC in repair since 1997, the Quebec Ministry of Transportation proposed in 2000 the following specifications shown in Table 3.1 and 3.2 for SCC as repair material (Hovington, 2000):

TABLE 3.1 FRESH PROPERTIES FOR REPAIR SCC (ACCORDING TO THE QUEBEC MINISTRY OF TRANSPORTATION)

f'c at 28 days	35 MPa
Cementitious materials (min.)	460 - 480 kg/m^3
w/cm	0.35 - 0.40
Coarse aggregate (MSA 10 mm)	330 L/m^3
Air volume	6 - 9%
Slump flow	650 ± 50 mm
Maximum flow time (V-funnel)	6 s
Sand-paste ratio in volume	0.60 - 0.75
Temperature	10 - 25° C

For hardened properties the Ministry refers to the following ASTM specifications:

TABLE 3.2 HARDENED PROPERTIES FOR REPAIR SCC

Air-void system, spacing factor (ASTM C457)	≤ 230 μm
Chloride-ion permeability (ASTM C1202)	≤ 1000 Coulomb
Scalling mass loss (50 cycles) (ASTM C672)	≤ 0.8 kg/m^2
Frost durability coefficient (ASTM C666)	≥ 60%

Based on previous studies, other recommendations are used for SCC (Khayat, 1998, Khayat, 2000; EFNARC 2002) as indicated in Table 3.3.

TABLE 3.3 OTHER FRESH PROPERTIES FOR REPAIR SCC

Filling capacity	≥ 80 %
J-ring flow difference with slump flow	≥ 10 mm
Surface settlement	≤ 0.5%
Slump flow loss (after 60 min)	≤ 50 mm
Blocking ratio (L-box, h2/h1)	≥ 0.8

3.5 Need of Research on Fresh Properties of SCC

Due to Canada's severe environment and its aging infrastructure, a considerable portion of bridges and parking structures need maintenance and repair.

Fresh properties of repair materials are sometimes overlooked, although they are as important as hardened properties in successful repairs. This is especially important when access for casting and vibration is difficult.

Better understanding of the behaviour of HRWRA, VMA, AEA, and different cementitious systems to produce SCC is necessary. Several polycarboxylate-based and polynaphtalene sulphonate-based HRWRAs have recently been introduced on the market, and their performance is not still well established, especially in terms of flowability, self-consolidation, and stability.

Furthermore the performance of SCC proportioned either low w/cm or moderate w/cm and VEA using these admixtures is not fully understood. This includes the compatibility between the cementitious materials and admixtures.

3.6 Objectives of this research

The Master's dissertation has been undertaken to achieve the following objectives:

- to compare fresh properties and rheological parameters of SCC made with low w/cm of 0.35 and no VEA versus SCC with moderate w/cm of 0.42 and VEA;
- to compare the effect of different brands of chemical admixtures available on the market on workability, self-consolidating properties and rheology of SCC;
- to compare the effect of different binders in SCC made with a moderate w/cm and VEA;
- to compare the performance of PCP and PNS based HRWRA;
- to confirm the limit values of different test methods used to asses workability of fresh SCC; and
- to recommend the application of field oriented test methods that can be used to control SCC quality on the jobsite.

Chapter 4

RESEARCH PROJECT

4.1 Introduction

At the present time SCC is beginning to be better known and understood. It is slowly gaining acceptance in the industry and every year, more structures are built or repaired using this technology. However, better understanding is required of its characteristics, mixture proportioning methods, and the influence of new cementitious materials and admixtures. Chemical admixtures producers offer a larger number of products to use in the production of SCC. A similar trend is occurring in the cement industry. The need to incorporate a high amount of fines in SCC to achieve proper self-consolidating properties requires the use of supplementary cementitious materials or blended cements.

The fresh state characteristics of SCC are what set it apart from the other types of high-performance concretes (HPC). Its low risk of blockage, adequate stability, and excellent deformability has made this concrete an excellent option to fill congested structural sections, restricted elements, and geometrically complicated formwork. Limited data are available regarding the effect of combined admixtures and new binder systems on key properties of SCC. More research is necessary to fully understand the effect of these components on fresh properties of SCC.The research project presented in this thesis is divided into two parts: a preliminary evaluation and an extensive investigation. The preliminary evaluation was started in the summer of 2001 were SCC mixtures were prepared using various combinations of cementitious materials and different combinations of chemical admixtures. In the first phase of the main research project, admixtures from five different producers were used to optimize SCC mixtures proportioned with 0.35 and 0.42 water-to-cementitious materials ratios (w/cm). The influence of binder type on workability of SCC mixtures with a 0.42 w/cm and VEA was investigated in the second phase of the detailed investigation. The dosage rates of the HRWRA and AEA were adjusted to obtain similar initial slump flow and air volume values in all of the evaluated mixtures.

In all the phases of this study, the concrete was tested for deformability, passing ability, filling capacity, and stability using the slump flow, L-box, V-funnel, filling capacity, J-ring, and surface settlement tests. The concrete was also evaluated for rheological parameters using a concrete rheometer. Fluidity retention and stability of entrained air was investigated.

4.2 Methodology

The mixtures prepared during the preliminary evaluation are shown in Table 4.1. First, mixtures were prepared without a set retarder. Two different w/cm were used: 0.35 and 0.42. For mixtures with w/cm of 0.35 different replacement values of fly ash were evaluated. For mixtures with w/cm of 0.42 different dosages of VEA were evaluated. Finally, mixtures with w/cm of 0.42 were proportioned with a set retarder.

The main research project is divided into two phases, as shown in Table 4.2. In Phase I, 10 mixtures were prepared to determine the influence of chemical admixtures on workability. Six different HRWRA obtained from Axim, Chryso, Euclid, W. R. Grace, and Master Builders were used in this research; this included five polycarboxylate based HRWRA and one polynaphtalene based HRWRA. Two different w/cm were used: 0.35 and 0.42. For 0.35 w/cm mixtures, a cementitious materials combination of 65% Type 10 cement, 30% Class F fly ash, and 5% silica fume is used. For mixtures with 0.42 w/cm, a ternary binder incorporating 63% of Type 10 cement, 32% fly ash and 5% silica fume was used.

In Phase II of the main research project, a parametric study was undertaken using 12 mixtures prepared with the same w/cm (0.42), a fixed dosage of VEA, and three different binders (two ternary binders and one quaternary binder). Four different HRWRA were used in the parametric study; three polycarboxylate based HRWRA and one polynaphtalene based. Also four different VEA types were used.

TABLE 4.1 MIXTURES PRELIMINARY EVALUATED

<table>
<tr><th></th><th>w/cm</th><th colspan="12">Mixture</th></tr>
<tr><td rowspan="2">Mixtures without set retarder</td><td>0.35</td><td colspan="6">5% SF, 30% FA</td><td colspan="6">5% SF, 35% FA</td></tr>
<tr><td>0.42</td><td colspan="3">0.6% VEA 1</td><td colspan="3">0.6% VEA 2</td><td colspan="3">0.4% VEA 1</td><td colspan="3">0.4% VEA 2</td></tr>
<tr><td>Mixtures with set retarder</td><td>0.42</td><td colspan="4">0.4% VEA 1</td><td colspan="4">0.4% VEA 1</td><td colspan="4">VEA 3</td></tr>
</table>

N.B. SF: silica fume, FA: fly ash, VEA: Viscosity Enhancement Admixture.

TABLE 4.2 OPTIMIZATION OF MIXTURES - MAIN RESEARCH PROJECT

18 Mixtures evaluated in Phases I and II						
Phase I						
Admixture combination	*w/cm* = 0.35 65%T10 + 5%SF + 30%FA		*w/cm* = 0.42 Ternary 1			
	1	PCP 1	*6*	PCP 1		
	2	PCP 2	*7*	PCP 2		
	3	PCP 3	*8*	PNS 1		
	4	PCP 4	*9*	PCP 4		
	5	PCP 5	*10*	PCP 5		
Phase II						
Binder type	*w/cm* = 0.42 Ternary 1		*w/cm* = 0.42 Ternary 2		*w/cm* = 0.42 Quaternary	
	6	PCP 1	*11*	PCP 1	*15*	PCP 1
	8	PNS 1	*12*	PNS 1	*16*	PNS 1
	9	PCP 4	*13*	PCP 4	*17*	PCP 4
	10	PCP 5	*14*	PCP 5	*18*	PCP 5

4.3. Materials used

Binders supplied by different cement companies were used: Saint Lawrence Cement, Lafarge Cement and Cement Quebec. Powder silica fume from SKW was also employed. The properties of these binders are presented in Table 4.2.

TABLE 4.3 PHYSICO-CHEMICAL CHARACTERISTICS OF CEMENTITIOUS MATERIALS.

	Silica Fume	**Fly Ash Class F**	**Cement Type 10**	**Ternary 1**	**Ternary 2**
SiO_2	92.39	43.6	19.9	32.3	26.5
Al_2O_3	0.42	23.6	4.5	8.7	5.1
Fe_20_3	0.52	21.4	3.3	5	2.7
CaO	1.93	4.06	62.4	45.5	55.8
MgO	-	0.33	2	1.4	4
Na_2O eq.	0.77	1.39	0.86	0.6	0.79
SO_3	-	3.02	3.6	3.5	3
L.O.I.	3.74	2.9	2.5	1.4	0.8
Specific gravity	2.22	2.38	3.07	2.89	2.98
Blaine fineness	-	270	405	585	615
BET	17500	-	-	-	-

A continuously graded crushed limestone aggregate with a maximum size of 10 mm and well-graded siliceous sand were employed. The bulk specific gravity of the sand was 2.64, and its fineness modulus and absorption values were 2.46 and 1.2% respectively. The bulk specific gravity of the coarse aggregate was 2.73 and its absorption 0.5%. The grain-size distribution of the fine aggregate is shown in Fig. 4.1. The grain-size distribution of coarse aggregate is shown in Fig. 4.2. Both the sand and coarse aggregate have grain-size distributions that lie within the CSA Standards A23.1 recommendations.

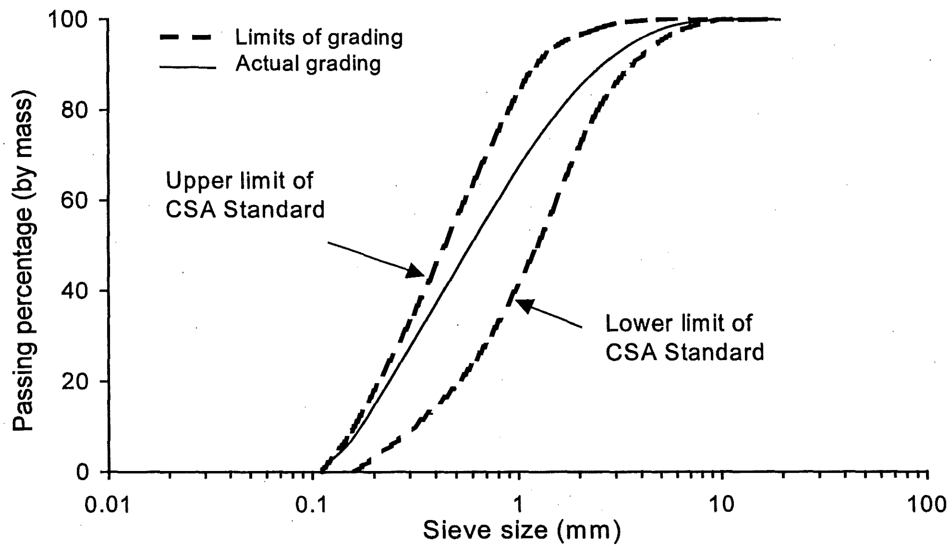


Fig. 4.1 Particle-size distribution of fine aggregate

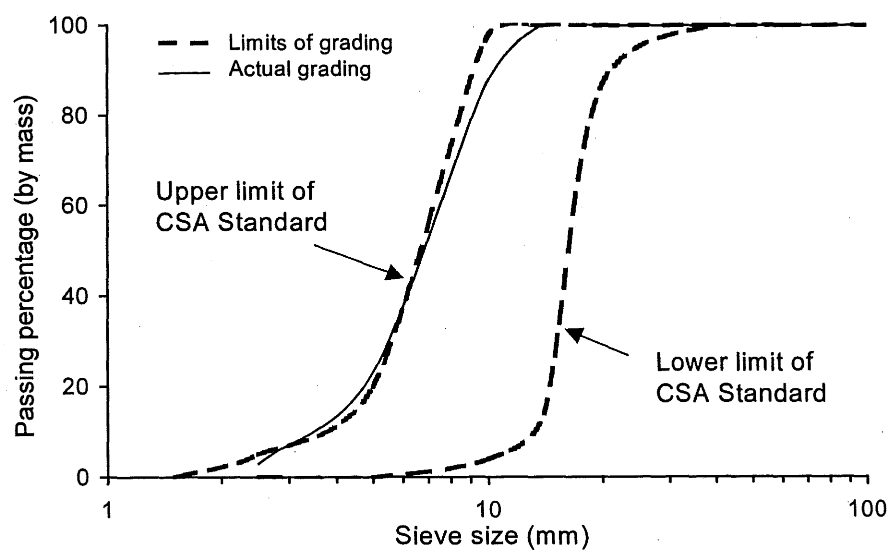


Fig. 4.2 Particle-size distribution of coarse aggregate

Different brands of chemical admixtures were used and supplied from different admixture producers. The commercial names, solid contents (SC), and specific gravities (SPG) of all these chemical admixtures are summarized in Table 4.3. Two types of HRWRA were used, including a polycarboxylate and a polynaphtalene along with five types of VEA and AEA.

TABLE 4.4 CHEMICAL ADMIXTURES USED IN THIS PROJECT

Company	HRWRA	VEA	AEA	Others
W.R. Grace	Adva Cast 540 SC: 20% SPG: 1.06	VEA 1090 SC: 50% SPG: 1.35	Darex EH SC: 0% SPG: 1	Daratard 17 SC: 49.3% SPG: 1.23
Euclid	Plastol 5000 SC: 32% SPG: 1.02 Eucon 37 SC: 40.5% SPG: 1.21	Euconivo L SC: 42.5 SPG: 1.21	Air Extra SC: 0% SPG: 1	Eucon DX SC: 28.5% SPG: 1.15
Chryso	Chrysofluid Optima SC: 30% SPG: 1.06	Chrysoplast SC: 50% SPG: 1.35	Chrysoair G100 SC: 0% SPG: 1	-
MBT	Glenium 3000 SC: 27.1% SPG: 1.09	Rheomac 362 SC: 39.1% SPG: 1.12	Micro Air SC: 0% SPG: 1	-
Axim	Superflux 3000 PC SC: 39 SPG: 1.09	Collaxim L-4 SC: 100 SPG: 0.95	Catexol AE 260 SC: 10 SPG: 1.01	-

4.4. Mixing procedure

All the mixtures were made in a 120-litre open-pan mixer using the following mixing procedure:

1. Sand and aggregate are mixed for one minute with half of the mixing water and the AEA.
2. Cementitious materials are added (0:00 min).
3. All materials are mixed for 30 sec, after which the rest of the water is added with the HRWRA diluted (0:00 to 0:30 min).
4. After three minutes of mixing, the mixer is stopped (0:00 to 3:00 min).
5. Concrete is allowed to rest for five minutes (3:00 to 8:00 min).
6. Mixing is restarted for another three minutes (8:00 to 11:00 min).
7. After one minute of rest the initial testing is started.
8. After initial testing, concrete is remixed for one minute every 10 minutes until 70 minutes after the initial water-binder contact.
9. At 70 minutes, final campaign of testing is carried out.

4.5 Test methods

Following concrete mixing, workability of SCC was assessed using several test methods. The description and procedures of the used test methods are discussed below.

Slump flow test

An ordinary slump cone is filled with concrete according to ASTM C-143. The cone is lifted, and the mean diameter of the concrete flow, after it has stopped, is measured (Fig. 4.3). The test evaluates the capability of SCC to deform under its own weight. For the mixture optimization in this research project, the target slump flow was 660 ± 20 mm.

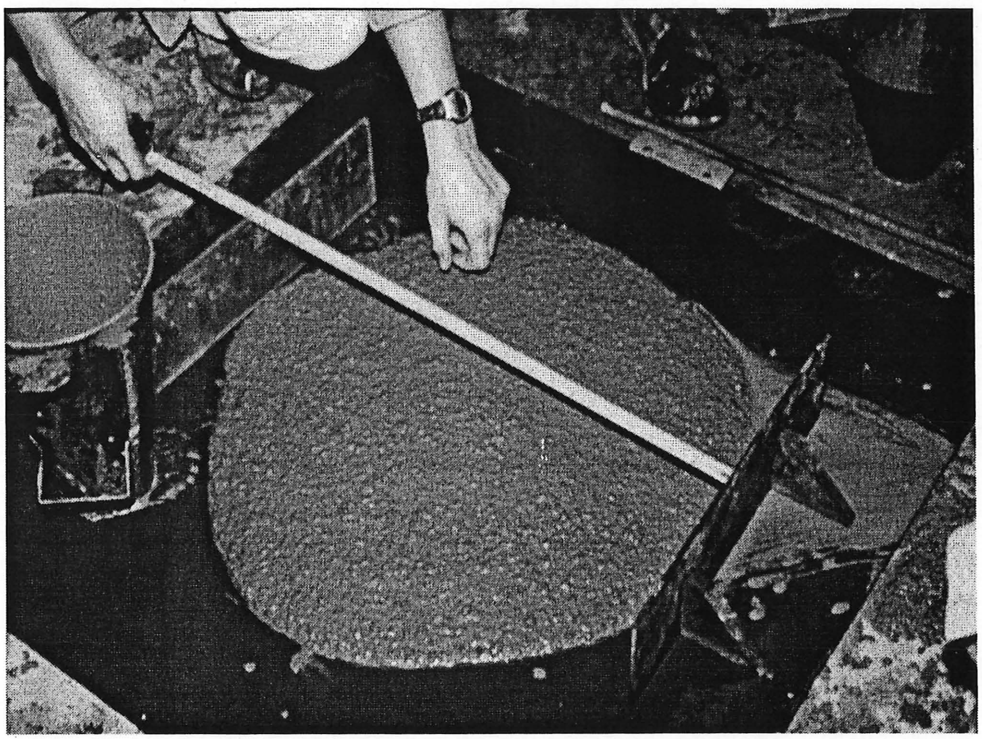


Fig. 4.3 Slump flow test

V-funnel test

The V-funnel consists of a V-shaped container with an opening of 75 x 75 mm in the bottom. It is filled with a 10-L sample and the bottom gate is opened. After 1 min, the bottom outlet is opened and the discharge time of the concrete through the opening is measured. The efflux time is referred to as the flow time and is measured in seconds.

This test is used to evaluate the ability of the fresh concrete along with aggregate particles and mortar to change their flow paths and spread through a restricted section without segregation and blockage. High coarse aggregate content can cause concrete to block affecting the result. High flow time can also be associated with low deformability due to a high paste viscosity, and with high inter-particle friction (EFNARC, 2002).

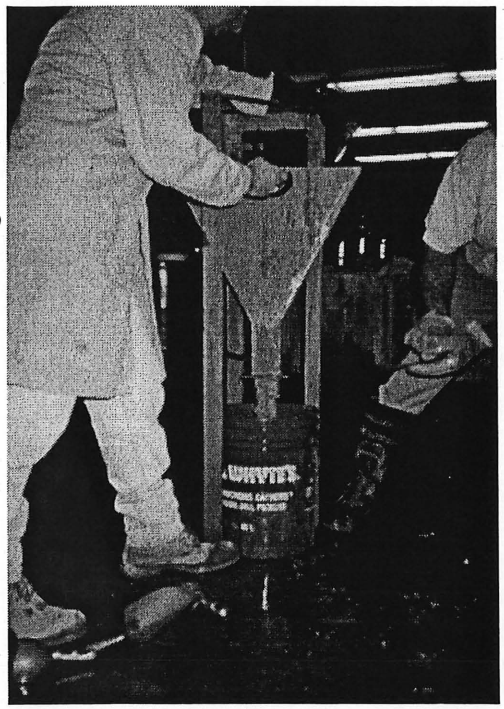


Fig. 4.4 V-funnel test apparatus

L-box

An L-shaped box is used to evaluate the passing ability of SCC through narrow openings. It consists of two compartments separated by a gate, one part is vertical and the other horizontal. Behind the gate, a set of reinforcing bars are located. The bars are 12 mm-diameter with a gap of 35 mm. The vertical compartment is filled with approximately 12.1 L of concrete, then the gate is lifted to let the concrete flow into the horizontal compartment. The time for the leading edge of the concrete to reach the end of the horizontal section is noted. When the flow has stopped, the height of the concrete at the end of the horizontal section (h_2) and the concrete remaining in the vertical section (h_1) are calculated with the following:

$h_2 = 150 - H_2$, Eq. 4.1

$h_1 = 600 - H_1$ Eq. 4.2

The blocking ratio (h_2/h_1) is then calculated. The EFNARC (2002) guidelines suggests a minimum acceptable value of 0.8. If concrete is highly flowable the final surface will be horizontal, in this case $h_2/h_1 = 1$.

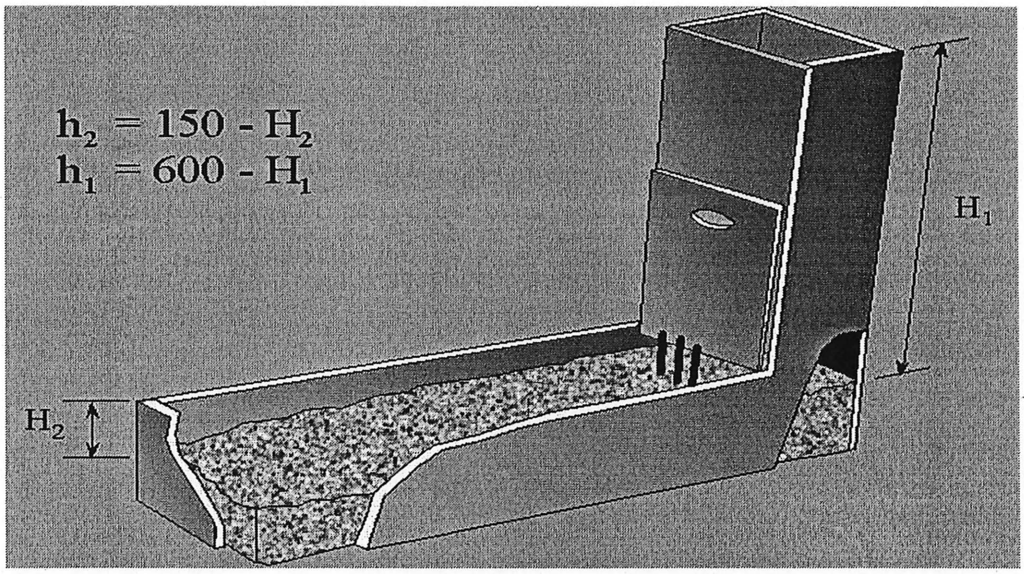


Fig. 4.5 L-box test

J-ring

The J-ring test method is used to assess the passing and blocking ability of SCC through closely spaced obstacles. It consists of a modified slump cone, as shown in Fig. 4.6, placed in the middle of a co-centring ring. The cone is slowly removed, and the mean diameter of the concrete flow after stopping is measured.

The reinforcing bars are 13 mm in diameter and have a clear spacing of 35 mm. The diameter of the ring is 300 mm, centre-to-centre. The result of this test can be compared with the slump flow. The difference between both measurements evaluates the passing ability of SCC through closed spaced reinforcement. The German SCC guideline proposed that the difference between the two tests should not exceed 50 mm (Brameshuber, 2002).

Fig. 4.6 J-ring test

Rheological parameters

The apparent yield stress (g) and torque plastic viscosity (h) were determined using an IBB rheometer. The IBB rheometer is a modified Tatterssal MK III rheometer that has an impeller rotating in planetary motion, as shown in Fig. 4.7.

For a given speed of rotation the torque resistance of the fluid in which the impeller is immersed is determined. The speed vs. torque data is plotted using a linear relationship. The g value represents the intersection of the graphic with the Y axis, while the h value represents the slope of the torque-speed linear relationship, assuming a Bingham fluid. The apparent torque value and the torque plastic viscosity are expressed in N.m and N.m.s, respectively.

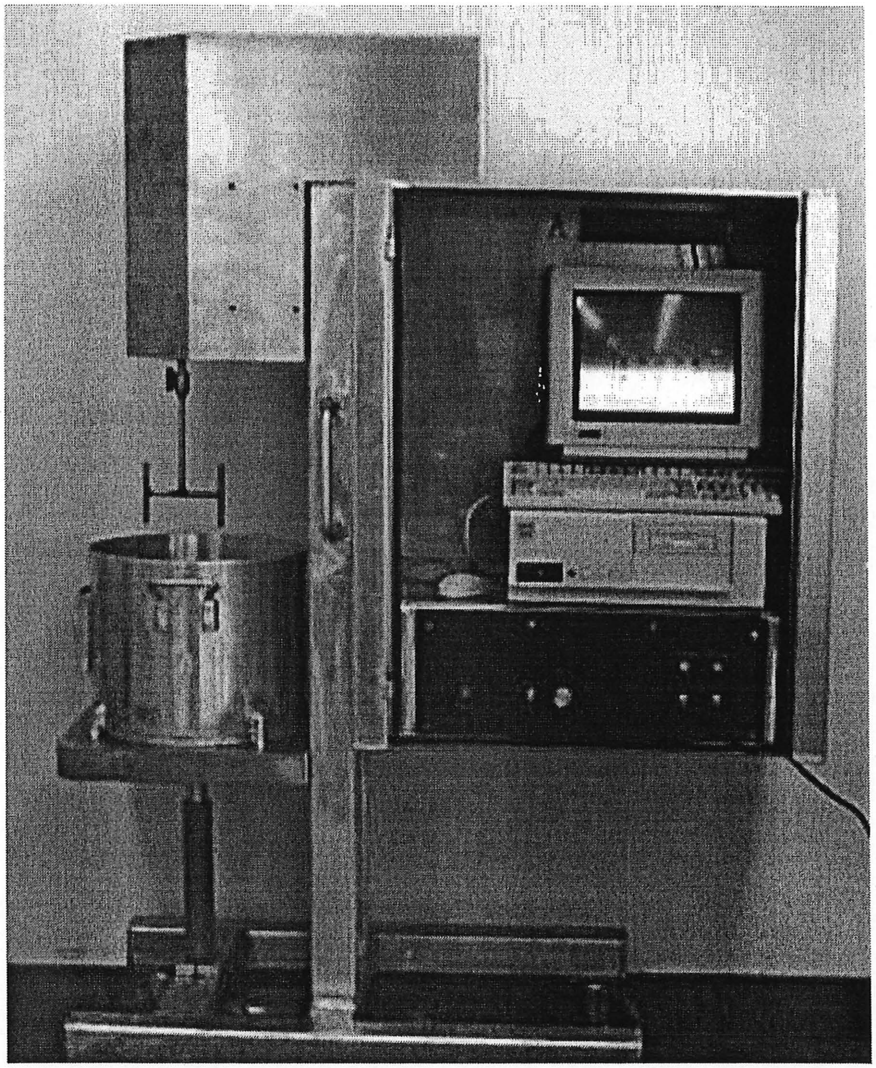


Fig. 4.7 IBB rheometer

Caisson filling capacity test

The filling capacity of SCC is determined by casting concrete in a box measuring 300 × 500 × 300 mm with one transparent side and a hopper for casting the concrete. In the box, 35 smooth copper bars, 16 mm in diameter with a clear spacing of 34 mm are provided (Fig. 4.8).

The test involves the casting of the concrete in the left non-reinforced section at a constant rate of 0.7 l/sec up to a height of 220 mm through the hopper (Khayat, 1999). The ability of the concrete to flow in the restricted region is then quantified.

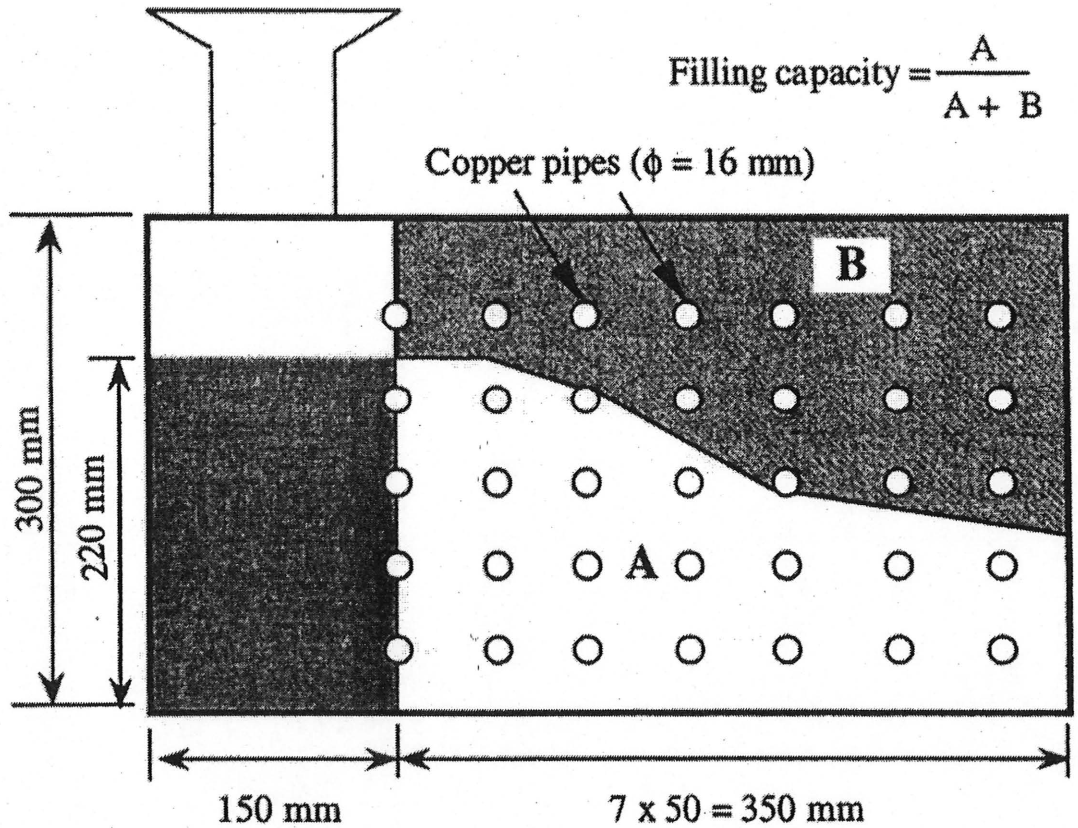


Fig. 4.7 Filling capacity box (Yurugi et al., 1993)

The maximum filling capacity is 100%, meaning that the final level of concrete is almost horizontal, and is calculated with the following formula:

Filling capacity = A / (A + B) Eq. 4.3

where:

A is the actual volume occupied by the concrete, and

A + B is the volume occupied if the box was completely filled.

When the level of the concrete is horizontal across the width of the caisson, the values A and B can be taken as the ones at an end.

Surface settlement

The surface settlement was assessed by casting concrete in a PVC column measuring 200 mm in diameter and 700 mm in height, as shown in Fig. 4.8. Settlement was monitored using a sample of fresh concrete measuring approximately 600 mm in height with LVDT fixed against a thin acrylic plate anchored to the top surface of the plastic concrete (Manai, 1995).

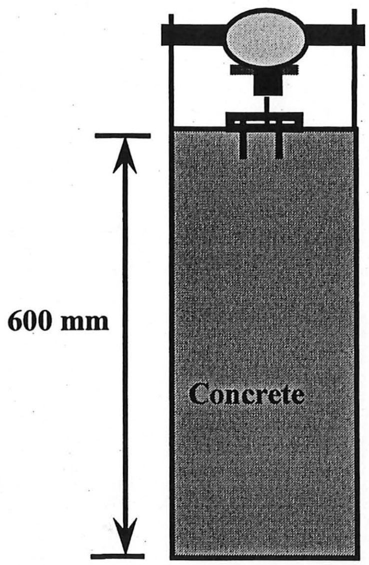


Fig. 4.8 Settlement test column

Temperature, unit weight, and air volume

The temperature, unit weight, and air volume of fresh concrete were determined at 10 and 70 minutes after the initial water-binder contact following ASTM C1064, ASTM C138, and ASTM C 231.

Chapter 5

PRELIMINARY RESULTS

5.1 Introduction

In the summer of 2001, the research project started with the work of David Foisy, an undergraduate student under the supervision of Prof. Khayat. The objective was to develop reference SCC mixtures using two different approaches: SCC made with low w/cm of 0.35 to enhance stability and SCC with moderate w/cm of 0.42 with VEA. Two different VEA types used at different dosage rates were used. The targeted 28-d compressive strength of the SCC designed for repair was 35 MPa. Therefore, several attempts were made to use combinations of fly ash with and without silica fume to achieve the targeted compressive strength in the mixtures with the 0.35 w/cm. In the case of the VEA content with 0.42 w/cm, a commercially available ternary cement was employed. For all mixtures, a proper type of polycarboxylate-based HRWRA was used, along with a highly efficient AEA.

The commercially available ternary binder used in the mixtures made with 0.42 w/cm was the TerC^3 cement from Saint-Lawrence Cement. This cement contains approximately 65% Type 10 cement (T-10), 25% Class F fly ash (FA), and 5% silica fume (SF). On the other hand, for the SCC made with 0.35 w/cm, different percentages of FA were used (30%, 35%, and 40%) to develop an SCC with 28-day compressive strength of approximately 35-40 MPa. when proportioned with such low w/cm. SF was also introduced at 5% replacement value. Two types of VEA were employed in this initial investigation: Viscocrete from Sika and Foxcrete from Avebe Building Chemistry at dosage rates of 0.4% and 0.6%, by mass of binder. In total, seven SCC mixtures were prepared: three with 0.35 w/cm and four with 0.42 w/cm, as shown in Table 5.1.

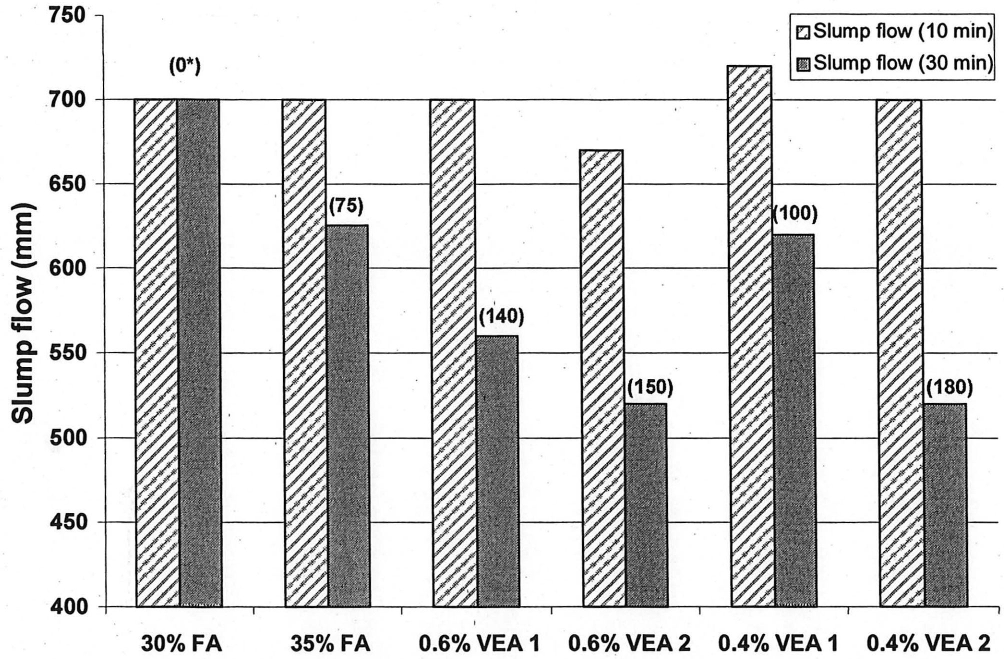
TABLE 5.1 MIXTURES PROPORTIONING OF SCC INVESTIGATED IN THE PRELIMINARY EVALUATION

		30% FA	35% FA	40% FA	0.60% VMA1	0.60% VMA2	0.40% VMA1	0.40% VMA2
w/cm		0.35	0.35	0.35	0.42	0.42	0.42	0.42
Cement		Type 10	Type 10	Type 10	Ter. 1	Ter. 1	Ter. 1	Ter. 1
Cement (kg/m^3)		309	285	262	475	475	475	475
Silica fume (kg/m^3)		24	24	24	-	-	-	-
Fly ash (kg/m^3)		143	166	190	-	-	-	-
Water (kg/m^3)		166	166	166	200	200	200	200
Sand (kg/m^3)		828	824	820	763	764	763	764
Coarse aggregate (kg/m^3)		822	822	822	822	822	822	822
VEA	**g/m^3**	-	-	-	235	-	169	-
	ml/m^3	-	-	-	-	285	-	190
HRWRA (kg/m^3)		3.87	3.2	3.0	2.34	1.72	2.34	1.77
AEA (ml/m^3)		68	70	72	80	72	72	68

The seven optimized SCC mixtures were tested in the fresh state. Slump flow, air volume, and filling capacity were measured at 10 and 30 minutes. As summarised in Table 5.2, the mean slump flow of the seven mixtures was 700 mm. The smallest value was 670 mm in the case of the 0.60% VMA2 mixture, and the largest value was 720 mm for the 0.40% VMA2 mixture. At 30 minutes, slump flow loss varied between 0 and 180 mm; the greater loss was obtained for the SCC proportioned with 0.42 w/cm and a ternary binder. The mixture with 40% FA replacement necessitated lots of water to achieve proper flowability, and does not appear in Table 5.2.

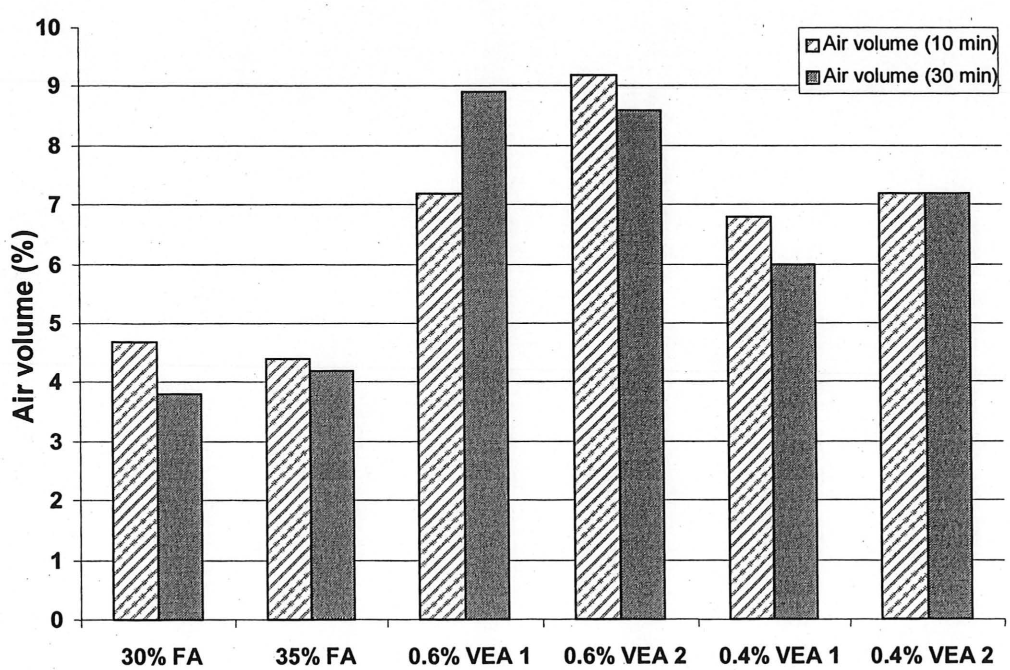
TABLE 5.2 PLASTIC PROPERTIES OF MIXTURES EVALUATED IN THE PRELIMINARY EVALUATION

		30% FA	35% FA	0.60% VMA1	0.60% VMA2	0.40% VMA1	0.40% VMA2
Slump flow (mm)	**10 min**	700	700	700	670	720	700
	30 min	700	625	560	520	620	520
Air volume (%)	**10 min**	4.7	4.4	7.2	9.2	6.8	7.2
	30 min	3.8	4.2	8.9	8.6	6	7.2
Filling Capacity	**10 min**	N/A	89	96	94	99	96
	30 min	86	84	77	68	82	77
Unit weight (kg/m^3)		2366	2348	2225	2208	2260	2234
Temperature (°C)		20	19	20	18.2	18.7	18.1



(*)=Slump flow loss after 30 min, FA=Fly ash, VEA=Viscosity-enhancing admixture

Fig. 5.1 Slump flow of preliminary mixtures



FA=Fly ash, VEA=Viscosity-enhancing admixture

Fig. 5.2 Percentage of entrained air in the fresh state at 10 and 30 minutes after water cement contact

The initial air volume was very different for similar dosages (between 68 and 80 ml), especially when comparing concretes made with 0.35 and 0.42 w/cm. The AEA was shown to be more effective when used in mixtures with a moderate w/cm and a ternary binder than with a 0.35 w/cm and different percentages of SF, FA, and T-10 cement.

The minimum filling capacity at 10 minutes was approximately 80%. However, the loss of filling capacity was quite different for both classes of SCC design. Relatively greater loss in filling capacity was obtained in the mixtures prepared with 0.42 w/cm. This behaviour is compatible with that of the slump loss results shown in Fig. 5.1.

From these preliminary results, the SCC made with 30% FA was selected for further investigation in the preliminary study given its high workability retention. The dosage of 0.40% VEA, was also chosen for both VEA types as it led to better workability and filling capacity characteristics, especially at 30 minutes, compared to the other dosage rates.

In the second stage of the preliminary study, mixtures prepared with 30% FA, 0.4% VMA1, and 0.4% VMA2 were repeated using the same composition, materials, and admixture contents. The mixtures were tested for workability and rheological properties, which are given in Table 5.3. The loss in workability was more pronounced in mixtures made with VEA, as shown in Fig. 5.5.

FA=Fly ash, VEA=Viscosity-enhancing admixture

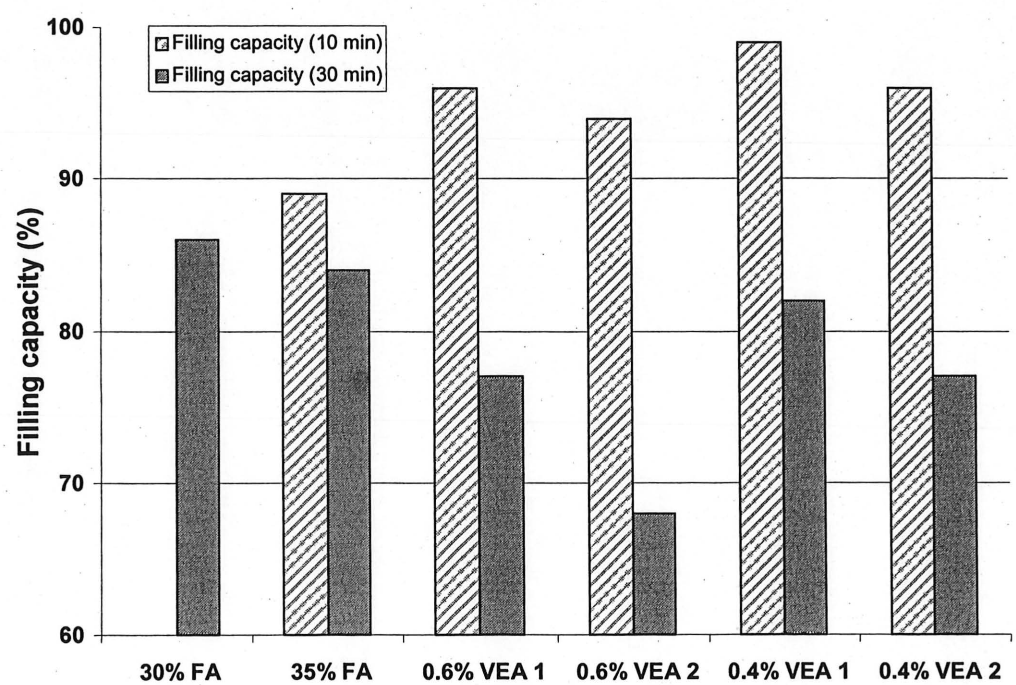
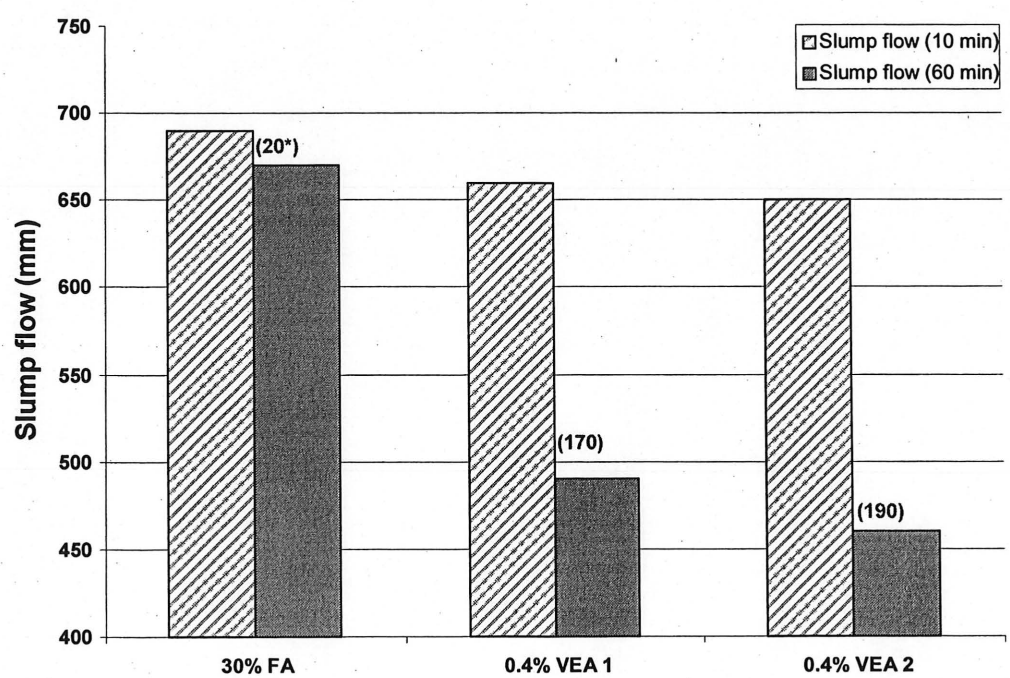


Fig. 5.4 Filling capacity values determined at 10 and 30 minutes

TABLE 5.3 FRESH STATE PROPERTIES OF MIXTURES IN PRELIMINARY PHASE II

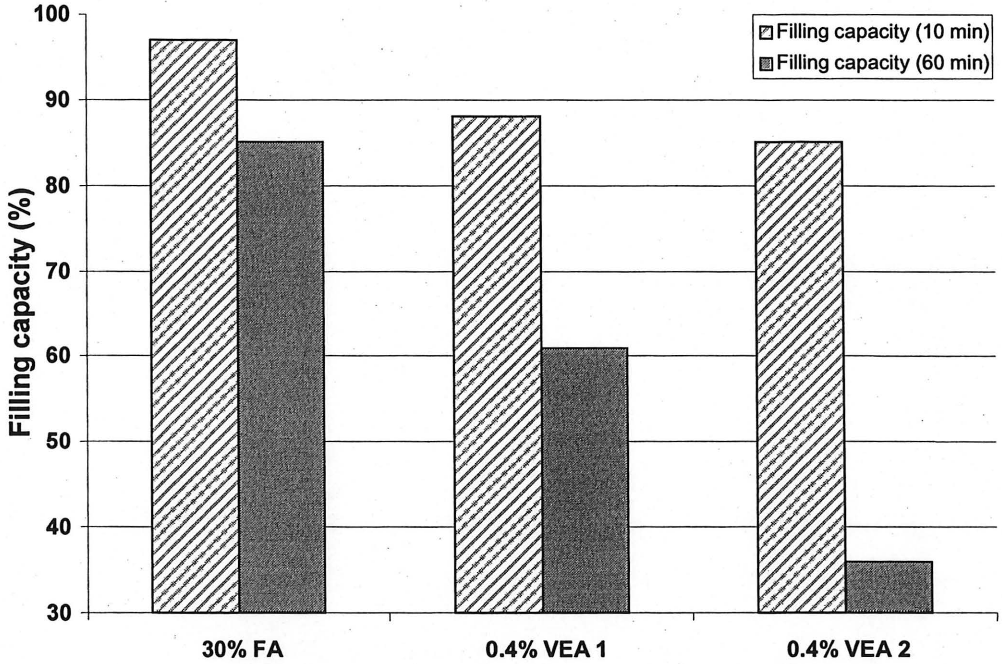
		30% FA	0.40% VMA1	0.40% VMA2
Slump flow (mm)	10 min	690	660	650
	60 min	670	490	460
Air volume (%)	10 min	4.5	6.6	8.8
	60 min	2.7	6.2	8.8
Filling capacity (%)	10 min	97	88	85
	60 min	85	61	36
V-funnel (s)	10 min	8.44	2.81	2.51
	60 min	7.34	3.25	2.82
Rheology	g	0.4	N/A	N/A
	h	20.3	N/A	N/A
Settlement (%)		0.27	1.17	N/A
Unit weight (kg/m^3)		2263	2229	2195
Temperature (°C)		20	20	18.1

The slump flow at 10 minutes was similar for all three mixtures. However, the slump flow loss was quite sharp at 60 minutes for both VEA mixtures and was less than 500 mm in both cases. Along with a sharp decrease in slump flow, the decrease in filling ability of the VEA mixtures was also high after 60 minutes (Fig. 5.6).



(*)=Slump flow loss after 60 min, FA=Fly ash, VEA=Viscosity-enhancing admixture

Fig. 5.5 Slump flow at 10 and 60 minutes



FA=Fly ash, VEA=Viscosity-enhancing admixture

Fig. 5.6 Filling capacity of the three mixtures at 10 and 60 minutes

Losses of filling capacity were larger in mixtures made with VEA and 0.42 w/cm than in mixtures with low w/cm and no VEA. Settlement of the two measured mixtures were also very different: the 30% FA mixture showed a small settlement of only 0.27% when measured in the 700 mm column. The settlement of the 0.40 VEA 1 SCC mixture was quite high at 1.17%. This value can decrease by reducing the HRWRA dosage or increasing the VEA content.

The V-funnel test showed a slight increase in time at 60 minutes, compared with results at 10 minutes for both concretes made with VEA, but there was also a decrease in time when used in the 30% FA mixture. These values reinforce the idea of a loss in workability for these two mixtures.

The 30% FA mixture had low yield value (g = 0.40 N.m) and high plastic viscosity (h = 20.3 N.m.s). The high viscosity can well be the cause for the low surface settlement obtained for this mixture.

Given the loss of workability of the VEA concrete, the use of a set retarder was adopted in the third stage of the preliminary study for the VEA concrete. A new VEA was also used (Rheomac 450 UW from Master Builders). The mixtures compositions of the concretes evaluated were as shown in Table 5.4. Results of the fresh concrete properties are summarized in Table 5.5.

TABLE 5.4 MIXTURE PROPORTIONING USING SET RETARDER AND VEA

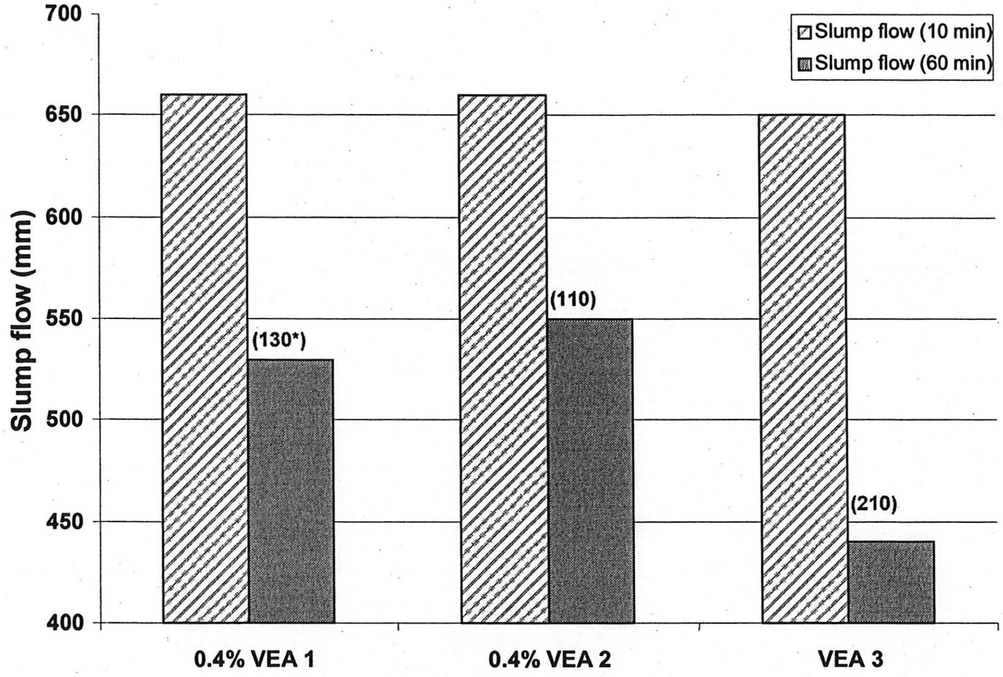
		0.40% VMA1	0.40% VMA2	3% Rheomac 450 UW
w/cm		0.42	0.42	0.42
Cement type		Ternary	Ternary	Ternary
Cement (kg/m^3)		475	475	475
Water (kg/m^3)		166	200	200
Sand (kg/m^3)		828	763	764
Coarse aggregate (kg/m^3)		822	822	822
VEA	(g/m^3)	-	169	-
	(ml/m^3)	2650	-	190
HRWRA (kg/m^3)		3.87	1.74	1.77
Set retarder (ml/m^3)		475	475	475
AEA (ml/m^3)		68	72	68

When the workability of all mixtures is compared at 10 minutes, all mixtures had good performance. However, at 60 minutes, the loss of workability was still high despite the use of a set retarder. For the SCC made with the VEA 3, the slump flow loss was high despite the incorporation of a set retarder (Fig. 5.7). This could be due to the type of HRWRA that may not be efficient in mixtures made with the VEA admixture.

TABLE 5.5 FRESH STATE PROPERTIES OF THE THREE CONCRETES MADE WITH SET RETARDER

		0.40% VEA 1	0.40% VEA 2	VEA 3
Slump flow (mm)	10 min	660	660	650
	60 min	530	550	440
Air volume (%)	10 min	8.0	7.5	4.2
	60 min	6.4	8.2	4
Filling capacity (%)	10 min	86	87	82
	60 min	53	72	56
V-funnel (s)	10 min	2.91	2.39	4.53
	60 min	3.05	3.91	14.87
Settlement (%)		0.33	N/A	0.49
Unit weight (kg/m^3)		2240	2230	2250
Temperature (°C)		19	18	20

High loss of slump flow was also observed for the 0.40% VEA 1 and 0.40% VEA 2 mixtures, although these values were less than those obtained for concretes with no set retarder. Fig. 5.8, compares the V-funnel flow time of the three mixtures, which better illustrates the loss of flowability of the VEA 3 concrete. A flow time of 14 sec at 60 minutes reflects low passing ability. The results of 0.40% VEA 1 and 0.40% VEA 2 mixtures were similar regardless of the use of set retarder, both at 10 and 60 minutes.



(*)=Slump flow loss after 60 min

Fig. 5.7 Slump flow at 10 and 60 minutes

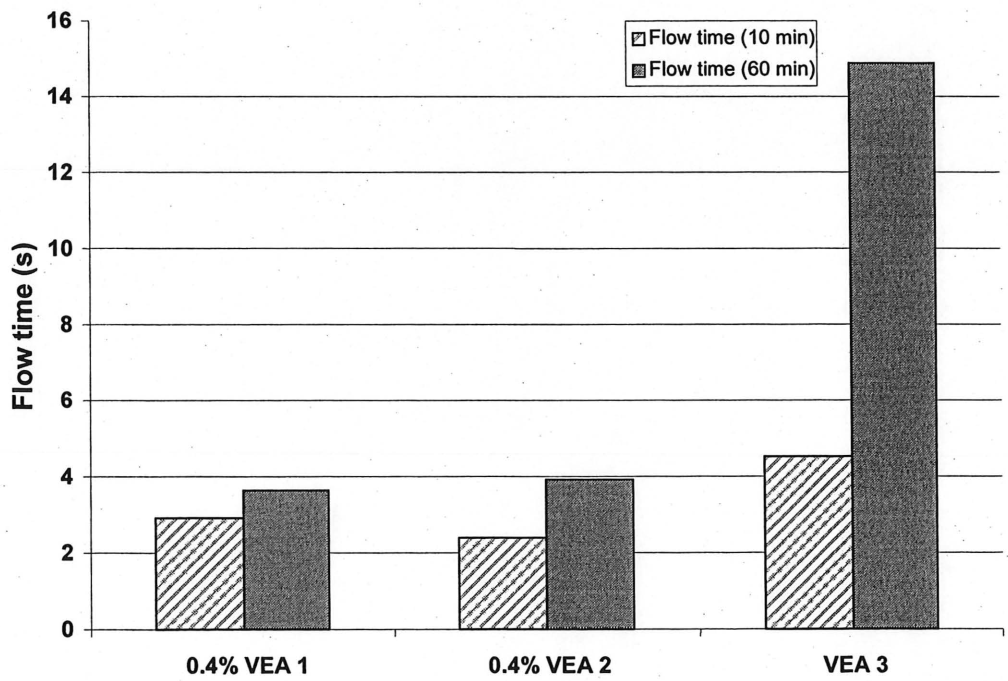
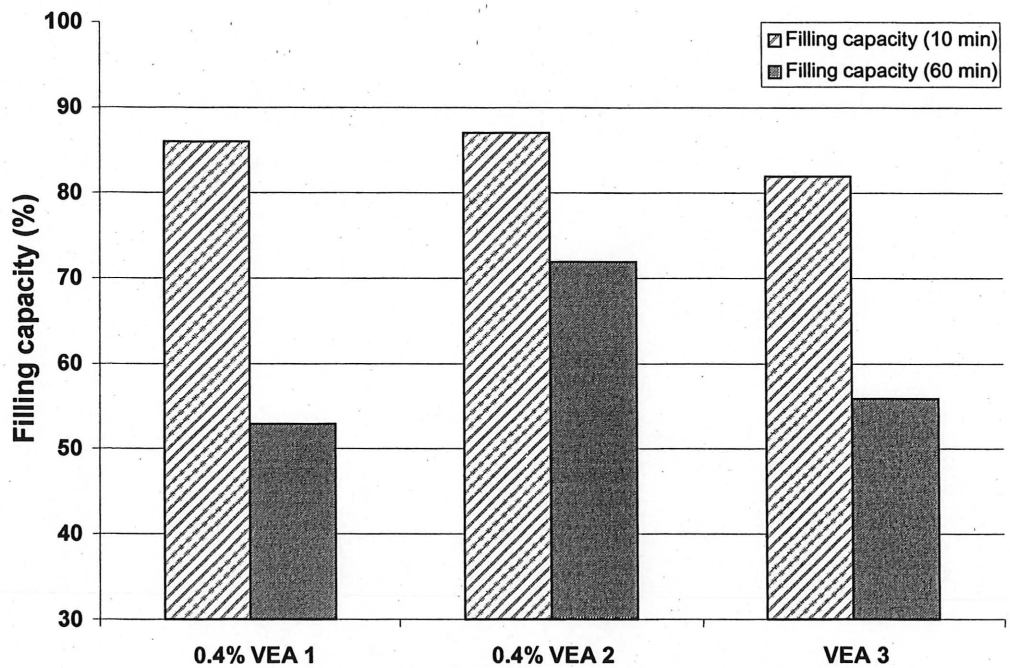


Fig. 5.8 V-funnel flow times at 10 and 60 minutes

For the 0.40% VEA 1 mixture, the reduction in HRWRA resulted in lower surface settlement with a slightly smaller slump flow value (660 mm). The settlement value decreased from 1.17% to 0.33% when the HRWRA was reduced from 2.15 to 1.6 L/m^3. It is important to highlight that the recommended maximum surface settlement was 0.50%.

The filling capacity was good (82% to 87%) at 10 minutes for all mixtures, over the minimum recommended filling capacity value of 80%. This is shown in Fig. 5.9. However, after 60 minutes the loss of filling capacity was still high, especially in the SCC made with VEA 3. The incorporation of a set retarder did not improve significantly the situation.



VEA=Viscosity enhancing admixture

Fig. 5.9 Filling capacity of SCC mixtures at 10 and 60 minutes

5.2 Conclusions

Based on the preliminary evaluation carried out to select reference SCC, the binder used in mixtures made with 0.35 w/cm was selected to contain 65%, 5%, and 30% of Type 10 cement, silica fume, and Class F fly ash, respectively. Such concrete should be proportioned with a PCP HRWRA compatible with the binder type. Such concrete exhibits limited loss of flowability over 60 minutes and achieves 28-d compressive strength of 32 MPa.

For the SCC mixtures made with moderate w/cm of 0.42 and VEA, the loss of flowability were high. The use of different types of VEA is required to enhance stability.

Chapter 6

ANALYSIS AND RESULTS

6.1 Introduction

The main part of this research includes the investigation of the influence of different brands of chemical admixtures on the workability of SCC. This included the use of five PCPs and one PNS, five different VMAs and five AEAs. Two commercially available ternary binders and one quaternary binder were used in mixtures made with a moderate w/cm of 0.42. The SCC mixtures tested in this research are presented in Table 6.1.

TABLE 6.1. OPTIMIZATION OF MIXTURES FOR PHASES I AND II

	18 Mixtures evaluated			
Phase I. Admixture combination	*w/cm* = 0.35 65%T10,5%SF,30%FA		*w/cm* = 0.42 Ternary 1	
	1	PCP 1	*6*	PCP 1
	2	PCP 2	*7*	PCP 2
	3	PCP 3	*8*	PNS 1
	4	PCP 4	*9*	PCP 4
	5	PCP 5	*10*	PCP 5
Phase II. Binder type	*w/cm* = 0.42 Ternary 2		*w/cm* = 0.42 Quaternary	
	11	PCP 1	*15*	PCP 1
	12	PCP 3	*16*	PCP 3
	13	PCP 4	*17*	PCP 4
	14	PCP 5	*18*	PCP 5

T10: cement type 10, SF: silica fume, FA : fly ash

The dosage of HRWRA was adjusted to secure slump flow of 660 ± 20 mm. The AEA was also adjusted to achieve an air volume of 5% to 8%. The binder content was fixed at 475 kg/m^3, regardless of the w/cm. The sand-to-total aggregate ratio, by volume, was set at the 0.50 with MSA of 10 mm, which is typical of repair applications. Mixture compositions of the 18 mixtures used in this research are presented in Tables 6.2 and 6.3.

In Phase I, the admixture combination was tested using two different approaches to achieve self-consolidating properties; a powder approach and an admixture approach. In Phase II, a parametric study was performed using different binders in SCC prepared with the same w/cm. In this parametric study, the VEA content was fixed for each admixture type obtained from different material suppliers, and only the dosages of the HRWRA and AEA were adjusted to achieve the proper slump flow and air volume, respectively. The results obtained from mixtures in Phase I are presented in Table 6.4, and those from Phase II are given in Table 6.5.

TABLE 6.2 MIXTURE COMPOSITION OF CONCRETES INVESTIGATED IN PHASES I AND II

Materials (kg/m^3)	w/cm = 0.35					w/cm = 0.42				
	PCP1-T10	PCP2-T10	PCP3-T10	PCP4-T10	PCP5-T10	PCP1-T1	PCP2-T1	PNS1-T1	PCP4-T1	PCP5-T1
Type 10 cement	309					-				
Ternary binder 1	-					475				
Ternary binder 2	-					-				
Quaternary binder	-					-				
Fly ash, Class F	142					-				
Silica fume	24					-				
Cementitious materials	475					475				
Water	166					200				
Coarse aggregate (MSA = 10 mm)	842					803				
Sand	814					775				
HRWRA (ml/m^3)	2375	9100	3300	3650	3150	2625	5000	7025	3750	2890
AEA (ml/m^3)	50	70	10	40	30	375	600	400	20	90
Set retarder (ml/m^3)	-	-	-	500	-	-	-	-	120	-
VEA (ml/m^3)	-					1310	5000	3700	220	1600
Water reducer (ml/m^3)	-					-	-	475	-	-

TABLE 6.3 MIXTURE COMPOSITION OF CONCRETES INVESTIGATED IN PHASE II

Materials (kg/m^3)	w/cm = 0.42				w/cm = 0.42			
	PCP1-T3	PNS1-T3	PCP4-T3	PCP5-T3	PCP1-T4	PNS1-T4	PCP4-T4	PCP5-T4
Type 10 cement	-				-			
Ternary binder 1	-				-			
Ternary binder 2	475				-			
Quaternary binder	-				475			
Fly ash, Class F	-				-			
Silica fume	-				-			
Cementitious materials	475				475			
Water	200				200			
Coarse aggregate (MSA = 10 mm)	812				790			
Sand	785				764			
HRWRA (ml/m^3)	2350	5000	3200	2125	3400	5500	5250	3200
AEA (ml/m^3)	375	350	30	60	650	780	348	130
Set retarder (ml/m^3)	-	-	120	-	-	-	120	-
VEA (ml/m^3)	1310	3700	220	1600	1310	3700	220	1600
Water reducer (ml/m^3)	-	475	-	-	-	475	-	-

TABLE 6.4 FRESH STATE PROPERTIES FOR CONCRETE MIXTURES INVESTIGATED IN PHASES I AND II

		w/cm = 0.35					w/cm = 0.42				
		PCP1-T10	PCP2-T10	PCP3-T10	PCP4-T10	PCP5-T10	PCP1-T1	PCP2-T1	PNS1-T1	PCP4-T1	PCP5-T1
Temperature (°C)	10 min	26	22	22	21	20	21	20	21	20	22
	70 min	26	21	20	20	19	22	19	20	19	18
Unit weight (kg/m3)	10 min	2300	2250	2180	2270	2215	2265	2350	2240	2265	2220
	70 min	2290	2290	2220	2275	2190	2265	2360	2300	2250	2225
Air volume (%)	10 min	6	7	8	7	7	6	2	6	6	7
	70 min	6	6	7	6	8	6	2	5	6	7
Slump flow (mm)	10 min	670	650	665	675	675	670	650	650	665	670
	70 min	620	685	635	665	670	680	655	600	650	640
J-ring (mm)	10 min	540	640	N/A	640	635	665	N/A	N/A	N/A	640
	70 min	515	670	N/A	640	630	670	N/A	N/A	N/A	630
V-funnel flow time (s)	10 min	4.6	3.2	3.8	5.5	4.2	3.9	3.5	4.0	3.0	2.7
	70 min	4.2	3.2	4.1	5.7	4.4	4.6	3.3	4.4	3.2	2.8
Filling capacity (%)	10 min	88	89	98	95	93.3	99	82	94	91	88
	70 min	81	97	90	93	96.3	97	89	85	97	94
Rheology (g : N.m) (h : N.m.s)	g, 10 min	0.4	0.4	0.2	0.6	0.2	0.6	0.2	0.6	0.2	0.4
	h, 10 min	8.2	5.2	10.6	10.7	8.0	5.2	3.8	6.0	5.2	4.0
	g, 70 min	0.8	0.2	0.4	0.8	0.4	0.5	0.2	0.6	0.3	0.4
	h, 70 min	8.5	5.6	11.6	12.6	5.6	7.1	5.4	7.3	4.9	4.6
Settlement (%)		0.16	0.21	0.15	0.19	0.16	0.33	0.43	0.44	0.17	0.21
L-box	time, 10 min	2.49	1.03	1.9	1.97	1.18	1.45	1.13	N/A	N/A	0.8
	h_2/h_1, 10 min	0.67	0.67	0.86	0.69	0.77	0.90	0.76	N/A	N/A	0.78
	time, 70 min	2.87	1.37	2.22	2.41	2.6	1.74	1.91	N/A	N/A	0.96
	h_2/h_1, 70 min	0.58	0.80	0.80	0.83	0.76	0.81	0.70	N/A	N/A	0.87

TABLE 6.5 FRESH STATE PROPERTIES FOR CONCRETE MIXTURES INVESTIGATED IN PHASE II

			w/cm = 0.42				w/cm = 0.42			
			PCP1-T2	PNS1-T2	PCP4-T2	PCP5-T2	PCP1-T3	PNS1-T3	PCP4-T3	PCP5-T3
Temperature (°C)		10 min	21	20	21	22	23	25	23	21
		70 min	20	20	20	21	23	24	24	19
Unit weight (kg/m3)		10 min	2240	2235	2275	2220	2210	2210	2175	2220
		70 min	2175	2285	2265	2210	2150	2265	2150	2230
Air volume (%)		10 min	8	8	7	7	7	7	9	6
		70 min	10	6	7	8	6	6	9	6
Slump flow (mm)		10 min	675	670	660	665	665	645	670	675
		70 min	570	670	420	500	628	610	600	625
J-ring (mm)		10 min	650	645	550	610	630	625	650	650
		70 min	510	670	400	438	580	570	540	580
V-funnel flow time (s)		10 min	3.3	4.7	3.1	2.8	3.8	5.4	2.8	2.4
		70 min	3.4	4.3	5.3	3.4	3.9	5.7	3.4	2.7
Filling capacity (%)		10 min	88	96	71	85	91	93	94	93
		70 min	60	94	14	41	86	88	86	83
Rheology (g : N.m) (h : N.m.s)	g	10 min	0.7	0.7	1.0	0.8	0.9	0.7	0.9	0.6
	h		6.2	6.6	5.4	5.0	8.8	7.8	4.7	5.0
	g	70 min	1.3	0.6	1.8	1.2	1.0	0.6	1.2	0.6
	h		5.9	8.2	6.8	5.4	11.2	11.2	5.8	5.7
Settlement (%)			0.25	0.71	0.21	0.21	0.38	0.54	0.24	0.45
L-box	time	10 min	1.18	1.78	1.35	0.74	2.86	3.39	1.07	0.53
	h_2/h_1		0.8	0.75	0.56	0.78	0.83	0.85	0.89	0.92
	time	70 min	1.87	1.7	5.14	1.36	2.39	3.78	1.57	0.96
	h_2/h_1		0.54	0.81	0.08	0.44	0.73	0.8	0.68	0.70

In order to achieve the final mixture compositions, several trial batches were carried out. The mixture proportions and fresh state properties of all trial batches are given in Appendix I. The number of trial batches necessary to meet the performance specifications for each set of admixtures is given in Table 6.6.

TABLE 6.6. NUMBER OF TRIAL BATCHES FOR EACH ADMIXTURE AND BINDER TYPE

	Type 10 0.35	**Ternary 1 0.42**	**Ternary 2 0.42**	**Quaternary 0.42**	**Total**
PCP 1	4	5	1	1	11
PCP 2	4	3	-	-	7
PCP 3	6	-	-	-	6
PCP 4	7	12	1	2	22
PCP 5	2	1	2	1	6
PNS 1	-	3	1	1	5
Total	23	24	5	5	**57**

The number of trial batches made with Type 10 cement and the ternary binder 1 (Phase I) was higher than the number of trial batches made with ternary binder 2 and quaternary binder (part of Phase II). The reason is that, the fresh properties of final mixtures in Phase I are optimized, whereas in Phase II a parametric study was carried out to observe the compatibility between a number of binders and admixtures commercially available in Quebec, Canada.

6.2 Analysis of results in Phase I

The results of the mixtures tested in Phase I were compared to determine the difference in properties of SCC proportioned with two different approaches to achieve self-consolidating properties. All mixtures were designed to achieve a slump flow value of 660 ± 20 mm and an air content of 5% to 8%. Only when using the PCP 2 admixture with ternary binder 1, and w/cm of 0.42, it was not possible to increase the air content above 2%. This mixture is not used in the analysis of the results.

The HRWRA demand for each set of admixtures is shown in Fig. 6.1. For the PCP 1, PCP 4, and PCP 5 HRWRA, the required dosage was almost the same when using either a 0.35 or 0.42 w/cm. With a 0.35 w/cm, the highest admixture demand was observed for the PCP 2 (9.1 L/m^3) and the lowest demand for the PCP 1 (2.4 L/m^3). For the rest of the mixtures, the HRWRA demand was around 3 L/m^3. When using PNS 1, the HRWRA demand was high (7

L/m^3), as it would be expected for a PNS. Comparing the PNS 1 to the other admixtures, the HRWRA demand was higher for the PNS than for PCP-based polymer, regardless of the w/cm. However, when the PCP 2 was used in SCC made with 0.35 w/cm, the required dosage was surprisingly high (9 L/m^3). This unexpected behaviour can be due to an incompatibility between the cementitious materials and HRWRA.

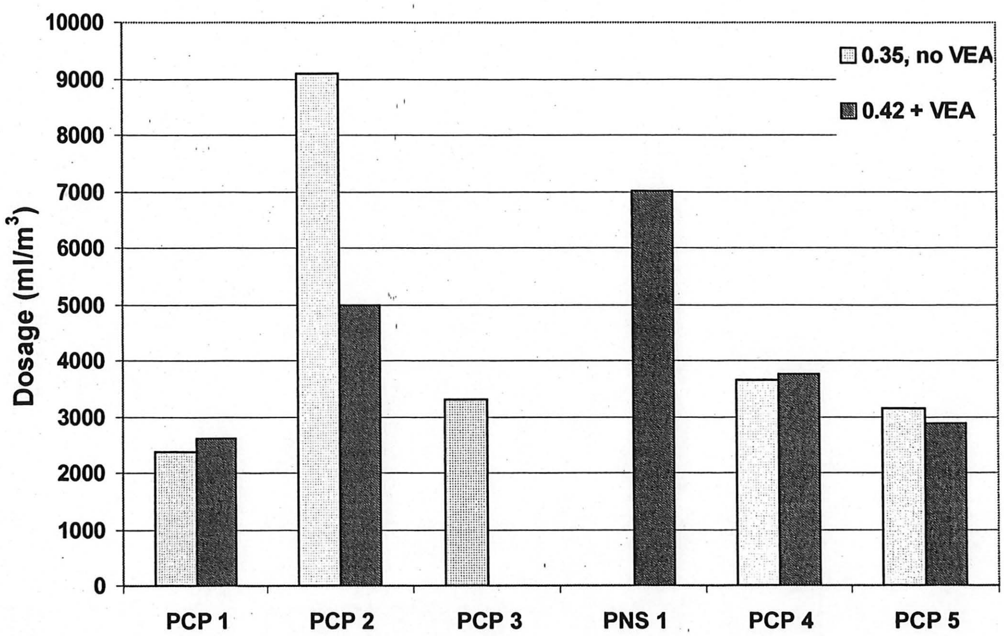


Fig. 6.1 HRWRA demand in SCC mixtures made with 0.35 and 0.42 w/cm with slump flow between 640 and 680 mm and air volume of 5% to 8%

When proportioning the SCC with 0.42 w/cm, it was necessary to incorporate VEA to enhance stability. The use of VEA increased the HRWRA demand, as shown in Fig. 6.1. However, the increase in HRWRA demand is not significant in most of the cases presented here.

In order to provide adequate durability against freezing and thawing, a proper air-void system is required. All mixtures were proportioned to achieve air volume of 5% to 8% in the fresh state. Fig. 6.2 shows the AEA dosage to achieve 5% to 8% of entrained air and a slump flow of 660 ± 20 mm.

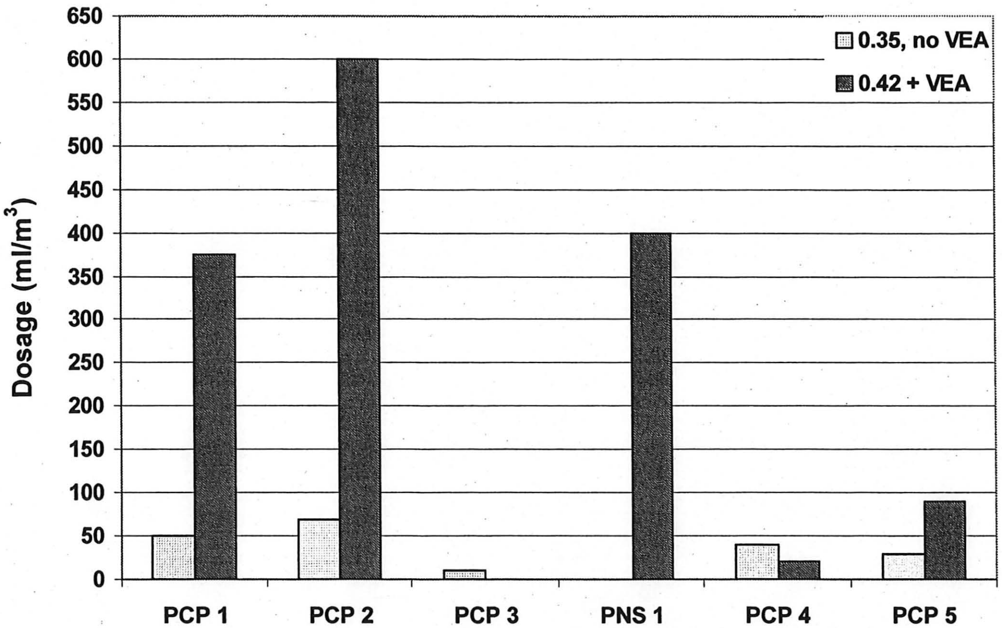


Fig. 6.2 AEA demand in concrete mixtures made with 0.35 and 0.42 w/cm, slump flow values of 640 to 680 mm and air volume of 5% to 8%

Based on Fig. 6.2, the AEA demand increased when the SCC was proportioned with 0.42 w/cm and VEA. Only the mixture made with PCP 4 proportioned with the admixture method required a lower dosage of AEA than the concrete proportioned with the powder method (w/cm of 0.42 vs. 0.35).

The highest dosage of AEA was 0.6 L/m^3 for the SCC proportioned with 0.42 w/cm and PCP 2. The lowest dosage of AEA was 10 mL/m^3 for PCP 3 with a w/cm of 0.35. For PCP 2 with a w/cm of 0.42, and an AEA dosage of 0.6 L/m^3 it was not possible to achieve the minimum 5% of entrained air. This demonstrated an incompatibility with the VEA 2. For PCP 1, there was a significant difference on AEA demand between both methods. For PCP 5, the difference in AEA demand was not significant. When using PNS, the AEA demand increased compared with the other PCPs, regardless of the w/cm.

In order to adequately place SCC, proper slump flow retention is required. In this research, slump flow measurements were taken at 10 and 70 minutes. During the 60 minutes elapsed time the SCC was covered in the mixer and subjected to one minute mixing at 10-minute intervals. The slump flow losses of mixtures in Phase I are shown in Fig. 6.3. The limit value for slump flow loss after 60 minutes was set under 50 mm. From Fig. 6.3, the highest slump flow loss was 50 mm for all mixtures. When the PCP4 was incorporated a set retarder was necessary in the SCC made with either 0.35 or 0.42 w/cm. The set retarder dosage was higher for the 0.35 w/cm mixture (0.5 L/m^3) than for the 0.42 w/cm mixture (0.12 L/m^3).

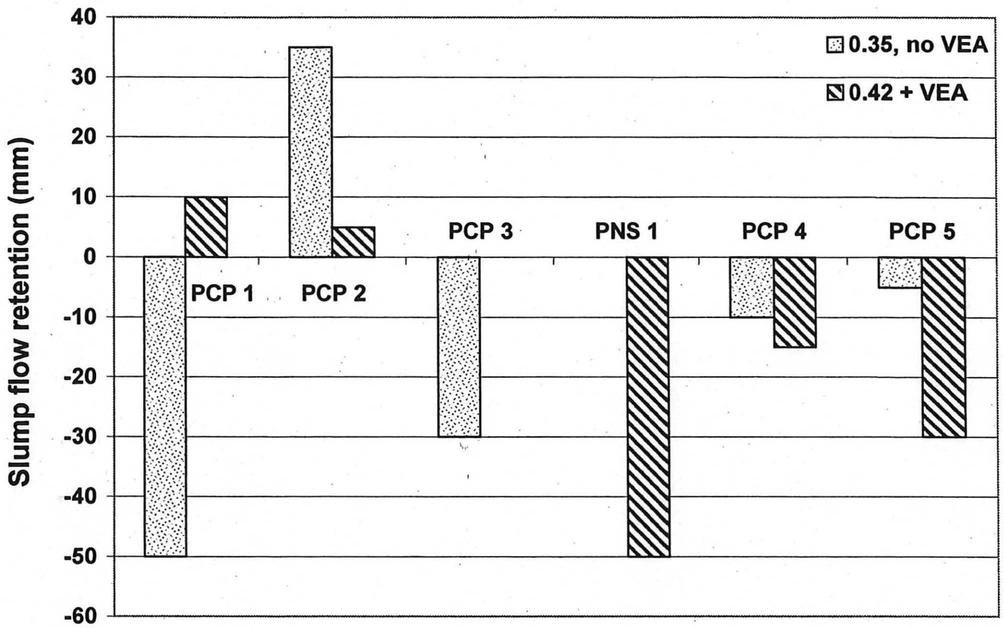


Fig. 6.3 Slump flow loss after 60 minutes in mixtures made with 0.35 and 0.42 w/cm, slump flow of 640 to 680 mm and air volume of 5% to 8%

For the PCP 1 and PCP 2 HRWRAs used in SCC proportioned with 0.42 w/cm, and for PCP 2 in SCC with 0.35 w/cm, the slump flow was larger at 70 minutes than initially at 10 minutes. This represents a delayed effect of the HRWRA. When the PNS was used, it did not show a different behaviour from the other PCP admixtures in terms of slump flow loss.

From these results, it can be established that good deformability and adequate air volume can be achieved by using both methods to proportion SCC: low w/cm of 0.35 with PCP or w/cm of 0.42 with PCP or PNS and VEA.

6.3 Assessment of static stability for mixtures investigated in Phase I

Static stability describes the lack of segregation, bleeding, and sedimentation of the concrete once cast in place in a stationary state and until it hardens (Khayat, 1999). In order to evaluate the static stability of concrete and its ability to properly suspend various solid particles and liquids, the surface settlement column was used to assess the resistance to consolidation.

This test gives the percentage of surface settlement in a PVC column of 700 mm filled with approximately 600 mm of concrete. According to Khayat (2002), the maximum percentage of settlement should be less than 0.50%.

All mixtures were prepared and tested to achieve minimum surface settlement with the proper slump flow and slump flow retention. The contradictory properties of SCC were balanced to obtain high fluidity with proper stability. For mixtures with 0.42 w/cm, the dosage of VEA was adjusted to respect the maximum surface settlement limit. Time vs. settlement graphics for all mixtures are presented in Appendix II. The maximum surface settlement values are shown in Fig. 6.4.

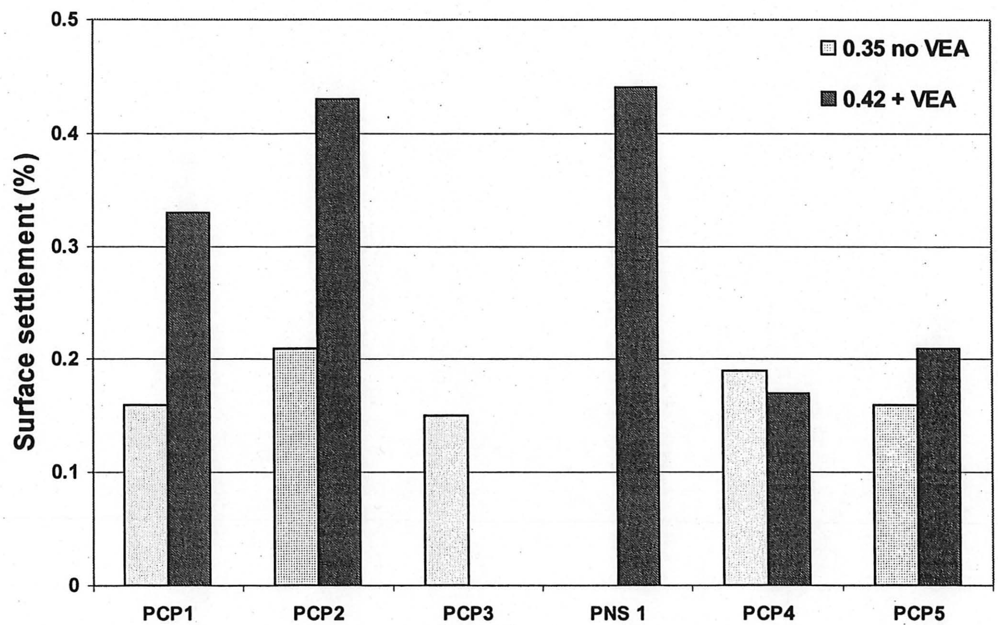


Fig. 6.4 Surface settlement of mixtures with w/cm of 0.35 and w/cm of 0.42 with VEA with slump flow of 640 to 680 mm and air volume of 5% to 8%

From Fig. 6.4, lower surface settlements were achieved with SCC made with 0.35 w/cm. All mixtures had a maximum settlement under 0.5% and can be considered to have adequate static stability. The highest surface settlement was measured when PNS based HRWRA was used at 0.42 w/cm with VEA. This can be due to a longer setting time induced by the higher dosage required for this HRWRA.

6.4 Assessment of dynamic stability for mixtures in Phase I

Different tests to assess dynamic stability were used in this research, including: J-ring, V-funnel flow time, filling capacity box, and L-box. The testing procedure and tests descriptions were given in chapter 4.

The J-ring test was performed immediately after measuring the slump flow at 10 and 70 minutes. It measures the narrow-opening passing ability of the mixtures, and its results can be presented in two ways: as the direct mean of two opposed diameters or as the difference between this measure and the final slump flow.

Unfortunately, not all the mixtures were tested using the J-ring. Only the two mixtures with PCP 1 and PCP 5, and only mixtures with a w/cm of 0.35 using PCP 2 and PCP 4 were tested. The results of this test are shown in Fig. 6.5.

According to German studies (Brameshuber et al., 2002), when the J-ring measure is compared versus the final slump flow, the difference must be under 50 mm. The comparisons between these two tests are presented in Fig. 6.6.The final diameters on the J-ring test were in the range of 640 - 680 mm, similar to those obtained from the slump flow test, except for the concrete made with PCP 1 with a w/cm of 0.35. The concrete flowing through the spaced bars of the J-ring was uniform and homogeneous.

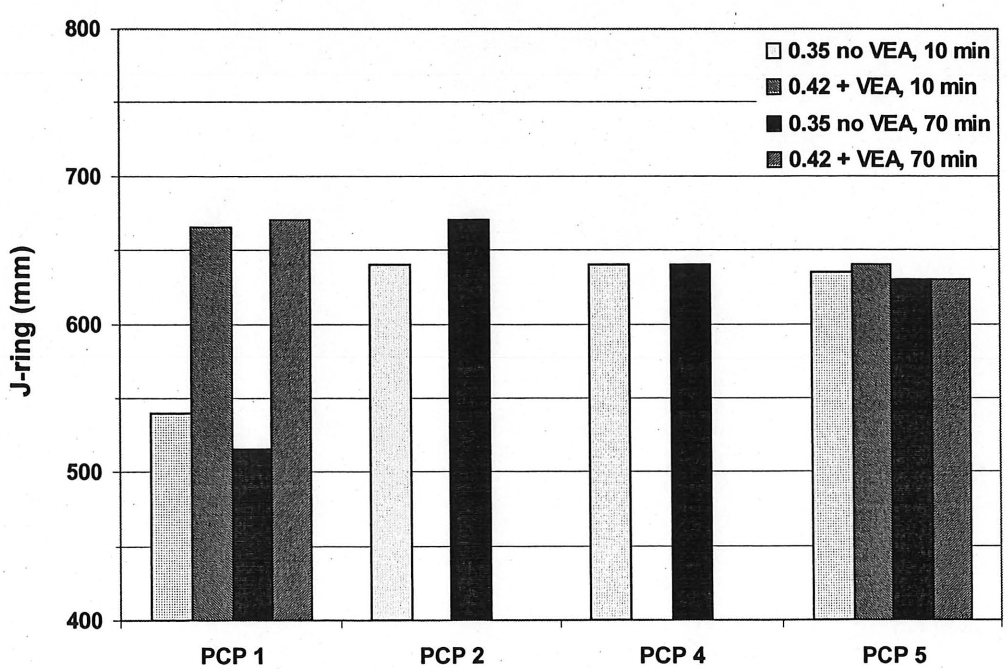


Fig. 6.5 J-ring results at 10 and 70 minutes for mixtures with a w/cm of 0.35 or 0.42, slump flow of 640 to 680 mm and air volume of 5% to 8%

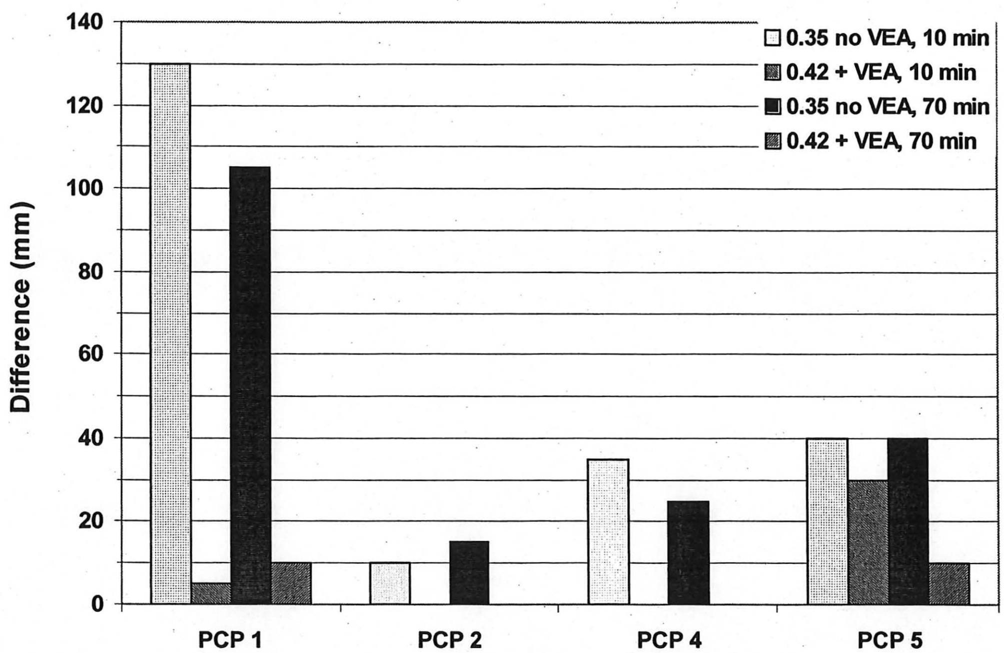


Fig. 6.6 Difference between the final slump flow versus the final diameter passing the J-ring for SCC with slump flow of 640 to 680 mm and air volume of 5% to 8%

From Fig. 6.6, the limits established by the German's investigations were not always respected. Usually all mixtures presented a difference under 50 mm and, if the mixture made with PCP 1 is excluded, they all presented a difference of under 40 mm. The only mixture that did not accomplish the target limit was the one containing PCP 1 and no VEA with a w/cm of 0.35. The differences are really large between values measured at 10 and 70 minutes.

The filling capacity of SCC can be considered as the combination of passing ability and filling ability of the mixtures, and is measured using the caisson filling capacity box. The concrete is poured, and the final volume is calculated. The occupied percentage of the total volume is reported.

From Fig. 6.7, all mixtures had filling capacity greater than 80% after 10 and 70 minutes. The value after 10 minutes was higher than the value after 70 minutes for almost all mixtures, except for mixtures made with PCP 2. This behaviour is reasonable if compared with the slump flow retention (Fig. 6.3). Concrete mixture made with PCP 2 exhibited an increase in slump flow at 70 minutes compared to that determined at 10 minutes.

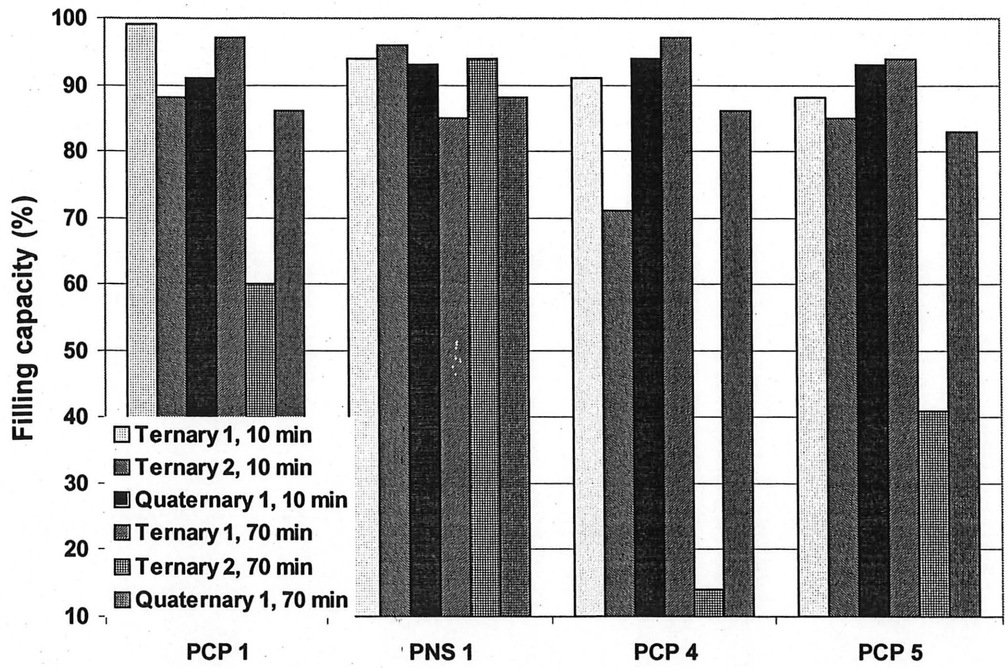


Fig. 6.7 Filling capacity of different SCC mixtures measured with the caisson test, slump flow of 640 to 680 mm, and air volume of 5% to 8%

The filling capacity values were larger in mixtures made with 0.42 w/cm, except for the mixtures proportioned using PCP 1. These results correspond well to those obtained with the J-ring used to assess the passing ability of the SCC. The mixture containing PCP 1 with moderate w/cm of 0.42 and VEA 1 showed better passing ability in the J-ring and better filling capacity compared to the mixture with a low w/cm of 0.35. For the concrete mixture using a PNS based HRWRA, the self-consolidting properties were similar to those concretes made with PCP HRWRA, regardless of the w/cm and the admixture producer.

The L-box test was also used to assess dynamic stability of SCC. This apparatus evaluates the passing ability of SCC. As mentioned earlier, the EFNARC (2003), the results of the blocking ratio (h_2/h_1) should be over 0.80 to ensure proper passing ability. Unfortunately, not all mixtures prepared in this study were tested with the L-box. However, for the mixtures tested with this method, blocking ratio value over 0.80 was not always possible to achieve (Fig. 6.8).

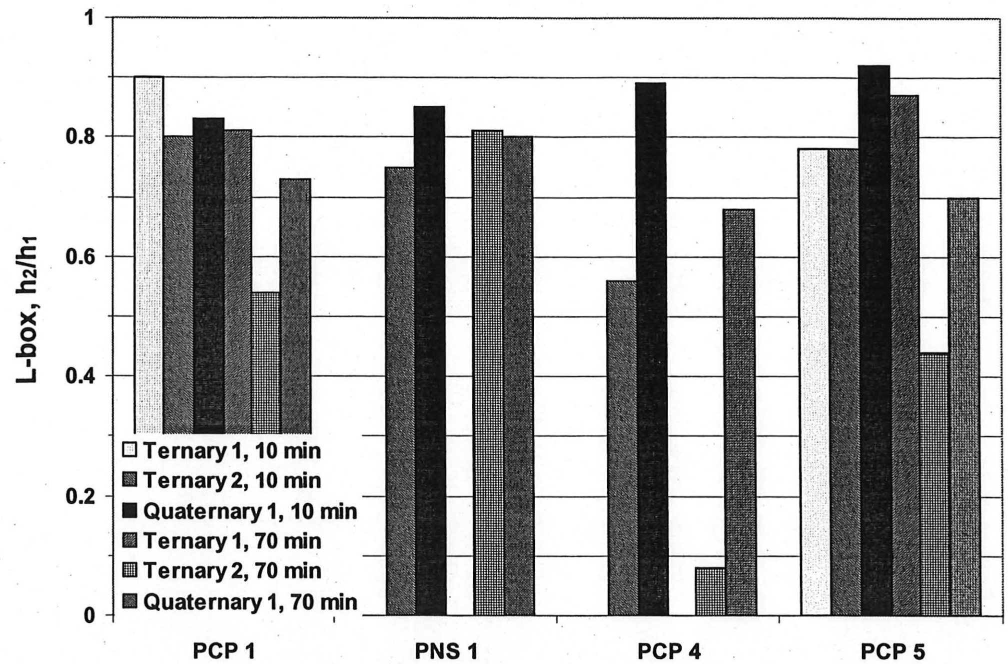


Fig. 6.8 Difference in heights measured in the L-box, blocking ratio (h_2/h_1), slump flow of 640 to 680 mm and air volume of 5% to 8%

Nevertheless, the filling capacity of all the mixtures was over 80%, showing that all the SCC on this study should properly encapsulate the reinforcing steel and properly fill all the voids in the formwork. Further research is necessary in this area to better correlate both tests using such a small maximum size aggregate.

The other parameter measured in the L-box was the time that the concrete takes to reach the opposite wall of the L-box. Due to the fact that the reinforcing bars are located at the exit of the gate, the passing ability is also assessed. The confined nature of the L-box represents the situation found inside of certain formwork, especially in restricted sections often found in repair applications. Fig. 6.9 shows the results of the mixtures tested with the L-box apparatus.

The time for the concrete to flow through the horizontal part of the L-box was no longer than 3 sec and in some cases it was less than 1 sec. The longest time measured at 10 minutes was 2.49 sec for the mixture made with PCP 1, no VEA, and a 0.35 w/cm. This mixture exhibited the highest time of all the other mixtures at 70 minutes. The passing ability for the SCC mixture made with PCP 1 and 0.35 w/cm was lower than the rest of the mixtures. Measured times for mixtures with 0.42 w/cm and VEA were either shorter or virtually the same as the time measured on mixtures with 0.35 w/cm and no VEA. These shorter values were also observed when the flow times in the V-funnel were measured. In consequence, mixtures made with 0.42 w/cm and VEA had higher passing ability than those with 0.35 w/cm and no VEA.

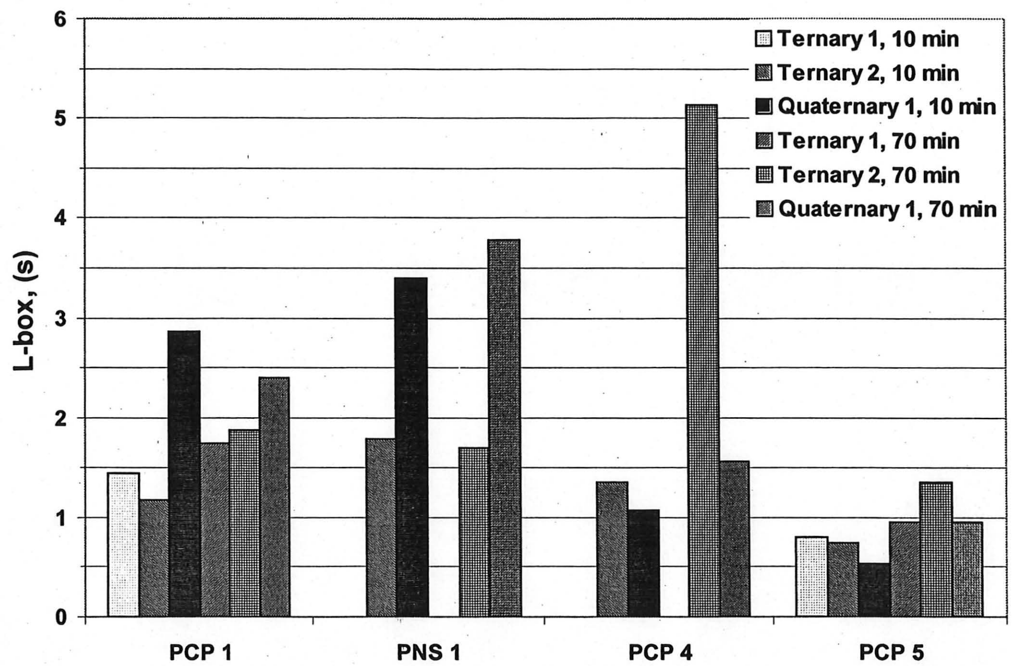


Fig. 6.9 Flow time measured in the L-box, slump flow of 640 to 680 mm and air volume of 5% to 8%

The flow time measured with the V-funnel test can be used to evaluate the passing ability of SCC. As it has already been said, good passing ability of SCC corresponds to short flow time.

From Fig. 6.10, it can be seen that the V-funnel flow time results were similar for almost all the tested mixtures. Only for mixtures made with PCP 4 and PCP 5, the difference between the flow time measured with the V-funnel and the L-box was significant. When the SCC was proportioned with 0.35 w/cm, the measured flow time was longer, showing a lower passing ability. Generally, the difference in flow time of SCC determined at 10 and 70 minutes was not significant. The loss of fluidity indicated by the flow time measured with the slump flow and the J-ring was not seen when the flow time was measured with the V-funnel. It is important to highlight that this applies to concrete with 10-mm MSA and slump flow loss under 50 mm. Although, the two flow times are used to assess the passing ability of the SCC, they did not reflect the same behaviour in this research. The increase of flow time measured after 60 minutes using the L-box test was not seen when testing the concrete with the V-funnel apparatus.

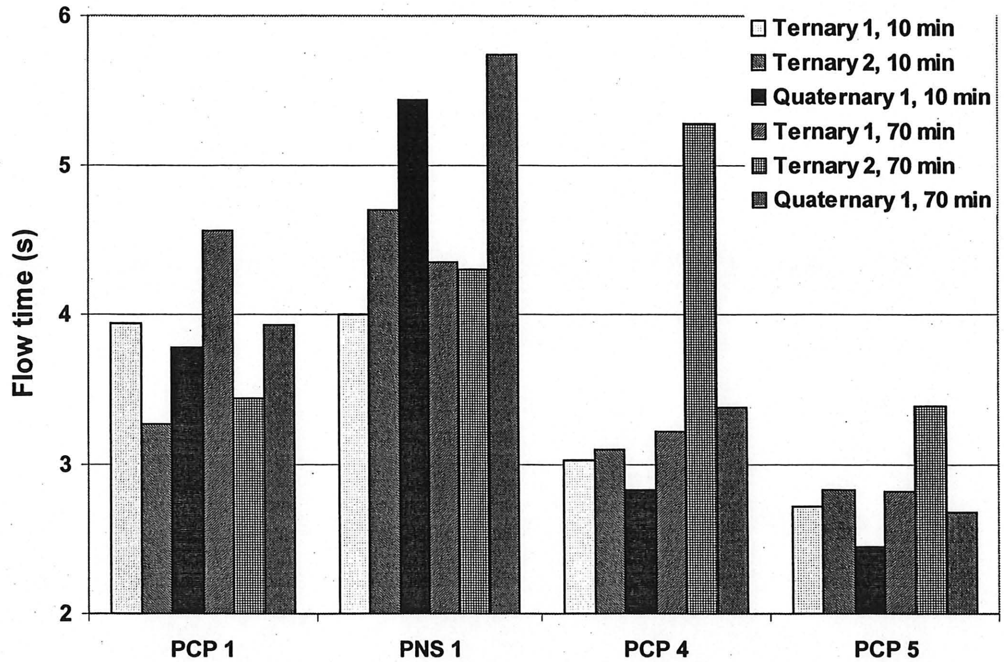


Fig. 6.10 V-funnel flow time of all the mixtures, slump flow between 640 and 680 mm and air volumes from 5% to 8%

The increased time, measured in the L-box, was significant for mixtures with 0.35 w/cm. This fact can be explained due to the fact that reinforcement bars in the L-box were not present in the V-funnel. According to the results obtained with the L-box, for mixtures with 0.35 w/cm, the passing ability decreased over time. On the other hand, for mixtures with 0.42 w/cm, the flow time measured with the L-box showed a similar passing ability at 10 and 70 minutes.

6.5 Rheological measurements for mixtures in Phase I

As mentioned earlier, an IBB rheometer was used to determine the apparent yield stress and torque viscosity. A graph is drawn using the rotational speeds versus torque data, and the apparent viscosity is determined as the slope of the derived linear relationship. The apparent yield stress is found when the line drawn crosses the y-axis. The apparent yield stress is expressed in Newton.meter (N.m), and the torque viscosity is expressed in Newton.meter.second (N.m.s).

SCC should have a moderate viscosity to resist segregation and low yield stress to flow under its own weight. Some years ago, these two properties were seen as impossible to achieve simultaneously. However, recent advances in the science of admixtures have made this possible.

The IBB rheometer uses a program to accelerate the motion of the impeller and measure the torque resistance at each given rotational speed. Since acceleration should increase and then decrease, the graph is constructed using only the decreasing speeds to ensure that all mixtures have the same shear stress history. For this project, a program with two increasing speeds and five decreasing speeds was used. The graphs for all mixtures are presented in Appendix II. The procedure used to calibrate the rheometer is presented in Appendix IV. Yield stress values determined for each mixture are shown in Fig. 6.11. All mixtures had similar yield stress values, which are directly related to the slump flow value. The viscosity values of the investigated mixtures are compared in Fig. 6.12.

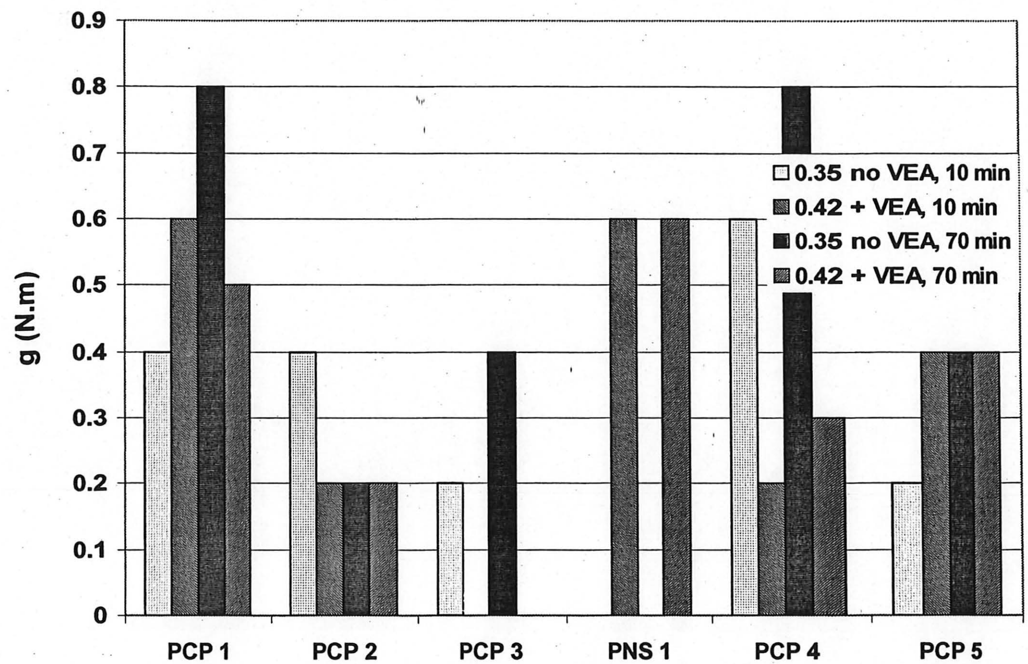


Fig. 6.11 Apparent yield stress (g) of SCC mixtures, with 640 to 680 mm slump flow and 5% to 8% air volume

In Fig. 6.12, it is possible to confirm that mixtures made with 0.35 w/cm and no VEA had higher viscosities than those made with 0.42 w/cm and VEA. Viscosity generally increased after 60 minutes of the first measurement. This was seen regardless of the w/cm and HRWRA in use (PCP or PNS).

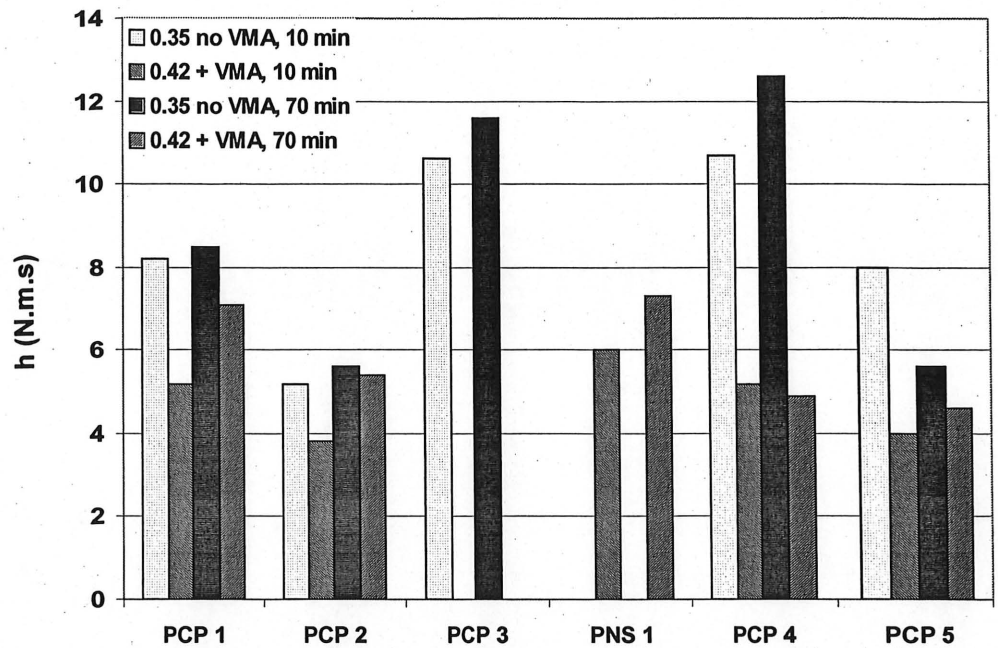


Fig. 6.12 Torque viscosity (h) of SCC mixtures, with 640 to 680 mm slump flow and 5% to 8% air volume

6.6. Discussion

From the data presented here it can be seen that it was possible to achieve good self-consolidating properties with almost all commercially available admixtures. Only with the PCP 2 HRWRA, the target fresh air volume was not possible to achieve. Both methods used to provide proper stability of the SCC (w/cm of 0.35 without any VEA and w/cm of 0.42 with VEA) ensured good filling ability (slump flow) and capacity (caisson test). The L-box blocking ratio and the final spread on the J-ring suggest that the passing ability of the concrete mixtures was good.

SCC with good deformability and proper passing ability was measured using the L-box and the V-funnel. At the same time proper static stability was achieved, as measured with the surface settlement column. From a rheological point of view, all mixtures had low yield stress and moderate plastic viscosity. For concrete with 475 kg/m^3 cementitious materials, coarse aggregate with maximum size of 10 mm and two different water-cementitious ratios (0.35 and 0.42), the yield stress results were between 0.2 and 0.8 N.m. Meanwhile, the plastic viscosity values were different for each mixture category. For the SCC with 0.35 w/cm, the values ranged between 5 and 13 N.m.s. On the other hand, for the mixtures with 0.42 w/cm and VEA the values ranged between 4 and 7 N.m.s.

6.7 Analysis of results in Phase II

In order to observe the effect of different commercially available binders on fresh properties of SCC, eight additional mixtures were prepared using two more binders. These binders included another ternary binder (ternary 2) and a quaternary binder (quaternary 1). This new ternary binder included Type 10 cement, silica fume, and blast furnace slag. The quaternary binder included Type 10 cement, silica fume, fly ash, and blast furnace slag. For Phase II, the PCP 2 HRWRA was not used, as it was not possible to entrain the desired air volume. A total of 12 mixtures were compared; four of which made with ternary 1 binder, four with the ternary 2 binder, and four with the quaternary 1 binder.

A parametric study was carried out in which the VEA dosage was fixed, the HRWRA dosage changed to achieve 660 ± 20 mm of slump flow, and the AEA was adjusted to secure 5% to 8% of air volume. Three PCP-based HRWRAs and one PNS-based HRWRA were used along with four different types of VEA and AEA. The HRWRA demand of the various mixtures is compared in Fig. 6.13. When using a PCP, the admixture demand for ternary binder 1 was around 2500 and 3800 ml/m^3. When a PNS was used, the demand increased to 7000 ml/m^3 for the same level of consistency. For ternary binder 2, the admixture demand was 2100 to 3100 mL/m^3 for the PCP based admixtures and 5000 mL/m^3 for PNS based admixtures. When the quaternary binder was used along with a PCP based HRWRA the admixture demand was the highest, from 3100 up to 5200 mL/m^3. When a PNS was used the required dosage was 5500 mL/m^3.

The admixture demand was higher when using PNS compared to PCP. The high dosage of PNS-based HRWRA, especially with ternary binder 1, can cause some side effects to concrete (larger setting times and low initial compressive strength). When the quaternary binder was used with the PCP 4, the HRWRA demand was similar to that of the PNS. The same side effects could arise.

The AEA dosage necessary to achieve an air content of 5% to 8% in the fresh state is shown in Fig. 6.14. The quaternary binder exhibited a higher AEA demand than the other binders, regardless of the HRWRA type. For ternary 1 and ternary 2, the AEA dosage was virtually the same. The AEA demand when using PCP 1 and PNS 1 was higher than with PCP 4 and PCP 5, regardless of the binder. For ternary 1, the dosage was near 400 mL/m^3 when PCP 1 and PNS 1 were used, but a decreased was observed below 100 mL/m^3 when PCP 4 and PCP 5 were used. The same results were observed when ternary 2 was used. When quaternary 1 was used, the dosage reached 650 mL/m^3 for PCP 1 and it was close to 800 mL/m^3 for PNS 1. For

PCP 4, the dosage decreased to 350 mL/m^3 while the lowest dosage was PCP 5 with only 120 mL/m^3, as it is observed in Fig. 6.14

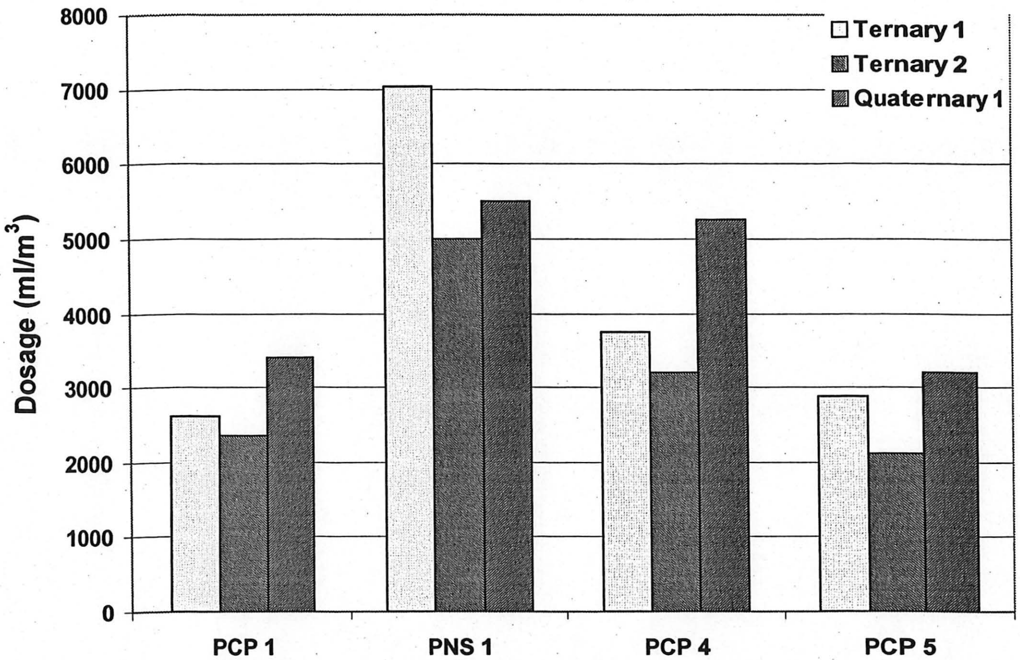


Fig. 6.13 HRWRA demand for mixtures made with 0.42 w/cm and three different binders, initial slump flow of 640 to 680 mm and air volume of 5% to 8%

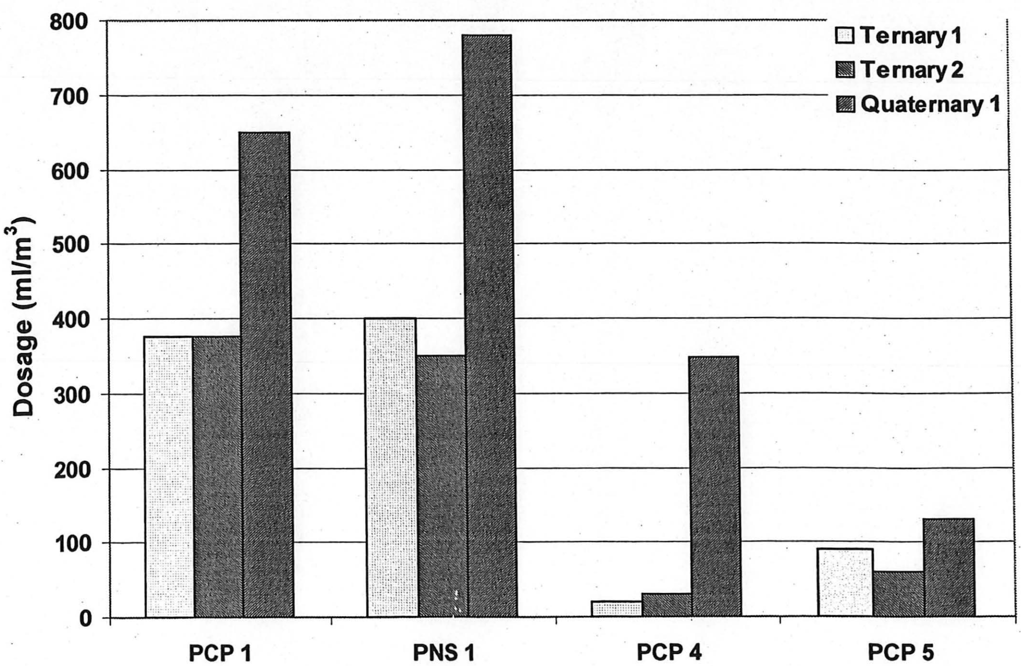


Fig. 6.14 AEA demand for concrete mixtures made with four different HRWRA and three different binders, initial slump flow of 640 to 680 mm and air volume of 5% to 8%

The time during which fresh concrete maintains its self-consolidating properties to successfully cast the intended elements is refered to as open time. In order to estimate the open time of the SCC mixtures, the slump flow was measured at 10 and 70 minutes after the water-cement contact time. The difference between these two values is shown in Fig. 6.15.

According to the Department of Transportation of Québec (Hovington, 2000) the value of slump flow loss must be limited to 50 mm. However, the parametric study revealed that this was not always possible. When ternary binder 1 was used, slump flow retention was optimized to respect the 50 mm limit. For the PCP 4 HRWRA, it was necessary to use a set retarder, therefore all mixtures made with PCP 4 contained the same amount of set retarder.

When ternary binder 2 was used with PCP admixture the slump flow loss was high, depending of the HRWRA in use, 100 mm to 250 mm difference was observed. This slump flow retention is not enough, and certain problems could occured on the jobsite when casting is delayed. On the other hand, when a PNS based admixture was used, the slump flow retention was excellent. Good compatibility between PNS and ternary binder 2 was observed. However, this binder exhibited an incompatibility with the PCP based admixtures.

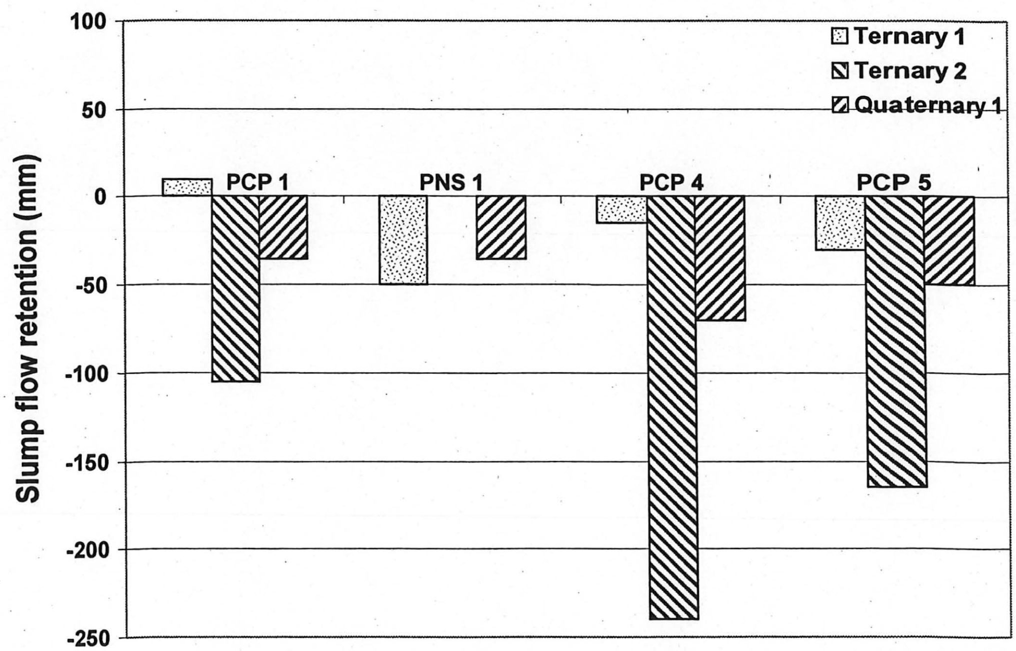


Fig. 6.15 Slump flow retention of mixtures with initial slump flow of 640 to 680 mm and 5% to 8% air volume

For the quaternary binder 1, the slump flow retention was generally good. For the PCP 4 HRWRA (with a set retarder) the difference in slump flows was slightly over the 50 mm maximum value (70 mm). It was possible to achieve the target slump flow and entrained air with this admixture and cement combination. Dynamic and static stability tests were conducted, and their results are discussed in the next sections. Comparisons were made to determine if the required self-consolidating properties could be achieved.

6.8 Assessment of static stability of mixtures in Phase II

In order to achieve the proper resistance to surface settlement, the maximum settlement should be lower than 0.5%. The mixtures made with ternary binder 1 were optimized to achieve such value. The VEA was incorporated to ensure both high flowability (slump flow of 660 ± 20 mm) and proper suspension of particles when the concrete is at rest. Surface settlement results obtained for each binder are presented in Fig. 6.16.

When PCP-based HRWRAs were used with a 0.42 w/cm, the surface settlements were under the maximum value of 0.5%. On the other hand, when a PNS-based HRWRA was used, the surface settlement was higher than the maximum allowable value, except with ternary binder 1 because it was optimized. The highest value was slightly above 0.70% and corresponds to the mixture made with ternary binder 2. The PNS 1-ternary binder 2 combination showed the best performance regarding slump flow retention. The HRWRA-binder interaction may delay hydration and setting of the cementitious system. This is important when considering the time prior to demoulding of the formwork.

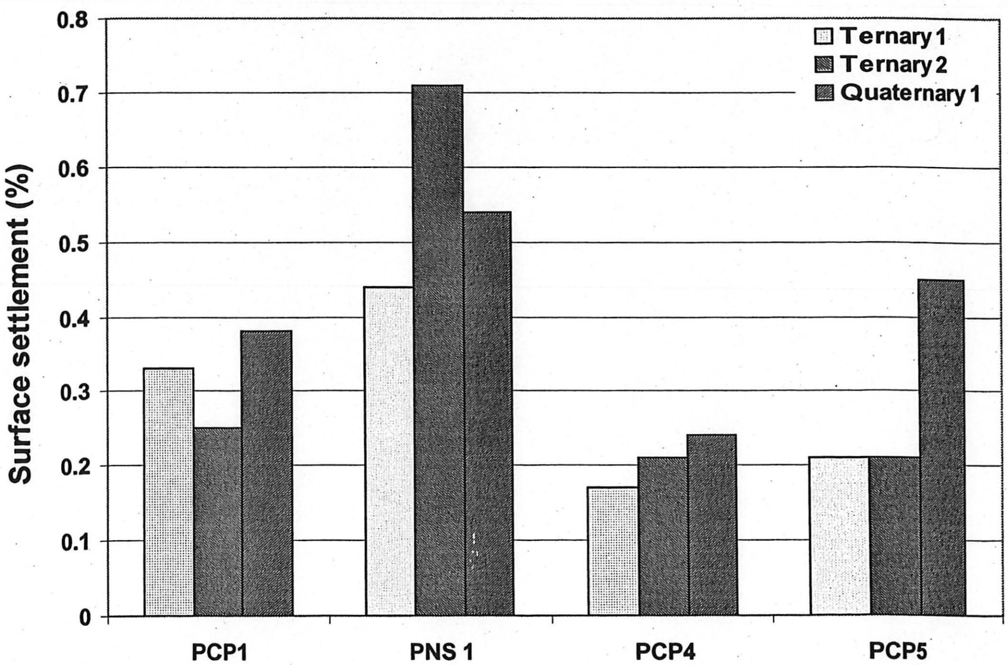


Fig. 6.16 Surface settlement measured using the 700 mm column, initial slump flow of 640 to 680 mm and 5% to 8% of air volume (w/cm = 0.42)

For the mixtures prepared with ternary binder 2 and quaternary binder, the dosage of VEA was the same as the dosage obtained with ternary binder 1. This parametric study aims to better understand the effect of this admixture when used with different binders, as well as the degree of compatibility between them. In general terms, static stability was not difficult to achieve, especially when using a PCP. For PNS-based HRWRA, the admixture demand required to achieve the target slump flow was high, causing an increase in surface settlement as a secondary effect.

6.9 Assessment of dynamic stability of mixtures in Phase II

In order to properly fill the formwork and to encapsulate the reinforcement bars, proper stability is required while the concrete is in movement; this is called dynamic stability. The same tests as in Phase I were used, starting with the measurement of slump flow, J-ring flow, V-funnel flow time, L-box time and blocking ratio, filling capacity, and rheological parameters. All tests were done at 10 and 70 minutes of age.

The J-ring measurements can be analyzed by themselves or compared with the slump flow values. The J-ring gives an idea of the passing ability among reinforcement bars. The final J-ring spread values are compared in Fig. 6.17. The J-ring diameters at 10 minutes are high for almost all mixtures; the lowest value was 550 mm when the PCP 4 HRWRA with the ternary binder 2 was used. The largest spread diameter measured with the J-ring was virtually the same for the rest of the admixture-binder combinations, 650 mm on the average. For the measurements at 70 minutes the results were quite different. The PCP HRWRA seems to work well with ternary binder 1 and quaternary binder 1. However, with the ternary binder 2, the PCP admixtures did not seem to have good compatibility. A different behaviour was observed when PNS admixture was used; the mixtures made with ternary binder 2 showed better compatibility than those made with the PCP-ternary 2 combination.

A good comparison is the difference between the slump flow diameter and the J-ring diameter. This difference is shown in Fig. 6.18. It is important to highlight that the target slump flow value (640 - 680 mm) was achieved at the beginning (10 min of age).

According to Brameshuber et al. (2002), the maximum difference between the slump flow diameter and the J-ring diameter should not be over 50 mm. When using the PCP 1 HRWRA, all binders achieved this value at 10 minutes. However, when tested at 70 minutes the losses in workability of the SCC made with the ternary binder 2 and quaternary binder are too high, being in the limit of the 50 mm or slightly above. When the ternary 2 and quaternary binders were used along with the PNS-based HRWRA, the SCC presented differences between the slump flow values at 10 and at 70 minutes were lower than 50 mm. The SCC with ternary binder 2 clearly showed an incompatibility with the PCP 4 HRWRA, at 10 minutes the difference was significant, and the slump flow loss was extremely high. For concretes made with PCP 5 HRWRA, only when the ternary binder 2 was used, the 50 mm difference was not respected.

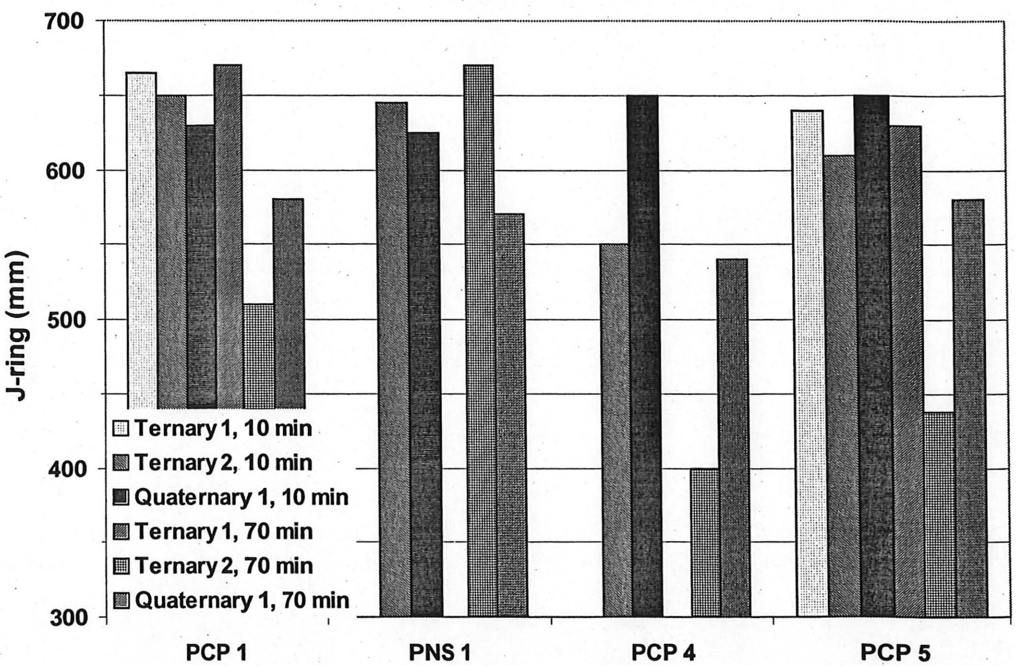


Fig. 6.17 J-ring final diameter for each admixture-binder combination, initial slump flow of 640 to 680 mm and 5% to 8% air volume

Fig. 6.18 shows that the PNS-based admixture works better than the PCP-based admixtures with ternary binder 2. The behaviour of the PNS-ternary 2 combination was improved after 70 minutes. There was no difference between the final diameters on slump flow and J-ring tests at this age.The use of PCP 4 along with ternary binder 2 is not recommended. The initial effect shows a large difference between the slump flow and the J-ring results.

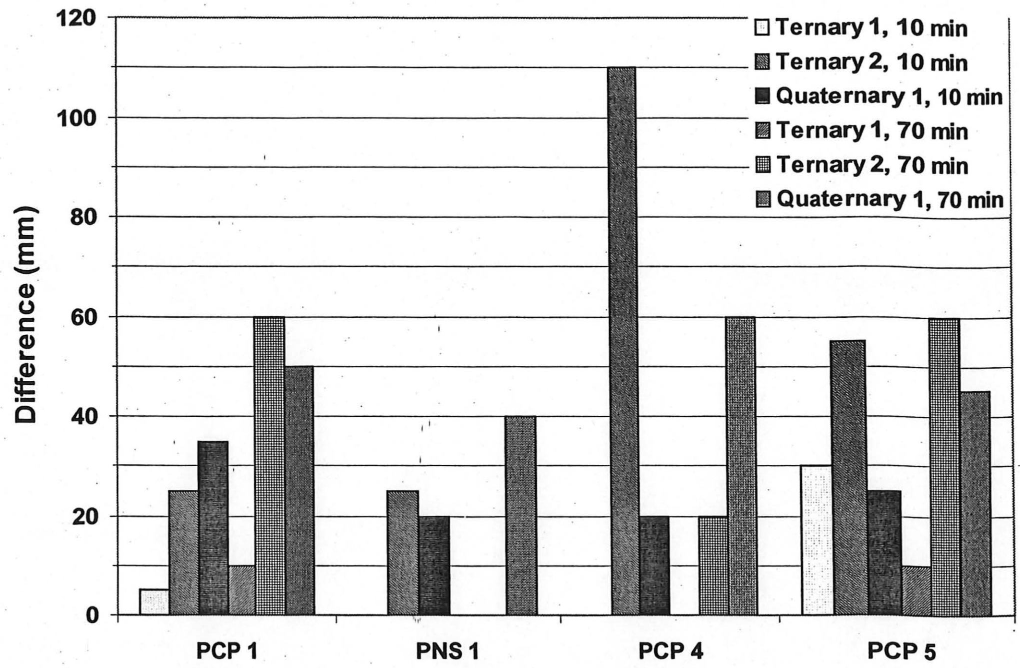


Fig. 6.18 Difference between slump flow and J-ring diameters

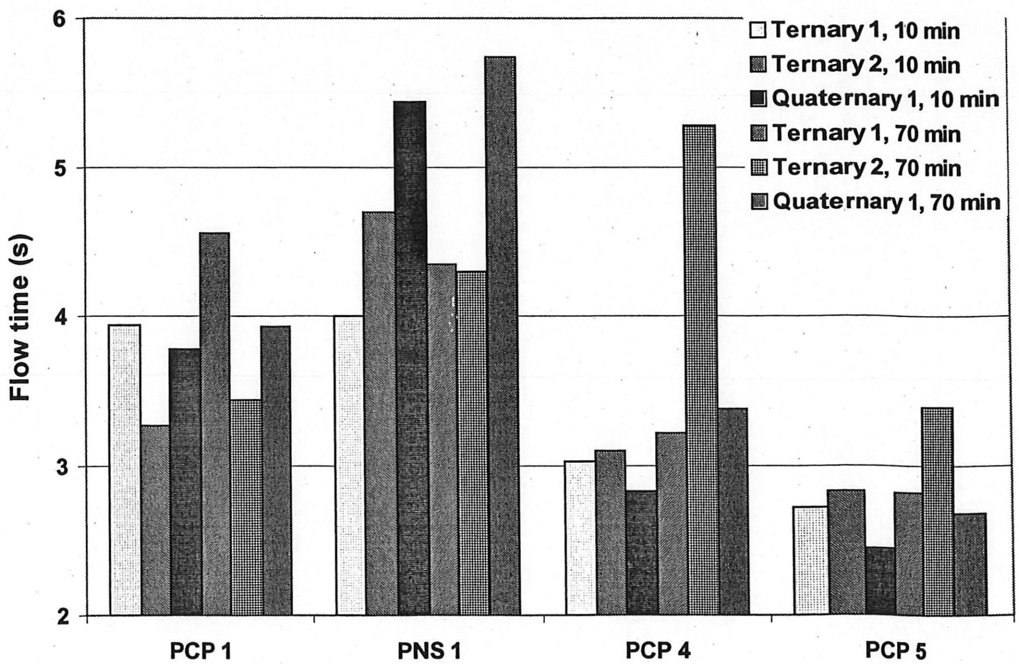


Fig. 6.19 Flow time in the V-funnel

The V-funnel values were close to one another; flow times were as short as 3 sec and as long as 5.5 sec. The combination the PCP 4 HRWRA and ternary binder 2 presented the larger difference between flow times at 10 and 70 minutes. The use of the PCP 5 HRWRA seemed to decrease the V-funnel flow time, thus indicating an increase in the passing ability of the concrete.

One of the tests that best fit the actual situation found in a cast-in-place structure is the filling capacity, or caisson test. The reinforcing bars are close to each other, and the SCC's ability to fill the spacing can be directly observed through the acrylic wall sections. The results of the filling capacity of the tested mixtures are compared in Fig. 6.20.

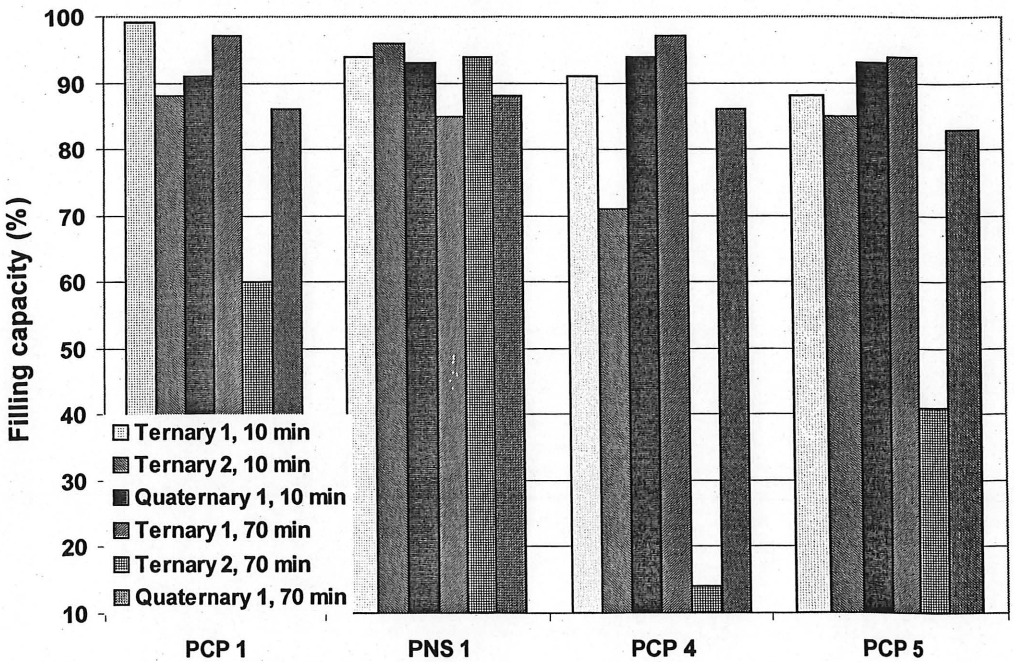


Fig. 6.20 Filling capacity values of all mixtures

All mixtures at 10 minutes had over 80% filling capacity, except for the PCP 4 HRWRA ternary 2 binder combination. This combination was under 80%. However, at the age of 70 minutes the loss of workability affected the filling capacity of the concrete. When ternary binder 2 was used along with a PCP, the loss in workability decreased the filling capacity, regardless of the use of a set retarder. This behaviour was concordant with the results saw in the other tests. Unfortunately, when ternary binder 2 was used with a PNS-based admixture the filling capacity loss was not measured.

As mentioned earlier, the passing ability of the SCC can be evaluated using the L-box test. The blocking ratio (h2/h1) results of the tested mixtures are compared in Fig. 6.21.

The EFNARC (2003) recommends maintaining a blocking ratio over 0.80. As can be seen in Fig. 6.22, this was not always possible. When using PCP 1 HRWRA, all concretes had blocking ratios over 0.80 at 10 minutes. However, at 70 minutes, only the PCP 1-Ternary 1 combination achieved this value. With the Ternary binder 2 and PCP 1 HRWRA, the loss in blocking ratio was significant, dropping from 0.80 at 10 minutes to 0.54 at 70 minutes. With the Quaternary 1 binder and PCP 1 HRWRA, this decrease was from 0.83 to 0.73.

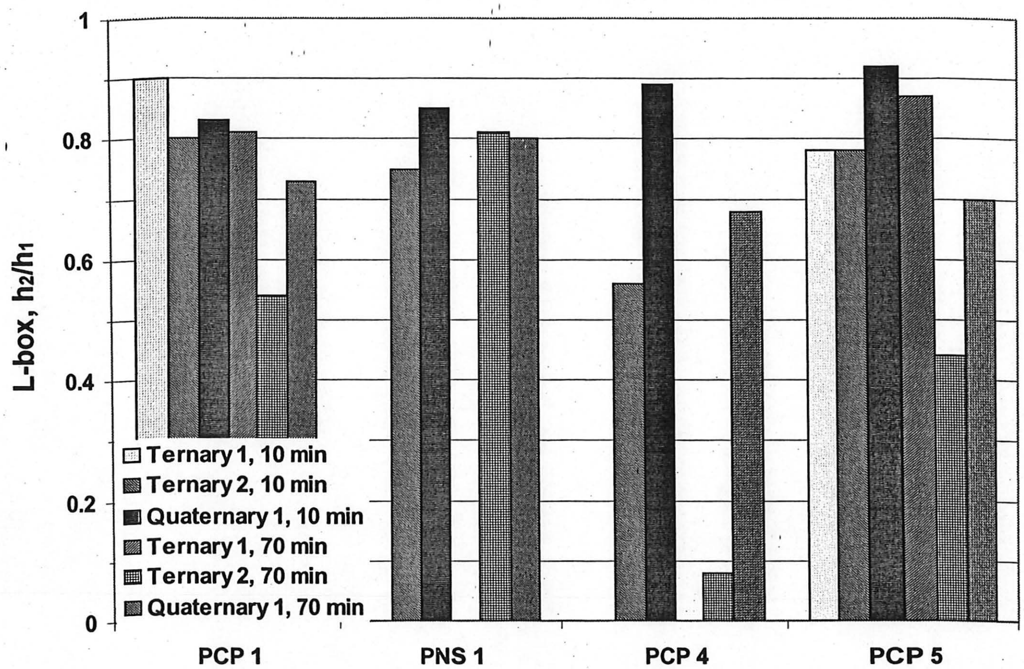


Fig. 6.21 Blocking ratio results of SCC mixtures

The results of the SCC made with PNS-Ternary binder 2 were the best at 70 minutes with the blocking ratio being slightly under 0.8 at 10 minutes with no loss at 70 minutes. When the Quaternary binder 1 was used with PNS HRWRA, good results were achieved at 10 and 70 minutes. Unfortunately, it was not possible to do this test with the Ternary binder 1.

The use of the PCP 4 HRWRA demonstrated a better compatibility with the Quaternary 1 binder than with the Ternary binder 2. The blocking values with the first binder were 0.89 and 0.68 at 10 and 70 minutes, while those for the second binder were 0.56 at 10 minutes and only 0.09 at 70 minutes. This showed a significant loss when using the Ternary 2 binder.

The PCP 5 HRWRA showed incompatibility with the Ternary 2 binder with a high loss after 70 minutes. However, this loss was not as high as for PCP 4. With Ternary 1 binder there was even an increase in the blocking ratio value, showing a better passing ability after 70 minutes. With the Quaternary 1 binder, after a good start at 10 minutes (over 0.90) the blocking ratio droped to 0.70. However, concrete was still considered to have a good passing ability.

The passing ability of SCC is an important characteristic, and the speed at which SCC flows is also important. When using the L-box, the flow time measured for each SCC giving an idea of the speed of deformation of the mixture. The L-box flow times for each mixture are presented in Fig. 6.23. When the PCP 1 HRWRA was analyzed, all binders had similar times at 10 and 70 min. On the other hand, PNS 1 was a clear example that the speed of deformation can make a difference between two concretes having the same passing ability. When the passing ability was measured, the Ternary 2 and Quaternary 1 binders showed almost the same blocking ratios. However, when the flow time was measured, the Ternary 2 binder flowed faster than the Quaternary 1 binder. This suggested that the mixture with the Quaternary 1 binder had a lower speed of deformation than the mixture with the Ternary 2 binder.

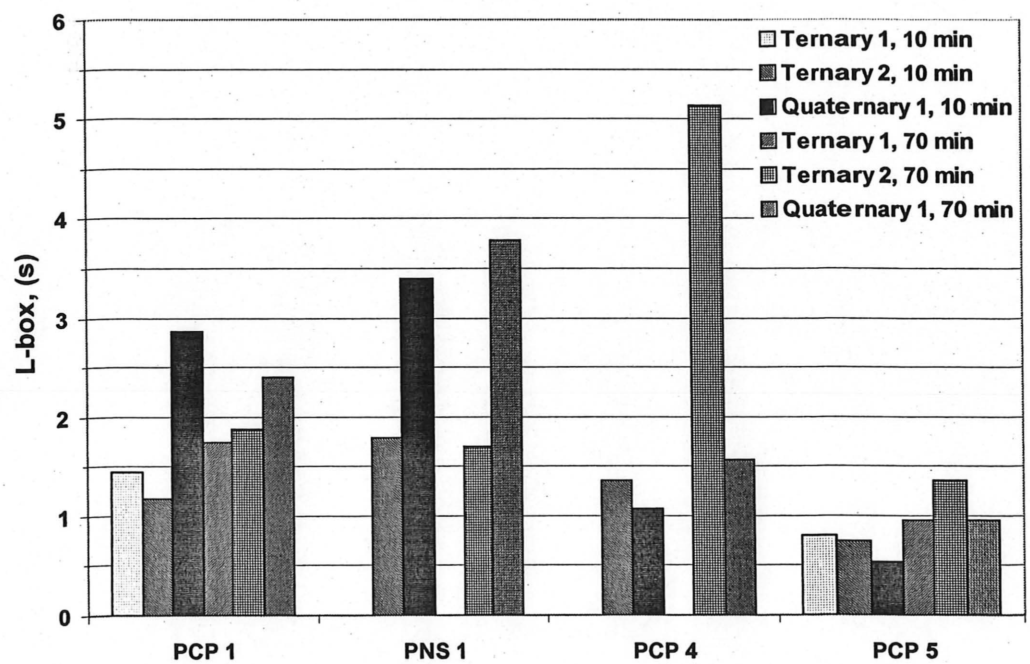


Fig. 6.23 L-box flow times (s) for SCC mixtures made with various admixture-binder combinations

For the PCP 4 HRWRA, the tendency shown with other tests was confirmed. There was an incompatibility between this admixture and the Ternary binder 2. The flow time was longer at 70 minutes than that at 10 minutes. In the same way, the blocking ratio was lower after 60 minutes of elapsed time. For the mixture with Quaternary binder 1, both flow times were similar showing no difference in the speed of deformation.

6.10 Rheological measurements for mixtures in Phase II

In order to completely understand the behaviour of SCC, the understanding of its rheological parameters is necessary. Yield stress and apparent viscosity are key factors to develop a good mixture. The goal of any SCC mixture composition is to decrease the yield stress as much as possible and achieve moderate viscosity. The yield stress values measured using the IBB rheometer are presented in Fig. 2.23 for each admixture-binder combination.

The yield stress values at 10 minutes were very similar to each other, ranging from 0.60 to 1 N.m, as the mixtures had similar slump flow target values. However, at 70 minutes, the yield stress values were related to slump flow loss. A significant slump flow loss resulted in a significant increase in the yield stress. A significant difference in yield stress represented approximately 50 mm slump flow loss. With the PCP-based HRWRA, the highest increase in yield stress was obtained with the Ternary binder 2. A high yield stress was especially observed when PCP 4 HRWRA was used along with the Ternary binder 2. This can be explained due to an incompatibility between the PCP HRWRA and the Ternary binder 2, which was confirmed by rheological measurements.

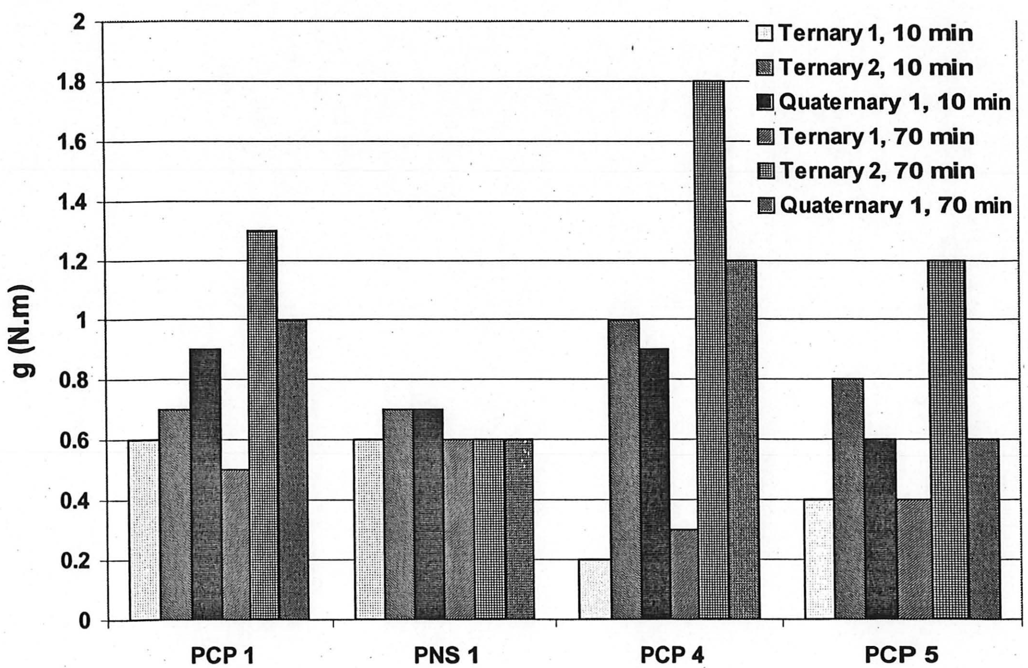


Fig. 6.23 Yield stress values for SCC mixtures made with four different admixture and three different binder combinations (initial slump flow of 640 to 680 mm and air volume of 5% to 8%)

The yield stress results of SCC mixtures made with PNS-HRWRA show that the yield stresses were similar and uniform, at 10 and 70 minutes. This demonstrated appropriate slump flow retention of SCC mixtures. Quaternary binder 1 had good compatibility with the tested HRWRA, except in the case of the PCP 4 HRWRA.

The other rheological parameter measured with the concrete rheometer was the torque viscosity. For each admixture-cementitious materials combination, the torque viscosity values are compared in Fig. 6.24.

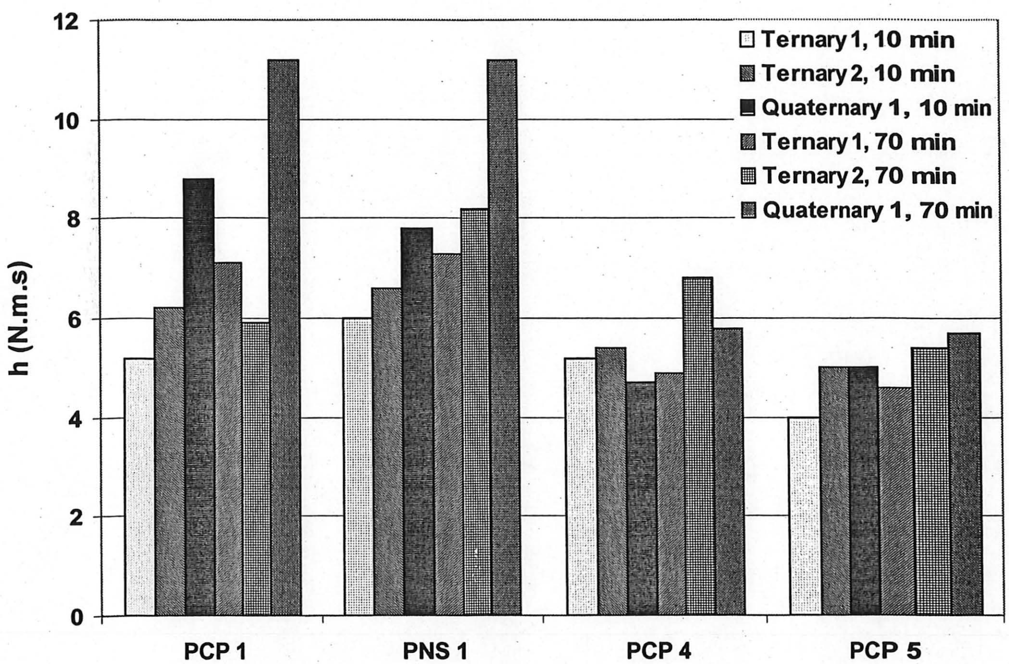


Fig. 6.24 Torque viscosities for SCC mixtures made with four different admixture and three different binder combinations (initial slump flow of 640 to 680 mm and air volume of 5% to 8%)

The torque viscosity is related to the speed at which SCC deforms. When the properties of SCC are measured, there is a concern about deformability. However, the speed at which final deformability is achieved is also important. The viscosity of the mixture controls this speed. On static conditions, the viscosity also influences surface settlement.

Among the mixtures presented in Fig. 6.24, the Quaternary binder showed the highest viscosity at 10 and 70 minutes. There was a clear tendency for plastic viscosity to increase after the 60 minutes of elapsed time. A similar behaviour was reported for almost all admixtures. For the rest of the mixtures, the difference was not significant. The final values were similar and they did not increase after 60 minutes of elapsed time. The plastic viscosity depends of the inner properties of the constitutive materials. In this research project, the values were approximately 4 and 7 N.m.s.

6.11. Discussion

Dynamic and static stability are important parameters used to define SCC properties. A given SCC can be rejected or accepted based on its performance in these tests. Limit values are imposed and should be targeted when designing SCC mixtures for various applications, as they should be compatible with the placement methods, section characteristics, etc.

With this in mind, our research program was designed to demonstrate that it is possible to produce good SCC for repair applications using different binder-admixture combinations that are commercially available. The tests were numerous, and in the end, some limit values were confirmed to be adequate, but others had to be reviewed.

In order to achieve similar self-consolidating properties, the admixture demand for PNS-based HRWRA was higher than that for PCP-based HRWRA. Among different PCPs, the cement that required the highest demand in superplasticizer was the Quaternary binder 1. The situation was the same for the AEA demand.

Slump flow retention was especially poor when a PCP admixture was used along with the Ternary binder 2. However, when a PNS-based HRWRA was used with the same binder, the slump flow retention was very good. According to Aïtcin (2003) usually when a binder is compatible with a PNS admixture it is incompatible with a PCP, and vice versa.

When the J-ring test was used, the PCP-ternary binder 2 combination was not adequate. On the other hand, the PNS-Ternary binder 2 combination seemed to be very good. However, the VEA dosage was optimized to control static stability.

The V-funnel test confirmed the incompatibility between the PCP-based HRWRA and Ternary binder 2. This incompatibility was more pronounced with the PCP 4. However, for SCC with low slump flow loss there was no great difference between the time measured at 10 and 70 minutes. This suggested that loss of workability was not detected with the V-funnel test method for concretes with the characteristics used in this research.

Almost all concretes had filling capacities over 80% at 10 and 70 minutes. Only when a PCP was used with Ternary binder 2 the filling capacity values at 70 minutes were under 80%. A special case was the combination of PCP 4-Ternary binder 2 using a w/cm of 0.42. At 10 minutes, this mixture had a filling capacity of 70%, despite the fact that the slump flow diameter was 660 mm. At 70 minutes the result hardly reached 15% of filling capacity. This confirmed the incompatibility observed between these two materials.

Two parameters were measured in the L-box: the blocking ratio (h_2/h_1) and the final flow time. It is recommended that the blocking ratio be over 0.80 (EFNARC, 2002). However, not all the mixtures achieved this value. Mixtures with blocking ratios under 0.70 achieved filling capacities over 80%. These mixtures usually had a blocking ratio over 0.70. On the other hand, the mixtures with low blocking ratio (usually under 0.60) were those showing a constant incompatibility, PCP HRWRA along with Ternary binder 2.

The flow time measured in the L-box showed two flowability zones of SCC. In the first zone, SCC flowed fast showing good passing ability. The times in this zone were mostly under 2 sec. The other SCC zone had a flow time between 2 and 4 seconds, showing a lower passing ability. Besides these two zones, it was possible to find the PCP 4-ternary binder 2 combination with a flowing time over 5 seconds. Once again the incompatibility between these two materials was demonstrated.

For a SCC with low slump flow values (420 mm to 600 mm) the correspondent yield stress values were high (1.8 Nm to 0.6 Nm). These low slump flow values were usually measured 70 minutes after the water-binder contact and were related to SCC with a high slump flow loss.

From the torque viscosity results, the higher viscosity values were registered when the Quaternary binder 1 was used, especially when it was combined with PCP 1 and PNS 1 HRWRA. The viscosity of the PCP 4-Ternary binder 2 mixture was not high either at 10 nor at 70 minutes. This was expected due to the incompatibility between these two materials found during different dynamic stability tests. This result suggested that the intrinsic properties of SCC are always dependent of each other, in this case the passing ability and flowability.

Chapter 7

EFFECT OF FIBRES IN SCC FOR REPAIR APPLICATIONS

7.1 Scope of experimental work

In order to develop fibrous SCC to be used in repair of concrete structures, several mixture were investigated including SCC mixtures reinforced with polypropylene fibres. The mixtures had a fixed w/cm of 0.40, binder content of 475 kg/m^3, and crush coarse aggregate with a 10 mm MSA. They included the use of two different PCP based HRWRAs (PCP 1 and PCP 2) and two different VEAs (VEA 1 and VEA 2). A commercially available Ternary binder and two different AEAs were used to achieve an air content between 5% and 8% in the fresh state (AEA 1 and AEA 2). Two different polypropylene fibres (PPF 1 and PPF 2) were investigated.

At first, the fibre volume was a variable, and the effect of the fibre content on self-consolidating properties was assessed. The flexural strength was then determined to evaluate the ductility of the fibrous-SCC. Finally, the impact of the sand-to-total aggregate volume ratio on fresh properties was evaluated for two SCC with the PPF 2 and a PCP 2-VEA 2-AEA 2 combinations.

The physical properties of the materials used in this research are shown in Table 7.1. A continuously graded crushed limestone aggregate with a maximum size of 10 mm and well-graded siliceous sand were employed. The bulk specific gravity of the sand was 2.64, with a fineness modulus of 2.46 and absorption of 1.2%. The bulk specific gravity of the coarse aggregate was 2.73 and its absorption 0.5%. Their particle-size distributions were within the CSA Standards A23.1 recommendations.

TABLE 7.1 PHYSICAL PROPERTIES OF MATERIALS USED IN THIS RESEARCH

	Density		
Binder	2.95		
Fibers	0.92		
	Density	**Absorption**	**F.M.**
Coarse Aggregate	2.73	0.5%	-
Fine Aggregate	2.64	1.2%	2.46
	Density	**Solid content (%)**	
PCP 1	1.07	32	
PCP 2	1.07	32	
VEA 1	1.35	50	
VEA 2	1.21	1.21	
AEA 1	1	19.3	
AEA 2	1	10.5	

Mixing procedure

All the mixtures were prepared in a 120-litre, open pan mixer using the following mixing procedure:

1. Sand and aggregate were mixed for one minute with half of the mixing water and the air entrainment admixture.
2. Cementitious materials were added (0:00 min).
3. All materials were mixed for 30 sec, after which the rest of the water was added with the HRWRA diluted (0:00 to 0:30 min).
4. After three minutes of mixing, the mixer was stopped (0:00 to 3:00 min).
5. Fibres were added (1:30 min).
6. Concrete was allowed to rest for 5 min (3:00 to 8:00 min).
7. Mixing was restarted for another 3 min (8:00 to 11:00 min).
8. After one minute of rest the initial testing was started.
9. After initial testing, concrete was remixed for one minute every 10 min until 70 min after water-binder contact.
10. At 70 min, final testing was carried out.

7.2 Effect of fibre volume

The first three mixtures used PCP 1, VEA 1, and AEA 1 along with PPF 1. The fibre contents were varied from 0.25% to 0.50% of the total concrete volume. For the mixtures made with 0.35% and 0.25% the sand-to-total aggregate ratio was 0.56. However, in the case of the concrete made with 0.5% fibre volume, the sand-to-total aggregate value was reduced to 0.53. The mixture proportioning and the properties of the fresh SCC are presented in Tables 7.2, 7.3.a, and 7.3.b, respectively.

TABLE 7.2 MIXTURE PROPORTIONING OF MIXTURES WITH DIFFERENT FIBRE CONTENTS

Mixture	PPF1-0.5%	PPF1-0.35%	PPF1-0.25%
w/cm	0.40		
Cem. materials (kg/m^3)	475		
Water (kg/m^3)	190		
Coarse agg. (kg/m^3)	822	877	877
Sand (kg/m^3)	770	717	720
Fibre (kg/m^3)	4.6	3.22	2.3
HRWRA (L/m^3)	5.3	5.75	5.75
VEA (L/m^3)	0.22	0.22	0.22
AEA (ml/m^3)	20	10	10
Set-retarder (L/m^3)	0.12	0.12	0.12

In order to evaluate the fresh properties of the SCC mixtures different tests were carried out. Two testing sets were performed, at 10 min and 70 min after cement-water contact, to determine the workability loss of the mixtures. The slump flow, V-funnel flow time, filling capacity, and surface settlement were measured. The rheological parameters of the SCC were determined using the IBB rheometer. Finally, air volume, temperature, and unit weight of each concrete were also determined.

TABLE 7.3. FRESH PROPERTIES OF TESTED MIXTURES

Mixture	Time		PPF1-0.5%	PPF1-0.35%	PPF1-0.25%
Temperature (°C)	10 min		20	21	21
	70 min		19	20	20
Unit weigth (kg/m^3)	10 min		2213	2293	2292
	70 min		2106	2281	2274
Air volume (%)	10 min		8.6	7.0	5.1
	70 min		13.5	5.8	6.4
Slump flow (mm)	10 min		640	670	675
	70 min		600	635	645
V-funnel flow time (s)	10 min		4.2	5.3	4.3
	70 min		5.2	5.4	4.5
Filling capacity (%)	10 min		65	83	94
	70 min		57	64	93
Rheology	10 min	g (Nm)	1.4	0.6	0.6
		h (Nms)	10.6	11.7	10.6
	70 min	g (Nm)	1.6	0.5	0.4
		h (Nms)	11.8	13.2	10.4
Surface settlement (%)			0.39	0.48	0.49

The slump flow results demonstrated the low filling ability of the mixture containing 0.5% of polypropylene fibres. For the mixtures containing 0.35% and 0.25% PPF the slump flow values were close one to the other (670 and 675 mm). However, the SCC with 0.25% fibres exhibited better filling capacity than the SCC with 0.35% fibre content (94% vs. 83% at 10 min and 93% vs. 64% at 70 min). This is shown in Fig. 7.1.

When the IBB rheometer was used to measure the rheological constants of these SCC, the viscosity values of the 0.25% mixture were lower than those for the 0.35% mixture. This variation in viscosities was especially notorious at 70 min (10.4 and 13.2 Nms, respectively). The low viscosity of the 0.25% mixture gave as a result shorter flow time values in the V-funnel at both ages.

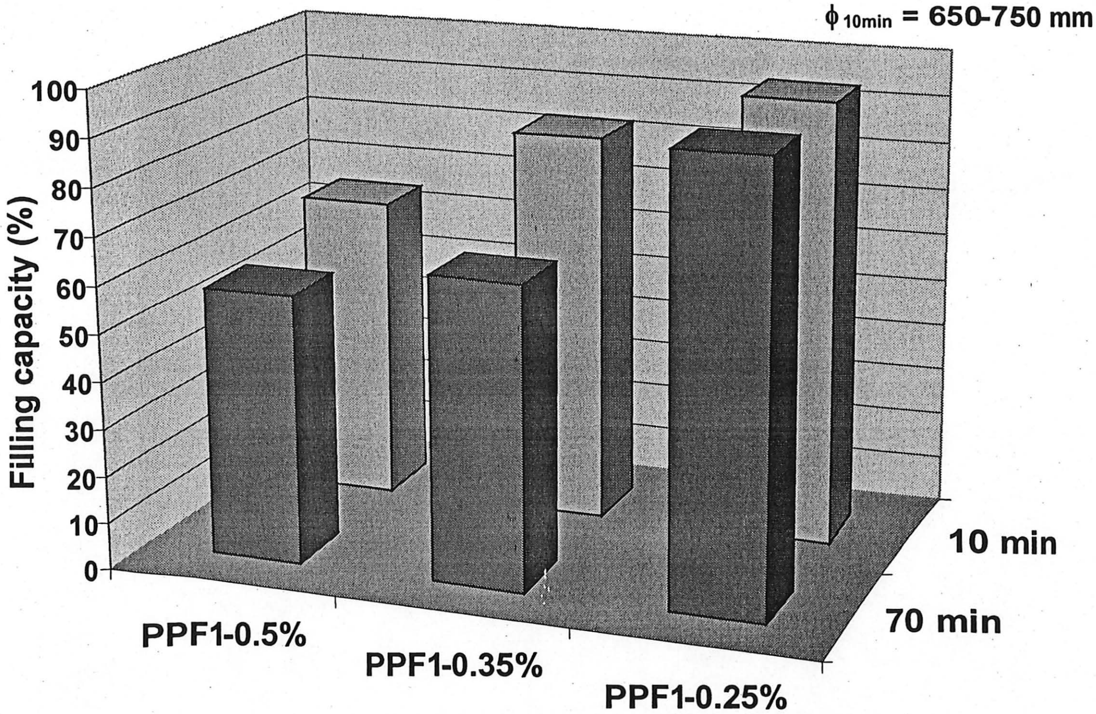


Fig. 7.1 Filling capacity of mixtures made with different fibre contents

For the two SCC mixtures with 0.25% and 0.35% fibre volume, a flexural test revealed that both mixtures had practically the same behaviour (Fig. 7.2). Also, compressive strength was determined for both concretes at 1, 7, 28, and 56 days as shown in Table 7.4 and Fig. 7.3. A variation at long term was observed between both concretes giving lower compressive strength the concrete with the higher percentage of fibres. This variation in compressive strength could be caused by a weak paste-fibre adherence causing a failure plane so reducing compressive strength.

TABLE 7.4 COMPRESSIVE STRENGTH OF CONCRETE MIXTURES MADE WITH PPF 1

	Time	PPF1-0.35%	PPF1-0.25%
f'c (MPa)	1 day	18	17.6
	7 days	33.5	33.6
	28 days	50.4	44
	56 days	61	53.1

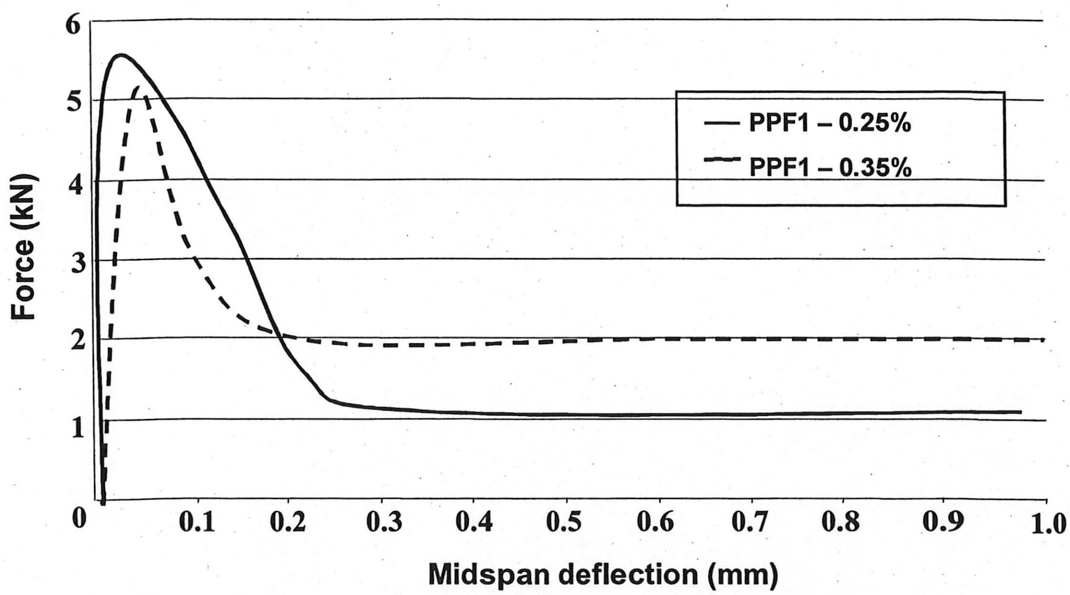


Fig. 7.2 Mean flexural strengths of mixtures made with different fibre dosages

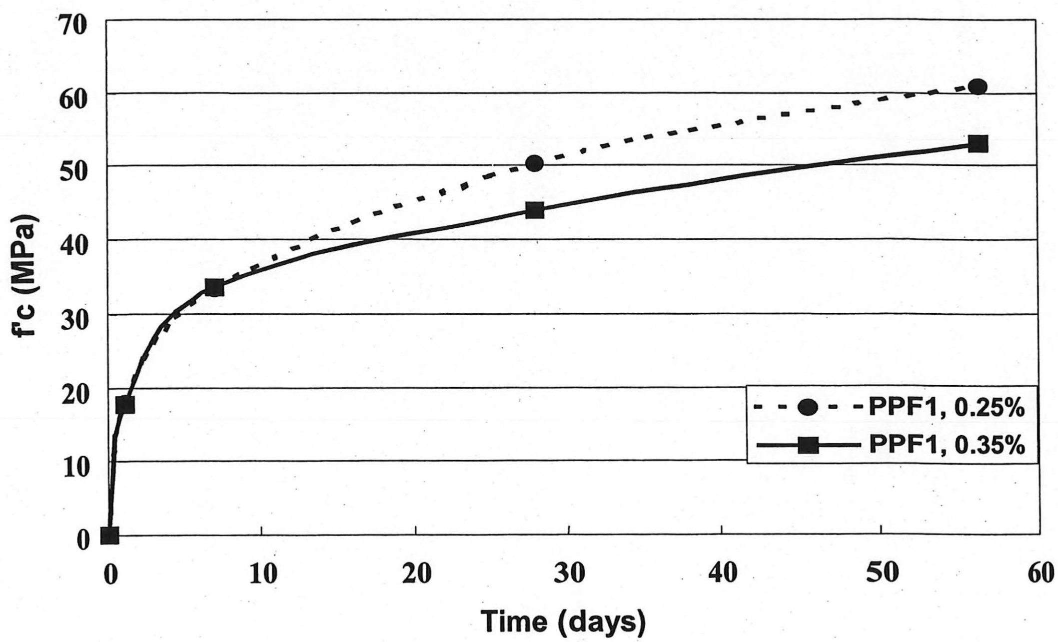


Fig. 7.3 Compressive strength of mixtures made with different fibre dosages

7.3 Effect of sand-to-total aggregate ratio

Once the fibre dosage was fixed, two more mixtures were prepared using the PPF 2, PCP 2, VEA 2, and AEA 2 materials. The difference between the mixtures was the fine-to-total aggregate ratio (S/AG) by volume. Two different ratios were used: 0.54 and 0.60. All mixtures had a constant w/cm of 0.40 and a total binder content of 475 kg/m^3. A PCP-based HRWRA was used along with an AEA. Each mixture was prepared with a different VEA dosage in order to ensure proper surface settlement. The mixtures proportioning are given in Table 7.5.

TABLE 7.5 PROPORTIONING OF SCC MIXTURES MADE WITH DIFFERENT SAND-TO-TOTAL AGGREGATE RATIOS

Mixture	PPF2-0.54	PPF2-0.60
S/AG	0.54	0.60
w/cm	0.40	0.40
Binder (kg/m^3)	475	475
Water (kg/m^3)	190	190
Coarse agg. (kg/m^3)	720	620
Sand (kg/m^3)	820	900
Total agg. (kg/m^3)	1540	1520
Fiber (kg/m^3)	2.3	2.3
HRWRA (L/m^3)	4.3	5.1
VEA (L/m^3)	0.26	0.5
AEA (ml/m^3)	50	71

Fresh state properties are summarized in Table 7.6 and compressive strengths in Table 7.7. The required slump flow was set at 700 mm ± 50 mm, and the maximum slump flow loss should be under 50 mm. The initial fresh air content was intended to be 6 ± 2%. However, for the mixture with a S/AG of 0.54, the air content was 8.8%. Both concretes had similar slump flow and slump flow retention values.

TABLE 7.6 FRESH PROPERTIES OF FIBRE-SCC MIXTURES MADE WITH DIFFERENT SAND-TO-TOTAL AGGREGATE RATIOS

Mixture	Time		PPF2-0.54	PPF2-0.60
Temperature (°C)	10 min		22.4	24
	70 min		22.0	24
Unit weigth (kg/m³)	10 min		2125	2218
	70 min		2170	2296
Air volume (%)	10 min		8.8	7.0
	70 min		6.0	4.5
Slump flow (mm)	10 min		700	710
	70 min		660	690
J-ring ϕ (mm)	10 min		680	630
	70 min		605	590
V-funnel flow time (s)	10 min		2.6	2.7
	70 min		3.7	3.3
Filling capacity (%)	10 min		96	94
	70 min		96	89
Rheology	10 min	g (Nm)	0.4	0.3
		h (Nms)	7.6	8.3
	70 min	g (Nm)	0.4	0.5
		h (Nms)	8.8	9.2
Settlement (%)			0.53	0.32

TABLE 7.7 COMPRESSIVE STRENGTH OF CONCRETE MIXTURES MADE WITH DIFFERENT SAND-TO-TOTAL AGGREGATE RATIOS

	Time	PPF2-0.54	PPF2-0.60
f'c (MPa)	1 day	17	17
	7 days	27	35
	28 days	49	50

The filling capacity values were virtually the same for both mixtures tested at 10 min, 94% for PPF 2-0.60 and 96% PPF 2-0.54. However, after 70 min the filling capacity of PPF 2-0.60 decreased to 89%, while for PPF 2-0.54 it remained the same. Although both percentages were over the minimum required value of 80%, PPF 2-0.54 had the highest value. The comparison of the filling capacity for these two mixtures is presented in Fig. 7.4.

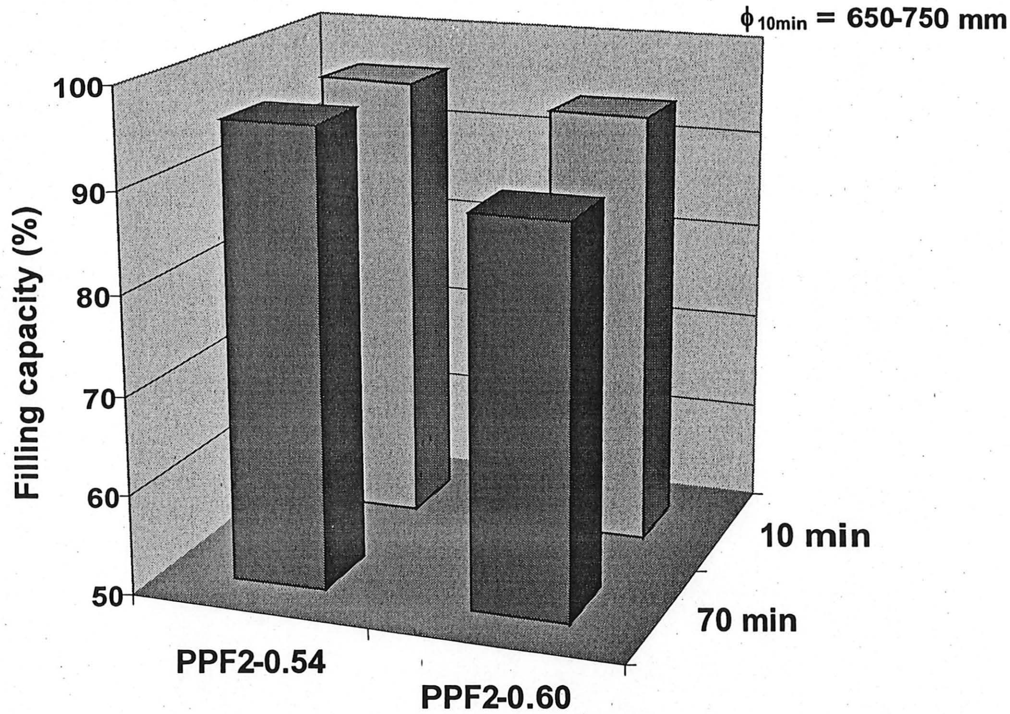


Fig. 7.4 Filling capacity values of mixtures made with different sand-to-total aggregate ratios

The final diameters measure with the J-ring are seen in Fig. 7.5

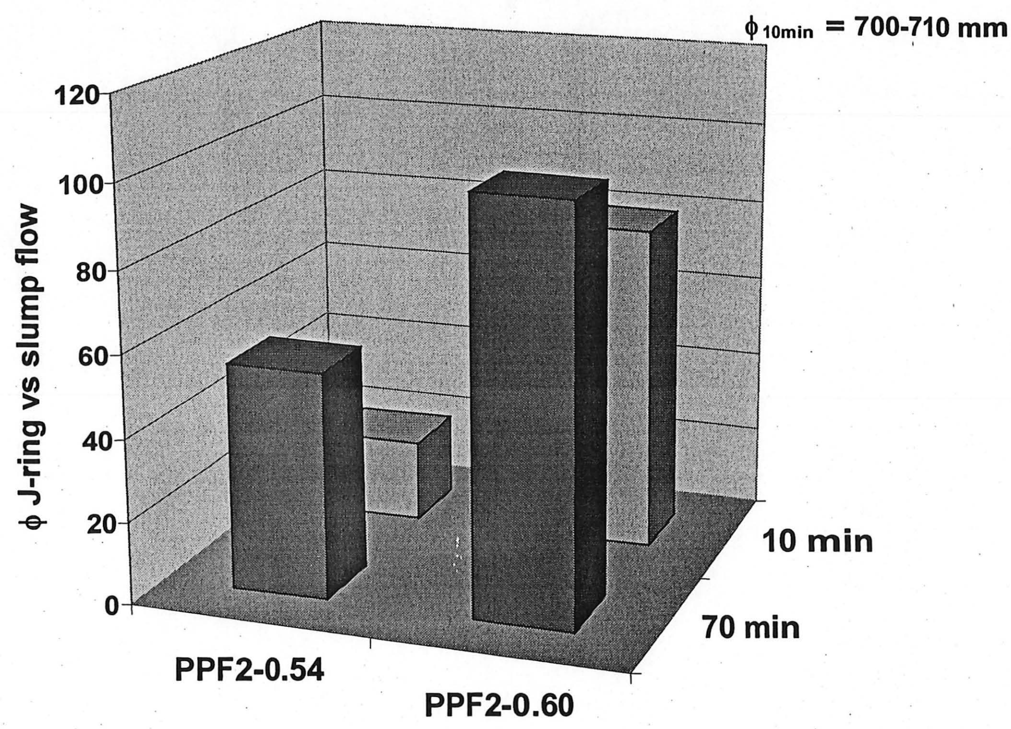


Fig. 7.5 ϕ J-ring vs. slump flow of mixtures with different sand-to-total aggregate ratios

When the spread values using the J-ring versus slump flow was compared, significant differences were seen for PCP2-0.60 at 10 and 70 minutes. The difference at 10 min was 80 mm, meanwhile at 70 min the difference increased up to 100 mm. This indicated a decrease in the passing ability of the mixture.

Surface settlement results for both concretes are compared in Fig. 7.6 and indicate that the PPF 2-0.54 mixture presents a higher surface settlement than that of PPF 2-0.60 (0.53% and 0.32%, respectively). Surface settlement of PPF 2-0.54 was even higher than the limit (0.50%).

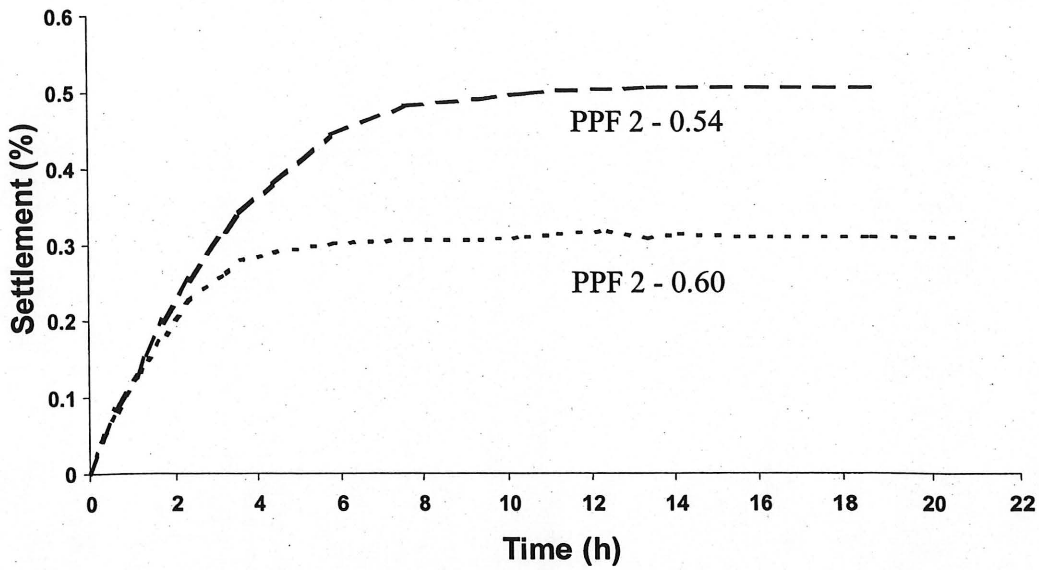


Fig. 7.6 Settlement of mixtures with different sand-to-total aggregate ratios

The compressive strengths at different ages of both mixtures from Table 7.7 are compared in Fig. 7.7. In Fig. 7.7 is possible to see that the early strength at 1 day is the same for both mixtures. This strength is higher than the 10 MPa required to demold the formwork. Also, despite a difference at 7 days, the compressive strength at 28 days remains the same for both mixtures. The strength at 28 days is 50 MPa.

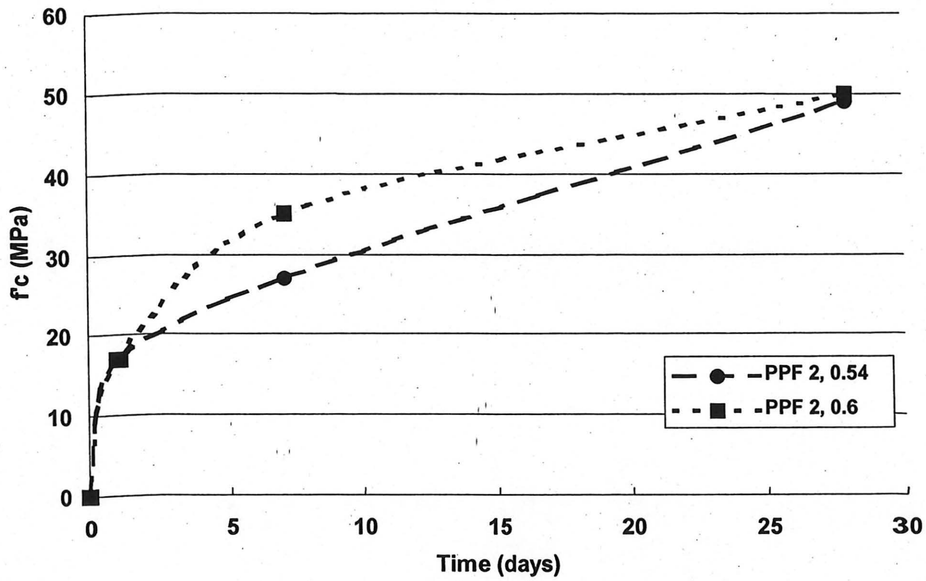


Fig. 7.7 Compressive strength development of fibrous SCC with different sand-to-total aggregate ratios

7.4 Discussion

The optimal fibre dosage was 0.25% to achieve maximum filling capacity. Proper filling ability was also achieved, as measured with the slump flow. The slump flow final diameter of 700 ± 50 mm indicated a low yield stress. The V-funnel flow time and torque viscosity measured with the IBB rheometer indicated moderate viscosity level.

When the optimal fibre dosage was used with two different sand-to-total aggregate ratios (0.54 and 0.60 by volume), the filling ability as per the slump flow was almost the same (700 ± 50 mm). The lowest sand –to-aggregate ratio concrete resulted in the highest passing ability, measured with the J-ring. The filling capacity was slightly better for the PPF 2-0.54 (96% and 96%) than for PPF 2-0.60 (94% and 89%).

Chapter 8

GENERAL CONCLUSIONS

8.1 Conclusions

Several objectives were proposed for this research, among the most important ones were:

- to compare the performance of high performance SCC for repair applications proportioned with either low w/cm or with moderate w/cm and VEA;
- to compare different commercially available admixtures and cementitious materials;
- to determine compatibility issues between various binders and HRWRAs;
- to investigate the effect of synthetic fiber volumeon SCC properties;
- as well, some secondary objectives were proposed to confirm and recommend values and test methods to assess workability of SCC.

After carefully performing the research plan, it is possible to establish the following major conclusions:

- the effectiveness of different PCP-based HRWRA in SCC technology was not the same. The HRWRA demands were quite different. PNS dosage must be higher to achieve similar self-consolidating properties;
- incompatibilities were observed between PCP-based HRWRAs and Ternary binder 2. The combination of PCP 2-Ternary binder 2 showed a severe loss of flowability, resulting in a lack of dynamic stability after 70 min of water-binder contact;
- the AEA demand was high when VEA was used. However, this increase in the AEA demand was not observed when the PCP 4 HRWRA was used. This increase was significant when the Quaternary binder 1 was used;

- the VEA dosage optimized with the Ternary binder 1 was also adequate when incorporated with the other tested binders. However, when the PNS-based HRWRA was used proper optimization was required,
- rheologically, the SCC mixtures with the same w/cm are not significantly different at 10 min. However, after 70 min, the loss of fluidity is directly proportioned to the rheological parameters;
- the test methods most recommended for quality control are the slump flow combined with the L-box or the filling capacity caisson. The blocking ratio measured with the L-box should be over 0.70 and the filling capacity over 80% for concretes with a 10 mm MSA. Under laboratory conditions, the rheometer has proved to be an excellent tool to characterize SCC; and
- fibre SCC with a low fibre dosage is easily achievable for repair applications. Despite the use of long fibres, the filling ability, passing ability, and filling capacity of the SCC mixtures were proven to be excellent.

8.2 Future research

The incorporation of new materials to elaborate SCC is always complicated. In order to better understand the intrinsic properties of different constituents several concrete mixtures must be elaborated. With the increase interest in this kind of special concretes, the market will require the testing and understanding of new binder-admixture compatibility issues. The work performed in this research aimed to improve such testing and understanding.

Further research is necessary to assess fresh state properties of SCC on the jobsite. Correlation between the results of easy test methods at the jobsite and more elaborated ones in the laboratory is necessary. The assessment of hardened state properties of SCC is also required for proven material combinations, including mechanical properties, viscoelastic characteristics, and durability. A research effort is already under way at the Universitè de Sherbrooke to assess the hardened properties of repair SCC mixtures (Hwang Ph.D. and Abdi M.Sc.A.)

REFERENCES

ASTM, (1996), *Annual Book of ASTM Standards*, Concrete and Aggregates, Vol. 04.02, American Society for Testing and Materials.

Aïtcin, P.C., Jolicoeur, C., and McGregor, J.G., (1994), "*Superplasticizers: How They Work and Why They Occasionally Don't?*," Concrete International, Vol. 16, No. 5, pp. 45-52.

Aïtcin, P.C. (2001), "*High Performance Concrete*," (in French), 1st Ed., Paris, France, Eyrolles 683 p.

Brit EuRam Proposal, #G6RD-CT-2001-00580 (2000), *"Rheology of Self-Consolidating Concrete",* Final Synthesis Report No. RT3-v1, 20 p.

Brower, L.E., and Ferraris, C.E., (2003), "*Comparison of Concrete Rheometers*," Concrete International, Vol. 25, No. 8, pp. 41-50.

Billberg, P., (1999), "*Self-Compacting Concrete For Civil Engineering Structures- The Swedish Experience*," 1st Ed., Stockholm, Sweden, Swedish Cement and Concrete Research Institute, 83 p.

Berke, N.S., Cornman, C.R., Jeknavorian, G.F., Knight, G.F., and Wallevik, O., (2002), "*The Effective Use of Superplasticizers and Viscosity-Modifying Agents in SCC*," Proc. of the 1st North American Conference on the Design and Use of Self-Consolidating Concrete, Chicago, USA, Ed. Shah, P., pp. 173-178.

Campbell-Allen, D., and Roper, H., "*Concrete Structures: Materials, Maintenance and Repair*," 1st Ed., London, England, Longman Scientific & Technical, 369 p.

Campion, M.J., and Jost, P., (2000), "*Self-Compacting Concrete: Expanding the Probabilities of Concrete Design and Placement*," Concrete International, Vol. 22, No. 4, pp. 31-34.

De Larrard, F., Ferraris, C. E., and Serdan, T., (1998), "*Fresh Concrete : a Hershell-Bulkley Material*," Materials and Structures, Vol. 31, No. 211, pp. 494-498.

De Larrard, F., Szitkar, J.C., Hu, C., and Joly, M., (1993), "*Design of a Rheometer for Fluid Concrete*," Proc. of the International RILEM Workshop on Special Concrete Workability and Mixing, Paisley, Scotland, Ed. Bartos, P., pp. 201-205

Ferraris, C. E., (1999), "*Measurement of the Rheological Properties of High-Performance Concrete; State of the Art Report*," Journal of Research of the National Institute of Standards and Technology, Vol. 104, No. 5, pp. 461-478. http://www.nist.gov/jres

Ferraris, C .F., and De Larrard, F., (1998), "*Testing and Modeling of Fresh Concrete Rheology*," NISTIR 6094, http://ciks.cbs.nist.gov/~garbocz /rheology NISTIR/FR97 html 61 p.

Folsey, D. (2001), "*SCC Used in Repair Applications: Preliminary Results,*" (in French), Internal comunication, Université de Sherbrooke, Sherbrooke, Canada, 18 p.

Gagné, R., (2003), "*Durability and Repair of Concrete*," (in French), Class Notes GCI 714, Université de Sherbrooke, Sherbrooke, Canada, 165 p.

Geicker, M.R., Brandl, M., Thrane, L.N., Bager, D.H. and Wallevik, O., (2002), "*The Effect of Measuring Procedure on the Apparent Rheological Properties of SCC*," Cement and Concrete Research , Vol. 32, No. 11, pp. 1791-1795..

Hovington, A., (2000), "*The Experience of the Department of Transport of Quebec with Self-Consolidating Concrete-1997-2000*," Progress in Concrete 2000, Quebec, Canada, ACI Quebec and Eastern Ontario Chapter, pp. 2-8.

Japan Society of Civil Engineers, (1999), "*Recommendation for Self-Compacting Concrete*", JSCE Concrete Engineering Series, Tokyo, Japan, Ed. Omoto, T., and Ozawa, K., 77 p.

Khayat, K.H., (2000), "*Optimization and Performance of Air-Entrained, Self-Consolidating Concrete*," ACI Materials Journal, Vol. 97, No. 5, pp. 526-535.

Khayat, K.H., (1998a), "*Viscosity-Enhancing Admixtures for Cement Based Materials - An Overview*," Cement and Concrete Composites, Vol. 20, pp. 171-188.

Khayat, K.H., (1998b), "*Use of Viscosity Modifying Admixtures to Reduce Top-Bar Effect of Anchored Bars Cast With Fluid Concrete*," ACI Materials Journal, Vol. 95, No. 2, pp. 158-167.

Khayat, K.H., and Guizani, Z., (1997), "*Use of Viscosity Modifying Admixtures to Enhance Stability of Fluid Concrete*," ACI Materials Journal, Vol. 94, No. 4, pp. 332-340.

Khayat, K.H., Hu, C., and Monty, H., (2000), "*Stability of Self-Consolidating Concrete, Advantages and Potential Applications*," Proc. of the 1st International Conference on SCC, Stockholm, Sweden, Ed. Skarendahl, Ä., and Petersson, Ö., pp. 143-152.

Khayat, K.H., (1999), "*Workability, Testing and Performance of Self-Compacting Concrete*," ACI Materials Journal, Vol. 96, No. 3, pp. 346-353.

Khayat, K.H., (1995), "*Effects of Antiwhashout Admixtures on Fresh Properties*", ACI Structural Journal, Vol. 92, No. 2, pp. 164-171.

Khayat, K.H., (1996), "*Effects of Antiwashout Admixtures on Properties of Hardened Concretes*," ACI Materials Journal, Vol. 93, No. 3, pp. 134-146.

Khayat, K.H. and Yahia, A., (1997), "*Effect of Welan Gum-High-Range Water Reducer Combinations on Rheology of Cement Grout*," ACI Materials Journal, Vol. 94, No.5, pp. 365-372.

Khayat, K.H., and Aïtcin, P.C., (1998), "*Use of Self-Consolidating Concrete in Canada, Present Situation and Perspectives*," Proceedings of the International Workshop on Self-Compacting Concrete, Kochi, Japan, Ed. Ozawa, K., and Ouchi, M., pp. 11-22.

Lacombe, P., Beaupre, D., and Pouliot, N., (1999), "*Rheology and Bonding Characteristics of Self-Levelling Concrete as a Repair Material*," Fifth CANMET/ACI International

Conference on Superplasticizers and Other Chemical Admixtures in Concrete-Suplementary Papers, Rome, Italy, Ed. Malhotra, V.M., pp. 163-184.

Malhotra, V.M., and Mehta, P.K., (1996), *"Pozzolanic and Cementitious Materials"*, 1st Ed., Amsterdam, Netherlands, Ed. Gordon and Breach Science Publishers SA., 191 p.

Manai, K., (1995), *"Effect of Chemical and Mineral Admixtures on Workability, Stability, and Performance of SCC,"* (in French), Master Thesis, Université de Sherbrooke, Sherbrooke, Canada, 182 p.

McLeish, A., (1994), *"Evaluating the Flow Properties of Flowable Concrete,"* Proc. of International RILEM Conference Production Methods and Workability of Concrete, Paisley, Scotland, Ed. Bartos, P., pp. 249-255.

Mehta, P.K., and Monteiro, P.J.M., (1993), *"Concrete.- Structures, Properties, and Materials,"* 2nd Ed., New Jersey, USA, Prentice Hall, 548 p.

Nawa, T., Izumi, T., and Edamatsu, Y., (1998), *"State of the Art Report on Materials and Design of Self-Compacting Concrete,"* Proc. of the International Workshop on Self-Compacting Concrete, Kochi, Japan, Ed. Ozawa, K., and Ouchi, M., pp. 160-190.

Neville, A.M., (1996), *"Properties of Concrete,"* 4th Ed., New York, USA, Ed. John Wiley & Sons, 844 p.

Okamura, H., (1997), *"Self-Compacting High-performance Concrete,"* Concrete International, Vol. 19, No. 7, pp. 50-54.

Okamura, T., Matsura, S., Hashimoto, S., and Uchida, S., (1995), *"Effect of Mixing Temperature on the Fluidity of Belite-Rich Cement,"* Concrete & Research Technology, Vol. 6, No. 2, pp. 127-137.

Pederson, B., and Mortsel E., (2001), *"Characterization of Fillers for SCC,"* Proc. of the 2nd International Symposium on Self-Compacting Concrete, Kochi, Japan, Ed. Ozawa, K., and Ouchi, M., pp. 257-266.

Petrov, N., (1998), *"Properties of an In-situ SCC and the Influence on the Steel-Concrete Interface,"* (in French), Master Thesis, Université de Sherbrooke, Sherbrooke, Canada, 158 p.

Petrov, N., Khayat, K.H., and Tagnit-Hamou, A., (2001), *"Effect of Stability of Self-Consolidating Concrete on the Distribution of Steel Corrosion Characteristics along Experimental Wall Elements,"* Proc. of the 2nd International Symposium on Self-Compacting Concrete, Kochi, Japan, Ed. Ozawa, K., and Ouchi, M., pp. 441-450.

Perenchio, W.F., Whiting, D.A., and Kantro,D.L., (1979), *"Water Reduction, Slump Loss and Entrained-Air Void Systems as Influenced by Superplasticizers,"* Proc. of First International Symposium on Superplasticizers in Concrete, ACI SP 62, Ed. Malhotra, V.M., pp. 137-155.

Ramachandra, V.S., Malhotra, V.M., Jolicoeur, C., and Spiratos, N, (1998), "*Superplasticizers: Properties and Applications in Concrete*," 1st Ed., Montreal, Canada, Ministry of Public Works and Government Services, 404 p.

RILEM TC 84-AAC, (1995), "*Application of Admixtures in Concrete*," RILEM Report No. 10, London, UK, Ed. Paillère, A.M., 131 p.

Rixom, R., and Mailvaganam, N., (1999), "*Chemical Admixtures for Concrete*," 3rd Ed., New York , USA, Ed. E&FN SPON, 437 p.

Rizzo, E.M., and Sobelman, M.B., (1989), "*Selection Criteria for Concrete Repair Materials*," Concrete International, Vol. 11, No. 9, pp. 46-49.

Shadle, R., and Somerville, S., (2002), "*The Benefits of Utilizing Fly Ash in Producing SCC*," Proc. of 1st North American Conference on the Design and Use of Self-Consolidating Concrete, Chicago, USA, Ed. Shah, S., pp. 235-242.

Shoya, M., Aba, M., Sugita, S., Tsukinaga, Y., and Tokuhashi, K. (1999), "*Self-Compactibility of Fresh Concrete with Non-Ferrous Metal Slag Fine Aggregate*," Proc. of 1st International Conference on SCC, Stockholm, Sweden, Ed. Skarendahl, Ä., and Petersson, Ö., pp. 143-152.

Skarendahl, Ä., and Petersson, Ö., (2001), "*State of the Art Report of RILEM Technical Comitee 174 SCC,*" Report No. 23, 141 p.

Struble, L. and Szecsy, R., (1996), "*Rheology of Fresh Concrete*," Proc. of the Materials Engineering Conference, Materials for the New Millennium, Vol. 2, Whasington, D.C., USA, N/A, pp. 7-29.

Tagnit-Hamou, A., (2002), "*Microstructure and Physico-Chemistry of cement and Concrete*," (in French), Class Notes GCI 712, Université de Sherbrooke, Sherbrooke, Canada, 289 p.

Tattersall, G. H., and Banfill, P. F. G., (1983), "*The Rheology of Fresh Concrete*," London, UK, Ed. Pittman Advanced Publishing Program, 135 p.

Tracy, R.G., and Fling, R.S., (1989), "*Rehabilitation Strategies*," Concrete International, Vol. 11, No. 9, pp. 41-45.

Trudel, A., (1996), "*Workability, Stability, and Structural Behaviour of High Performance SCC*," (in French), Master Thesis, Université de Sherbrooke, Sherbrooke, Canada, 198 p.

Wallevik, O. H., and Nielsson, I., (1998), "*Self-Compacting Concrete- A Rheological Approach*," Proc. of International Workshop on Self-Compacting Concrete, Kochi, Japan, Ed. Ozawa, K., and Ouchi, M., pp. 136-159.

Wallevik, O., Khayat, K. H., and Beaupre, D., (2003), "*Rheology of Cement Suspensions,*" IBRI, Intensive Course on Rheology of Cement-Based Materials and Specialty Concretes, Sherbrooke, Canada.

Wallevik, O., and Gjork, O.E., (1990), "*Modification of the Two-Point Workability Apparatus*," Magazine of Concrete Research, Vol. 42, No. 152, pp. 135-142.

Weyers, R.E., Powell, B.D., Sprinkel, M.M., and Vorster, M., (1993), "*Concrete Bridge Protection, Repair and Rehabilitation Relative to Reinforcement Corrosion: A Methods Application Manual*," Strategic Highway Research Program, Washington, D.C, USA, 268 p.

Yamada, K., Yanagisawa, T., and Hanehara, S., (1999), "*Influence of Temperature on the Dispersability of Polycarboxylate Type Superplasticizer for Highly Fluid Concrete*," Proc. of the 1st International Conference on SCC, Stockholm, Sweden, Ed. Skarendahl, Ä., and Petersson, Ö., pp. 437-448.

Yurugi, M., Sakata, N., Iwai, M., and Sakai, G., (1993) "*Mix Proportion for Highly Workable Concrete,*" Proc. Concrete 2000, Dundee, Scotland, N/A, pp. 579-589.

APPENDIX I
OPTIMIZATION OF MIXTURES EVALUATED IN CHAPTER 6

TABLE I.1 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TYPE 10 CEMENT AND PCP 1

Mixture			w/cm = 0.35			
			I	II	III	Final
type 10 cement (kg/m^3)			309			
Fly ash (kg/m^3)			142			
Silica fume (kg/m^3)			24			
Total cementitious materials (kg/m^3)			475			
Water (kg/m^3)			166			
Coarse aggregate (kg/m^3)			840			
Sand (kg/m^3)			815			
HRWRA (L/m^3)			2.38	1.7	2.13	2.38
Air-entraining admixture (ml/m^3)			952	480	100	50
Temperature (°C)	10 min		23	22	25	26
	70 min		21	21	26	26
Unit weigth (kg/m^3)	10 min		2157	2140	2206	2297
	70 min		2138	2086	2184	2291
Air volume (%)	10 min		9.2	10.0	8.0	5.5
	70 min		10.5	11.0	9.5	6.2
Slump flow (mm)	10 min		715	720	675	675
	70 min		695	695	500	615
J-ring (mm)	10 min		740	670	550	540
	70 min		690	680	500	515
V-funnel flow time (s)	10 min		4.5	3.4	4.6	4.6
	70 min		4.0	2.8	4.6	4.2
L-box	10 min	time (sec)	2.1	1.0	2.1	2.5
		h_2/h_1	1.00	0.90	0.66	0.67
	70 min	time (sec)	2.5	1.0	2.7	2.9
		h_2/h_1	1.00	0.85	0.34	0.58
Filling capacity (%)	10 min		100	100	83	88
	70 min		100	100	50	81
Maximum settlement [%]			0.53	0.34	0.28	0.38
Rheological parameters	10 min	g (N.m)	0.00	0.40	0.70	0.40
		h (N.m.s)	7.0	5.6	8.4	8.2
	70 min	g (N.m)	0.70	0.80	1.60	0.80
		h (N.m.s)	6.6	5.4	9.0	8.5

TABLE I.2 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TYPE 10 CEMENT AND PCP 2

Mixture			w/cm = 0.35			
			I	II	III	Final
Cement type 10 (kg/m ^{3})			309			
Fly ash (kg/m ^{3})			142			
Silica fume (kg/m ^{3})			24			
Total cementitious content (kg/m ^{3})			475			
Water (kg/m ^{3})			166			
Coarse aggregate (kg/m ^{3})			840			
Sand (kg/m ^{3})			815			
HRWRA (L/m ^{3})			8.00	9.00	9.50	9.10
Air-entraining admixture (ml/m ^{3})			125	100	70	70
Temperature (°C)	10 min		21	22	23	22
	70 min		20	21	22	21
Unit weigth (kg/m ^{3})	10 min		2222	2228	2241	2252
	70 min		2280	2257	2269	2293
Air volume (%)	10 min		8.0	8.0	7.5	7.2
	70 min		7.0	7.5	7.0	6.2
Slump flow (mm)	10 min		655	640	675	650
	70 min		635	620	685	685
J-ring (mm)	10 min		660	570	665	640
	70 min		605	610	650	670
V-funnel flow time (sec)	10 min		2.7	3.2	2.6	3.2
	70 min		2.8	3.6	3.5	3.2
L-box	10 min	time (sec)	0.7	1.8	0.9	1.0
		h_2/h_1	0.73	0.83	0.79	0.66
	70 min	time (sec)	2.9	1.9	1.2	1.4
		h_2/h_1	0.50	0.84	0.78	0.80
Filling capacity (%)	10 min		92	82	95	89
	70 min		88	86	96	97
Maximum settlement [%]			0.43	0.44	0.54	0.50
Rheological parameters	10 min	g (N.m)	0.50	-	0.40	0.40
		h (N.m.s)	5.0	-	4.6	5.2
	70 min	g (N.m)	0.40	-	0.00	0.20
		h (N.m.s)	6.8	-	6.4	5.6

TABLE I.3 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TYPE 10 CEMENT AND PCP 3

Mixture			w/cm = 0.35					
			I	II	III	IV	V	Final
Cement type 10 (kg/m³)			309					
Fly ash (kg/m³)			142					
Silica fume (kg/m³)			24					
Total cementitious content (kg/m³)			475					
Water (kg/m³)			166					
Coarse aggregate (kg/m³)			840					
Sand (kg/m³)			815					
HRWRA (L/m³)			4.58	5.00	5.00	4.20	3.30	3.30
Air-entraining admixture (ml/m³)			400	200	100	80	20	10
Temperature (°C)	10 min		20	20	21	20	20	22
	70 min		19	18	20	20	19	20
Unit weight (kg/m³)	10 min		2080	2087	2207	2282	2197	2180
	70 min		2056	2235	2288	2310	2221	2220
Air volume (%)	10 min		13.5	12.0	8.5	5.6	10.8	8.0
	70 min		13.0	6.6	5.8	5.0	9.2	7.0
Slump flow (mm)	10 min		675	690	705	685	670	665
	70 min		650	695	715	675	660	635
J-ring (mm)	10 min		-	-	-	-	-	-
	70 min		-	-	-	-	-	-
V-funnel flow time (sec)	10 min		-	3.8	4.8	4.0	3.7	3.8
	70 min		-	5.2	5.2	4.4	4.2	4.1
L-box	10 min	time (sec)	-	-	-	-	-	1.9
		h_2/h_1	-	-	-	-	-	0.86
	70 min	time (sec)	-	-	-	-	-	2.2
		h_2/h_1	-	-	-	-	-	0.80
Filling capacity (%)	10 min		99	-	99	100	96	98
	70 min		92	-	98	100	94	90
Maximum settlement (%)			-	0.15	0.32	0.31	0.29	0.36
Rheological parameters	10 min	g (N.m)	-	-	-	0.20	0.20	0.20
		h (N.m.s)	-	-	-	7.6	7.8	10.6
	70 min	g (N.m)	-	-	-	0.20	0.40	0.40
		h (N.m.s)	-	-	-	10.2	10.7	11.6

TABLE I.4 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TYPE 10 CEMENT AND PCP 4

Mixture			I	II	III	IV	V	VI	Final
			w/cm =						
Cement type 10 ^{3})			309						
Fly ash ^{3})			142						
Silica fume ^{3})			24						
Total cementitious content (kg/m^3)			475						
Water ^{3})			166						
Coarse aggregate ^{3})			840						
Sand ^{3})			815						
HRWRA ^{3})			6.75	7.50	7.08	6.00	5.00	3.63	3.65
AEA ^{3})			100	50	50	20	40	60	40
Set-retarding agent ^{3})			-	-	950	-	-	-	500
Temperature ($^{\circ}$C)	10 min		21	20	20	18	19	21	21
	70 min		20	20	19	17	18	20	20
Unit weight (kg/m^3)	10 min		2061	2142	2319	2353	2336	2183	2271
	70 min		1907	2091	2236	2377	2310	2164	2275
Air volume (%)	10 min		12.0	9.0	4.2	2.7	3.6	9.6	6.5
	70 min		15.0	10.5	7.2	2.4	5.1	9.0	6.2
Slump flow (mm)	10 min		685	730	725	750	750	660	675
	70 min		560	700	700	740	720	530	665
J-ring (mm)	10 min		-	-	-	800	730	-	-
	70 min		-	-	-	725	680	-	-
V-funnel flow time	10 min		4.9	3.4	5.3	5.4	5.5	4.4	5.5
	70 min		3.7	3.0	4.9	9.7	10.0	5.2	5.7
L-box	10 min	time	-	-	-	1.8	2.3	2.5	2.0
		h2/h1	-	-	-	0.82	0.91	0.8	0.69
	70 min	time	-	-	-	2.9	4.9	3.4	2.4
		h2/h1	-	-	-	0.86	0.77	0.46	0.83
Filling capacity	10 min		98	100	-	100	100	79	95
	70 min		91	100	-	100	98	45	93
Maximum settlement			0.17	0.18	1.14	0.43	0.37	-	0.45
Rheological parameter	10 min	g (N.m)	-	-	-	-	0.00	1.80	0.60
		h (N.m.s)	-	-	-	-	11.8	8	10.7
	70 min	g (N.m)	-	-	-	-	0.10	2.20	0.80
		h (N.m.s)	-	-	-	-	20.7	9.2	12.6

TABLE I.5 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TYPE 10 CEMENT AND PCP 5

Mixture			w/cm = 0.35	
			I	Final
Cement type 10 (kg/m^3)			309	
Fly ash (kg/m^3)			142	
Silica fume (kg/m^3)			24	
Total cementitious content (kg/m^3)			475	
Water (kg/m^3)			166	
Coarse aggregate (kg/m^3)			840	
Sand (kg/m^3)			815	
HRWRA (L/m^3)			3.15	3.15
Air-entraining admixture (ml/m^3)			60	30
Temperature (°C)	10 min		20	20
	70 min		19	19
Unit weight (kg/m^3)	10 min		2216	2216
	70 min		2187	2187
Air volume (%)	10 min		9.2	6.5
	70 min		11.2	8.0
Slump flow (mm)	10 min		670	675
	70 min		660	670
J-ring (mm)	10 min		635	635
	70 min		630	630
V-funnel flow time (sec)	10 min		4.2	4.2
	70 min		4.4	4.4
L-box	10 min	time (sec)	1.2	1.2
		h_2/h_1	0.77	0.77
	70 min	time (sec)	2.6	2.6
		h_2/h_1	0.76	0.76
Filling capacity (%)	10 min		93	93
	70 min		96	96
Maximum settlement (%)			0.39	0.39
Rheological parameters	10 min	g (N.m)	0.60	0.20
		h (N.m.s)	8.4	8.0
	70 min	g (N.m)	0.80	0.40
		h (N.m.s)	7.0	5.6

TABLE I.6 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TERNARY BINDER 1 AND PCP 1

Mixture			w/cm = 0.42				
			I	II	III	IV	Final
Ternary binder 1 (kg/m³)			475				
Water (kg/m³)			200				
Coarse aggregate (kg/m³)			803				
Sand (kg/m³)			775				
HRWRA (L/m³)			2.25	2.25	2.50	2.31	2.63
VMA (L/m³)			1.19	1.31	2.50	3.00	1.31
Air-entraining admixture (ml/m³)			375	375	525	563	375
Temperature (°C)	10 min		25	21	21	20	21
	70 min		23	22	22	20	22
Unit weight (kg/m³)	10 min		2267	2286	2279	2259	2264
	70 min		2224	2272	2294	2274	2263
Air volume (%)	10 min		5.0	5.0	4.7	6.2	5.7
	70 min		7.2	5.4	5.0	6.2	5.9
Slump flow (mm)	10 min		715	660	690	640	670
	70 min		650	630	660	585	680
J-ring (mm)	10 min		660	635	665	625	665
	70 min		600	580	645	560	670
V-funnel flow time (s)	10 min		2.5	3.1	2.8	3.4	3.9
	70 min		2.9	3.2	2.8	4.4	4.6
L-box	10 min	time (sec)	0.7	1.2	0.9	1.1	1.5
		h_2/h_1	0.84	0.79	0.78	0.74	0.90
	70 min	time (sec)	1.0	2.0	1.3	1.4	1.7
		h_2/h_1	0.57	0.39	0.63	0.63	0.81
Filling capacity (%)	10 min		96	94	94	93	99
	70 min		89	89	96	78	97
Maximum settlement [%]			0.85	0.80	0.74	0.70	0.33
Rheological parameters	10 min	g (N.m)	0.40	0.30	0.40	0.30	0.60
		h (N.m.s)	4.1	6.4	5.2	6.0	5.2
	70 min	g (N.m)	0.80	0.50	0.30	0.40	0.50
		h (N.m.s)	4.3	5.8	5.4	7.0	7.1

TABLE I.7 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TERNARY BINDER 1 AND PCP 2

Mixture			w/cm = 0.42		
			I	II	Final
Ternary binder 1 (kg/m^3)				475	
Water (kg/m^3)				200	
Coarse aggregate (kg/m^3)				803	
Sand (kg/m^3)				775	
HRWRA (L/m^3)			5.00	5.00	5.00
VMA (L/m^3)			1.80	2.60	5.00
Air-entraining admixture (ml/m^3)			145	300	600
Temperature (°C)	10 min		19	20	20
	70 min		19	19	19
Unit weight (kg/m^3)	10 min		2341	2359	2349
	70 min		2335	2341	2359
Air volume (%)	10 min		2.9	2.2	2
	70 min		3.2	2.5	1.8
Slump flow (mm)	10 min		640	645	650
	70 min		620	620	655
J-ring (mm)	10 min		-	-	-
	70 min		-	-	-
V-funnel flow time (s)	10 min		2.6	3.4	3.5
	70 min		3.6	3.4	3.3
L-box	10 min	time (sec)	0.9	-	1.1
		h_2/h_1	0.70	-	0.76
	70 min	time (sec)	1.3	-	1.9
		h_2/h_1	0.73	-	0.70
Filling capacity (%)	10 min		89	92	82
	70 min		88	86	89
Maximum settlement [%]			1.07	1.09	1.01
Rheological parameters	10 min	g (N.m)	0.30	0.20	0.20
		h (N.m.s)	5.0	5.7	3.8
	70 min	g (N.m)	0.40	0.20	0.20
		h (N.m.s)	5.0	5.0	5.4

TABLE I.8 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TERNARY BINDER 1 AND PNS

Mixture			w/cm = 0.42		
			I	II	Final
Ternary binder 1 (kg/m³)			475		
Water (kg/m³)			200		
Coarse aggregate (kg/m³)			803		
Sand (kg/m³)			775		
HRWRA (L/m³)			6.62	6.00	7.00
VMA (L/m³)			2.43	2.43	3.69
Water reducer (ml/m³)			-	475	475
Air-entraining admixture (ml/m³)			300	400	400
Temperature (°C)	10 min		21	25	21
	70 min		21	25	20
Unit weight (kg/m³)	10 min		2283	2313	2238
	70 min		2314	2356	2298
Air volume (%)	10 min		4.7	4.8	6.2
	70 min		4.0	4.0	5.0
Slump flow (mm)	10 min		565	720	650
	70 min		550	690	590
J-ring (mm)	10 min		-	683	-
	70 min		-	668	-
V-funnel flow time (s)	10 min		5.9	3.5	4
	70 min		7.7	3.5	4.4
Filling capacity (%)	10 min		95	99	94
	70 min		72	95	85
Maximum settlement [%]			-	1.20	0.44
Rheological parameters	10 min	g (N.m)	-	-	0.60
		h (N.m.s)	-	-	6.0
	70 min	g (N.m)	-	-	0.60
		h (N.m.s)	-	-	7.3

TABLE I.9.A TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TERNARY BINDER 1 AND PCP 4

Mixture			w/cm = 0.42					
			I	II	III	IV	V	VI
Ternary binder 1 (kg/m^3)			475					
Water (kg/m^3)			200					
Coarse aggregate (kg/m^3)			803					
Sand (kg/m^3)			775					
HRWRA (L/m^3)			10.8	2.9	3.6	3.6	3.6	3.6
Air-entraining admixture			300	200	150	150	125	-
Set-retarding agent (ml/m^3)			-	-	-	-	950	950
Temperature (°C)	10 min		21	20	20	22	20	20
	70 min		20	20	19	23	19	19
Unit weight (kg/m^3)	10 min		2048	2069	2185	2175	2250	2336
	70 min		1995	2091	2073	2027	2100	2316
Air volume (%)	10 min		10.0	10.0	7.3	8.2	6.4	2.8
	70 min		7.8	9.5	10.2	14.0	10.0	4.4
Slump flow (mm)	10 min		785	750	715	685	685	710
	70 min		715	710	625	565	568	675
J-ring (mm)	10 min		-	-	645	620	-	-
	70 min		-	-	585	545	-	-
V-funnel flow time (s)	10 min		3.2	1.9	1.8	2.9	2.3	3.4
	70 min		4.5	2.3	2.5	3.2	3.2	3.5
L-box	10 min	time (sec	-	-	-	1.5	-	-
		h_2/h_1	-	-	-	-	-	-
	70 min	time (sec	-	-	-	1.2	-	-
		h_2/h_1	-	-	-	-	-	-
Filling capacity (%)	10 min		100	99	97	93	-	96
	70 min		100	100	94	85		98
Maximum settlement [%]			-	-	0.39	0.35	1.05	-
Rheological parameters	10 min	g (N.m)	-	-	-	-	-	-
		h (N.m.s	-	-	-	-	-	-
	70 min	g (N.m)	-	-	-	-	-	-
		h (N.m.s	-	-	-	-	-	-

TABLE I.9.B TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TERNARY BINDER 1 AND PCP 4

Mixture			wcm = 0.42					
			VII	VIII	IX	X	XI	Final
Ternary binder 1 (kg/m^3)			475					
Water (kg/m^3)			200					
Coarse aggregate (kg/m^3)			803					
Sand (kg/m^3)			775					
HRWRA (L/m^3)			3.6	3.6	3.6	3.4	3.9	3.8
VMA (L/m^3)			-	-	-	0.2	0.22	0.22
AEA (ml/m^3)			-	312.5	312.5	40	40	20
Set-retarding agent (ml/m^3)			1425	475	235	240	120	120
Temperature (°C)	10 min		21	22	22	20	20	20
	70 min		19	20	22	-	19	19
Unit weight (kg/m^3)	10 min		2377	2305	2323	-	2223	2265
	70 min		2386	2246	2267	-	2160	2250
Air volume (%)	10 min		1.2	4.4	3.5	-	6.3	6.4
	70 min		1.2	7.2	7.0	-	8.8	5.7
Slump flow (mm)	10 min		705	720	720	600	690	665
	70 min		645	675	665	630	700	650
J-ring (mm)	10 min		-	680	600	-	-	-
	70 min		-	635	665	-	-	-
V-funnel flow time (s)	10 min		3.2	3.1	2.1	-	2.5	3.0
	70 min		3.5	4.0	3.6	-	2.2	3.2
L-box	10 min	time (sec)	-	1.3	1.1	-	-	-
		h_2/h_1	-	-	-	-	-	-
	70 min	time (sec)	-	2.3	1.2	-	-	-
		h_2/h_1	-	-	-	-	-	-
Filling capacity (%)	10 min		97	97	98	64	95	91
	70 min		93	96	97	87	98	97
Maximum settlement [%]			0.75	0.69	0.64	0.57	0.36	0.39
Rheological parameters	10 min	g (N.m)	-	-	-	0.60	0.30	0.20
		h (N.m.s)	-	-	-	7.6	3.7	5.2
	70 min	g (N.m)	-	-	-	0.60	0.40	0.30
		h (N.m.s)	-	-	-	5.0	4.5	4.9

TABLE I.10 TRIAL BATCH DOSIFICATION MIXTURE OPTIMIZATION OF SCC MADE WITH TERNARY BINDER 1 AND PCP 5

Mixture			w/cm = 0.42
			Final
Ternary binder 1 (kg/m^3)			475
Water (kg/m^3)			200
Coarse aggregate (kg/m^3)			803
Sand (kg/m^3)			775
HRWRA (L/m^3)			2.89
VMA (L/m^3)			1.6
Air-entraining admixture (ml/m^3)			90
Temperature (°C)	10 min		22
	70 min		18.2
Unit weight (kg/m^3)	10 min		2222
	70 min		2226
Air volume (%)	10 min		7.2
	70 min		7
Slump flow (mm)	10 min		670
	70 min		640
J-ring (mm)	10 min		640
	70 min		630
V-funnel flow time (s)	10 min		2.7
	70 min		2.8
L-box	10 min	time (sec)	0.8
		h_2/h_1	0.78
	70 min	time (sec)	1.0
		h_2/h_1	0.87
Filling capacity (%)	10 min		88
	70 min		94
Maximum settlement [%]			0.5
Rheological parameters	10 min	g (N.m)	0.40
		h (N.m.s)	4.0
	70 min	g (N.m)	0.40
		h (N.m.s)	4.6

APPENDIX II

DETERMINATION OF RHEOLOGICAL PARAMETERS OF OPTIMIZED MIXTURES FOR MIXTURES EVALUATED IN CHAPTER 5

This appendix presents Rheogramss of the variations of torque with rotational velocities measured at 10 and 70 minutes for optimized SCC mixtures made with 0.35 and 0.42 w/cm evaluated in Chapter 5. The data were collected from the descending part of the rheological curves using the Bingham model.

II.1. SCC mixtures made with 65% of Type 10 cement, 30% Class F fly ash, and 5% silica fume

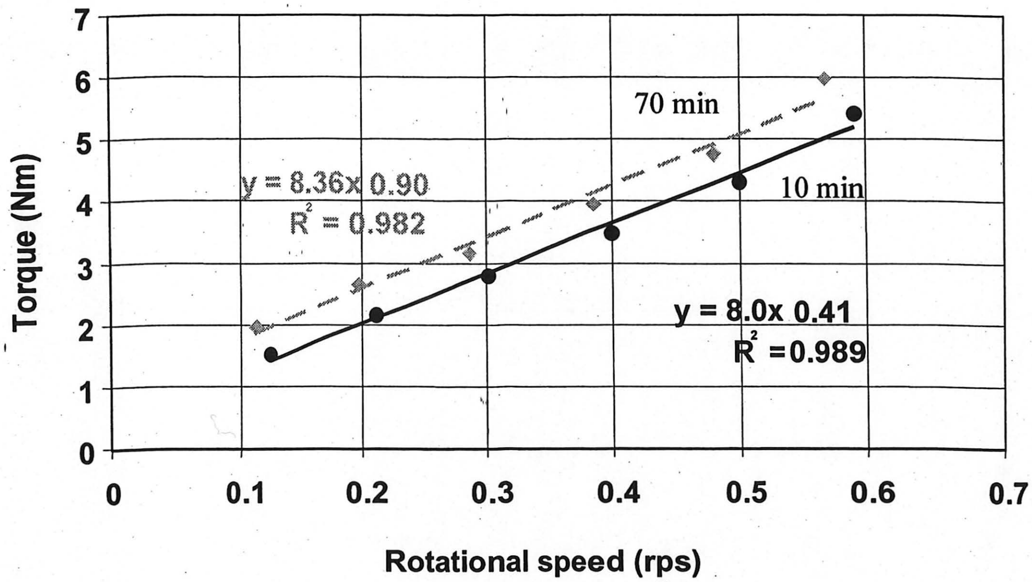


Fig. II.1 Rheogramss for SCC mixtures made with PCP 1 evaluated after 10 and 70 min of age

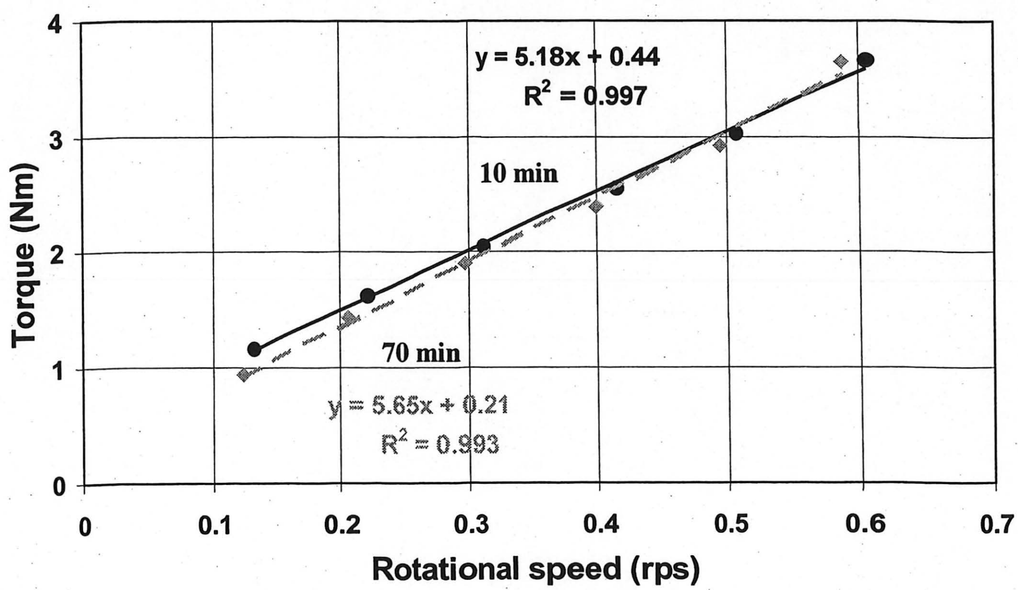


Fig. II.2 Rheograms for SCC mixtures made with PCP 2 evaluated after 10 and 70 min of age

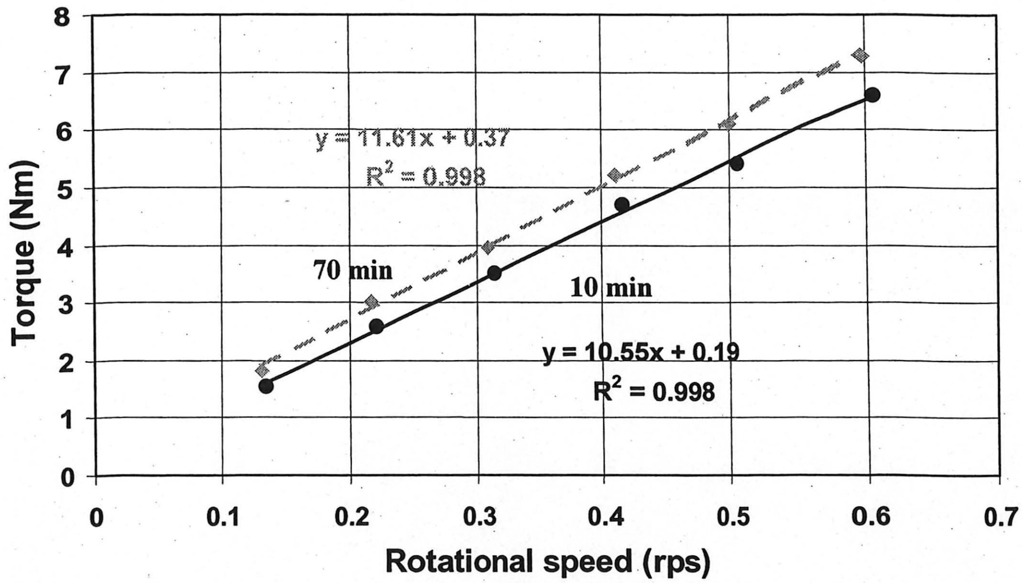


Fig. II.3 Rheograms for SCC mixtures made with PCP 3 evaluated after 10 and 70 min of age

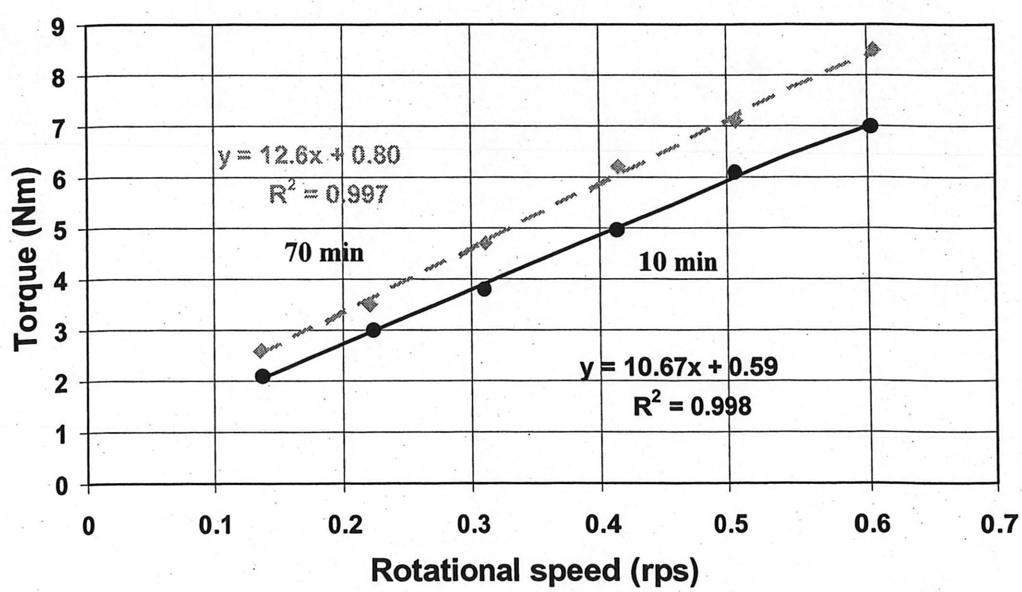


Fig. II.4 Rheograms for SCC mixtures made with PCP 4 evaluated after 10 and 70 min of age

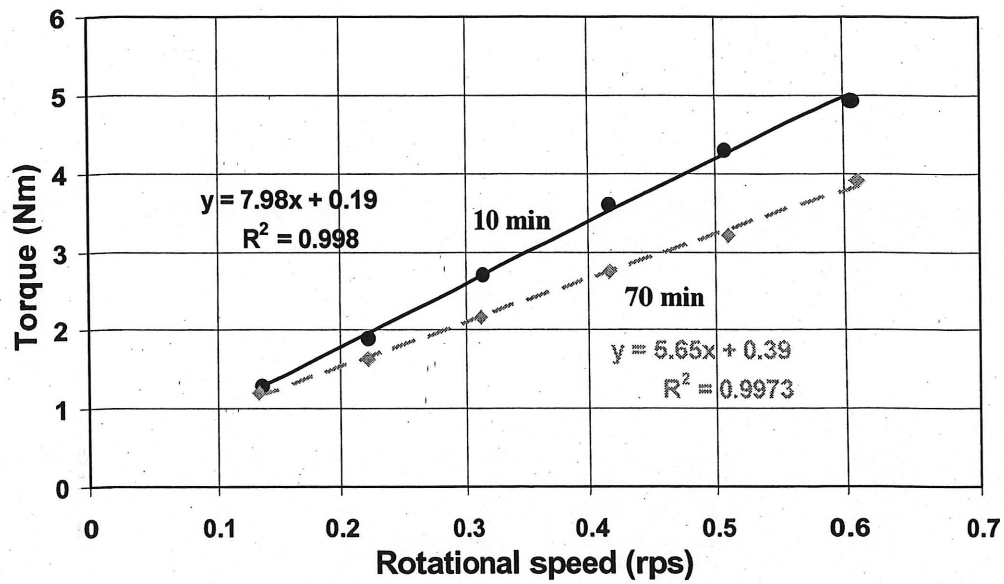


Fig. II.5 Rheograms for SCC mixtures made with PCP 5 evaluated after 10 and 70 min of age

II.2 SCC mixtures made with Ternary binder I

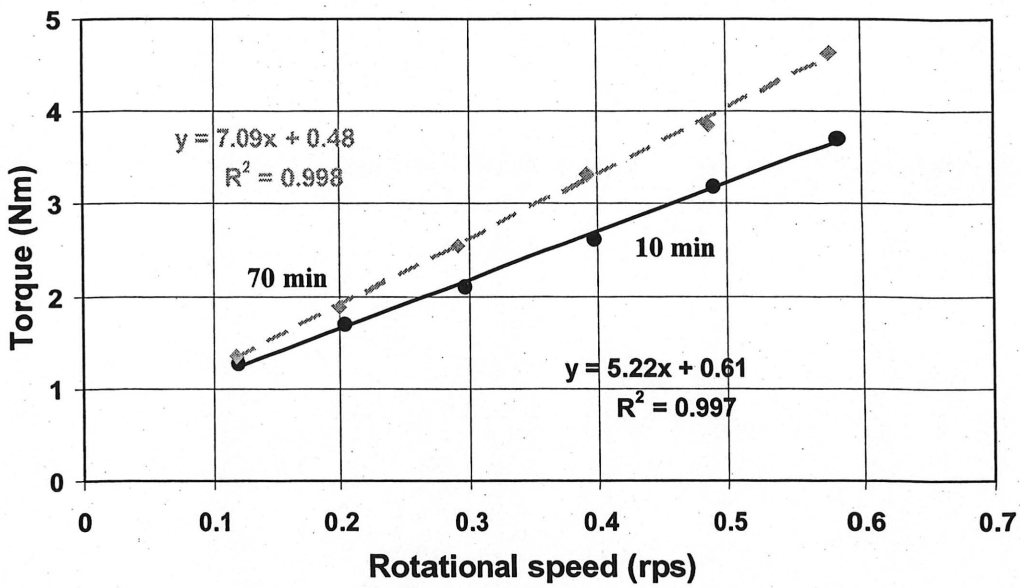


Fig. II.6 Rheograms for SCC mixtures made with PCP 1 evaluated after 10 and 70 min of age

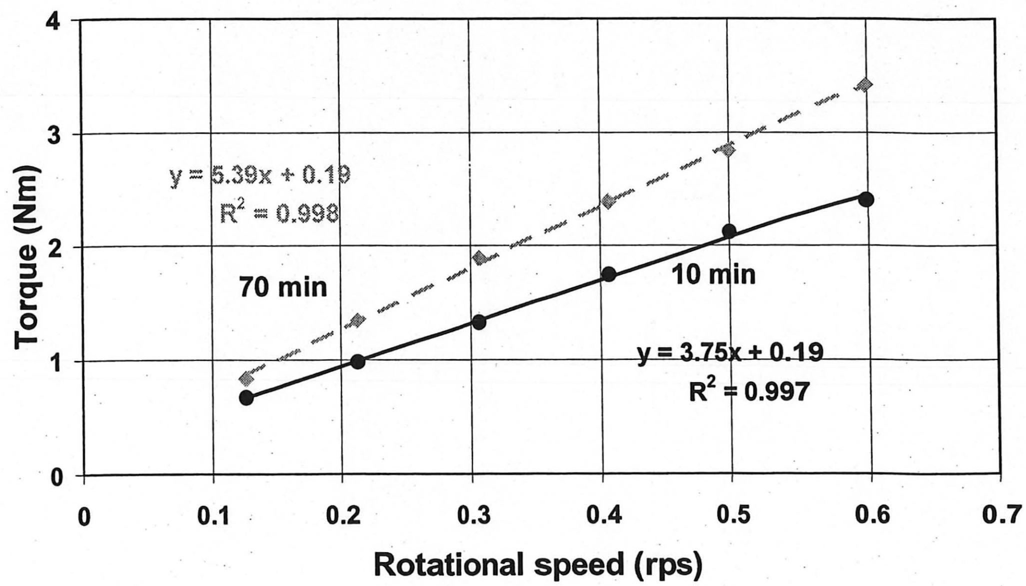


Fig. II.7 Rheograms for SCC mixtures made with PCP 2 evaluated after 10 and 70 min of age

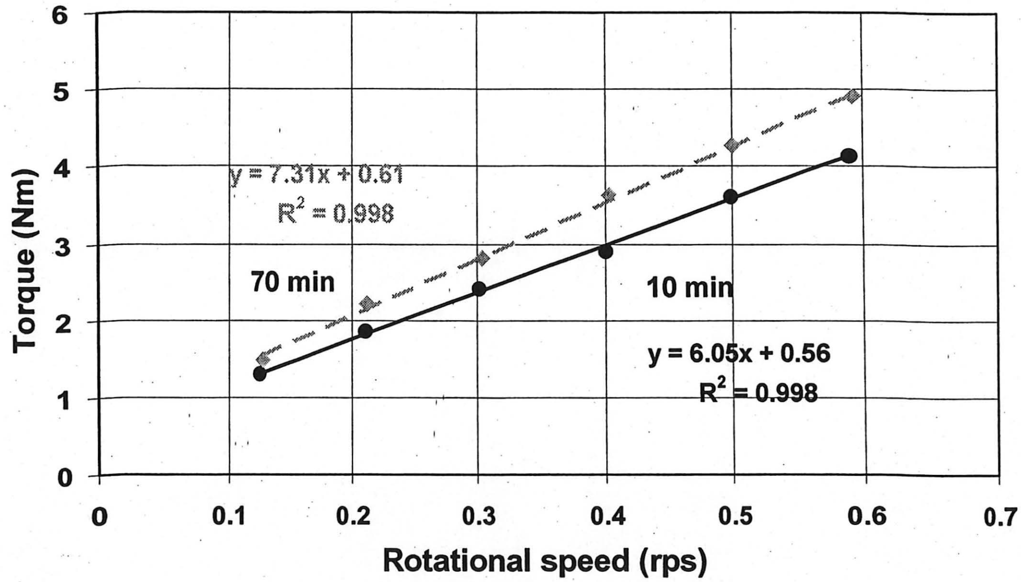


Fig. II.8 Rheograms for SCC mixtures made with PNS evaluated after 10 and 70 min of age

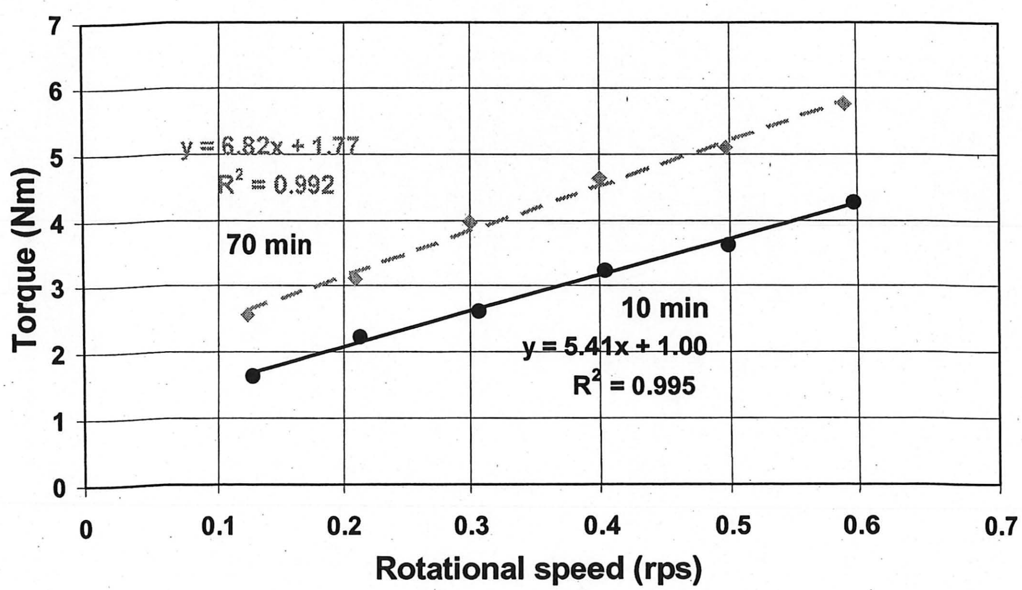


Fig. II.9 Rheograms for SCC mixtures made with PCP 4 evaluated after 10 and 70 min of age

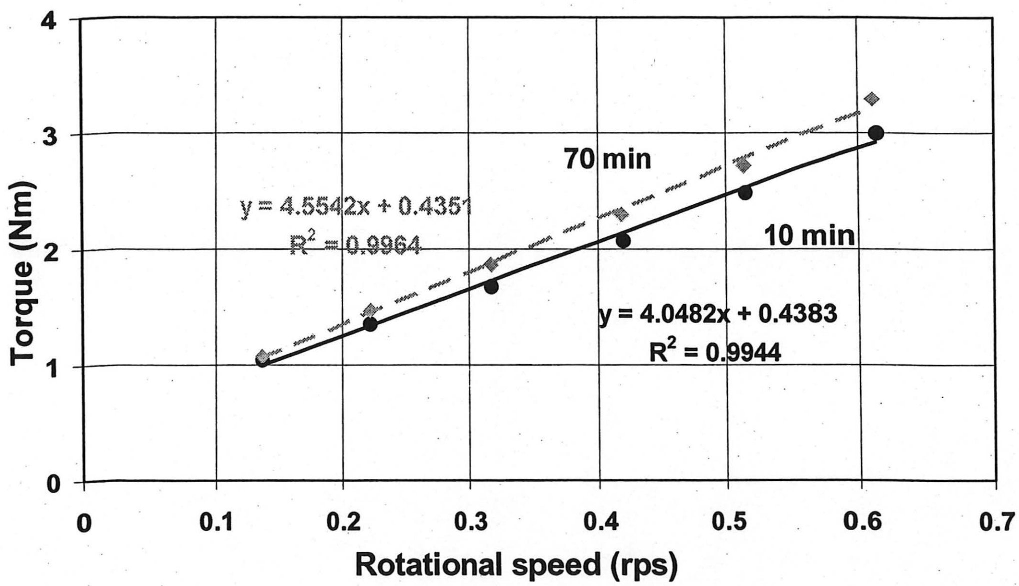


Fig. II.10 Rheograms for SCC mixtures made with PCP 5 evaluated after 10 and 70 min of age

II.3 SCC mixtures made with Ternary binder II

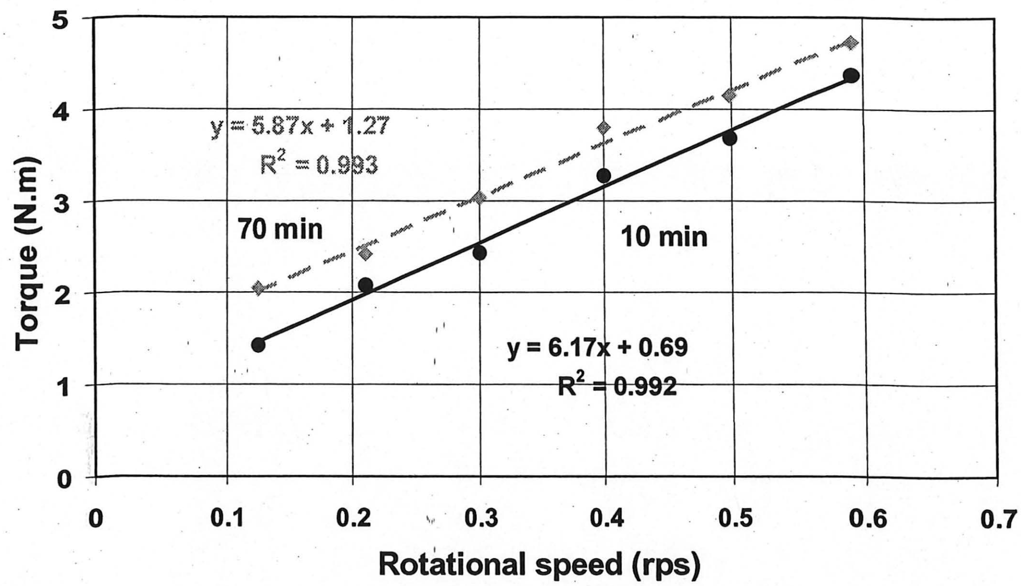


Fig. II.11 Rheogramss for SCC mixtures made with PCP 1 evaluated after 10 and 70 min of age

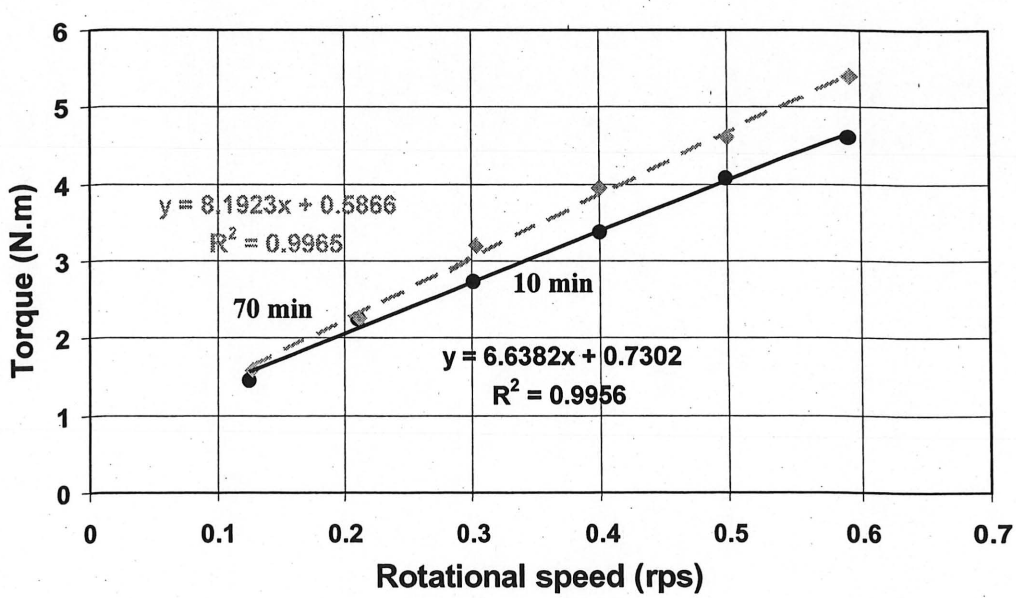


Fig. II.12 Rheogramss for SCC mixtures made with PNS evaluated after 10 and 70 min of age

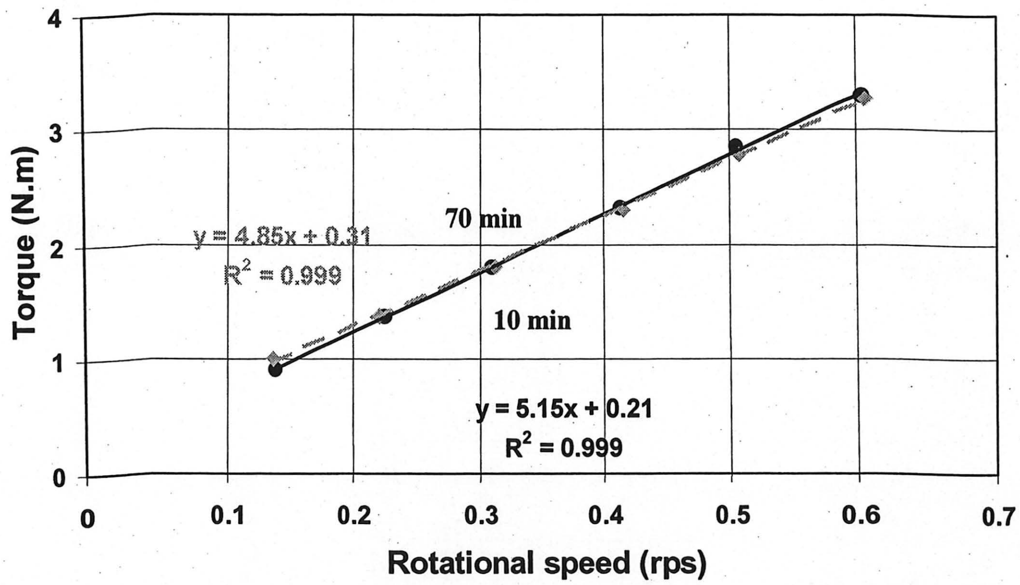


Fig. II.13 Rheogramss for SCC mixtures made with PCP 4 evaluated after 10 and 70 min of age

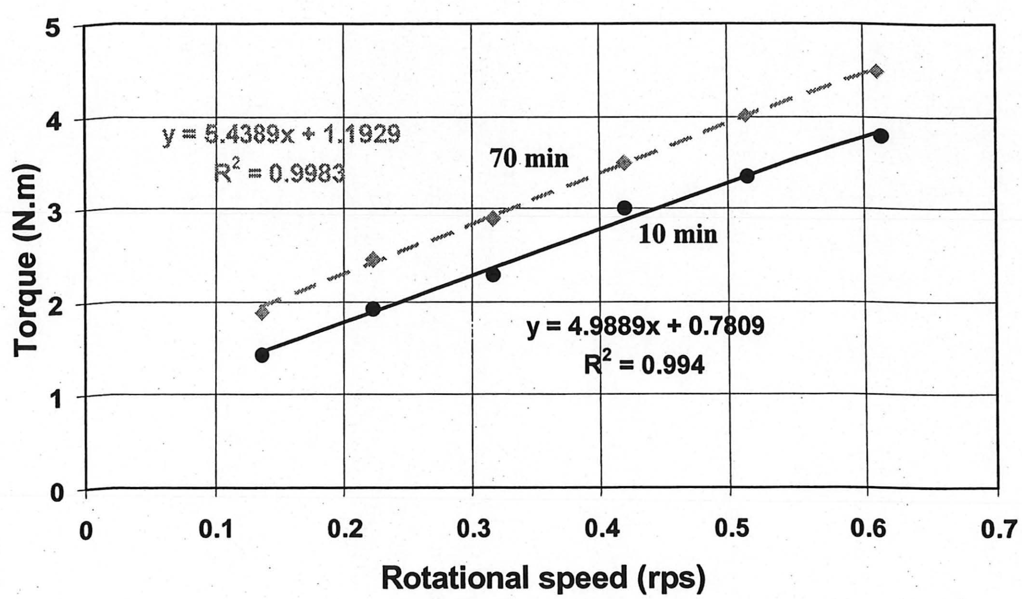


Fig. II.14 Rheogramss for SCC mixtures made with PCP 5 evaluated after 10 and 70 min of age

II.4. SCC mixtures made with Quaternary binder

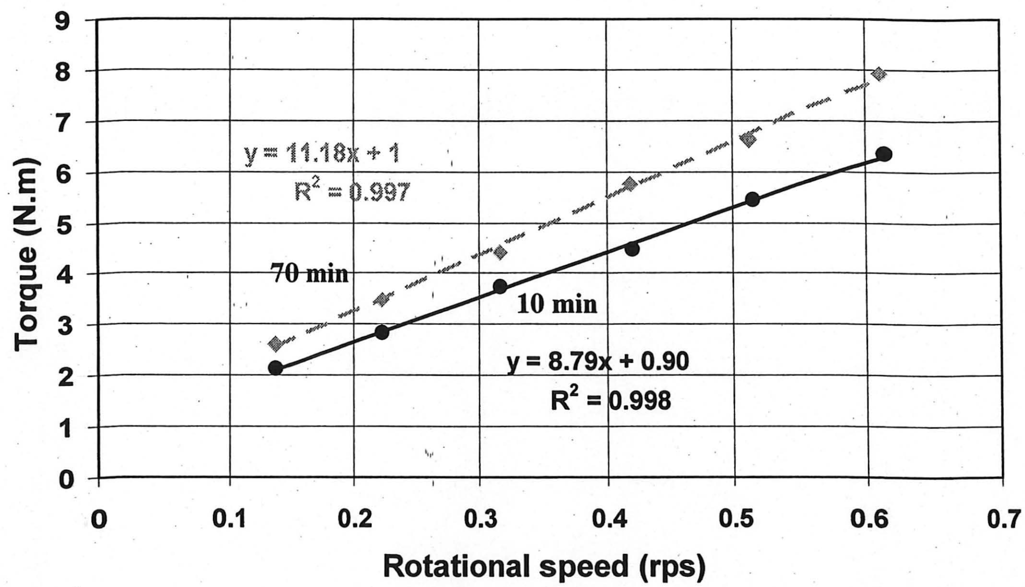


Fig. II.15 Rheogramss for SCC mixtures made with PCP 1 evaluated after 10 and 70 min of age

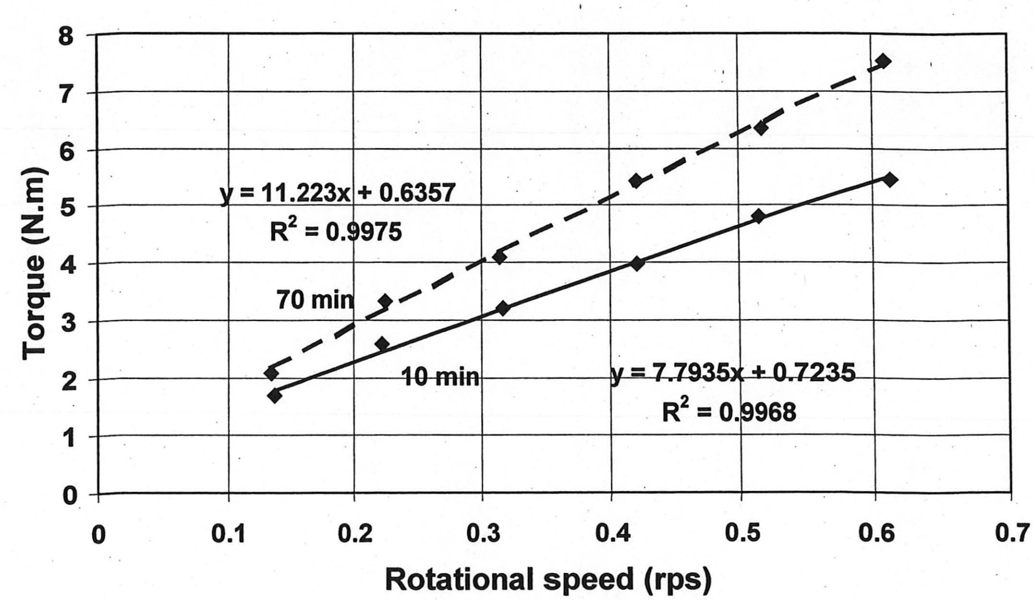


Fig. II.16 Rheogramss for SCC mixtures made with PNS evaluated after 10 and 70 min of age

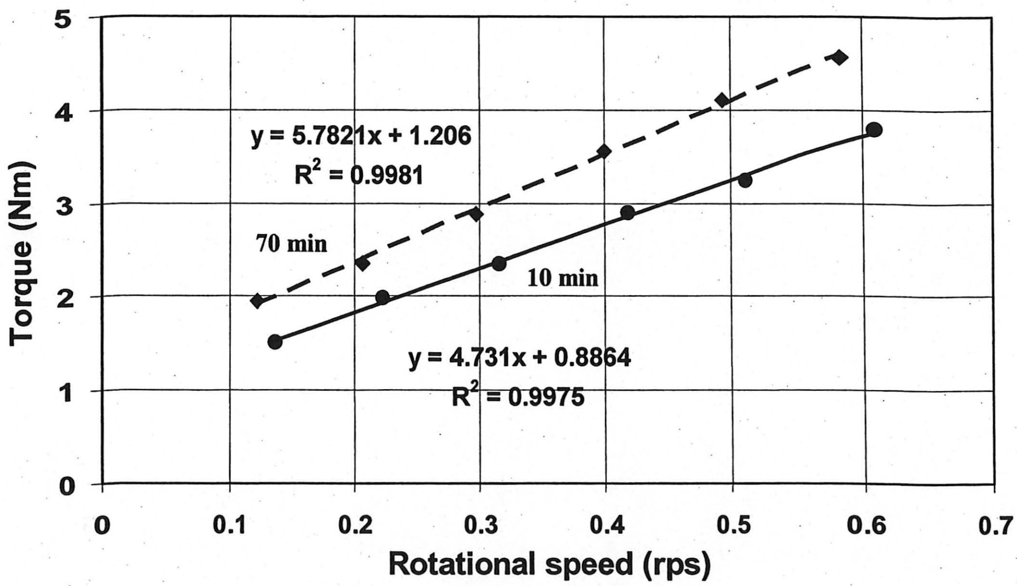


Fig. II.17 Rheogramss for SCC mixtures made with PCP 4 evaluated after 10 and 70 min of age

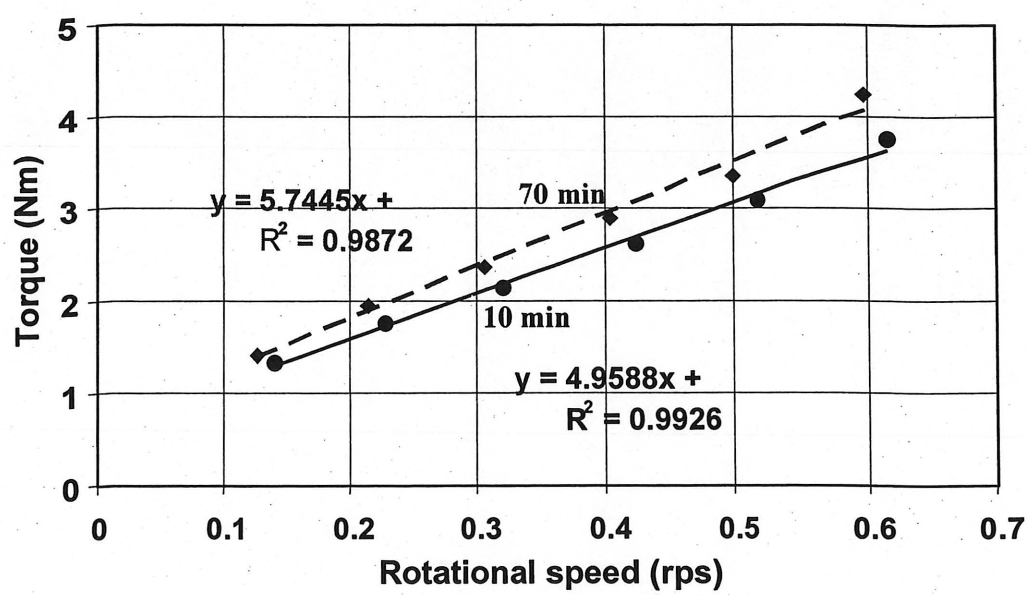


Fig. II.18 Rheogramss for SCC mixtures made with PCP 5 evaluated after 10 and 70 min of age

APPENDIX III

VARIATIONS IN SURFACE SETTLEMENT OF OPTIMIZED SCC MIXTURES EVALUATED IN CHAPTER 5

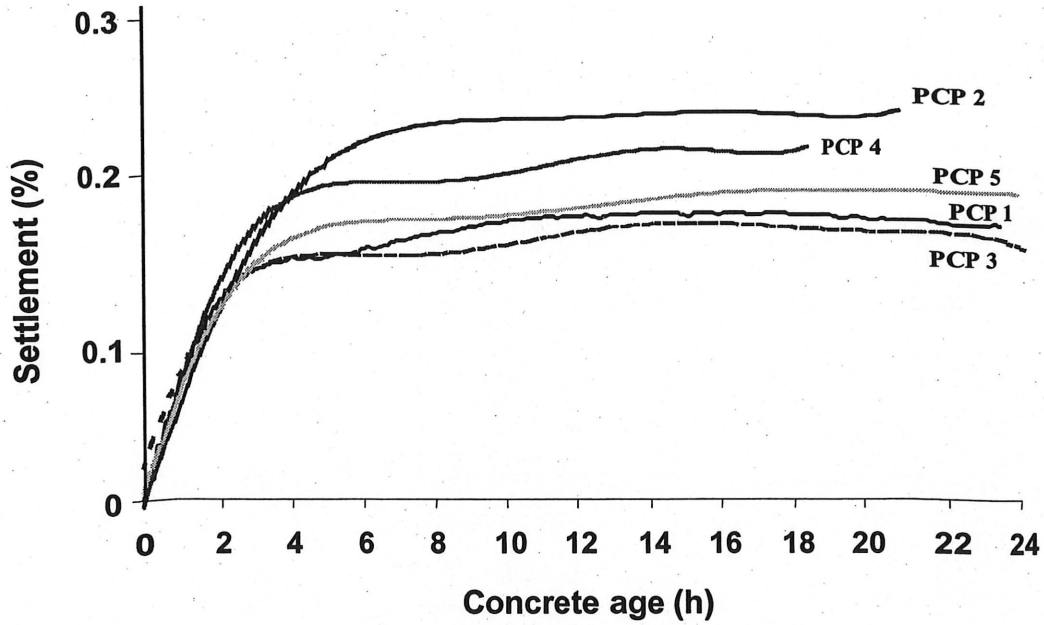


Fig. III.1 Surface settlement of SCC mixtures made with 65% Type 10 Cement, 30% Class F fly ash, and 5% silica fume

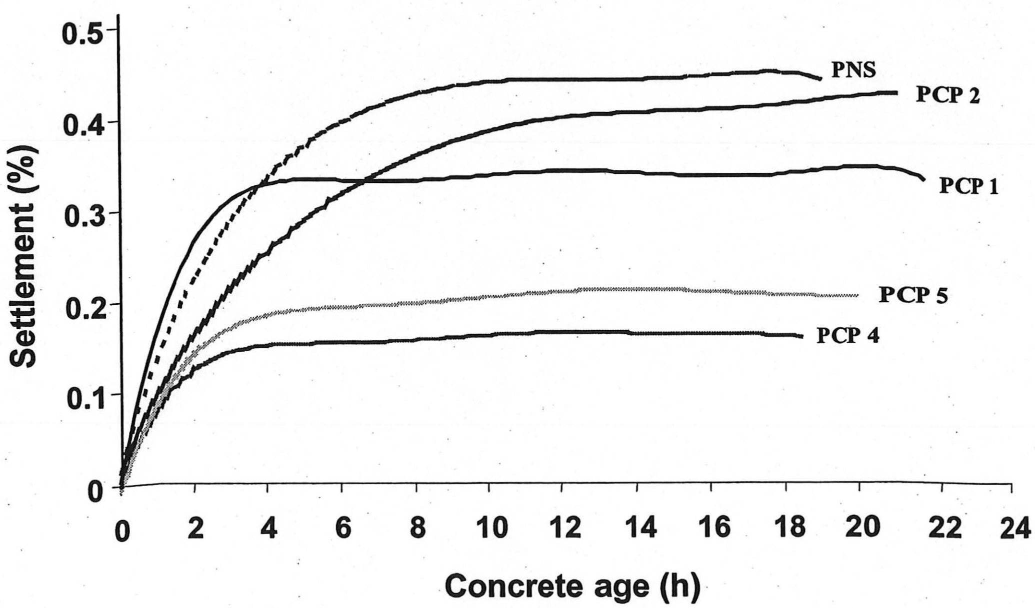


Fig. III.2 Surface settlement of SCC mixtures made with Ternary binder 1

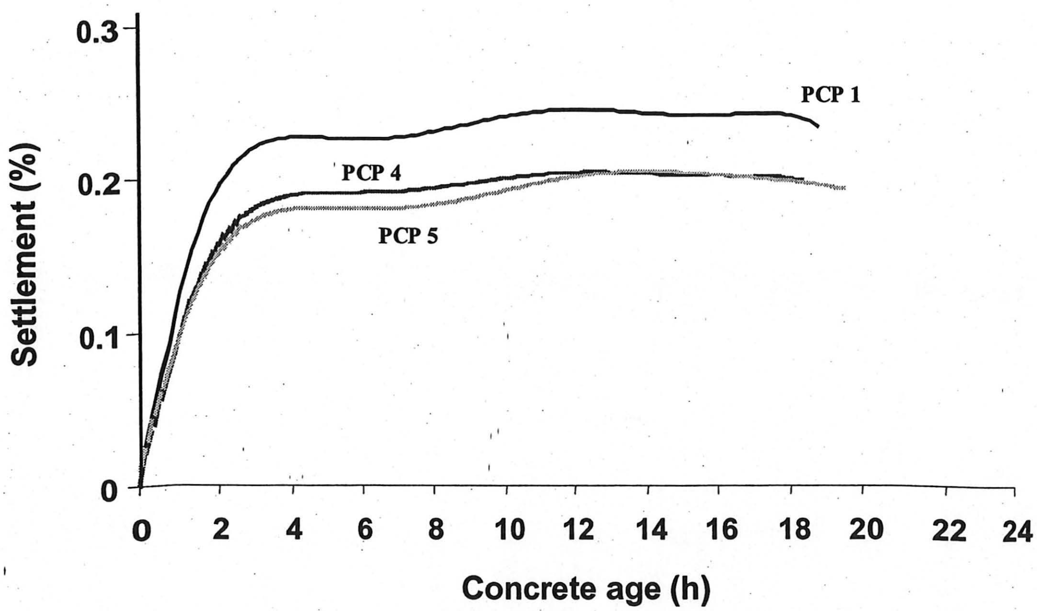


Fig. III.3 Surface settlement of SCC mixtures made with Ternary binder 2

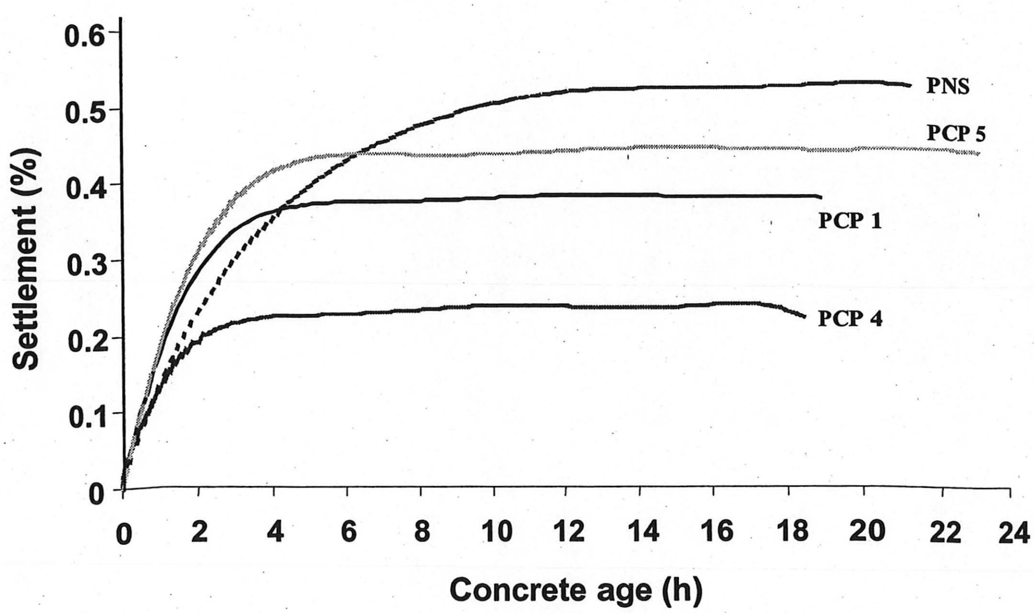


Fig. III.4 Surface settlement of SCC mixtures made with Quaternary binder

APPENDIX IV

CALIBRATION OF THE IBB RHEOMETER

IV.1. Introduction

The program RHEOM.EXE is used with the IBB rheometer to transform, in a non-visible manner for the user, signals obtained from the pressure load cell and the angular velocity measurements into Newtons and m/s, respectively. This transformation of units is possible after a detailed calibration of the apparatus. The transformation factors depend of the geometry of the rheometer and internal friction. These second factors do change with use, so a calibration is required to enhance the accurate of the results.

IV.2. Procedure

The procedure of the calibration is inspired from the M.Sc.A. thesis of Yanéric Roussel (2000). It consists of calculating the numerical constants necessary to mathematically treat the set of signals received from the electrical and mechanical parts of the rheometer and transforms them into the desired units. These numerical constants from the linear regression of a set of values are then introduced in the file CONST.PRM in the field C:\RHEOM\. This is done in the following order: speed constant, torque constant, gap of the torque reading, and gap of the speed-reading.

In order to perform the calibration of the pressure load cell, a known torque must be imposed to measure the result with the internal units of the TORQUE.EXE program. In order to measure the voltage, the TESTPROG.EXE program was used. In order to read the speed, the apparatus must be operated in a manual mode to control the speed. In this way, the number of revolutions can be determined as a function of time. This value can then be correlated with the internal units of the SPEED.EXE program or the voltage reading with the TESTPROG.EXE program.

IV.3. Analysis of results

IV.3.1. Constant speed

The relationships used to determine the speed constant are illustrated in Fig. IV.1 and Fig. IV.2, respectively. The linear regressions derived from the data are used to determine the intersection and slope values. For the RHEOM.EXE program, the two input values correspond to the slope of the line and its intersection with the vertical axis, when the apparatus is at rest. These values are considered as 0.000555 and 4, respectively.

For the voltage output, the numerical equation must be calculated to transform directly the volt reading into rev/s. This equation is calculated from Fig. IV.2, as follows:

Speed (rev/s) = - 0.00845 + [0.226809 x Speed (Volts)]   Eq. IV.1.

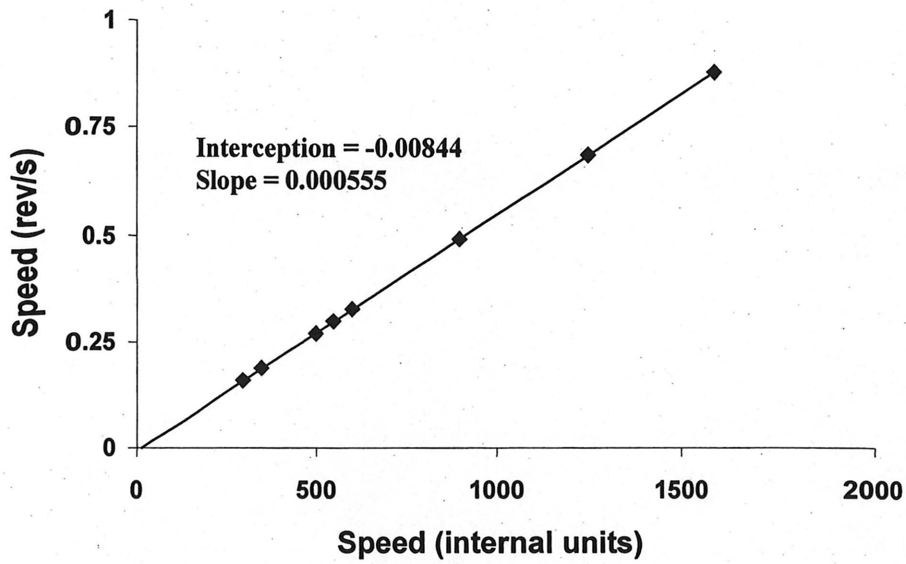


Fig. IV.1 Correlation between the speed in internal units versus the speed in rev/s

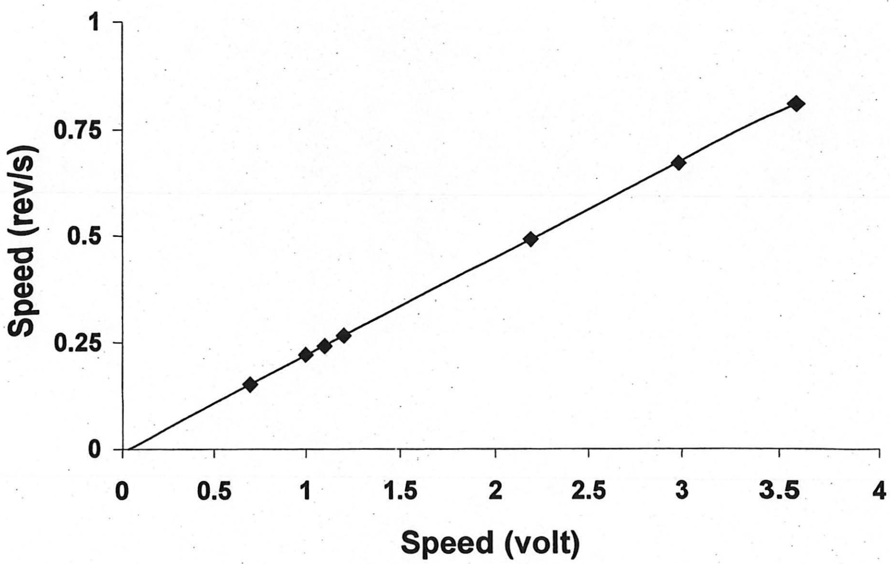


Fig. IV.2 Correlation between the speed in volt versus the speed in rev/s

IV.3.2. Torque constant

The linear regressions required to determine the torque constant can be derived from Fig. IV.3 and Fig. IV.4, respectively. For the RHEOM.EXE program, the constants, in the same way as in the case of speed measurements, are 0.034396 and 15.5, respectively. For the volts, the numerical equation can be expressed as follows:

$$\text{Torque (N.m)} = -0.4874 + [14.08787 \times \text{Torque (Volts)}] \qquad \text{Eq. IV.2.}$$

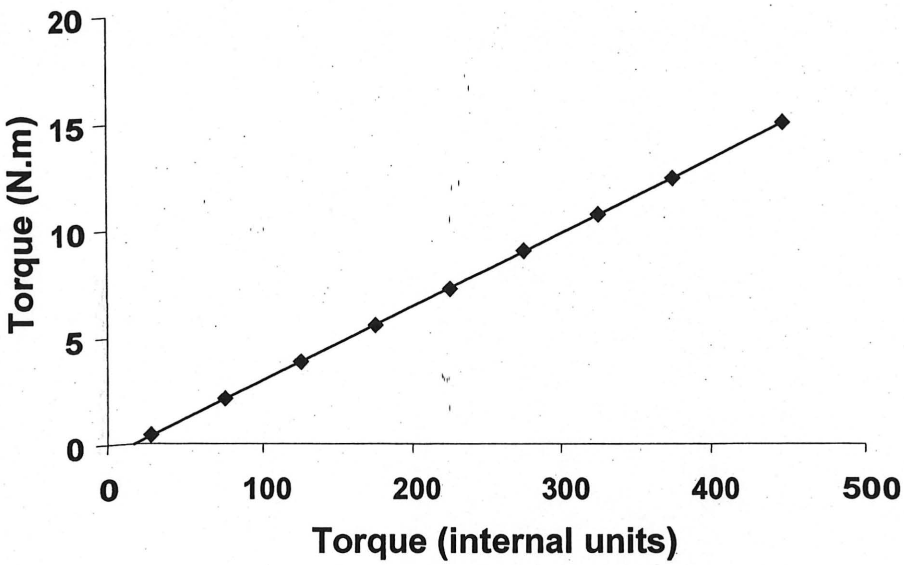


Fig. IV.3 Correlation between the torque in internal units versus the torque in N.m

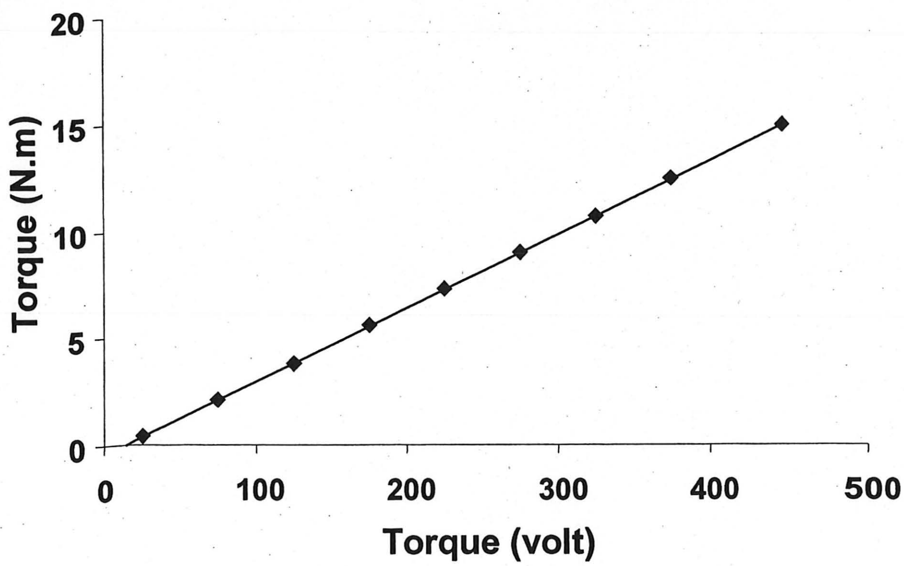


Fig. IV.4 Correlation between the torque in volt versus the torque in N.m