Optimum Mix Design for Self-Compacting Concrete
Using Pulverized Fuel Ash as Cement Replacement Material

By

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Dissertation submitted in partial fulfilment of

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CERTIFICATION OF APPROVAL

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Approved by,

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January 2007

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

`AISYAH BT AHMAD

ABSTRACT

Since last one decade self-compacting concrete is gaining interest as niche research area in advancement in concrete technology. This research study aimed to determine the mix design for optimum rheological properties of self compacting concrete when using pulverized fly ash as the cement replacement material. A number of trial mixes were designed to determine the rheological properties using V-funnel and flow measurement tests. The mixes that did comply with the specified rheological properties are to be tested for strength and porosity, in order to assess their engineering properties and durability characteristic. Under the optimal superplasticizer identified in this study (7kg/m^3), adding fly ash to the mix did not give much variation from the control mix (55Mpa for control mix, 51Mpa for fly ash mix at 56-days), but the result for fly ash show high potential to achieve higher strength at later age.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

Self-compacting concrete (SCC), also known as self-consolidating concrete or high performance concrete was developed in Japan during the late 1980s. The development of SCC started when the need of more durable concrete arises, and since durability of concrete directly connected to the adequate compaction after placing the concrete, concrete that can move into every corner of the formwork on its own weight is the ideal solution.

Like the name suggests, SCC is highly flowable, non-segregating concrete that can spread into places, fill the formworks and encapsulate the reinforcements without any mechanical equipment to help the compaction. The three key fresh properties of SCC are:

- **Filling ability** – the ability of the concrete to flow freely under its own weight, both horizontally and vertically upwards if necessary, and to completely fill formwork of any dimension and shape without leaving voids. Some people consider that rate of flow is a distinct fourth property, but this approach was not adopted here.
- **Passing ability** – the ability of concrete to flow freely in and around dense reinforcement without blocking.
- **Resistance to segregation** – during placement and while flowing, the concrete should retain its homogeneity. There should be no separation of aggregate from paste or water from solids, and no tendency for coarse aggregate to sink downwards through the fresh concrete mass under gravity.

There were many researches that had been done concerning the optimum mix proportioning problems of SCC. Generally, the methods employed to achieve successful self-compactibility are to limit the coarse aggregate content, usage of superplasticizer, and low water-powder ratio.

The characteristics of rheology of fresh concrete are its limiting yield stress and plastic viscosity. For SCC, the rheological property is expected to have near zero yield stress, so that is behaves like Newtonian fluid. It should also maintain low, but adequate viscosity to minimize segregation potential. These criteria must fulfill the filling ability, passability and segregation resistance that had been mentioned earlier.

The main reasons for the employment of self-compacting concrete can be summarized as follows:

1. to shorten construction period
2. to reduce the labor cost
3. to assure compaction in the structure, especially in confined zones where vibrating compaction is difficult
4. to eliminate noise due to vibration, effective especially at concrete products plants

Various researches had been done to produce concrete which have the characteristics of high flowability and workability during its fresh (plastic) state, but very strong and durable once it has hardened. The hardened concrete is dense, homogeneous and has the same engineering properties and durability as traditional vibrated concrete. Self-compacting concrete is more sensitive than normal concrete to variation in the physical properties of its constituents and especially to changes in aggregate moisture content, grading and shape of aggregate and the most important thing is the free water content.

1.2 PROBLEM STATEMENT

One of the disadvantages of SCC is its cost, associated with the use of chemical admixtures and use of high volume of Portland cement. One alternative to reduce the cost of SCC is the use of mineral additives such as fly ash, which is a finely divided material added to concrete. As the mineral additive replaces part of the Portland cement, the cost of SCC could be reduced especially if the mineral additive is an industrial by-product or waste. It is also known that fly ash generally increases the workability, durability and long term properties of concrete. Therefore, the use of this type of mineral additive in SCC will make it possible, not only to decrease the cost of SCC but also to increase its long term performance.

1.3 OBJECTIVE AND SCOPE OF STUDY

Main objectives of this research are:

- To determine the optimum mix design of Self-compacting concrete
- To analyze the rheological properties of Self-Compacting Concrete
- To revise the effect of superplasticizer addition in SCC
- To analyze the performance of SCC incorporated with pulverized fuel ash (PFA)

The scope of work for this project was to investigate flowability and workability of SCC in fresh state. Once the concrete hardened, it shall be tested for compressive strength and porosity. These two tests shall indicate the performance of SCC in the long run.

The parameters in this project were kept constant throughout all trial mixes, except for the dosage of superplasticizer (T-series) and the amount of fly ash (PFA-series) added in the mix. Otherwise, all the variables and lab conditions were kept constant as much as possible.

CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

Concrete in its simplest explanation is a composite construction material made from the combination of aggregates and cementations binder. The composition of concrete is determined initially during mixing and finally during placing of fresh concrete. The type of structure being built as well as the method of construction determined how the concrete is placed and therefore also the composition of the concrete mix. The composition of concrete is made of cement, water, aggregates, admixtures, and additives.

Various types of concrete have been developed for special application and the most common ones are regular concrete, self-compacting concrete, shotcrete and asphalt concrete. Self-compacting concrete (SCC) are characterized by their extreme fluidity, behaving more like a thick fluid that is self leveling, as opposed to conventional concrete that needs consolidating which are normally vibration or packing.

2.2 SELF-COMPACTING CONCRETE

Self-compacting concrete was first developed by Professor Okamura in Japan during the 1980s, and it can be produced by a number of approaches. The self-compaction of fresh concrete is described as the ability to fill up formwork and encapsulate reinforcing bars through the action of gravity alone, while maintaining adequate homogeneity. This ability is achieved by ensuring suitable rheological properties of fresh concrete, a low yield stress value associated with adequate plastic viscosity.

Various researches had been carried out in order to obtain rational SCC mix-design method. Several methods were developed by different researchers. Okamura and Ozawa (1995) have proposed a simple mix proportioning system; the coarse and fine aggregate contents are kept constant so that self-compactability can be achieved by adjusting the water/cement ratio and superplasticizer dosage only. The Chinese Method was developed by Su and Miao (2003) to obtain SCC with less paste, hence reducing the cost. This method starts with the packing of all aggregates (fine and coarse together), and later filled the aggregates voids with paste. In Sweden, Peterson and Billberg (1999) developed an alternative method for mix design including the criterion of blocking, void and paste volume as well as the test result derived from paste rheology studies.

Okamura (1993) stated that the method for achieving self-compactibility involves not only high deformability of paste or mortar, but also resistance to segregation between coarse aggregates and mortar when the concrete flows through the confined zone of reinforcement bars. The following methods are employed to achieve self-compactability.

1. limited aggregate content
2. low water-powder ratio
3. use of superplasticizer.

One of the differences between normal concrete and SCC is the mix-proportioning. In the mix-proportioning of normal concrete, the water/cement ratio is kept constant in order to obtain the required strength and durability. However, with SCC, the water/powder ratio has to be chosen by taking self-compactability into account, since self-compactibality is very sensitive with this ratio. For the time being, the concerns of researchers are more on the self-compactability (slump flow) rather than the compressive strength.

As mentioned before, the rheological properties of SCC is characterized by low yield stress that is necessary for high capacity of deformation, as well as moderate viscosity to ensure uniform suspension of solid particles during casting. The stability of concrete can be obtained by reducing the free water content and increasing the concentration of fine particles to enhance the cohesion and viscosity. Free water is the total water minus water that is physically and chemically retained by aggregate, powder materials and any water bound by chemical admixtures. According to Felekoglu, Turkel and Baradan (2005), in general, the approach of minimizing free water content can result in SCC mixtures with a low yield stress and moderate viscosity levels. However, the low water content requires relatively high dosage of high range water reducers, in order to obtain the required deformability especially with the lower binder contents.

To achieve high-strength and workability while reducing creep and shrinkage, Chang (2003) suggested using superplasticizer and pozzolanic materials in the mix designs for high performance concrete. Use of pozzolanic materials can decreased the amount of cement required, thus reducing the occurrence of creep and shrinkage.

Incorporating of mineral additives had proven to be beneficial effects, such as improvement in rheological and durability properties. Previous studies show that the use of fly ash in SCC reduces the dosage of superplasticizer needed to obtain similar slump flow as compared to commom Portland cement only. This had been discussed by Yahia and Tanimura (1999).

Since SCC is relatively new to construction industry, many ambiguities are still being investigated by researchers. For example, there was no clear relation yet between the characteristics obtained in laboratory tests (slump flow and funnel test) and various conditions at building site (density of reinforcement and casting height). Because of this, there is no standard yet for SCC. However, this is not because lack of trying. Many different test methods have been developed in attempts to characterize the properties of SCC. So far, no single method or combination of methods has achieved universal approval and most of then have their adherents. Similarly no single method has been found which characterizes all the relevant workability aspects, thus each mix design should be tested by more than one test method in order to obtain different workability parameters.

In this study, several mixes with the same water/cement ratio were produced to investigate the performance of SCC incorporating pulverized fly ash as cement replacement material. To the best knowledge of the author, the durability of SCC is yet to be discerned, and this study shall be carried out by using vacuum absorption test (porosity test).

2.3 POZZOLANIC REACTION AND CONCRETE

A pozzolana is a natural or artificial material containing silica in a reactive form. By themselves, pozzolanas have little or no cementatios value. However, in a finely divided form and in the presence of moisture they will chemically react with alkalis to form cementing compounds. Pozzolanas must be finely divided in order to expose a large surface area to the alkali solutions for the reaction to proceed. Examples of pozzolanic materials are volcanic ash, pumice, opaline shales, rice husk ash and fly ash.

2.4 PULVERIZED FLY ASH

The idea of using PFA in concrete was first suggested by McMillan and Powers in 1934 and the following years, many subsequent researches were being conducted. The research had led to the construction of Lednock, Clatworthy and Lubreoch Dams during 1950s, with fly ash as partial cementitious material. These structures are reportedly still in excellent condition, even after more than 50 years.

When fly ash is added to concrete the pozzolanic reaction occurs between the silica glass and the lime, this is a by-product of the hydration of Portland cement. The hydration products produced fill the interstitial pores thus reducing the permeability. The reaction products formed differ from the products found in Portland cement-only concrete. A finer pore structure is produced with time, assuming there is access to water to maintain the hydration process.

Little pozzolanic reaction occurs during the first 24 hours at 20°C. Thus, it is expected for higher fly ash content in the concrete to achieve lower early strength development. The cause of slower strength development is that the presence of fly ash retards the reaction of alite within the Portland cement at early stages. However, alite production is accelerated in the middle stages due to the provision of nucleation sites on the surface of the fly ash particles. At later stages the contribution of fly ash to strength gain increases greatly, provided there is adequate moisture to continue the reaction process.

Fly ash particles less than 50μm are generally spherical and the larger sizes tend to be more irregular. The spherical particles confer significant benefits to the fluidity of the concrete in a plastic state by optimizing the packing of particles. The fly ash spheres appear to act as ball bearings within the concrete reducing the amount of water required for a given workability.

According to Ping Kun Chang (2003) pozzolanic materials are crucial to high performance concrete as far as flowability is concerned. In addition to lowering the heat of hydration, the use of fly ash and slag can improve the workability, plasticity, water tightness, resistance to sulfate and seawater attack. The mixture design of HPC emphasizes the amount of binder used. A higher content of pozzolanic materials implies that less cement is needed. Controlling the water content and the water-to-solid (W/S) ratio is an indirect approach to stabilizing the volume, thus ensuring greater durability achieved in the mixture proportion of concrete.

2.5 SUPERPLASTICIZER (HIGH RANGE WATER REDUCER)

Superplasticizers are chemical admixtures that can be added to concrete mixtures to improve workability. Strength of concrete is inversely proportional to the amount of water added or water-cement (w/c) ratio. In order to produce stronger concrete, less water is added, which makes the concrete mixture very unworkable and difficult to mix, necessitating the use of plasticizers and superplasticizers.

Superplasticizers are also often used when pozzolanic ash is added to concrete to improve strength. This method of mix proportioning is especially popular when producing high strength concrete and fiber reinforced concrete.

Adding 2% superplasticizer per unit weight of cement is usually sufficient. However, note that most commercially available superplasticizers come dissolved in water, so the extra water added has to be accounted for in mix proportioning. Adding an excessive amount of superplasticizer will result in excessive segregation of concrete and is not advisable. Some studies also show that too much superplasticizer will result in a retarding effect.

Plasticizers are commonly manufactured from lignosulfonates, a by-product from the paper industry. Superplasticizers have generally been manufactured from sulfonated naphthalene formaldehyde or sulfonated melamine formaldehye, although new generation products based on polycarboxylic ethers are now available. Traditional lignosulfonate based plasticisers and naphthalene and melamine based superplasticisers disperse the flocculated cement particles through a mechanism of electrostatic repulsion. In normal plasticisers, the active substances are adsorbed on to the cement particles, giving them a negative charge, which leads to repulsion between particles. Naphthalene and melamine superplasticisers are organic polymers. The long molecules wrap themselves around the cement particles, giving them a highly negative charge so that they repel each other.

Polycarboxylate Ethers (PCE), the new generation of superplasticisers is not only chemically different to the older sulphonated melamine and naphthalene based products but their action mechanism is also different, giving cement dispersion by steric stabilisation, instead of electrostatic repulsion. This form of dispersion is more powerful in its effect and gives improved workability retention to the cementitious mix. Furthermore, the chemical structure of PCE allows for a greater degree of chemical modification than the older generation products, offering a range of performance that can be tailored to meet specific needs.

Table 1 History of HRWR development

Year	Chemical Base	Generation	Water Reduction
1930	Ligno-sulphonates, Gluconates	1^{st}	10%
1970	Sulphonated Melamine/Naphtalin polymers	2^{nd}	20%
1990	Vinyl-copolymers	3^{rd}	30%
2000	Modified Polycarboxylates	4^{th}	40%

2.6 DURABILITY

Durability is defined as the capability of concrete to maintain the long-term structural performances. Durability of concrete is a relative property since it simultaneously depends on the chemical and physical characteristic of concrete and environmental conditions. The environmental in which the concrete is exposed – atmosphere, soil condition and water shall affect the durability of concrete, as it is subjected to physical and chemical attacks. Among the attacks that concrete are subjected into are sulfate attack, acid attack, carbonation, alkali-aggregate reaction, freezing-thawing and abrasion. Performance of concrete against all of this attack is named as durability. Water ingress is one of the most important reasons that increase the deterioration of concrete. Carbonation is a major risk for reinforced concrete because it can lower alkalinity of the concrete to such extent that iron may rust and spall the cover. In the design of concrete structures, carbonation is one of the many important factors that determine the service life of a concrete structure.

A number of studies have been conducted on the durability and strength of concrete made with mineral admixtures. Fly ash and silica fume is commonly used as concrete admixture to increase performance of concrete.

CHAPTER 3
METHODOLOGY

3.1 PROJECT IDENTIFICATION

In this project, the methodology is as follows

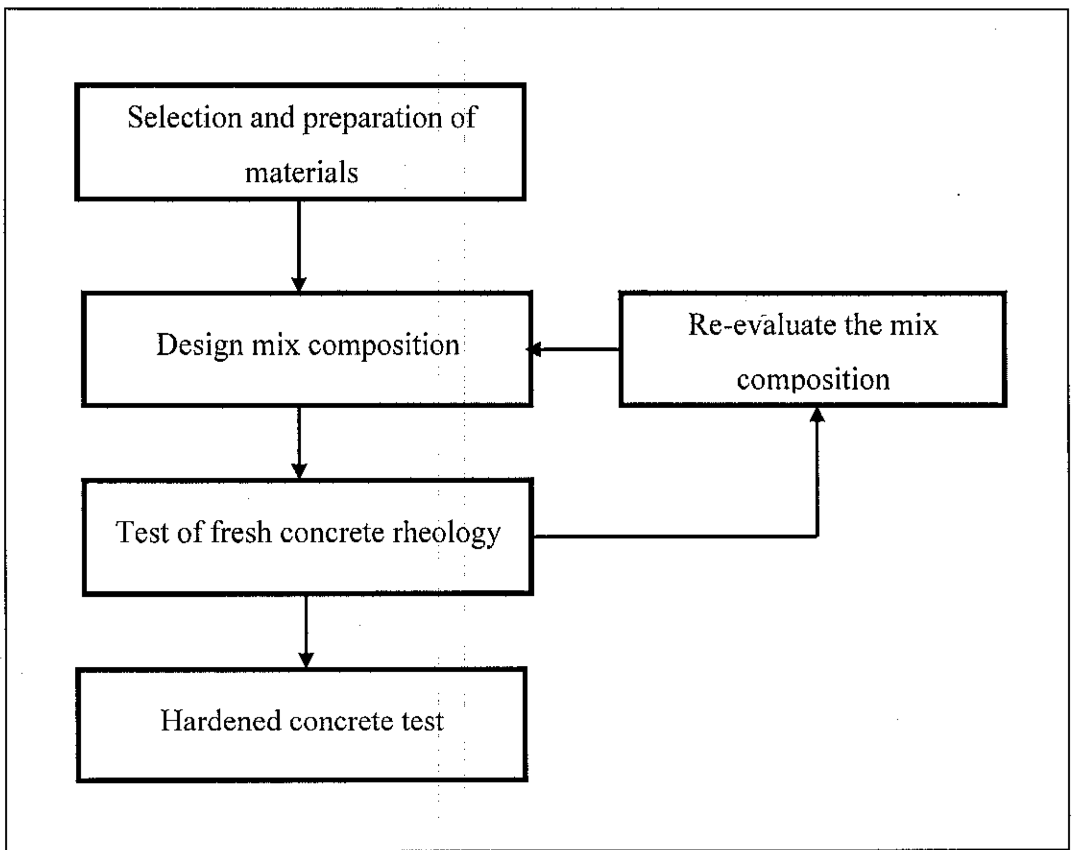


Figure 1 Flow chart of activities

Mix design often use volume as a key parameter because of the importance of the need to over fill the voids between the aggregate particles. The mix composition is chosen to satisfy all performance criteria for the concrete in both the fresh and hardened states.

Curing is important for all concrete but especially so for the top-surface of elements made with SCC. These can dry quickly because of the increased quantity of paste, the low water/fines ratio and the lack of bleed water at the surface. Initial curing should therefore commence as soon as practicable after placing and finishing in order to minimize the risk of surface crusting and shrinkage cracks caused by early age moisture evaporation.

3.2 MATERIALS PREPARATION

3.2.1 Aggregates

The materials used in this study were locally available. Crushed limestone with a maximum nominal size of 20mm was used as the course aggregate, and local river sand was used as the fine aggregate in the concrete mixture. The grading of the aggregates is presented in *Table 2.*

Table 2 Grading of the coarse and fine aggregate

BS Sieve Size (mm)	Passing (%)	
	Coarse Aggregate	Fine Aggregate
20.00	99.2	-
14.00	72.4	-
10.00	31.3	-
5.00	3.0	95.9
3.35	2.1	92.3
2.36	1.8	86.6
2.00	-	83.6
1.18	-	69.2
0.60	-	48
0.30	-	24.8
0.21	-	14.4
0.15	-	7.7
Pan	0	0

3.2.2 Cement

ASTM, Type I, ordinary Portland cement (OPC) was used in this project. Its physical properties and chemical compositions are presented in *Table 3* and *Table 4* respectively.

3.2.3 Pulverized fly ash

The fly ash in this study is provided by Slag Cement Sdn Bhd. It complies with BS EN 450: 1995 based on compliance to all requirements. The physical properties and chemical compositions are provided in *Table 3* and *Table 4* as well.

Table 3 Physical properties of materials used

Physical tests	Portland cement	PFA
45μm sieve residue, (%)	6	22.32
Density (kg/m3)	-	2290
Compressive strength (Mpa)		
7-day	26	-
28 -day	31.9	-
Time of setting, Vicat test, (min)		
initial setting	220	-
final setting	325	-
Pozzolanic activity index (%)		
28 -day	-	84
90 -day	-	97

Table 4 Chemical composition analysis of materials used

Chemical composition	Portland cement	PFA
Loss on ignition	2	4.2
Free Calcium Oxide	-	0.1
Sulfur trioxide (SO_3)	3.5	0.9
Silicon dioxide (SiO_2)	20.3	51.2
Calcium oxide (CaO)	62	5.6
Magnesium Oxide (MgO)	2.8	2.4
Ferric oxide (Fe_2O_3)	3	6.6
Aluminum Oxide (Al_2O_3)	4.2	24.0
Potassium Oxide (K_2O)	0.9	1.1
Sodium Oxide (Na_2O)	0.2	2.1

3.3 MIX DESIGN COMPOSITION

The objective was to find the optimum mix proportion that shall produce very workable and at the same time very durable concrete. Accordingly, trial mixes using different mix proportions were performed. Throughout the project, 12 trial mixes were carried out. The proportions of concrete mixtures are summarized in *Table 5.*

Table 5 Mix design for the trial mixes

Mix No	OPC	PFA	Coarse Aggregate		Fine Agg	w/c	Water	S/P
			(16-8mm)	(8-4mm)	(<4mm)			
M1	330	0	330	610.5	990	0.42	138.6	4.29
M2	330	0	330	610.5	990	0.42	138.6	4.29
M3	330	0	330	610.5	990	0.42	138.6	10.89
M4	330	0	330	610.5	990	0.42	138.6	17.89
M5	330	0	330	610.5	990	0.42	138.6	24.09
T3	500	0	250	467	1018	0.34	170	6
T4	500	0	250	470	1020	0.34	170	7
T5	500	0	250	470	1020	0.34	170	5
PFA1	450	50	250	470	1020	0.34	170	7
PFA2(FAIL)	400	100	250	470	1020	0.36	190	7
PFA2(FAIL)	400	100	250	470	1020	0.34	170	7
PFA2	400	100	250	470	1020	0.34	170	7
PFA3	350	150	250	470	1020	0.34	170	7

* All units are in kg/m^3

SCC mix design varies from the conventional concrete in many ways. The first is that it has high volume of paste, which means that the cement and water in the SCC mix design is higher than conventional concrete. However, the paste ratio should not be too excessive to avoid heat of hydration. This is where the cement replacement materials are recommended to lower the heat of hydration.

Next, SCC mix design needs high volume of fine particles (< 80 micrometer) to ensure good workability and reduce risk of segregation or bleeding. High dosage of superplastiser is essential to obtain good fluidity. However, a dosage near saturation amount can lead to concrete segregation. To enhance the flowability, SCC requires low volume of coarse aggregate (10-20mm), as this can reduce the chances of a coarse aggregate being stuck at reinforcement bars.

The mix proportions were divided into three series to ease the analysis. The series were M-series, T-series and PFA-series.

The superplasticizer was incorporated in all mixes. In order to keep constant water/binder ratio, superplasticizer had been used in different dosages in M-series and T-series. The content of SP was adjusted slightly for each mix to find the most efficient dispersion of the cementitious particles. Once the optimum superplasticizer is determined, the dosage of that superplasticizer is used for PFA-series; in this case, a dosage of 7% is used.

In PFA-series, all the parameters were kept constant, except for the amount of PFA that was used as cement replacement material. Cement was replaced by PFA at three proportions; 10%, 20% and 30% by weight. In PFA-series also, there were two mixes that were using different water to cement ratio, to investigate the behavior of PFA under different conditions.

3.4 MIXING AND CASTING

The concrete mixes were prepared using a tilting drum mixer. The interior of the drum was initially washed with water to prevent absorption. The coarse and fine aggregate were mixed first, followed by half of water. The mix was left for 8 minutes to let the water to be absorbed by the aggregates. Then the cement and PFA (if needed) is added, followed by the rest of water containing superplasticizer. The mix was left in the mixer for 5 minutes to allow the reaction of superplasticizer is completed.

After the mixing was completed, tests were conducted on fresh concrete to determine the rheological properties. The tests conducted were slump flow test and v-funnel test. Segregation and bleeding was visually inspected during the slump flow test. 100-mm cubic specimens were prepared for each mix proportion. No compaction was applied in any of the mixtures. After 1-day, the specimens were demoulded, and stored in curing tank.

3.5 FRESH CONCRETE TESTS

For determining the self-compactibility properties slump flow and v-funnel tests were performed and measured. All fresh test measurements were duplicated and average of measurement was given. In order to reduce the effect of workability loss on variability of test results, the fresh-state properties of mixtures were determined in a period of 30min after mixing.

All the tests for fresh concrete tests are in accordance with *The European Guidelines for Self Compacting Concrete (2005),* which reference standards is European Standard.

3.5.1 Slump flow

Slump flow test is proposed for testing workability and deformability. Slump flow test judges the capability of concrete to deform under its own weight against the friction of the surface with no external restraint present. No compaction energy must be applied during the test so that the SCC flows only under the influence of gravity. It is based on the slump test described in EN 12350-2. The result is an indication of the filling ability of self-compacting concrete.

The procedure is to pour the fresh concrete into a standard slump cone. Then withdraw the cone vertically upwards in one movement, without interfering with the flow of concrete. Without disturbing the base plate or the concrete, the largest diameter of the flow spread of the concrete to the nearest 10mm. Then the diameter of the flow spread at right angles to it is measured, and the mean of the reading is the slump flow.

The concrete spread is also checked for segregation. If segregation is observed, then the test is considered unsatisfactory.

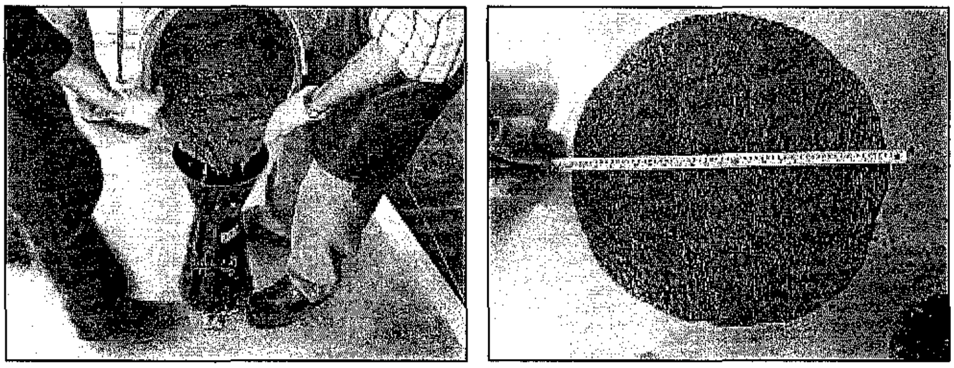


Figure 2 Slump flow test

3.5.2 V-funnel

V-funnel test is proposed for testing viscosity and deformability of concrete. The viscosity of a suspension is dependent mainly on the water/solids ratio and the overall grading curve. This means that a SCC with higher water content flows faster out of the funnel and has a lower viscosity than SCC with lower water content.

The test is carried out by filling a V shaped funnel with fresh concrete, and the time taken for the concrete to flow out of the funnel is measured and recorded as the V-funnel flow time.

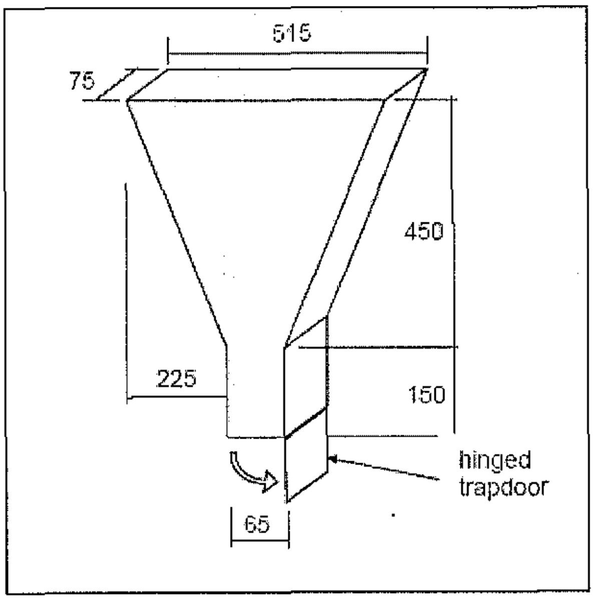


Figure 3 V-funnel dimension

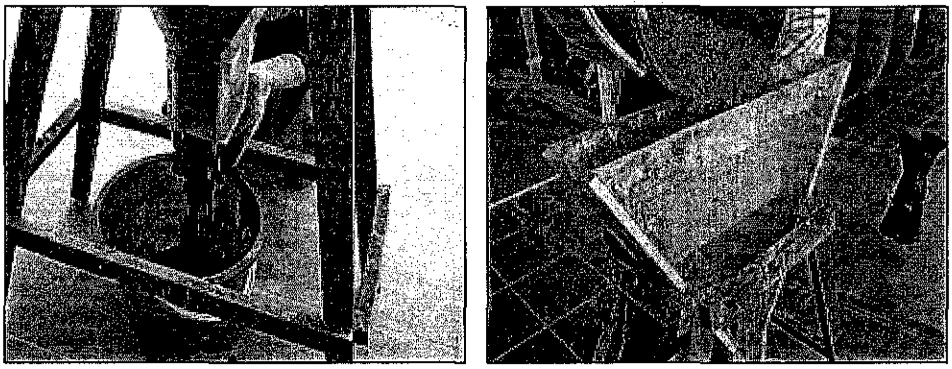


Figure 4 V-funnel test

3.6 HARDENED CONCRETE TESTS

3.6.1 Compressive strength test

In BS 5328, the compressive strength is expressed as 'grade', which is the minimum characteristic cube strength. The industry still uses the old standard when dealing with concrete types. In the new BS EN 206-1 and BS8500, the characteristic compressive strength is expressed as a strength class.

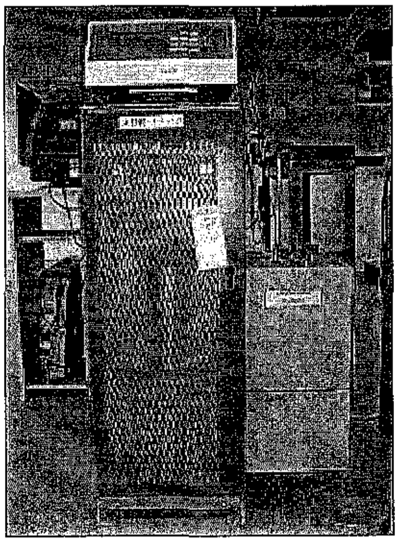


Figure 5 Compression machine (ADR 1500)

3.6.2 Porosity test

Porosity of concrete is an important factor is classifying its durability. Generally, concrete of a low porosity will afford better protection to reinforcement within it than concrete of high porosity.

There are no vacuum absorption tests in the British Standards, although an earlier version of BS 3921 did contain such a test. There are a number of variations on vacuum absorption in the RILEM tests in which various reduced pressures and soaking times are recommended.

The porosity test for this project is using vacuum saturation method. Vacuum saturation is a method of assessing the total water absorption porosity of a material. Porosity can be determined by measuring its weight gain and expressing this as a percentage of the mass of the sample.

The porosity measurements were conducted on slices of cylinders cores that have been casted into (0.048 x 0.315 x 0.205)m slabs. The cored slices were put inside vacuumed desiccator for 30 minutes, and then the desiccator is filled with water for 6 hours. After 24-hours soaked in water, the samples were dried at 100 ± 5°C.

The vacuum saturation porosity, P is calculated from:

$$P = \frac{volume\ of\ water\ absorbed}{volume\ of\ sample} \quad 100$$

$$P = \frac{W_{sat} - W_{oven}}{W_{sat} - W_{water}} \quad 100$$

Where P is the vacuum saturation porosity (%), W_{sat} the weight in air of saturated sample, W_{wat} *the weight in water of saturated sample, and* W_{dry} the weight of oven-dried sample.

Figure 6 Desiccator

CHAPTER 4
RESULT AND DISCUSSION

4.1 FRESH CONCRETE RESULTS

Table 6 Results on fresh concrete properties

Mix No	V-funnel		Slump flow			
	1st Trial (s)	2nd Trial (s)	1st Trial (mm)		2nd Trial (mm)	
			0°	90°	0°	90°
M1	-	-	-	-	-	-
M2	-	-	-	-	-	-
M3	41	-	-	-	-	-
M4	45	-	-	-	-	-
M5	20	-	-	-	-	-
T3	8.47	4.54	630	610	-	0
T4	5.77	5.26	440	400	400	420
T5	6.2	6.56	600	590	590	600
PFA1	4.75	5.62	530	530	500	530
PFA2	29.72	20.1	700	690	680	690
PFA2(FAIL)	-	-	-	-	-	-
PFA3	11.2	5.97	700	650	500	500

From *Table 6*, it can be seen that the slump flow diameters vary between 500mm and 700mm. From the European guidelines, this slump flow class satisfies for SF1(520 - 650mm) and SF2 (660-750mm) which is suitable for many normal application, or slightly reinforced concrete structures (slab, walls, column).

As for v-funnel test, the result obtained was less than 10 seconds, except for PFA2 mix (25 seconds).

4.2 M-SERIES

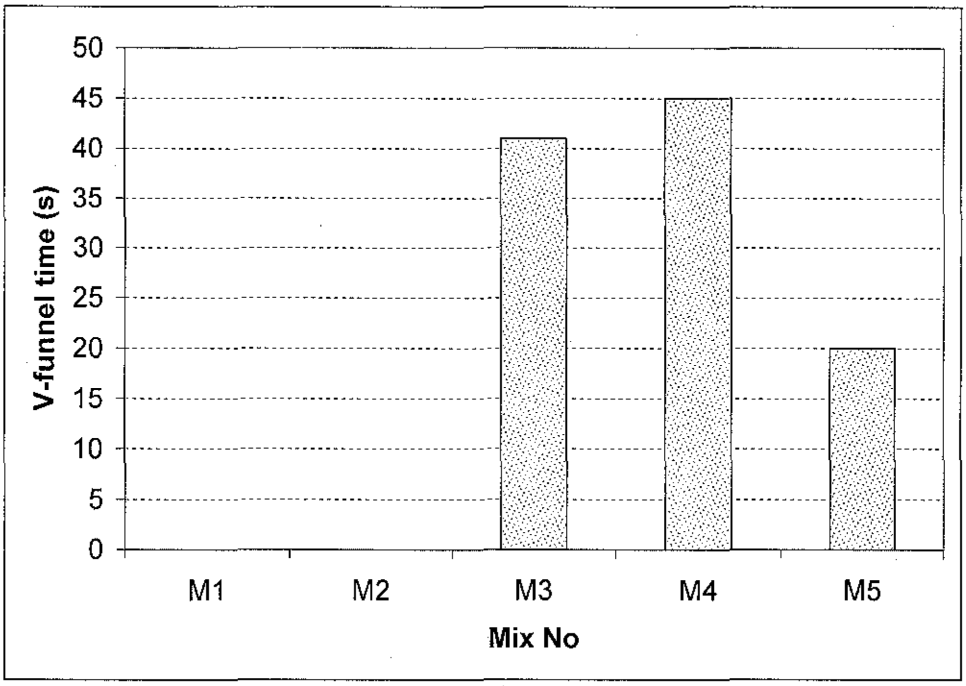


Figure 7 V-funnel test for M-series

The M-series were the first trial mix series that was conducted for this project. In this series, it was targeted to produce satisfactory SCC, but it did not. The slump flow test was not carried out since all the results for V-funnel tests are unsatisfactory and can be visually observed that the mix is not workable and deformable at all.

From *Figure 7*, it was observed that M1 and M2 failed V-funnel test, as the mix is not flowable. The mixes did not flow under gravity force at all; a rod had to be used to prod into the funnel in order to make it fall.

M1 was using a superplasticizer which is not polycarboxylate-based, which leads to the failure of producing self-compacting concrete. Polycarboxylate-based superplasticizer can reduce water up until 40%, thus the usage of the correct SP is important to produce self-compacting concrete. Even though M2 is using poly-carboxylate - based superplasticizer, the amount is not enough to make the mix flowable, as the v-funnel test is still a failure.

For M3, M4, and M5, there was flowability, but there were not considered as self-compacting concrete, due to no self-compactibility. Further more, due to the high dosage of superplasticizer, segregation were observed for the three mixes. During the placing of concrete into mould, the concrete was bleeding profusely, which resulted in serious honeycombs after the demoulding. The demoulding took place after 3 days of casting – where as normal demoulding can be done on the first day after casting. The concrete obtained was very brittle and not condensed.

4.3 T-SERIES

4.3.1 Introduction

The aim of the T-series is to establish a working mix for SCC, as well as to further examine the influence of SP addition on workability, strength, porosity and pore structure of concrete at a constant water to cement ratio. T4 mix had the highest dosage of SP, with 7kg/m^3, followed by T3, 6kg/m^3, and lastly T5, 5kg/m^3. The following is the T-series' fresh concrete result for slump flow and v-funnel test.

4.3.2 Fresh concrete result for T-series

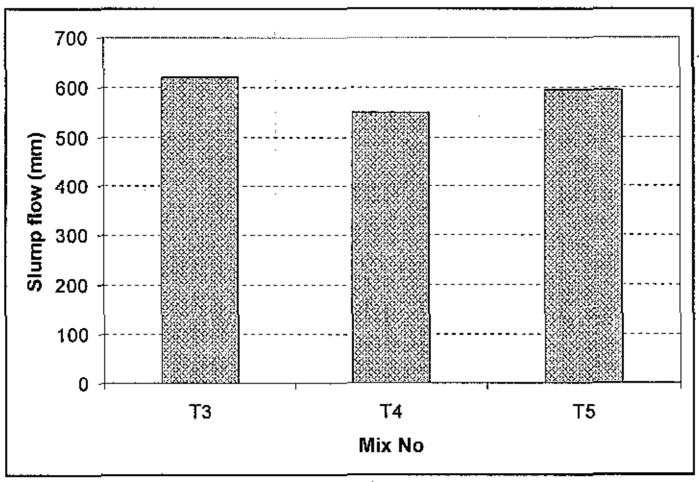


Figure 8 Slump flow result for T-series

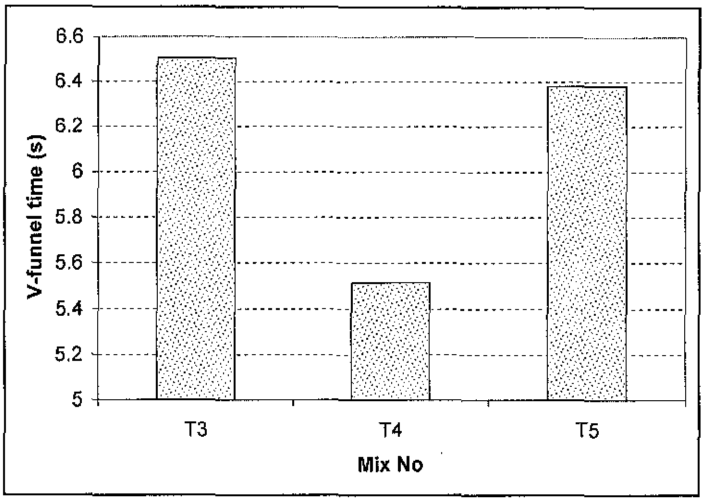


Figure 9 V-funnel result for T-series

As seen in figures above, the different dosages of SP did not greatly influence the workability, i.e. the slump flow diameter. The slump flow diameters obtained show good deformability, and no segregation were observed during the testing. The same was the same with the v-funnel result; the difference is about 1 second, which would not greatly influence the workability since it is still in the acceptable range (European Guidelines for SCC).

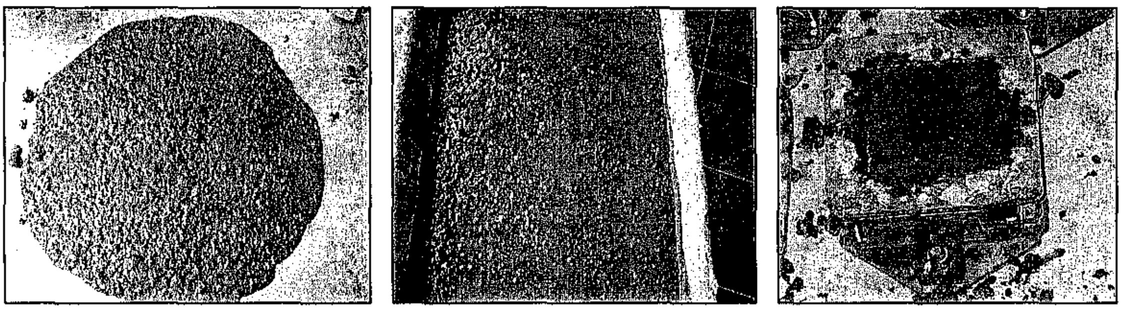


Figure 10 SCC in plastic state – homogenuous, non-segregating and no bleeding

Generally, the results obtained for the mixes were as shown in figures above. The left figure shows homogeneity of the mix; where as the right figure shows no segregation is observed.

It is to be noted that some unavoidable technical problem occurred during this project. One of them was equipment breakdown, which had caused some of the mix were not being mixed in the same mixer. Using different mixer had influenced the mix considerably, in terms of the thoroughness of mixing the concrete.

4.3.3 Hardened concrete result for T-series

The compressive strength development of T-series within time is presented in *Figure 11*. Generally, for the three dosages of SP, no significant comment can be made on the trend, as all three lines are almost similar. The strength development was slower at the early age, but it catches up once it had reached 28-days. All three had achieved strength of 50Mpa at the age of 56-days. T4 achieved the highest strength, with 55Mpa, followed by T5.

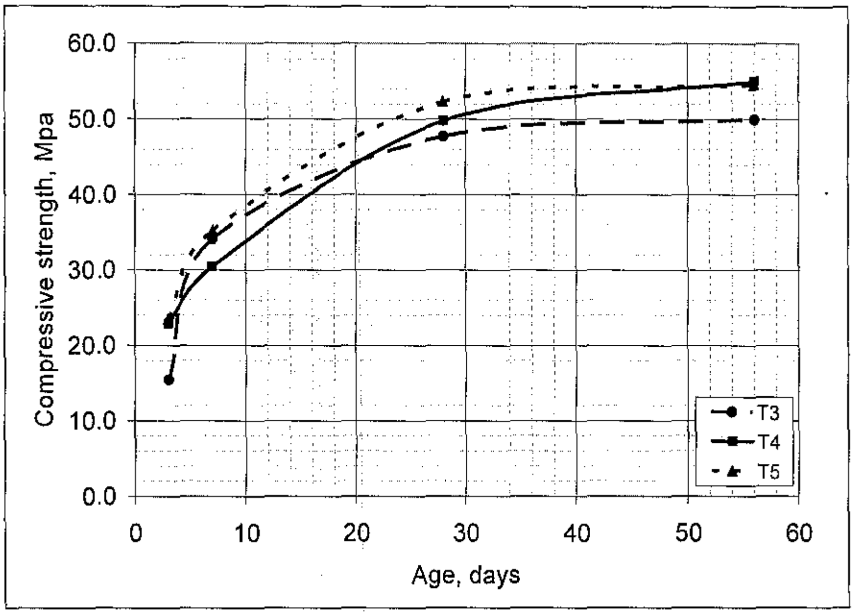


Figure 11 Compressive strength for T-series

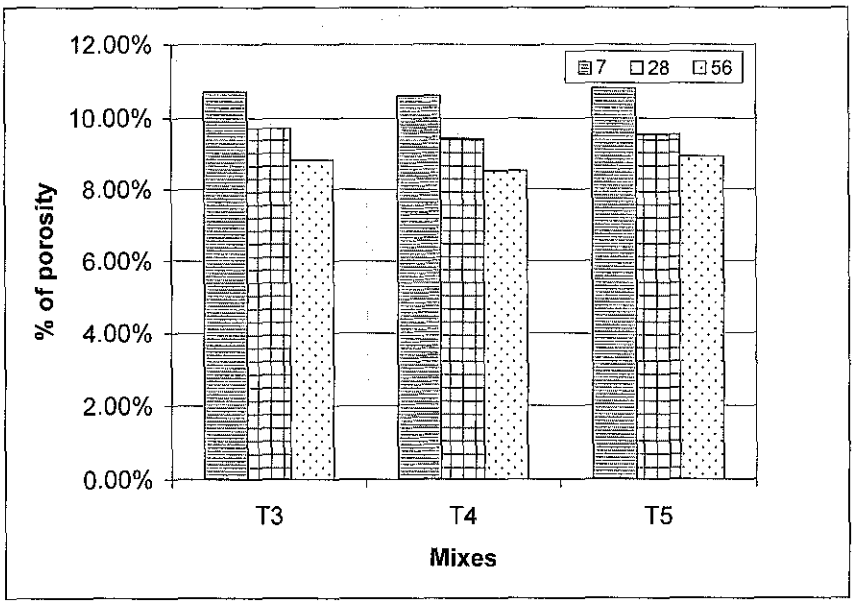


Figure 12 Porosity for T-series

According to the literature, at a constant water to cement ratio, the addition of SP is found out to decrease the porosity of concrete. This is due to the refinement of the pore structure is obtained in the presence of SP. However, for this project, the increment of SP did not give significant value for the porosity of concrete. All three shows more or less the same percentage of porosity at different ages. Nevertheless, T4 (the highest dosage SP) did show the lowest porosity percentage by the age of 56 days, though the difference is not very remarkable. However, it is to be noted that the porosity for all mixes did decrease within time, which indicates a good performance in the long run.

4.4 PFA-SERIES

4.4.1 Introduction

Since trial mix for workable SCC had been achieved in T-series, PFA-series concentrates on the influence of PFA addition on the workability, strength and porosity of concrete at a constant water to cement ratio. The actual mixing for PFA-series were five mixes, but only three were considered as successful mix. PFA was used to replace cement by weight in three amount, 10%, 20%, and 30% (PFA1, PFA2, and PFA3 respectively).

For this series, there were two mixes that were experimenting the influence of increase water to cement ratio and increase of free water in the mix. The usual water to cement ratio used in this project was 0.34, but one of the mix (using 20% of PFA replacement) was using 0.36. The result was unfavorable, as severe bleeding and segregation took place. The same goes to increase of free water content, in this case, the aggregates used were saturated aggregates. The result obtained was severe segregation of the concrete.

Figure 13 Non-desirable result for SCC – segregation and bleeding

Aside from these two mixes, the other mixes were considerably satisfactory as SCC. The result of the mixes will be discussed below.

4.4.2 Fresh concrete result for PFA-series

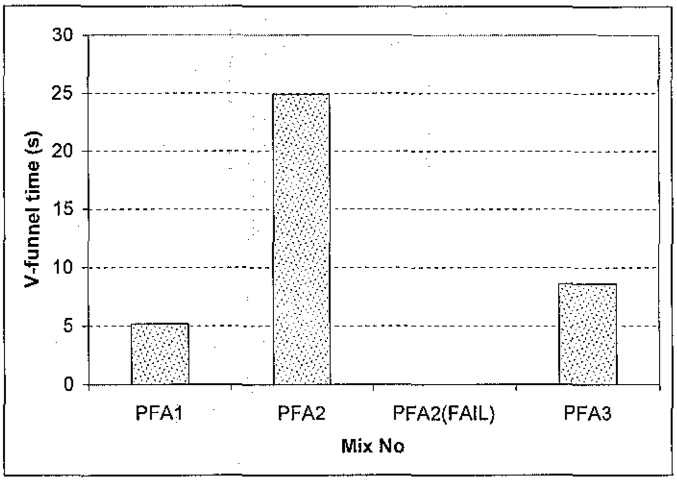


Figure 14 V-funnel result for PFA-series

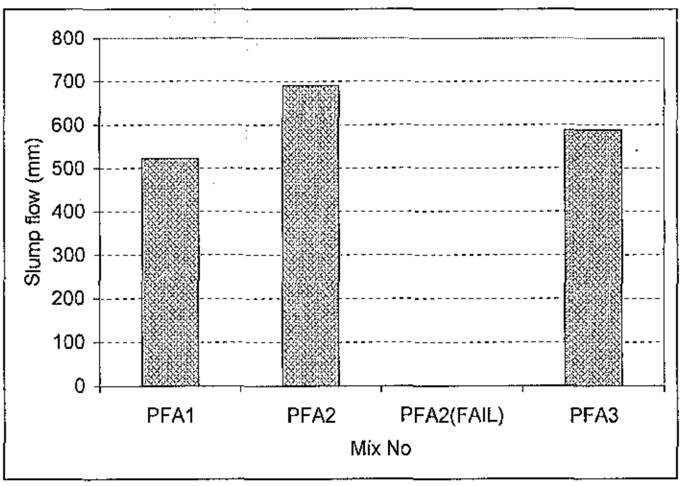


Figure 15 Slump result for PFA-series

For this series, the fresh properties of concrete showed promising result for the performance in terms of workability and deformability. The slump flow obtained were ranging between 520-700mm. PFA2 reached up until 700mm, which none of the mixes before this were able to produce such deformability. However, the two mixes which using increased free water content did not satisfy the SCC characteristic due to severe segregation. Because of this, the two mixes were not tested for the v-funnel test.

For the v-funnel test, there was one anomaly occurred. PFA2, which achieved the highest slump flow, took the longest to flow out of v-funnel test. The period it had taken to flow out of the v-funnel was too large, and thus can not be ignored. This may due to discrepancies during mixing that affect the viscosity of the concrete. Any variation in material characteristics can affect self-compatibility. The most influential variant is the water content of the concrete itself. As for the other mixes (PFA1 and PFA3), yield result less than 10 seconds.

4.4.3 Hardened concrete result for PFA-series

The compressive strength development of PFA-series within time is presented in *Figure 16*. The result shows that all three mixes had slower strength development as compared to T-series. PFA2 shows that it has the best strength curve as compared to PFA1 and PFA3. It is commonly found in the literature that the strength development for PFA is quite slow. Thus, this can be said true for this project too.

Figure 17 shows percentage of porosity of PFA-series within time. The most notable trend is that the porosity decreases as the percentage of PFA added increases. PFA3, having the highest amount of cement replacement (30%), have the lowest permeability. This is due to the fact that PFA particles are much finer than cement, thus enabling the particles to fill in gaps. This had lead to the refinement in pore structure.

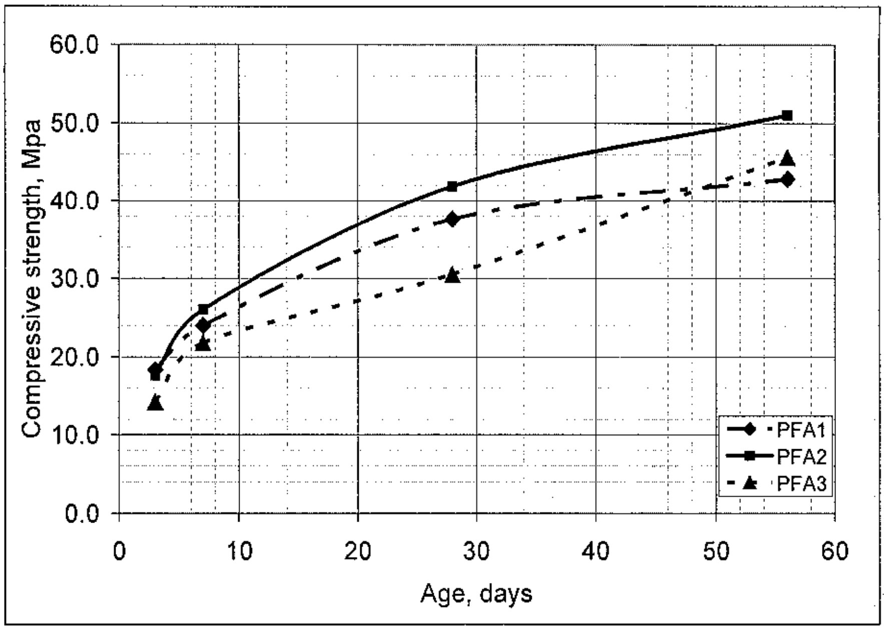


Figure 16 Compressive strength for PFA-series

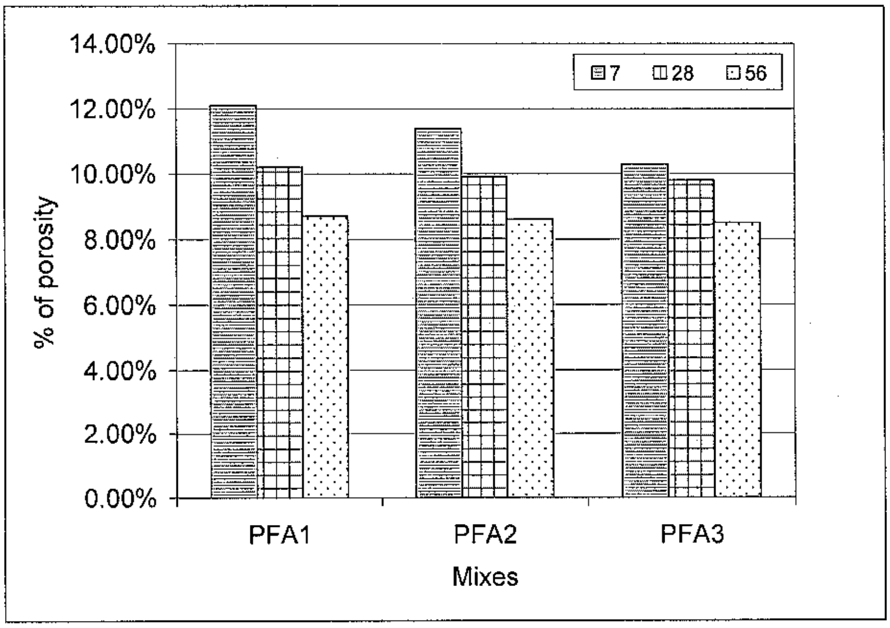
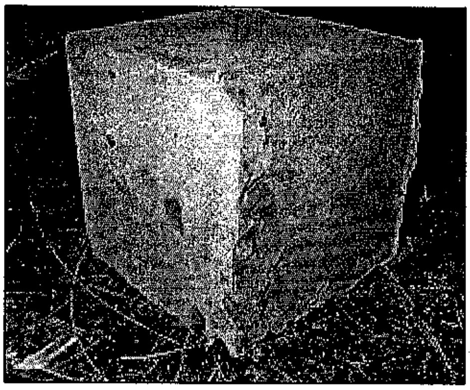


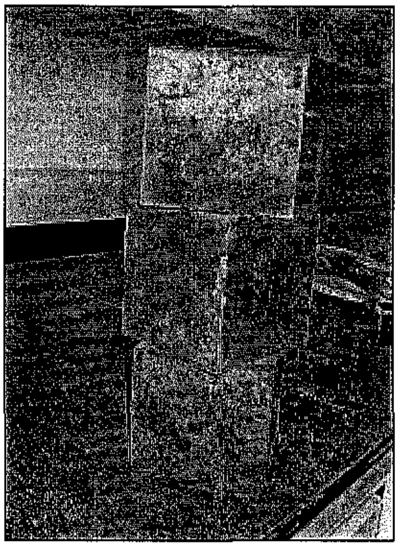
Figure 17 Porosity for PFA-series

4.5 COMPARISON BETWEEN T-SERIES AND PFA-SERIES

4.5.1 Finishing



(a)T-series



(b) PFA-series

Figure 18 Finishing of SCC

The main distinction of the result obtained for T-series and PFA-series was the finishing. For T-series, there were minor honeycomb formed at the edge of the mould. This defect is important to SCC characteristic and performance, since there was no compaction being done to the mix. However, for PFA-series, there were almost none honeycomb defect detected. All cubes gave perfect finishing, as if ample compaction had been given to the concrete. This is due to the fact that PFA particles had spherical geometry. The spherical particles give significant benefits to the fluidity of the concrete in a plastic state by optimizing the packing of particles. Thus, the finishing work is better than the ones without PFA.

4.5.2 Fresh concrete properties

From the figures below, it can be said that the difference between T-series and PFA-series is not distinguishable. Both series did not give any relevant trend in terms of workability and deformability, as the slump flow and v-funnel tests obtained is almost similar.

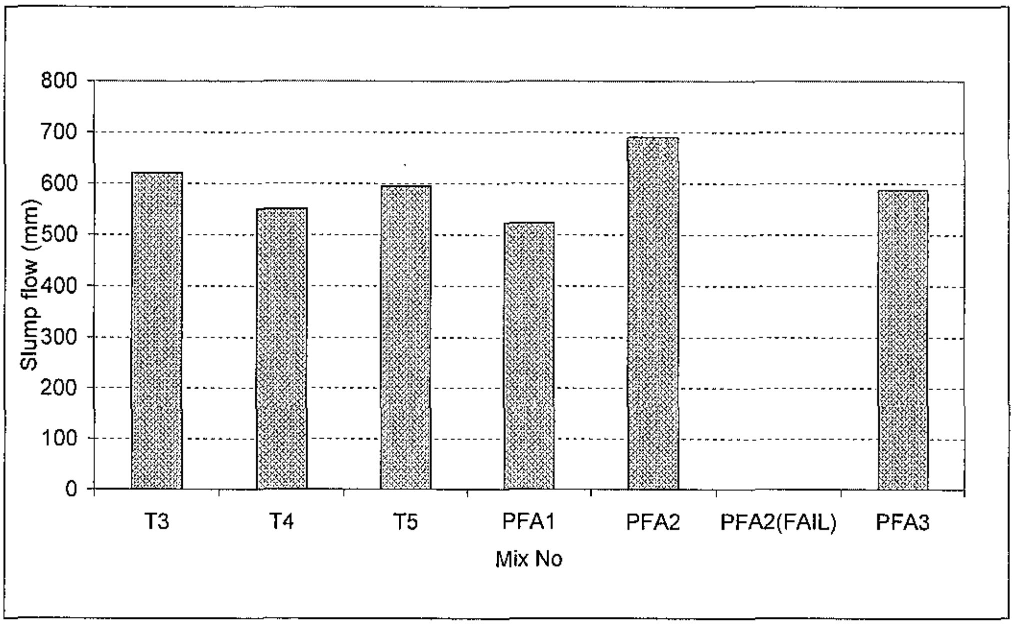


Figure 19 Slump flow for all mixes

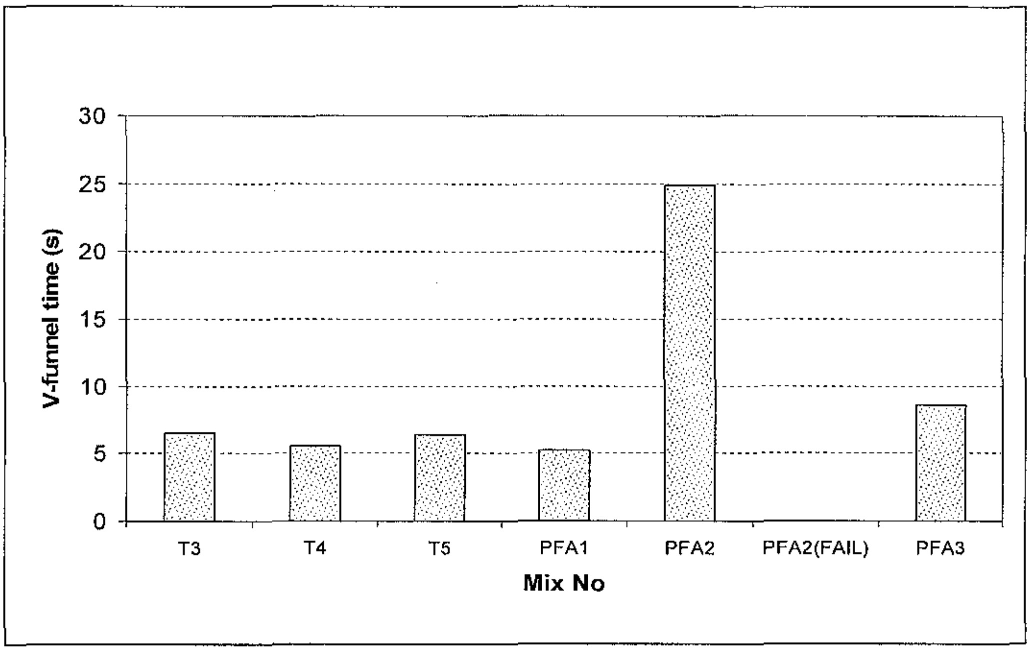


Figure 20 V-funnel time for all mixes

4.5.3 Hardened concrete properties

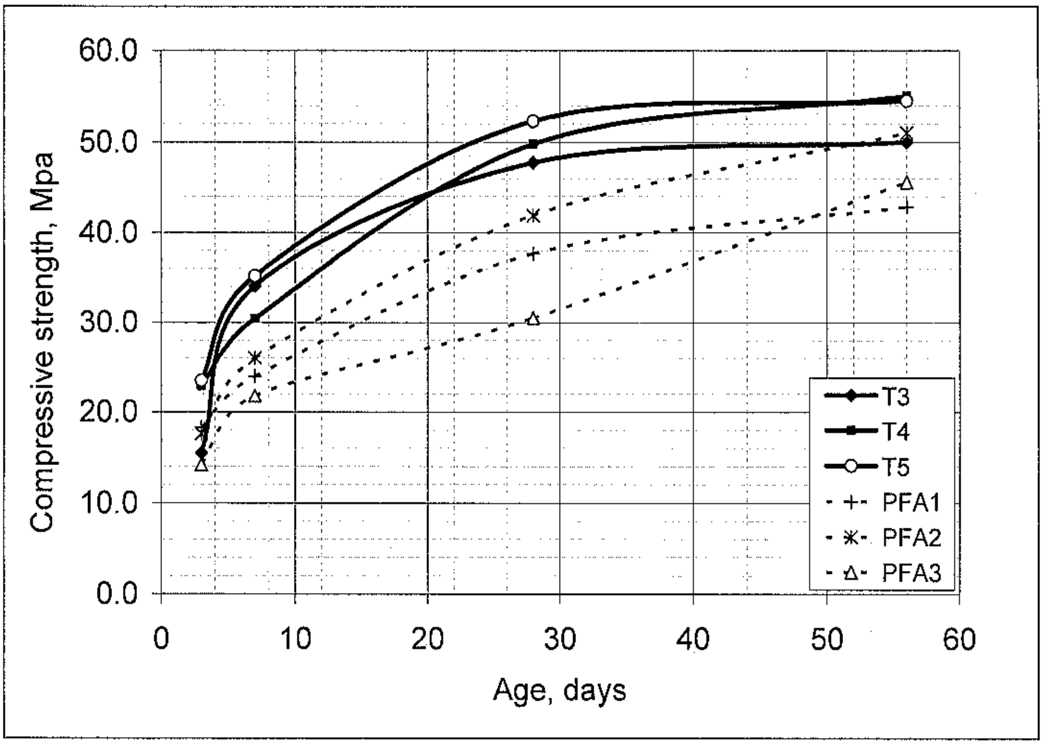


Figure 21 Compressive strength (Mpa) for all mixes

Figure 21 shows the compressive strength for all the mixtures. As seen from the graph, the compressive strength for PFA-series were developed slower than the T-series. For T-series, there was not much strength growth obtained from 28-days and 56-days. It's averaging up until around 5Mpa only. As for PFA-series, it can be seen that the strength development from 28-days and 56-days was still rapidly in process, as the slope is still steep, not reaching its plateau state as compared to T-series.

This phenomenon occurred because of little pozzolanic reaction occurs during the first 24 hours. Thus, with increasing PFA content, lower early strength are achieved, as can be seen that PFA3 (with the most PFA content), had the lowest strength. Taylor (1997) explains the hydration processes involved in some particular detail. The presence of fly ash retards the reaction of alite within the Portland cement at early stages. However, alite production is accelerated in the middle stages due to the provision of nucleation sites on the surface of fly ash particles. Therefore, it is expected that the PFA-series to achieved higher strength at later ages, but due to time constraint, this can not be proven in this project.

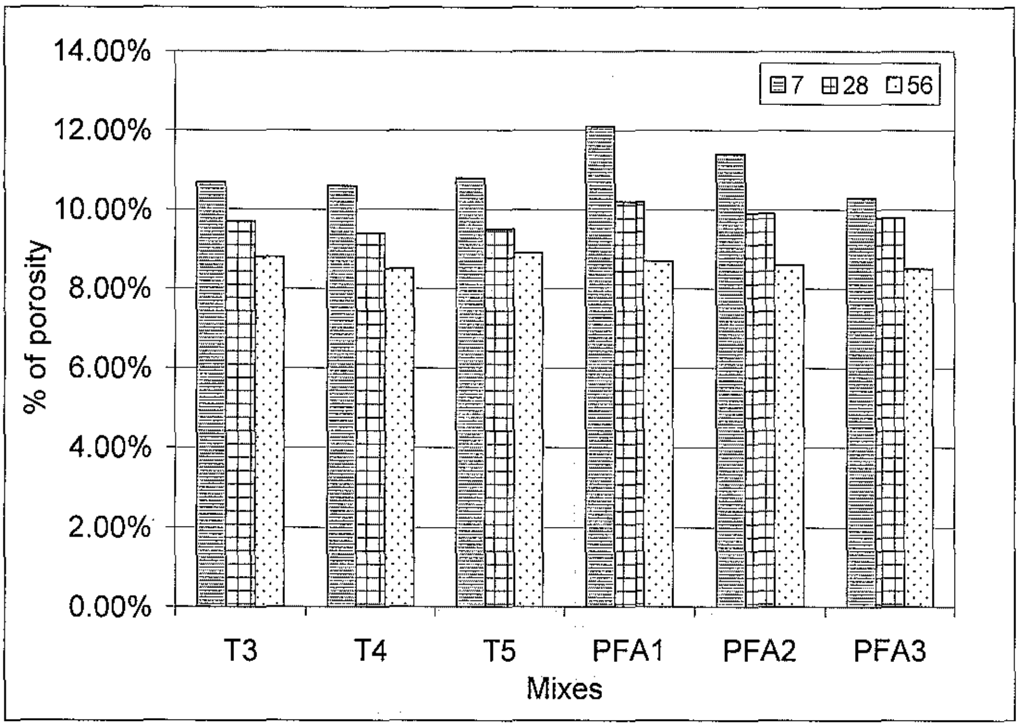


Figure 22 Porosity (%) for all mixes

It is generally known that by incorporating PFA into concrete mixture can improves its durability. From the figure, it can be observed that PFA-series had substantially reduced the porosity of the concrete, as initially the porosity for each mix is quite high. This is probably the outcome of the continuous generation of pozzolanic reaction products that fill the pores.

The reaction products formed were explained by Roy (1987), how PFA differs from the products found in Portland cement only concrete. A very much finer pore structure is produced with time presuming there is access to water to maintain the hydration process. With a continuing supply of moisture, the lime reacts with the fly ash by pozzolanic reaction, producing additional hydration products of fine pore structure. It is also expected that the porosity of the concrete mixes of PFA-series to be reduced as the age is increasing. However, due to the time constraint for this project, it can only been investigated up until 56-days.

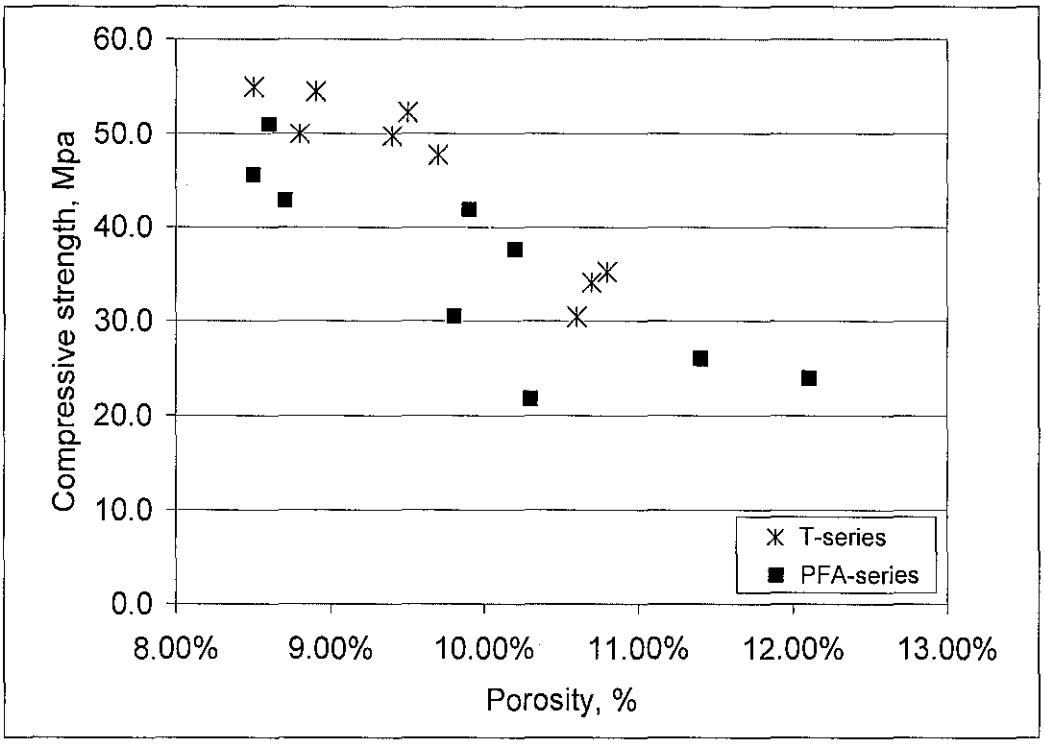


Figure 23 Relationship between compressive strength and porosity

Figure 23 shows the relationship between porosity and compressive strength of both T-series and PFA-series. From what can be observed here is that the strength development and porosity of concrete is directly proportionate with each other, i.e. if the strength is high, so does the porosity. This can be shown in T-series trend; since the T-series' strength development is gained earlier than PFA-series, the porosity of T-series were lower than PFA-series. PFA-series' strength which was retarded at early stage yields higher porosity, but once the strength development catches up with T-series, the porosity level also improved.

This can be explained by the packing of the particles during hydration process. At early age, hydration process is not yet completed, thus leaving substantial spaces/voids between the interlocking aggregates. Theoretically, the larger the void is, the weaker the bond between the aggregate. When the bond is weak, therefore, the compressive strength achieved is also affected. That is why the age of the concrete is important because it represent the period of hydration process for concrete. The porosity is also affected by the hydration process, given that the hydration process will fill in the void, thus reducing the porosity. It is expected for the PFA-series to yield higher strength and porosity as the age is older, as it had been discussed before.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

Improving the performance of SCC is of great importance for modern construction material. The objectives of this project are to determine the optimum mix design for SCC and also to investigate the effect of PFA as cement replacement material in SCC. In this study, PFA had been added in order to improve the performance of concrete. A total of six successful mixes had been achieved for this project. All the six mixes had been tested for fresh concrete and hardened concrete properties. Based on the results presented in this paper, the following conclusion can be drawn.

1. Increase of SP in the T-series does not affect the workability, strength and porosity of concrete. It indicates that for a successful SCC mix, the most important parameter is the amount of free water in the mix. Adequate water to cement ratio should be observed, as well as the saturation level of the aggregates.
2. Incorporation of PFA in SCC yields results that are quite consistent with the data obtain for incorporation of PFA in normal concrete. The similarities in the behaviors that have been observed in the study are improved workability, late development of early strength, and improved finishing.
3. The strength development of PFA for 28-days to 56-days still shows encouraging result, the strength development is still in progress. It is expected to rise once it reaches 90-days.
4. Compressive strength and porosity of concrete are directly proportionate with each other. Lower compressive strength yields higher porosity of concrete.

5.2 RECOMMENDATIONS

The following is the recommendations in dealing with SCC, which are proposed for future researches.

1. The research shall tests for PFA incorporated concrete up until 90-days to get more accurate result, since in this project, 56-days concrete shows potential in obtaining greater strength and lower porosity.
2. To study the effect of SP at constant water to cement ratio, a wider range of SP dosage is needed. Strict control of dosage is to be maintained all the time.
3. During the mixing of SCC, tests of moisture content should be carried out more frequently, since SCC is more sensitive than normal concrete to variations. Aggregate moisture should be kept constant for all mixes.

REFERENCES

Bilal, E.A., 1999, "Mix design for self compacting concrete," in *The Sixth Annual U.A.E. University Research Conference,* U.A.E. University

Bouzoubaa, N. and Lachemi, M., 2001, "Self-compacting concrete incorporating high volumes of class F fly ash - Preliminary results," *Cement and Concrete Research* **31 (2001):** 413-420

Brouwers, H.J.H. and Radix, H.J., 2005, "Self-compacting Concrete: Theoretical and Experimental Studies," *Cement and Concrete Research* **35 (2005):** 2116-2136

Chan, P.K., 2004, " An approach to optimizing mix design for properties of high-performance concrete," *Cement and Concrete Research* **34 (2004):** 623 – 629

Domone, P.L., 2006, "Self-compacting concrete: An analysis of 11 years of case studies," *Cement and Concrete Composites* **28 (2006): 197-208**

Durecovic, A., 1999, "Cement pastes of low water to solid ratio: an investigation of the porosity characteristics under the influence of a superplasticizer and silica fume," *Cement and Concrete Research* **25 (1999):** 365-375

Felekoglu, B., Turkel, S. and Baradan, B., 2006, "Effect of water/cement ratio on the fresh and hardened properties of self-compacting concrete," *Building and Environment* 01(012)

Khatib, J.M. and Mangat, P.S., 1999, "Infuence of superplasticizer and curing on porosity and pore structure of cement paste" *Cement and Concrete Research* **21 (1999):** 433-437

Kurita, M. and Nomura, T. 1998, "Highly-flowable steel fiber-reinforced concrete containing fly ash" in VM Malhotra (Ed.), *Am. Concr. Ins. SP 178 (1998) 159-175*

Mustafa, S., Heru, A.C. and Ismail, O.Y., 2006, "The effect of chemical admixtures and mineral additives on the properties of self-compacting mortars," *Cement and Concrete Research* **28 (2006):** 432-440

Nan, S., Kung, C. H., and Chai, H. S., 2001, "A Simple Mix Design Method for Self-Compacting Concrete," *Cement and Concrete Research* **31 (2001):** 1799 – 1807

Okamura, H. and Ouchi, M., 2003, "Self Compacting Concrete," *Journal of Advance Concrete Technology*, **Vol 1** , 5-15

Okamura, H. and Ozawa K., 1995, "Mix-design for self-compacting concrete," *Concrete Library of JSCE* **25**: 107-120

Papadakis, V.G. 1999, "Effect of fly ash on Portland cement systems Part I. Low-calcium fly ash," *Cement and Concrete Research* **29 (1999):** 1727-1736

Petersson, O. and Billberg, P. 1999, "Investigation on blocking of self-compacting concrete with different maximum aggregate size and use of viscosity agent instead of filler," in *First International RILEM Symposium on SCC, Rilem Publication s.a.r.l.*

Poon, C.S., and Ho D.W.S., 2004, "A feasibility study on the utilization of r-FA" *Cement and Concrete Research* **34 (2004):** 2337-2339

Reiner, M. and Rens, K., 2006, "High-Volume Fly Ash Concrete: Analysis and Application," *Practice Periodical on Structural Design and Construction* **11(1):** 58-64

Shannag, M.J., 2000, " High strength concrete containing natural pozzolan and silica fume," *Cement and Concrete Composites* **22 (2000): 399-406**

Su, N. and Miao, B., 2003, "A new method for mix design of medium strength concrete with low cement content," *Cement & Concrete Composites* **25(2003):** 215-222

Tahir, G. and Yazicioglu, S., 2006, "The influence of mineral admixtures on the short and long-term performance of concrete," *Building and Environment* **10 (019)**

Taylor, H.F.W. 1997 *Cement Chemistry (2nd Ed),* Thomas Telford Publishing London

The Self-compacting Concrete European Project Group, 2005, *The European Guidelines for Self-Compacting Concrete, Specification,Production and Use*, European Project Group

Xie,Y., Liu, B., Yin, J. and Zhou, S., 2001, "Optimum mix parameters of high-strength self-compacting concrete with ultrapulverised fly-ash," *Cement and Concrete Research* **32 (2002):** 477 – 480

Yahia, A., Tanimura, M., Shimabukuro, A., and Shimoyama, Y. 1999, "Effect of rheological parameter on self compactability of concrete containing various mineral admixture," in *First international RILEM symposium on SCC, Rilem Publication s.a.r.l*

Yazıcı, H., 2007, "The effect of silica fume and high-volume Class C fly ash on mechanical properties, chloride penetration and freeze–thaw resistance of self-compacting concrete," *Construction and Building Materials* **01(002)**

APPENDIX A RAW DATA

FRESH CONCRETE PROPERTIES

Table 7 Fresh concrete properties

	V-funnel		Slump flow			
	1st Trial	2nd Trial	1st Trial (mm)		2nd Trial (mm)	
Mix No	(s)	(s)	0°	90°	0°	90°
M1	-	-	-	-	-	-
M2	-	-	-	-	-	-
M3	41	-	-	-	-	-
M4	45	-	-	-	-	-
M5	20	-	-	-	-	-
T3	8.47	4.54	630	610	-	0
T4	5.77	5.26	440	400	400	420
T5	6.2	6.56	600	590	590	600
PFA1	4.75	5.62	530	530	500	530
PFA2	29.72	20.1	700	690	680	690
PFA2(FAIL)	-	-	-	-	-	-
PFA3	11.2	5.97	700	650	500	500

MIX NO: T4

DATE OF CASTING: 29 SEPTEMBER 2006

Table 8 Compressive strength result for T4

Day	Date	Weight(kg)	Max Loading (kN)	Stress (N/mm^2)
3	30-Sep-06	2.36	147.20	14.72
		2.41	162.00	16.20
		2.41	162.00	16.20
7	4-Oct-06	2.37	329.00	32.90
		2.35	207.60	20.76
		2.36	352.20	35.22
28	25-Oct-06	2.44	554.60	55.46
		2.37	441.80	44.18
		2.36	435.50	43.55
90	26-Dec-06	2.37	503.00	50.30
		2.35	496.00	49.60
		2.36	504.00	50.40

Table 9 Porosity result for T4

Day	Date	Weight in air (g)	Weight in water (g)	Weight oven dry (g)	Porosity
7	4-Oct-06	162.3	64.3	151.5	11.02%
		158.9	63.8	147.9	11.57%
		165	66.5	155.2	9.95%
28	25-Oct-06	171.5	70.2	161.8	9.58%
		168.3	66.9	158.5	9.66%
		172.3	68.3	162.1	9.81%
90	26-Dec-06	165.3	65.3	156.4	8.90%
		162.3	63.2	153.5	8.88%
		161.3	65.3	152.8	8.85%

MIX NO: T5

DATE OF CASTING: 3 OCTOBER 2006

Table 10 Compressive strength result for T5

Day	Date	Weight (kg)	Max Loading (kN)	Stress (N/mm^2)
1	4-Oct-06	2.23	91.7	9.17
		2.92	118.3	11.3
		2.301	127	12.7
3	6-Oct-06	2.281	237.5	23.75
		2.298	142.1	14.21
		2.281	220.1	22.01
7	10-Oct-06	2.32	319.1	31.91
		2.325	286.7	28.67
		2.35	307.1	30.71
28	31-Oct-06	2.31	493.3	49.33
		2.309	456.3	45.63
		2.372	502.3	50.23
90	1-Jan-07	2.36	463.1	46.31
		2.28	537.7	53.77
		2.33	606.7	60.67

Table 11 Porosity result for T5

Day	Date	Weight in air (g)	Weight in water (g)	Weight oven dry (g)	Porosity
7	10-Oct-06	169	65.8	158.1	10.6%
		155.6	58.9	145.2	10.8%
		165.1	64.2	154.5	10.5%
28	7-Nov-06	177	68.5	166.8	9.4%
		165.4	63	157.3	7.9%
		144.7	51.2	136	9.3%
90	5-Feb-07	161.7	59.2	152.9	8.6%
		162	60.3	152.3	9.5%
		155.7	57.3	148.5	7.3%

MIX NO: T6

DATE OF CASTING: 4 OCTOBER 2006

Table 12 Compressive strength result for T6

Day	Date	Weight (kg)	Max Loading (kN)	Stress (N/mm^2)
1	5-Oct-06	2.346	117.7	11.77
		2.411	93.3	9.33
		2.428	127.7	12.77
5	9-Oct-06	2.401	342.2	34.22
		2.381	346.5	34.65
		2.403	271.5	27.15
7	11-Oct-06	2.394	362.2	36.22
		2.445	214.6	21.46
		2.376	341.8	34.18
28	1-Nov-06	2.411	508.5	50.85
		2.407	541	54.1
		2.423	540.4	54.04
90	2-Jan-07	2.393	504.8	50.48
		2.381	445.7	44.57
		2.383	498.8	49.88

Table 13 Porosity result for T6

Day	Date	Weight in air (g)	Weight in water (g)	Weight oven dry (g)	Porosity
7	11-Oct-06	162.3	64.3	152.9	9.6%
		158.9	63.8	148.1	11.4%
		165	66.5	154.9	10.3%
28	1-Nov-06	170.8	70.2	161	9.7%
		167.2	66.9	157.8	9.4%
		170	68.3	160.5	9.3%
90	2-Jan-07	164.2	64.9	156.4	7.9%
		149.6	56.4	140.9	9.3%
		160.3	63.2	151.2	9.4%

MIX NO: PFA1

DATE OF CASTING: 11 DECEMBER 2006

Table 14 Compressive strength result for PFA1

Day	Date	Weight (kg)	Max Loading (kN)	Stress (N/mm^2)
1	12-Dec-06	2.233	71.3	7.13
		2.242	71.2	7.12
		2.18	69.84	6.984
3	14-Dec-06	2.312	187.3	18.73
		2.78	178.6	17.86
		2.235	184	18.4
7	18-Dec-06	2.244	227	22.78
		2.28	252	25.21
		2.3	239	23.95
28	8-Jan-07	2.296	375	37.53
		2.272	377	37.7
		2.294	338	33.82
56	5-Feb-07	2.26	369.4	36.94
		2.28	429.5	42.95
		2.25	427.4	42.74

Table 15 Porosity result for PFA1

Day	Date	Weight in air (g)	Weight in water (g)	Weight oven dry (g)	Porosity (%)
7	18-Dec-06	162.5	62.8	150.1	12.4%
		153.8	60.1	143	11.5%
		166.6	65.5	154.2	12.3%
28	8-Jan-07	166.3	67.5	156.7	9.7%
		166.8	66.9	155.8	11.0%
		164.3	65.3	154.6	9.8%
56	5-Feb-07	160.4	62	152.3	8.2%
		160.8	59.9	154.6	6.1%
		168.2	64	155.9	11.8%

MIX NO: PFA2

DATE OF CASTING: 9 FEBRUARY 2007

Table 16 Compressive strength result for PFA2

Day	Date	Weight (kg)	Max Loading (kN)	Stress (N/mm^2)
3	12-Feb-07	2.28	187	18.7
		2.26	155	15.5
		2.29	185.8	18.58
7	16-Feb-07	2.32	268.4	26.84
		2.38	272.3	27.23
		2.3	240.1	24.01
28	9-Mar-07	2.3	428.1	42.81
		2.36	389.5	38.95
		2.33	409.4	40.94
56	6-Apr-07	2.35	506.3	50.63
		2.34	513.9	51.39
		2.33	452.9	45.29

Table 17 Porosity result for PFA2

Day	Date	Weight in air (g)	Weight in water (g)	Weight oven dry (g)	Porosity (%)
7	16-Feb-07	144.3	62.3	135.2	11.1%
		148.4	64.5	138.6	11.7%
		147	63.2	138.8	9.8%
28	9-Mar-07	145.6	67.3	137.5	10.3%
		149.9	67.4	141.6	10.1%
		146.2	67.5	138.9	9.3%
56	6-Apr-07	140.1	52	132.4	8.7%
		151	61.2	143.4	8.5%
		173	71.8	162.8	10.1%

MIX NO: PFA3

DATE OF CASTING: 26 FEBRUARY 2007

Table 18 Compressive strength result for PFA3

Day	Date	Weight (kg)	Max Loading (kN)	Stress (N/mm^2)
3	1-Mar-07	2.33	138.1	13.81
		2.39	135.7	13.57
		2.34	152.5	15.25
7	5-Mar-07	2.32	201.5	20.15
		2.36	224.5	22.45
		2.31	227.3	22.73
28	26-Mar-07	2.32	313.7	31.37
		2.26	295.8	29.58
		2.39	250.3	25.03
56	23-Apr-07	2.34	459	45.9
		2.33	446	44.6
		2.37	462	46.2

Table 19 Porosity result for PFA3

Day	Date	Weight in air (g)	Weight in water (g)	Weight oven dry (g)	Porosity
7	5-Mar-07	176	69.7	165.5	9.9%
		179.5	71.6	168.3	10.4%
		176.5	69.5	165	10.7%
28	26-Mar-07	185.8	70.1	174.7	9.6%
		169.5	61.3	158.9	9.8%
		167.4	60.2	156.8	9.9%
56	23-Apr-07	182.3	70.3	172.3	8.9%
		178.2	69.5	169.3	8.2%
		177.8	70.3	168.7	8.5%