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Using Ceramic Waste Powder in Producing Self-Compacting Concrete

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United Arab Emirates University

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College of Engineering

Department of Civil and Environmental Engineering

USING CERAMIC WASTE POWDER IN PRODUCING SELF-COMPACTING CONCRETE

Sama Tarek Sayed Taha

This thesis is submitted in partial fulfilment of the requirements for the degree of Master of Science in Civil Engineering

Under the Supervision of Professor Amr S. El-Dieb

May 2016

Declaration of Original Work

I, Sama Tarek Sayed Taha, the undersigned, a graduate student at the United Arab Emirates University (UAEU), and the author of this thesis entitled "*Using Ceramic Waste Powder in Producing Self-Compacting Concrete*", hereby, solemnly declare that this thesis is my own original research work that has been done and prepared by me under the supervision of Professor Amr S. El-Dieb, in the College of Engineering at UAEU. This work has not previously been presented or published, or formed the basis for the award of any academic degree, diploma or a similar title at this or any other university. Any materials borrowed from other sources (whether published or unpublished) and relied upon or included in my thesis have been properly cited and acknowledged in accordance with appropriate academic conventions. I further declare that there is no potential conflict of interest with respect to the research, data collection, authorship, presentation and/or publication of this thesis.

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Abstract

Self-compacted (i.e. consolidated) concrete (SCC) is a special type of concrete that represents a great advancement towards a better quality of sustainable concrete. This unique type is known for its high flowability and superior levels of surface finish without tendency for segregation. The inherited distinct features can be achieved by the addition of high powder content as filler (i.e. size < 0.125 mm) in the concrete mixture. The filler enhances the rheological properties of the SCC mixture without the need for using higher cement contents and hence, reduces the cost and heat of hydration. Lately, various regulating measures were imposed by governments and environmental organizations all over the world to seize the negative impact on the ecosystem resulting from huge amounts of solid waste materials being dumped in landfills causing major environmental problems. As a result, the utilization of alternative industrial waste constituents in construction materials has been the research focus for many years to evaluate their competence in SCC industry, and their feasibility as filler materials. In this study, ceramic waste powder (CWP) produced during the polishing process of ceramic tiles will be particularly investigated. Fresh and hardened tests are conducted to evaluate the influence of CWP on the rheological and mechanical properties of SCC mixtures. It was concluded that CWP can be used to successfully produce SCC mixtures with improved fresh and hardened properties. The inclusion of CWP up to 200 kg/m^3 in SCC mixtures resulted in denser compacted mixtures with low permeability characteristics and high strength values. In addition to enhanced segregation resistance with good deformability and passing abilities for the mixtures under their own weight. The successful completion of this study can lead to the application of CWP in SCC, thus widening the types of fillers available for SCC, saving landfill and reducing CO_2 emissions from cement manufacturing. CWP might not be a typical material for SCC, but it certainly is a promising addition considering its feasibility in producing SCC with enhanced fresh and hardened properties and potential environmental benefits.

Keywords: Self-Compacted Concrete, Ceramic Waste Powder, Filler, Recycling.

Title and Abstract (in Arabic)

استخدام مخلفات مسحوق السيراميك في صناعة خرسانة ذاتية الدمك

الملخص

الخرسانة ذاتية الدمك هي نوع خاص من الخرسانة والتي تمثل تقدما كبيرا صوب الخرسانه المستدامة ذات الجودة العاليه. ويتميز هذا النوع من الخرسانة بالانسيابية العاليه مع مستوي فائق من تشطيب السطح الخارجي بدون أي انفصال للمكونات الاساسية. هذه الصفات المميزة نتيجة لإضافة محتوي عال من المواد المالئة ذات حجم حبيبات أقل من 0.125 مم. هذه الإضافات تعزز من انسيابية الخليط دون الحاجة لإضافة كميات أعلي من سمنت، وبالتالي تقلل من التكلفة والحرارة الناتجة عن التفاعل. في الآونة الأخيرة، فرضت الحكومات والمنظمات البيئية تدابير لوقف التأثير السلبي علي البيئة الناتج عن إلقاء كميات ضخمة من المخلفات الصلبة لصناعات متعددة في مكب النفاياتت مسببا مشاكل بيئية رئيسية. وبناء على ذلك، فإن استخدام مكونات النفايات الصلبة كبدائل لمواد البناء شغل حيزا كبيرا في مجال صناعة الخرسانة وجودتها النهائية. وفي هذه الدراسة سيتم استخدام مخلفات مسحوق السيراميك الناتجة أثناء عملية الصقل، وسيتم اجراء اختبارات لتقييم تأثيرها على خواص الخرسانة الطازجة و المتصلدة لخلطات الخرسانة ذاتية الدمك. أهم نتائج هذه الدراسة هو امكانية استخدام مخلفات السيراميك لإنتاج خلطات خرسانة ذاتية الدمك مع خصائص طازجة ومتصلدة محسنة. بعد الانتهاء بنجاح من هذه الدراسة، سيتمكن الباحثون من الانتفاع من مخلفات مسحوق السيراميك في خلطات الخرسانة ذاتية الدمك وبالتالي توسيع أنواع المواد المالئة المتاحه في هذا المجال مع وتوفير أماكن مكب النفايات آمن، وبالتالي الحد من التلوث البيئي وانبعاثات ثاني اكسيد الكربون الناتج عن صناعة الإسمنت. مخلفات مسحوق السيراميك قد لا تكون من ا نات التقليدية المستخدمه في إنتاج الخرسانة ولكنها تعتبر إضافة واعدة مع الأخذ في الاعتبار جودة الخرسانة المنتجه والتي تتميز بخصائص طازجة ومتصلدة محسنة بالإضافة إلى الفوائد البيئية التابعه لها.

مفاهيم البحث الرئيسية: خرسانة ذاتية الدمك، مخلفات مسحوق السيراميك، التدوير، المواد المالئة.

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Special recognition is due to the people who brought me to existence and dedicated their life to my well-being and happiness. I would like to thank my parents for the precious motivation and unlimited support that I have received from them during my whole life. I would like to express them my deepest gratitude for believing in me, sharing their life experience with me, and helping me to overcome the obstacles that I have faced. I am truly thankful to their blessing which have always been the source of encouragement in achieving every success in my life. It would have been impossible to complete this thesis without their endless support and untold blessings. I'm truly very much indebted to them.

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Dedication

To my beloved parents and family

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List of Abbreviations and Symbols

A	Cross-Sectional Area
ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
C-S-H	Calcium Silicate Hydrate
CA_B	Mass of Coarse Aggregate Retained on the Sieve from the Bottom Section of the Concrete Mold
CA_T	Mass of Coarse Aggregate Retained on the Sieve from the Top Section of the Concrete Mold
CH	Calcium Hydroxide
C_i	Weight Ranking
CO_2	Carbon Dioxide
COV	Coefficient of Variation
CVC	Conventional Vibrated Concrete
CWP	Ceramic Waste Powder
EFNARC	European Federation of National Associations Representing for Concrete
FA	Fly Ash
GGBS	Ground Granulated Blast Furnace Slag
HRWR	High Range Water Reducer
i	Penetration Depth
L	Length of the Specimen
L_{14}	Length of the Prism at 14 days of Age
L_f	Length of the Prism at 150 Days
L_o	Initial Length of the Prism
OH^-	Hydroxide Ions
PI	Performance Index

Q_{100}	Total Charge When Disc Diameter is 100 mm
Q_{95}	Total Charge When Disc Diameter is 95 mm
RCPT	Rapid Chloride Permeability Test
R_i	Numeric Index
S	Segregation Percentage
s	Rate of Absorption
S.G.	Specific Gravity
S.S.A	Specific Surface Area
SCC	Self-Compacting Concrete
SF	Silica Fume
SP	Superplasticizer
t	Elapsed Time
UPV	Ultrasonic Pulse Velocity
VMA	Viscosity Modifying Admixture
W/b	Water Binder ratio
W/C	Water Cement ratio
w/cm	Water Cementitious ratio
W_{Boiled}	Mass of the Specimen After 5 hours Boiling in Water
W_{dry}	Mass of the Specimen After 24 hours Drying in the Oven
$W_{submerged}$	Mass of the Specimen Under Water
W_{Wet}	Mass of the Specimen After 48 hours Immersion in Water
Z	Impedance (Resistance)
ΔW	Change in Specimen's Weight
γ	Water Density

ρ Resistivity

Chapter 1: Introduction

1.1 Problem Statement

The development of SCC is considered a milestone achievement in concrete technology due to the multiple advantages it offers. The production of SCC mixtures requires the inclusion of increased amounts of paste volume. However, the use of excess amounts of cement will greatly increase the cost of materials and influence other vital properties such as drying shrinkage (Su et al., 2001), and hence, as a substitute, other filler materials have been the research focus for many years to evaluate their efficiency on the SCC industry.

The trend worldwide now is to utilize recycled materials in construction, this is considered an effective way of sustainable waste management and to save the exhausted landfills occupied with huge amounts of solid waste. Recycling will also reduce the footprint over the environment from the great energy consumption required to produce cement. In the years to come, the use of recycled industrial cementitious materials may increase, as it is considered the easiest way for the cement industry to drastically reduce its CO_2 levels of emission while adding value to the by-products of other industries. Studies showed that the manufacturing of one ton of cement generates 0.55 ton of CO_2 and requires 0.39 tons of CO_2 in fuel emissions, accounting for a total of 0.94 tons of CO_2 (Sadek et al., 2014).

Ceramic products are extensively used in construction; the ceramic industry produces high quantities and different ceramic waste. According to Exeed Industries Companies ®, that in Abu Dhabi alone one ceramic factory produces 10,000 tons per year of ceramic powder which represent a huge environmental problem in terms of safe disposal. Ceramic waste powder (CWP) is obtained from the polishing process of final ceramic products. It should be noted that, few studies investigated the use of CWP as cement replacement in conventional vibrated concrete (Lopez et al., 2007; Pacheco et al., 2010; Fatima et al., 2013). But none of the researches conducted addressed the inclusion of CWP in SCC industry.

1.2 Goals and Objectives

Globally construction industry is taking forward steps in the direction of sustainability developed concrete through utilizing industrial solid waste as alternative constituent. Several solid wastes and by-products have been widely used and studied as a replacement for the typical concrete ingredients mainly cement. The primary goal of this research is to conduct an exploratory investigation for the ceramic waste powder (CWP) as filler in self compacted concrete mixtures, the main objectives are as follows:

- Evaluate the production of SCC incorporating locally available industrial waste material specifically ceramic waste powder (CWP).
- Investigate the effect of CWP on the fresh and hardened properties of SCC mixtures.
- Identify the optimal content of CWP to be used in SCC mixtures yielding desired fresh and hardened concrete properties.

1.3 Methodology and Approach

The work will start by conducting preliminary trial mixtures to determine the proportions of SCC mixtures for two groups (i.e. addition and replacement groups) using Type I Portland cement and adjusting the w/c ratio and admixture dosage. A total of ten mixtures were designed and cast. The mixtures were divided into two groups: addition group and replacement group. The main parameter in all tested mixtures was the CWP content either as addition or cement replacement. A summary of the mix proportions used for the two designed groups is presented in Table 1-1 and Table 1-2.

Table 1-1: Summary of mix proportions for addition group mixtures

Ingredients' proportions	Addition group mixtures					
	A-S-100	A-S-200	A-S-300	A-C-100	A-C-200	A-C-300
Cement	350	250	150	350	250	150
Slag	100	200	300	-	-	-
CWP	-	-	-	100	200	300

Table 1-2: Summary of mix proportions for the replacement group

Ingredients' proportions	Replacement group mixtures			
	R-0	R-100	R-200	R-300
Cement	500	400	300	200
CWP	0	100	200	300

The effect of CWP will be assessed through the results of several fresh and hardened concrete tests such as slump-flow, J-ring, V-funnel, column segregation, compressive strength, ultrasound pulse velocity (UPV), water absorption and absorption rate, permeable pores, bulk electrical resistivity and chloride permeability tests.

The outcomes of the laboratory work and the analysis of the results will assist in determining the viability of using CWP in producing SCC mixes with the optimal quantity. Recommendations and suggestions for extended research will be stated at the end of the work.

1.4 Study Contribution and Innovation

SCC is one of the concrete technologies promoting sustainable development through the use of recycled and industrial by-product materials as fillers. The successful completion of this study can lead to the application of CWP in SCC, thus widening the types of fillers available for SCC, saving landfill and reducing CO_2 emissions from cement manufacturing. CWP might not be a typical material for SCC, but it certainly is a promising addition considering its feasibility in producing SCC with enhanced fresh and hardened properties and potential environmental benefits.

1.5 Organization of the Report

This thesis is divided into six chapters as follows:

Chapter 1: a brief introduction is given about self-compacting concrete and the problems associated with this unique concrete type, followed by the research objectives, significance and organization of the thesis.

Chapter 2: a detailed literature review on various topics on self-compacted concrete is presented, topics include background, mix design procedure and principle, and different commonly used filler materials.

Chapter 3: in this chapter, materials, design and mixing processes, along with conducted fresh and hardened tests were described in details. Description of the concrete ingredients used in addition to fillers (slag and CWP) and chemical admixtures (superplasticizers and VMAs) is given.

Chapter 4: this chapter includes all the test results of both the fresh and hardened stages and brief discussion of the expected reasons behind the obtained trends.

Chapter 5: performance evaluation of concrete mixtures.

Chapter 6: main conclusions drawn from the results and discussions are given in this chapter, and further research needs in this area are recommended.

Chapter 2: Literature Review

2.1 Introduction

This experimental work aims at investigating the influence of CWP as a cement replacement on SCC mixtures. The fresh and hardened characteristics are examined using typical concrete tests. The coming subsections highlight on the history, design procedure of SCC, and former cement replacement materials used in the literature.

2.2 Background

Back in the 1980's, a decline in the number of skilled labor in the construction industry in Japan occurred. The effect negatively influenced the concrete production especially in terms of concrete consolidation. Generally, the under consolidation causes an increase in the entrapped air content and surface defects which finally leads to a reduction in the structure's strength. On the other hand, the over consolidation/vibration results in multiple flaws such as: segregation, bleeding, and destruction in the air void system that ultimately affects the strength and durability. Hence, the need for durable concrete structures that are independent of the quality of construction work had arised. The idea was first implemented by a Japanese professor, Okamura, and the prototype was first developed by Ozawa at the university of Tokyo in 1988 (Okamura et al., 2003; Shi et al., 2015). He believed that the problem can be overcome if concrete can be compacted in every corner of the formwork under its own weight without the need for skilled workers conducting mechanical vibration. Since then the idea of self-compacting concrete was introduced and received a great attention worldwide (Spitek, 2014).

Self-compacting concrete or self-consolidating concrete, often abbreviated as SCC. Since its first development in the late 20th century in Japan, the concrete industry was revolutionized. This great innovation resulted in a flowable, uniform and, dense concrete showing absolutely no signs of segregation or bleeding and achieving full compaction during the casting process. Self-compacting concrete inherits superior advantages over the traditional concrete. It is featured with high fluidity yet no segregation, and is placed purely under its own weight without the need for vibration filling every corner of a formwork. Due to its high flowability, it is typically adopted in casting structural members with highly congested reinforcements (Siddique and Kunal, 2015; Ashtiani et al., 2013). SCC is an innovative extension of the already existing concrete technology where generally the same materials as conventional concrete are used. The principal difference between SCC and conventional concrete is the performance in their fresh stage. Large quantities of powder materials named generally as fillers or mineral admixtures are used to reduce the frequency of collision between particles and hence improve the flowability (Siddique and Kunal, 2015).

2.3 Advantages and Disadvantages of Self Compacting Concrete

This new variety of concrete is often employed in the concrete industry worldwide for various advantages, some of which are:

- It completely eliminates the noise of vibration (i.e. reduce pollution noise).
- Reduces on-site working.
- Enhances filling capacity of highly congested structural members.
- Provides superior level of finish and placement with faster construction.

- Improves the interfacial transitional zone between cement paste and aggregate.

Despite the various advantages associated with the use of SCC, there arises a few drawbacks with its implementation:

- Depending upon the ingredients used, SCC mixtures could cost higher than conventional concrete. This issue made SCC mixtures only limited to applications where conventional concrete is not applicable rather than being applied in all construction applications.
- Great precautions should be taken into consideration during the design stage of the SCC mixture. Fundamental combined requirements should be met in a SCC mixture (i.e. flowability, passing ability, and segregation resistance). These previously mentioned factors may contradict, in the sense of obtaining a high flowable mixture but yet with no segregation and good viscosity. In addition to the fresh properties, strength, volume stability, and durability of the hardened concrete should be acceptable. This requires casting several trial mixtures or gathering information from previously developed SCC mixtures, as up to this moment no standardized method for designing SCC exists.

2.4 Mix Design Principle

Several adjustments are to be applied to the mixture to produce this new generation of concrete as it greatly depends on the composition and characteristic of its ingredients (Srishaila et al., 2014). The coarse aggregate content is reduced, and accordingly the fine aggregate and powder contents are increased. The powder content is increased through the use of fillers rather than solely increasing the amount of cement, hence, reducing the high cost and negative environmental impact caused by the cement production (Le et al., 2016). The use of filler materials other than cement has become of great concern to researchers. The global trend worldwide nowadays is the use of recycled and by-product materials as fillers. This sustainable waste management technique is accomplished through the utilization of recycled waste products in construction particularly concrete industry. This approach is considered an efficient way both economically and environmentally towards saving the exhausted landfills where huge amounts of industrial solid waste are being deposited annually. Moreover, it contributes toward reducing the carbon footprint on our ecological system produced from the great energy consumption used during cement manufacturing. It's estimated that the production of one ton of cement generates an equivalent amount of CO_2 (Sadek et al., 2014). The incorporation of industrial waste as alternative constituents in concrete industry will reduce the reliance on natural non-renewable ingredients, and hence lower the quick depletion rate of raw minerals (Rahhal et al., 2014). Moreover, it will add value to the by-products of other industries. The use of recycled materials will also help reduce the construction cost. Various industrial by-products have been widely used as less expensive cement substitutes and were proven to enhance the produced concrete properties both fresh and hardened (Uysal and Yilmaz, 2011).

2.5 Mix Design Procedure

Since the development of SCC, several attempts have been carried out aiming at optimizing a mix design procedure. A study performed by Su et al. (2001) highlighted on Okamura's proposed mix design method in 1993. It simply depends on performing quality tests on paste and mortar afterwards casting trial mixtures of

SCC. This approach saves on both time and labor needed for repeating the same tests on concrete trial mixtures. On the other hand, Okamura's technique requires quality control of paste and mortar before the mixing. Additionally, the mix design method can be too complicated for practical implementation. Moreover, the study also pointed out the subsequent methods proposed such as the Japanese Ready Mixed Concrete Association (JRMCA) method in 1998, which is considered an easier form of the previously outlined method. The implementation of the JRMCA's designing process can lead to SCC mixtures with large amounts of powder materials with a water to binder ratio of less than 0.30. The authors in the current study suggested a new way for designing a SCC mixture. The following nine steps summarize the method: (1) calculation of coarse and fine aggregate content, (2) calculation of the cement content (for good fresh properties, the binder content should not be too low), (3) calculation of mixing water content required by cement (despite the influence of fine and coarse aggregates, proportions of the ingredients, curing age on compressive strength, the water to binder ratio has the most dominant effect), (4) calculation of binding material other than cement (increased amounts of cement will increase the cost, drying shrinkage, slump loss, and more importantly the yielded compressive strength will be higher than the required in the design), (5) calculation of the mixing water content needed in SCC, (6) calculation of superplasticizer dosage, (7) adjustment of mixing water content needed (based on the moisture content of the aggregates to be used), (8) trial mixes and tests on SCC properties, (9) adjustment of mix proportions (until the properties of the produced SCC mixtures meet with the specified requirements of the design). Equations for each calculation step are provided in the paper. A sample calculation using the proposed method was carried out using Fly Ash (FA) and Ground Granular Blast-Furnace Slag (GGBS) as binding materials in addition to the cement. The adopted mix proportions are presented in Table 2-1. Results showed that the compressive strength decreased with increasing the amounts of coarse and fine aggregates. The used method resulted in the use of greater amounts of sand with less coarse aggregates and more binders in comparison with other design methods. The study concluded by giving recommendations on further investigations to assess the effect on elastic modulus due to increased fine aggregate content.

Table 2-1: Mix proportions of SCC (kg/m^3) (Su et al., 2001)

f'_c (MPa)	Coarse aggregate	Fine aggregate	Cement	FA	GGBS	Water	SP
27.5	743	961	200	157	67	176	7.6
34.3	731	945	250	154	66	173	8.5
41.2	718	928	300	148	63	172	8.2
48.0	706	912	350	142	61	170	8.8

A summary of the existing mixture design methods for SCC in the literature is presented in Table 2-2.

Table 2-2: SCC existing mixture design methods in the literature (Shi et al., 2015)

Classification	Authors	Year	Main Features
Empirical design method	Okamura, and Ozawa	1995	Fix coarse and fine aggregate first, and then obtain self-compactability by adjusting W/B and superplasticizer dosage.
	Edamatsa, Sugamata, and Ouchi	2003	Use mortar flow and mortar V-funnel testing to select the fine aggregate volume, volumetric water-to- powder ratio and superplasticizer dosage.
	Domone	2009	For a given set of required properties, make the best estimation of the mixture proportions, and then carry out trial mixes to prove.
	Khaleel and Razak	2014	Conduct in three phases, i.e. paste, mortar and concrete.

Classification	**Authors**	**Year**	**Main Features**
Compressive strength method	Ghazi, and Al Jadiri	2010	Based on the ACI 211.1 method for proportioning conventional concrete and the EFNARC method for proportioning SCC.
	Dinakar, Sethy, Sahoo	2013	Use GGBS in SCC based on the strength requirements and consider the efficiency of GGBS.
Close aggregate packing method	Hwang, and Tsai	2005	Use Densified Mixture Design Algorithm (DMDA), derived from the maximum density theory and excess paste theory.
	Petersson, Billberg, and Van	1996	Mainly based on the void content and the blocking criteria.
	Su, Hsu, and Chai	2001	Use packing factor (PF) to control the content of fine and coarse aggregate in mixture proportion.
	Sedran, and De Larrard	1996	Use software to design SCC based on the compressible packing model (CPM).
	Shi, and Yang	2005	Use a combination of the excessive paste theory and ACI guidelines to design self-consolidating lightweight concretes.
	Sebaibi, Benzerzour, Sebaibi, and Abriak	2013	Based on FN EN 206-1 standard, compressible packing mode (CPM) and packing factor (PF).
	Kanadasan and Razak	2014	Integrate the actual packing level of aggregate and paste volume into the proportioning method based on the particle packing to obtain the final mixture design.
Statistical factorial model	Khayat, Ghezal, and Hadriche	1999	Obtain a statistical relationship between five mixture parameters and the properties of concrete.
	Ozbay, Oztas, Baykasoglu, Ozbebek	2009	Design in a L18 orthogonal array with six factors, namely, W/C ratio, water content (W), fine aggregate to total aggregate (S/a) percent, fly ash content (FA), air entraining agent (AE) content, and superplasticizer content (SP).
	Bouziani	2013	Useful to evaluate the effect of three types of sand proportions (river sand, crushed sand and dune sand), in binary and ternary systems, on fresh and hardened properties of SCC.

Classification	Authors	Year	Main Features
Rheology of paste model	Saak, Jennings, and Shah	2001	Avoid segregation of the aggregates as a critical design parameter, then a new segregation-controlled design methodology is introduced for SCC.
	Bui, Akkaya, and Shah	2002	Expand Saak's concepts to include the effects of aggregate (and paste) volume ratio, particle size distribution of the aggregates and fine to coarse aggregate ratio, to propose a new paste rheology model.
	Ferrara, Park, and Shah	2007	Steel fiber-reinforced self-compacting concrete based on the paste rheology model.

2.6 Types of Fillers

The performance of the SCC mixture is driven by the combined properties of its constituent materials. Yet it should be taken into consideration that it's nearly impossible to achieve mixtures with identical performance produced by ingredients from different locations. Therefore, the producer must understand these differences and adjust the proportions accordingly. The increased amount of fines is what distinguishes the SCC from the conventional concrete, but they both require understanding of the project requirements and placement conditions prior to the mix design procedure. A number of powders/fines exist, and they can be one of three categories: cements, pozzolans (both natural and artificial), and fillers. According to the EFNARC 2005 guidelines the particle size of the used powders should be smaller than 0.125 mm and its desirable that 70% pass through the 0.063 mm sieve. The first type of powders which is cements are hydraulic in nature. This implies that they react and undergo hydration on their own and consequently influence the strength. The second group of fines inherit latent hydraulic properties; that is their hydraulic activity and contribution to strength starts when they react with the products of other chemical reactions, i.e. the hydration products of Portland cement. The third type, fillers, is when the material is chemically inert, and their effect is observed through acting as a catalyst or through their own physical properties (Neville, 1998). It should be noted that the ACI's commonly used terminology for the non-hydraulic supplementary materials is "mineral admixtures". Despite this, Neville (1998) states that the word "admixtures" constitutes a minor quantity of a component, but the supplementary materials are usually added in large amounts.

Given the advantages SCC offers, many researchers have examined the role of different types of fillers both inert and reactive such as limestone powder, fly ash, slag, rice husk ash, and marble stone dust. A classification of mineral admixtures according to the pozzolanic and/or cementitious characteristics was provided by Mehta (1986) and Ramachandran (1996), and is presented in Table 2-3.

Table 2-3: Classification, composition, and partcile characteristics of commonly used mineral admixtures for concrete (Mehta, 1986) (Ramachandran, 1996)

Classification	**Chemical and mineralogical composition**	**Particle characteristics**
Cementitious and pozzolanic		
Granulated blast-furnace slag (cementitious)	Mostly silicate glass containing mainly calcium, magnesium, aluminum, and silica.	Unprocessed material is of sand size and contains 10-15% moisture. Before use it is dried and ground to particles less than 45μm (usually about 500 m^2/kg Blaine). Particle has rough texture.

Classification	**Chemical and mineralogical composition**	**Particle characteristics**
High-calcium fly ash (cementitious and pozzolanic)	Mostly silicate glass containing mainly calcium, magnesium, aluminum, and alkalis. The small quantity of crystalline matter present generally consists of quartz and C_3A.	Powder corresponding to 10-15% particles larger than 45μm (usually 300-400 m^2/kg Blaine). Most particles are solid spheres less than 20 μm in diameter. Particle surface is generally smooth but not as clean as in low-calcium fly ashes.
Highly active pozzolans		
Condensed silica fume	Consists essentially of pure silica in non-crystalline form.	Extremely fine powder consisting of 0.1 μm average diameter (about 20 m^2/g surface area by nitrogen adsorption).
Rice husk ash (Mehta-pitt process)	Consists essentially of pure silica in non-crystalline form.	Particles are generally less than 45 μm but they are highly cellular (about 60 m^2/g surface area by nitrogen adsorption).
Normal pozzolans		
Low-calcium fly ash	Mostly silica glass containing aluminum, iron, and alkalis.	Powder corresponding to 15-30% particles larger than 45 μm (usually 200-300 m^2/kg Blaine). Most particles are solid spheres with average diameter 20 μm. cenospheres and plerospheres may be present.

Classification	Chemical and mineralogical composition	Particle characteristics
Natural materials	Besides aluminosilicate glass, natural pozzolans contain quartz, feldspar, and mica.	Particles are ground to mostly under 45 μm and have rough texture.
Weak pozzolans		
Slowly cooled blast-furnace slag, bottom ash, boiler slag, field burnt rice husk ash	Consists essentially of crystalline silicate materials, and only a small amount of non-crystalline matter.	The materials must be pulverized to very fine particle size in order to develop some pozzolanic activity. Ground particles are rough in texture.

2.7 Studies on Self Compacting Concrete with Different Fillers

Zhu and Gibbs (2005) conducted a study using different types of limestone and chalk powders as fillers in self-compacting concrete (SCC) and examined their effects on superplasticizer's demand and the strength properties of concrete mixes. The limestone/chalk powders were used to replace 40% of Portland cement by mass in the paste mixes with two dosages of superplasticizer (Glenium 27 and Glenium C315) as per the producer recommendations. A total of 15 SCC mixtures (i.e. three types of limestone and two types of chalk powders and each with three addition levels: 55%, 44% and 25%) were prepared with adjustments to the dosage percentage of superplasticizer while maintaining a total powder content of 540 kg/m^3 and water content of around 170 kg/m^3. Three conventional vibrated concrete mixtures were also prepared as references, with the same w/c ratios as those of the basic SCC mixtures. The results of the mini-slump flow test conducted on concrete pastes revealed higher absolute slump flow values with Glenium C315 regardless of the amount of powder or superplasticizer added. Whereas, when Glenium 27 was used, an increase in the flowability was observed as the dosage of superplasticizer increased. All the fresh SCC mixtures achieved the target slump flow value of 600 – 650 mm and indicated good passing ability and little sign of segregation when evaluated using slump flow and J-ring tests. The compressive strength test was carried out at 7, 28 and 90 days while the indirect tensile/splitting strength test was conducted only at the age of 28 days. The results showed a high compressive strength gain in SCC mixtures at 7 days of age (60-80%) and at 28 days of age (30-40%) compared to the corresponding reference mixtures. It was concluded that the amount of superplasticizer to be used in a mixture depends more on the type of the powder rather than its fineness. Furthermore, increasing the amount of the limestone/chalk powder could lead to a reduction in superplasticizer dosage and a more economic SCC mixture, as the Portland cement was found to require higher amount of superplasticizer than limestone and chalk powders.

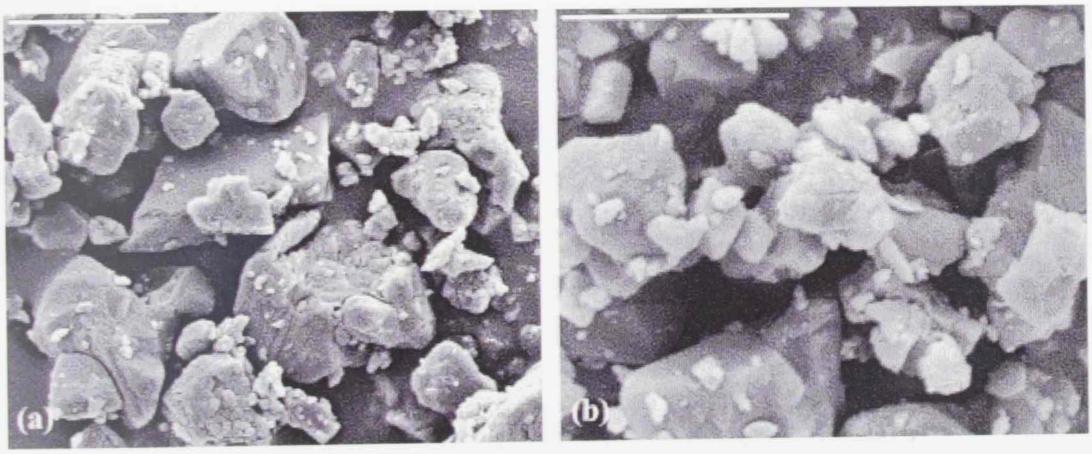
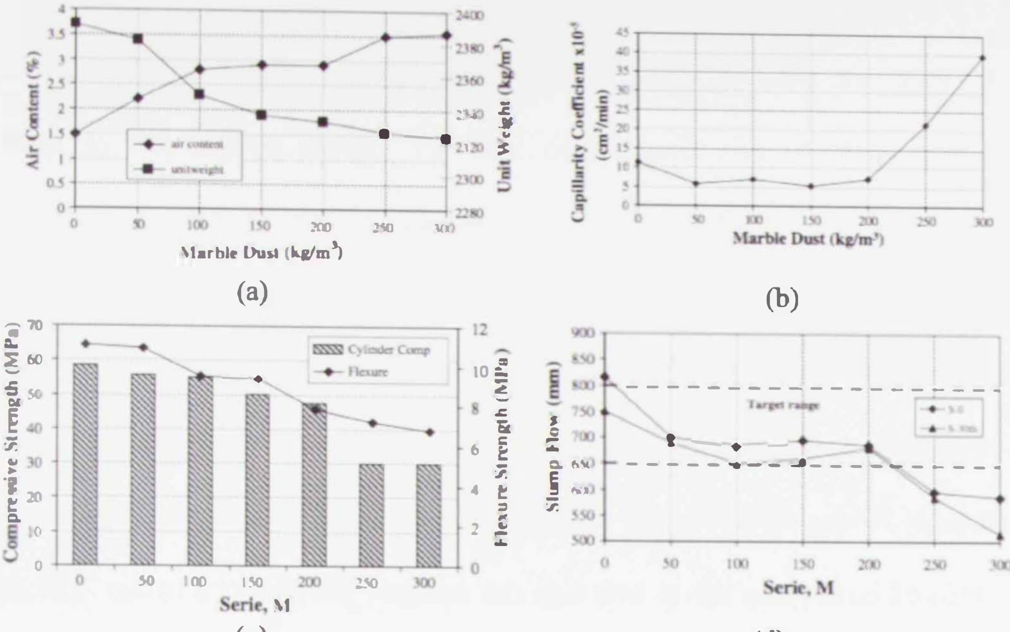


Figure 2-1: Typical particle shape of (a) limestone and (b) chalk powder (Zhu and Gibbs, 2005)

Another type of filler utilized in SCC mixtures was marble dust (MD); which was examined by Topcu et al. (2009). The experimental work was based on partially replacing the binder in the SCC with certain amount of MD specifically 0 (control), 50, 100, 150, 200, 250, and 300 kg/m^3 which was obtained from a marble managing plant in Afyonkarahisar. The binder content in the mixture consisted of ordinary Portland cement and fly ash Class F (FA) and the total amount of binder was kept constant at 550 kg/m^3. The FA partially replaced the cement at a constant level of 10% by weight. Type F superplasticizer was also used in the mixtures at the ratio of 2.5% of binder materials by weight for reducing the water/binder ratio of SCC. A total of seven mixtures were prepared and typical SCC fresh and hardened concrete tests were performed. Based on the results, all six mixtures containing MD resulted in slump flow values within the recommended range (650 and 800 mm) unlike the control mixture (M0) where its slump flow values exceeded the upper limit as presented in Figure 2-2 (d). Regarding the passing ability which was evaluated using the L-box test, it can be said that only mixtures M250 and M300 resulted in blocking ratios out of the target range. On the other hand, in the hardened tests, the results of the compressive strength showed that up to a replacement level of 200 kg/m^3, the produced concrete can be considered as high strength concrete (>40MPa) with porosity ranging from 5 to 11%. Additionally, the microstructure of mixtures utilizing MD was investigated, the researchers determined that the use of MD as filler resulted in a good bond between the aggregate and the cement matrix. The study finally concluded that the optimum dosage of MD to be used is 200 kg/m^3 based on the enhanced fresh properties such as: slump flow, and blocking ratio, as well as the improved hardened mixture properties such as: capillary coefficient, and compressive strengths.



(a) (b)

(c) (d)

Figure 2-2: Effect of MD on (a) air content (b) capillary coefficient (c) compressive strength (d) slump flow (Topcu et al., 2009)

Pakistan consumes approximately 42 million tons of sugarcane in the sugar manufacturing industry and accordingly generates over 0.26 million tons of bagasse ash. For an environmental friendly disposal of this waste material, it has been employed by Akram et al. (2009) into the SCC industry as a viscosity modifying agent. The present study consisted of twenty-five mixtures, and the proportions of the ingredients are presented in Table 2-4. As the percentage of superplasticizers increases in the mixtures, the slump flow and the L-box ratio increases with less viscous mixtures. On the other hand, when the quantity of bagasse ash increases in the mixtures, the resulting slump flow diameters and L-box ratio show a decreasing trend unlike the V-funnel flow times that start to increase. Due to the micro-filling effect the bagasse ash particles possess, the density of the hardened mixtures increases with the increase in bagasse ash percentage up to 15% beyond which density slightly decreases. The reduced water/binder ratio in the group of mixtures with higher bagasse amounts result in an increase in the compressive strength values. This is noticeable from the 28 days' compressive strength results where mixtures

15B2SP and 20B2SP achieve the highest values at 39.59 MPa and 37.93 MPa compared to the highest among the five control mixtures (CC2SP) that only developed 37.71 MPa at the age of 28 days. Finally, the study also estimated the total cost of materials used in producing the designed mixtures. The selected mixtures for comparison were two mixtures that yielded best fresh properties and acceptable compressive strength one from the control mixtures (CC2.5SP) and another from the mixtures containing bagasse ash (15B2.5SP). It was found that the cost of ingredients for the SCC mixture containing bagasse ash included in the analysis is 35.63% less than the control mixture.

Table 2-4: Mix design proportions (Akram et al., 2009)

Mix design	Water / binder ratio	Water (kg/m^3)	Cement (kg/m^3)	Bagasse ash (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Sikament NN (% by wt. of binder)	Sika Viscocorete (% by wt. of binder)
CC2SP	0.45	225	500	-	875	750	2	2
CC2.5SP	0.45	225	500	-	875	750	2.5	2
CC3SP	0.45	225	500	-	875	750	3	2
CC3.5SP	0.45	225	500	-	875	750	3.5	2
CC4SP	0.45	225	500	-	875	750	4	2
[a]5B2SP	0.43	225	500	25	875	750	2	-
5B2.5SP	0.43	225	500	25	875	750	2.5	-
5B3SP	0.43	225	500	25	875	750	3	-
5B3.5SP	0.43	225	500	25	875	750	3.5	-
5B4SP	0.43	225	500	25	875	750	4	-
10B2SP	0.41	225	500	50	875	750	2	-
10B2.5SP	0.41	225	500	50	875	750	2.5	-
10B3SP	0.41	225	500	50	875	750	3	-
10B3.5SP	0.41	225	500	50	875	750	3.5	-
10B4SP	0.41	225	500	50	875	750	4	-
15B2SP	0.39	225	500	75	875	750	2	-
15B2.5SP	0.39	225	500	75	875	750	2.5	-
15B3SP	0.39	225	500	75	875	750	3	-
15B3.5SP	0.39	225	500	75	875	750	3.5	-
15B4SP	0.39	225	500	75	875	750	4	-
20B2SP	0.37	225	500	100	875	750	2	-
20B2.5SP	0.37	225	500	100	875	750	2.5	-
20B3SP	0.37	225	500	100	875	750	3	-
20B3.5SP	0.37	225	500	100	875	750	3.5	-
20B4SP	0.37	225	500	100	875	750	4	-

[a] In 5B2SP, 5B refers to the percentage of the bagasse ash by weight of binder content and 2SP refers to the amount of superplasticizer in percent by weight of binder content. This particular designation represents mix having 5% bagasse ash with 2% superplasticizer by weight of binder content.

Fly Ash (FA), Blast Furnace Slag (S), and Silica Fume (SF) have been widely used as Portland cement replacements. They have been even utilized together to form binary, ternary, and quaternary SCC mixtures. In the current study conducted by Gesoglu et al. (2009) 22 concrete mixtures were designed comprising of one control mixture with Portland cement as the sole binding material and the remaining mixtures incorporating the previously mentioned mineral admixtures each in three different percentages with constant water to binder ratio of 0.44. The ingredients' proportions along with the mixture designations are presented in Table 2-5. All the obtained slump flow diameters lie between 670 and 730 mm which is the target range. It was observed that the use of ternary and quaternary mixtures provided better performance than binary blends as far as the slump flow is concerned. The use of the mineral admixtures increased the L-box ratios and hence, improved the filling and passing abilities. The results of the V-funnel flow times ranged from 3.2 to 14 seconds with the lowest being in the control mixture and the highest in the mixture consisting of 40% S. It was noticed that the use of either SF or S increased the viscosity of the mixtures. Noteworthy, all ternary mixtures met with the EFNARC requirements for all the conducted fresh tests. In the matter of durability results, the control mixture had the lowest chloride permeability resistance (moderate class) and electrical resistivity, while the inclusion of mineral admixtures significantly enhanced the chloride permeability resistance of the SCC mixtures as the resistivity was enhanced in the order of two classes in almost all the ternary and quaternary mixtures (from moderate to very low), yet the most effective mineral was the slag. The mixture with 45% S and 15% SF achieved the highest chloride permeability resistance (216 C) as well as the highest electrical resistivity (18.9 kohms cm). Similarly, the sorptivity was progressively decreased with the presence of mineral admixtures regardless of the replacement level. Additionally, the water permeability test was conducted and was greatly enhanced with the addition of the mineral admixtures, especially the quaternary mixture where the permeability was 45% less than that of the control mixture. In terms of concrete quality examined through the UPV test, all produced mixtures were classified as excellent as all the results exceeded 4500 m/s. The study indicated that concretes containing FA generally resulted in lower compressive strength values, however, mixtures containing S and SF produced concretes with strength values comparable to that of the control mixture. The mineral admixtures FA and S reduced the free shrinkage while SF increased the drying shrinkage. This increase was overcome by blending SF with other minerals and hence reduce the shrinkage.

Table 2-5: Concrete mix proportions (Gesoğlu et al., 2009)

Mix ID	Mix description	PC	FA	S	SF	Natural sand	Crushed sand	Coarse aggregate	SP
M1	Control-PC	450	0	0	0	592	234	868	3.5
M2	20FA	360	90	0	0	583	230	855	3.2
M3	40FA	270	180	0	0	574	227	842	2.9
M4	60FA	180	270	0	0	565	223	829	3.0
M5	20S	360	0	90	0	591	233	866	3.7
M6	40S	270	0	180	0	589	232	863	3.4
M7	60S	180	0	270	0	587	232	861	2.8
M8	5SF	428	0	0	22.5	590	233	865	4.9
M9	10SF	405	0	0	45	587	232	861	5.2
M10	15SF	383	0	0	67.5	585	231	858	7.8
M11	15FA5SF	360	67.5	0	22.5	583	230	855	4.2
M12	30FA10SF	270	135	0	45	574	227	841	4.5
M13	45FA15SF	180	202.5	0	67.5	565	223	828	4.8
M14	15S5SF	360	0	67.5	22.5	589	232	863	4.0
M15	30S10SF	270	0	135	45	585	231	857	4.6
M16	45S15SF	180	0	202.5	67.5	581	229	852	5.8
M17	10FA10S	360	45	45	0	587	232	861	3.2
M18	20FA20S	270	90	90	0	581	230	853	3.2
M19	30FA30S	180	135	135	0	576	227	845	2.8
M20	7.5FA7.5S5SF	360	33.8	33.8	22.5	586	231	859	4.2
M21	15FA15S10SF	270	67.5	67.5	45	579	229	849	4.2
M22	22.5FA22.5S15SF	180	101.3	101.3	67.5	573	226	840	5.0

* **All quantities are measured in kg/m^3**

Pulverized fuel ash or as commonly known as fly ash (FA) has been extensively investigated throughout the years as a cement replacement. Recently researchers have examined its use in high volumes for the environmental and sustainable benefits it offers. Liu (2010) designed SCC with different levels (0%. 20%. 40%. 60%. 80%. and 100%) of FA replacing Portland cement. The study involved typical SCC tests for assessing the produced mixtures' fresh and hardened properties. It was found that when FA replaces cement. a lower dosage of superplasticizer along with increased quantity of water were required to maintain the same flowability characteristics within the six cast mixtures. It was assumed that the FA acted as a lubricant material and hence didn't interact with the superplasticizer which in turn only acted on the cement. The highest segregation resistance was achieved in mixtures incorporating 80% and 100% FA. and accordingly attained an increase in the step height during the J-ring test and the highest V-funnel times indicating an increase in the viscosity of the mixtures. The consistency of the produced mixtures decreased with time. this was examined through the measured slump flow and V-funnel times at 65 ± 5 minutes. where the obtained flow diameters decreased and the recorded V-funnel flow times increased. The change in the hardened properties from the 0% to the 20% FA mixtures was not significant. however. beyond the 40% replacement. the reduction in compressive strength was considerable in such a way that the strength at 80% replacement level was denoted the lowest and accounted only one forth that of the 20% FA mixture. Curing had a positive effect on lowering the porosity detected through the reduction in the sorptivity rates in all mixtures from 7 to 90 days. Despite this. the lowest sorptivity was obtained when 40% FA replaced cement as a greater replacement level caused a higher porosity in the mixtures. Good correlations were obtained between compressive strength, splitting strength, UPV and, dynamic elasticity. Finally, the study concluded that for producing SCC utilizing FA and characterized with adequate fresh and hardened properties, the amount of FA should be limited to 40%.

Uysal and Sumer (2011) attempted an experimental program to differentiate between several known mineral admixtures in terms of their influence on fresh and hardened properties of SCC. The study utilized Fly Ash (FA), Granulated Blast Furnace Slag (GBFS), Limestone Powder (LP), Basalt Powder (BP), and Marble Powder (MP) as a Portland cement replacement at various levels. With three different proportions from each material (MP, BP, LP = 10%, 20%, 30%, GBFS = 20%, 40%, 60%, FA = 15%, 25%, 35%), fifteen mixtures were cast in addition to one control mixture with no minerals. The FA resulted in an increase in the slump flow obtained diameters, while the MP led to a reduction in the slump flow diameters, whereas each of the GBFS, LP, and BP resulted in an increase up to the second replacement percentage then caused a reduction in the slump flow. Regarding the two other properties of SCC (i.e. viscosity, and passing ability) all the cast mixtures' v-funnel flow times and L-box ratios ranged from 9 to 18 seconds and 0.8 to 1.0 respectively. According to the author's interpretation of the results, all the mixtures do not meet with the requirements of the allowable flow times but yet inherit acceptable passing abilities. Moreover, FA set of mixtures require lower dosages of superplasticizers to maintain the same flowability and is perhaps due to the spherical shape of the FA particles causing a reduction in the water demand. All strength values at the four testing ages (7, 28, 90, and 400 days) were compared by proportioning the strength of all the mixtures to the strength of the control mixture at 28 days of age. The obtained strength values at the early age of 7 days ranged from

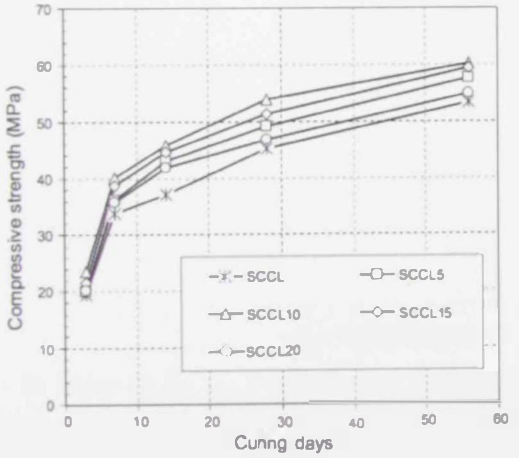
54.8 to 64.8 MPa with the highest achieved by the control mixture. As the mixtures undergo curing till 28, 90, and 400 days, a considerable gain in strength occurs increasing the range of strength values to 62.2 - 77.9 MPa, 67.2 – 89.1 MPa, and 72.4 – 105.7 MPa respectively. Replacing 25% of cement with FA yielded the highest strength (105.7 MPa) at 400 days. The replacement by both FA and GBFS contributed positively to the late age strength of the mixtures as pozzolanic materials. The study correlated between the compressive strength and the UPV values obtaining a strong R of 0.85, indicating that as the compressive strength values increase, the UPV test results increase as well.

The recent rapid development in the industry using glass produces three million tons of waste a year in the UK alone. This resulted in increased social and environmental concerns leading to a growing interest in utilizing the waste glass, especially when taking into consideration that glass is non-biodegradable, and hence dumping in landfills is not the best solution environmentally. The total reactive pozzolanic components (SiO_2, Al_2O_3, and Fe_2O_3) in the glass's chemical composition are very much similar to that of the fly ash. Moreover, it can be concluded from the X-ray results that the glass is amorphous, and thereby it is expected to perform as a pozzolan when substituting cement making full use of its chemical and physical properties. Two colors of ground glass (i.e. green and white) were incorporated into SCC mixtures as a partial replacement for cement. The investigation revealed that satisfactory fresh characteristics are possible to be obtained with a 10% cement replacement without the need for VMA. Due to the angular and flaky shape of the glass particles, the SCC mixtures required a slight increase in the water to powder ratio and a small reduction in the amount of superplasticizers. The inclusion of glass also resulted in increasing the viscosity and ultimately enhancing the segregation resistance. The utilization of the ground glass resulted in a general reduction in the tested hardened properties (strength, UPV, and, elastic modulus). The 28 days' compressive strength values ranged from 58 to 75 MPa with the highest being achieved by the control mixtures. All mixtures resulted in UPV values greater than 4.5 km/s indicating good quality concrete. In regards to the durability characteristics, the glass content resulted in increased sorptivity rates, yet with prolonged curing times sorptivity was significantly improved maintaining the same trend. Nine mortar bars were cast and tested for alkali silica reactions. The results showed similar expansions for both control and replacement mixtures, suggesting that ground glass doesn't induce additional ASR risks. The effect of difference in color on the SCC properties was negligible in both fresh and hardened stages (Liu, 2011).

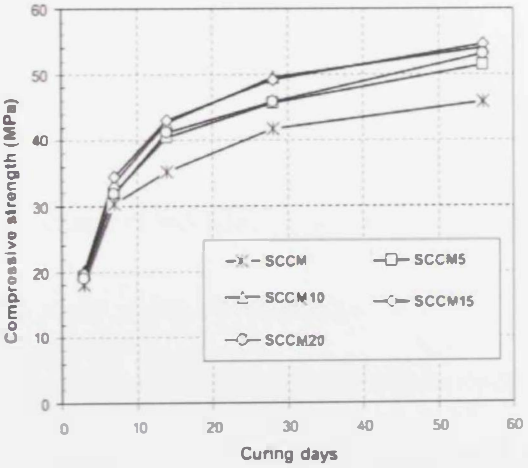
Another study conducted using limestone powder (LP) as filler in SCC was performed by Panesar and Aqel (2014). The main aim of the work was to determine the relation between the amount of limestone filler (0% and 15%) and two cement types (general use cement GU and high-early strength cement HE). Four mixtures were prepared: GU cement with no replacements, GU cement with 15% replaced by limestone, HE with no replacements, and HE with 15% amount replaced by limestone. The various tests conducted revealed several outcomes regarding the 15% addition of limestone powder; it reduced the initial setting time (from 94 min for 100% GU and 91 min for 100% HE to 81 min and 77 min for GU and HE with 15% LP respectively) and led to a higher and earlier occurrence of the heat of hydration. This was the same conclusion to be drawn out regarding changing the cement type from GU to HE. The measured reactivity increased with age as well as when using

HE instead of GU cement. Regarding the hardened properties, using 15% limestone powder in mixtures with HE cement type resulted in an early age (i.e. 16 hours) compressive strength increase (57 to 70 MPa) over its corresponding mixture using GU cement type, but little effect on the late age strength (28 days) (80 to 84 MPa). Regarding the durability properties, the influence of the 15% limestone on the rapid chloride permeability test (RCPT) of the concrete mixtures was greater than the influence of changing the cement type. But it should be noted that both variable factors (amount of limestone and cement content) had no effect on the freeze-thaw and salt scaling properties.

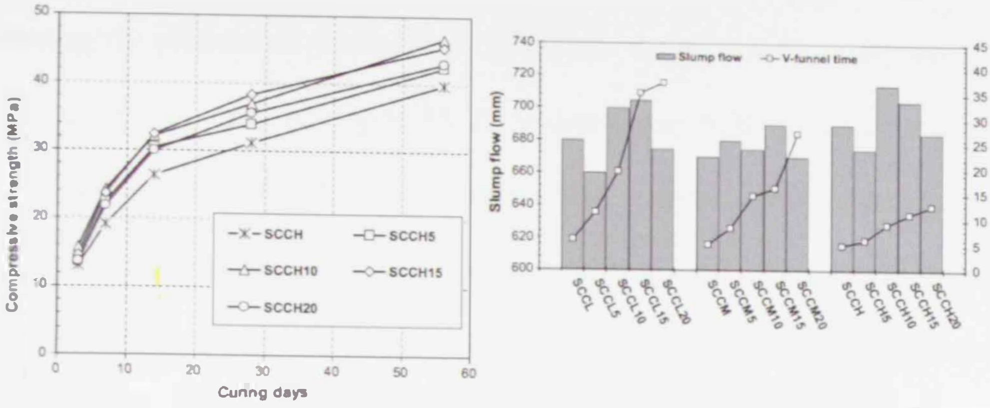
Another study completed on the use of Metakaolin (MK) in SCC addressed its influence on both fresh and hardened properties (Mandanoust and Mousavi, 2012). Fifteen mixtures were cast, and they were divided into three groups each with a different water to binder ratio (G1= 0.32, G2 = 0.38, and G3 = 0.45) and with 0%, 5%, 10%, 15%, and 20% MK replacing Portland cement. The consumed MK was characterized physically with a high specific surface area equal to 2540 m^2/kg and chemically with a high combined ratio of alumina and silica oxides (94.9 %). All measured slump flow values ranged from 660 mm to 715 mm with a tendency for a reduction in flowability with higher MK percentages as in Figure 2-9 (d). This is interpreted by the high specific surface area of MK compared to Portland cement (S.S.A = 330 m^2/kg) increasing the water demand. The effect of MK on slump flow loss was tested through measuring the slump flow after 8, 30, and 60 minutes. It was found that as the percentage of MK increases in the mixtures, the rate at which slump flow was lost increased. Another conclusion drawn out from this test, was that the mixture containing 20% MK could not be categorized as SCC as after 60 min it resulted in a slump flow value less than 500 mm. Proper stability and segregation resistance were visually inspected during the slump flow test and by additionally observing the broken split tensile test specimens that revealed adequate distribution of the coarse aggregate. In regard to the other tested fresh properties, the incorporation of MK increased both the T_{50} and the V-funnel flow times and reduced the blocking ratio, yet no blocking between reinforcement was observed by the authors. Typically, the compressive strength increased with age and decreased with the increase in the water to binder ratio. The inclusion of MK significantly increased the early and late age compressive strength, with the highest strength development rate in the first 14 days, the values are plotted in Figure 2- 3 (a), (b), and (c). This trend is similar to that of the splitting tensile strength test. Moreover, all fifteen cast mixtures were rated as "very good" and "excellent" in terms of concrete quality using UPV test results. Regarding the durability results, the water absorption decreased whereas electrical resistivity increased with the higher replacement levels of MK and lower water to binder ratio as presented in Figure 2-3 (f) and (e) respectively. Furthermore, Finally, the study suggested 10% MK replacement level for yielding the best fresh and hardened properties.



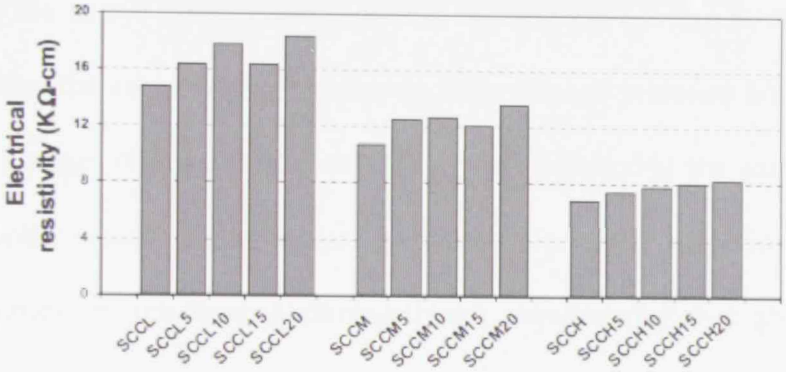
(a) compressive strength of G1 group



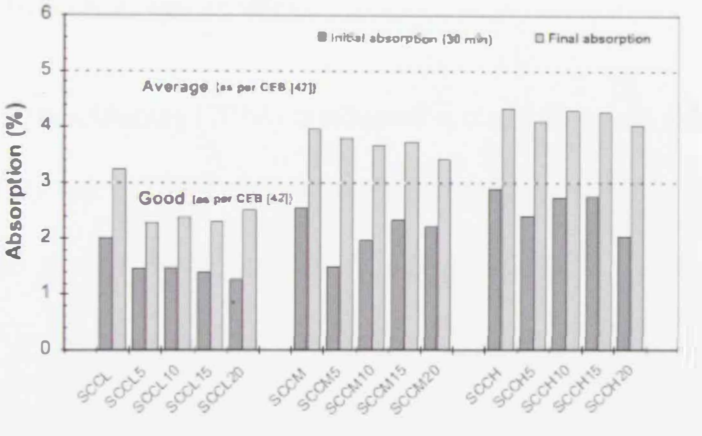
(b) compressive strength of G2 group



(c) compressive strength of G3 group (d) slump flow and V-funnel time



(e) electrical resistivty of MK mixtures

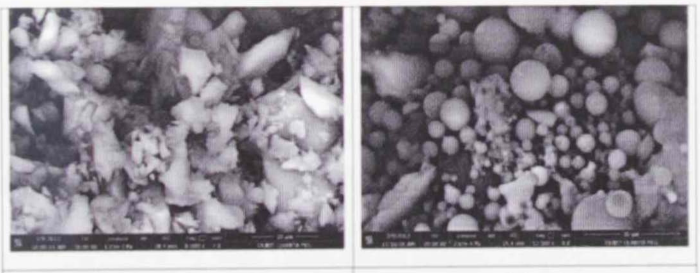


(f) absorption of MK mixtures

Figure 2-3: Graphical illustration of MK mixtures (Mandanoust and Mousavi, 2012)

In 2013, Cuenca et al. carried out a study using olive residue biomass fly ash as filler in SCC. Its characteristics were studied and laboratory tests were conducted to obtain the optimum fly ash dosage to be used in SCC. The utilized fly ash was physically characterized with 80% of its particles passing through the 0.063 mm sieve and chemically featured with around 50% of its chemical composition as CaO. Regarding the pozzolanic reactivity of the fly ash, the pozzolanic components (SiO_2, Al_2O_3, and Fe_2O_3) only sum up to 15.2% which is way below other commonly used pozzolanic materials (>70%). For comparison purposes two reference concrete mixtures that incorporated conventional filler (commercial limestone) were cast. The amount of fines and the w/c ratio for the two reference SCC mixtures prepared with limestone were the same as the SCC containing fly ash with the optimal dosage. By the end of the study, it was concluded that biomass fly ash can be used as filler in SCC yielding the same flow properties as the reference mixtures but would require increased dosages of superplasticizers. This was attributed to the particle's irregular shape which required higher water quantities. Moreover, regarding the hardened SCC properties, the mixtures containing fly ash acquired slightly higher compressive strength values compared to the reference mixtures without the incorporation of fly ash at all testing ages (3, 7, and 28 days).

Beycioğlu and Aruntaş (2014) conducted a research using different minerals namely low lime fly ash (LLFA), ground blast furnace slag (GBFS), and micronized calcite (MC). The aim of the investigation was to study the effect of the utilized materials on the workability and mechanical properties of SCC mixtures. Specific gravities of the used PC, LLFA, and GBFS are 3.18, 2.09, and 2.80 respectively. Nineteen mixtures were designed and cast including one reference mixture with Portland cement as the only binding material. The remaining eighteen mixtures were equally divided into two replacement groups of LLFA and GBFS, and each group was in turn divided into three sets. The first set includes 20%, 40%, and 60% replacement of cement by either of the two minerals (i.e. LLFA and GBFS). The second set primarily consists of three mixtures with the same cement replacement levels but with MC replacing 5% of the total aggregate content. Similarly, in the third set, the three remaining mixtures continue with the previously used replacement levels of cement but with MC replacing 10% of the total aggregate content. The results of the study indicated that the incorporation of LLFA, GBFS, and MC positively influenced the fresh properties of the produced SCC mixtures. Both the flowability and passing ability evaluated through slump flow, L-box, J-ring, U-box tests were improved. There was a slight reduction in the viscosity, yet all mixtures conformed with the recommended ranges. As far as the hardened properties are concerned, as the replacement level increased, both the compressive and split tensile strengths decreased. Despite this, the gain in strength continued in each individual mixture as the curing age increased. There was no meaningful relation correlating the UPV values to the replacement level of either material. Despite this, all produced SCC mixtures exhibited good or excellent quality in terms of UPV results. Finally, the static modulus of elasticity for the replacement mixtures was lower than that for the reference mixture, which is the expected trend as the replacement rates of mineral admixtures increase.



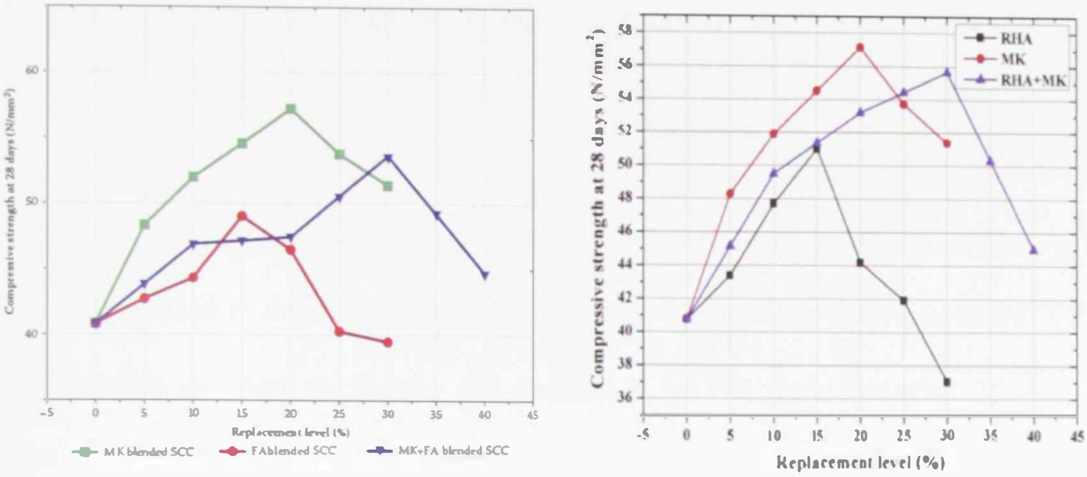
(a) PC (b) LLFA

(c) GBFS (d) MC

Figure 2-4: SEM images (Beycioğlu and Aruntaş, 2014)

Metakaolin (MK). Rice Husk Ash (RHA) and Fly Ash (FA) are commonly used fillers in SCC. Several studies have been conducted to investigate their effect on the fresh and hardened properties. V. Kannan and K. Ganesan designed sixteen binary and ternary mixtures in addition to one SCC mixture containing Portland cement as the sole binding material (control mixture) in two different studies. In the first study conducted by Kannan and Ganesan (2014-a), twelve binary mixtures were cast where half of them were produced using MK and the other half using FA as a replacement for cement. The replacement percentages varied from 5% up to 30% with an increment of 5%. In the remaining four mixtures, cement was partially replaced by a combination of 5%, 10%, 15%, and 20% of each of MK and FA. In all mixtures the water to cementitious ratio and superplasticizers percentage were maintained constant at 0.55 and 2% respectively. In the second study conducted by Kannan and Ganesan (2014-b), the number of mixtures, ingredient proportions and all other properties were the same except RHA was used instead of FA. The MK used is featured with a very high specific surface area (2350 m^2/kg), this is almost seven times higher than that of cement (318 m^2/kg) and five times higher than the S.S.A of FA (400 m^2/kg), while the RHA had a S.S.A of 943 m^2/kg. MK, RHA, and FA share very high combined percentages of SiO_2 and Al_2O_3 (95.55%, 88.08% and 85.95% respectively) promoting for possible pozzolanic reactivity. Typical concrete tests were conducted, and important conclusions regarding the optimum replacement percentage were drawn out. It was found that as the MK% increased in the mixtures, the slump flow diameter (SFD) was decreased, but the SFD in mixtures containing FA/RHA tend to act in a reverse manner as the replacement percentage increases. This phenomenon was attributed to the high S.S.A of MK. Regarding the rest of the measured fresh properties, the V-funnel recorded times varied from 3.9 to 7.9

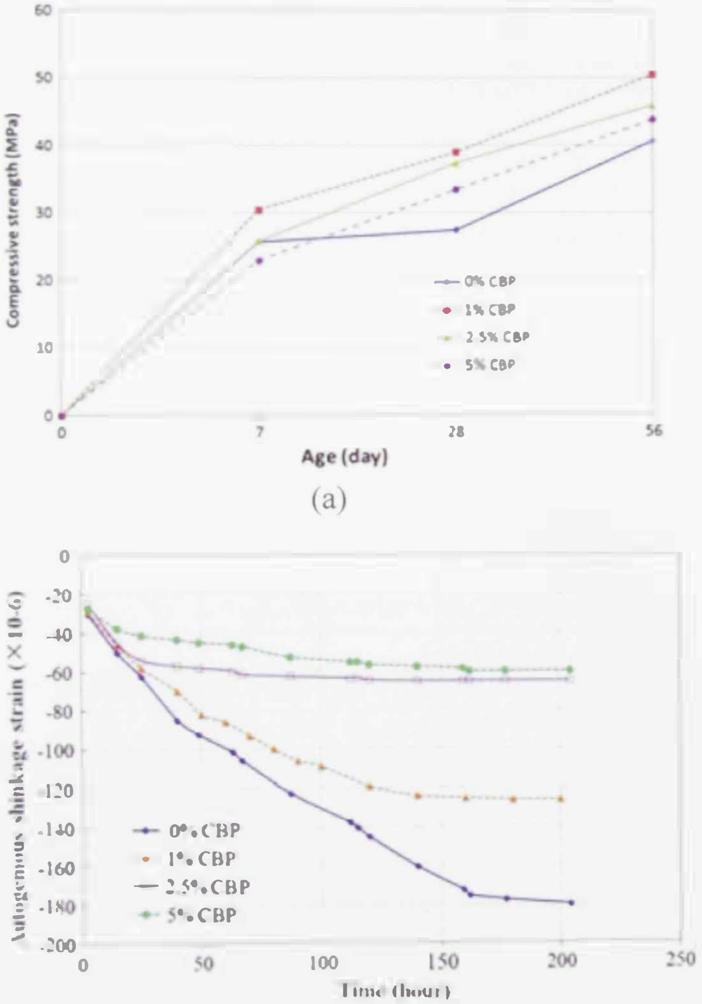
seconds in the first study and from 3.9 to 8.4 seconds in the second study with the lowest being achieved by the control mixture. The accepted L-box ratios in the EFNARC (2005) guidelines are between 0.8-1.00, and hence the blocking of the produced SCC was satisfactory up to the replacement of 15% MK, 30% of FA, 15% RHA, 30% RHA + MK, and 20% MK + FA. When the mixtures were tested for compressive and tensile strength, both strengths continued to increase as the replacement percentage increased up to 15% FA, 15% RHA, 20% MK, 30% MK + RHA, and 30% MK + FA (but in the second study, only compressive strength test was performed). The strength results agree with another research conducted on MK as well with 15% replacement of cement, the results also yielded higher compressive and tensile strength values than the reference mixture with no MK (Anjali, Vivek, and Dhinakaran, 2015). In the study where SCC was blended with MK and FA, all the replacement mixtures exhibited excellent quality expressed through the UPV results that were all above 4.5 km/s except for the mixture with 30% replacement of FA. The authors conducted durability tests only on mixtures containing RHA and MK. The sorptivity test indicated that the amount of capillary pores decreased in the mixtures up to 15% RHA, and 20% MK, whereas all the ternary mixtures resulted in sorptivity rates lower than that of the control mixture. Regarding the chloride penetration test, it was observed from the results that there was a great improvement in the chloride permeation resistivity and the minimum total charge was achieved in mixtures with 15% RHA, 30%MK, and 40% MK + RHA. This suggests that MK has a better role than RHA in refining the discontinuity of the pore network. The authors concluded that the use of ternary mixtures is preferable as it allows greater replacement of the cement and combination of two filler materials with superior properties eliminating the drawbacks of one particular filler when being used in excess percentages.



(a) (b)

Figure 2-5: Compressive strength of (a) MK + FA (b) RHA + MK (Kannan and Ganesan, 2014-a) (Kannan and Ganesan, 2014-b)

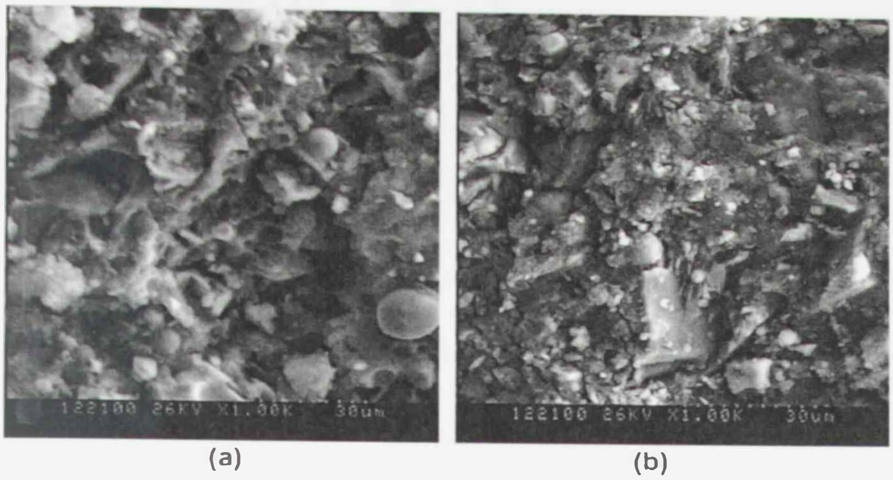
Clay brick powder (CBP) originates primarily from the demolition processes. In order to overcome the environmental contaminations caused by the disposal of CBP, investigators tried incorporating the recycled CBP into the concrete industry. This research in hand utilized recycled CBP as a partial replacement for cementitious materials (cement and fly ash) at different percentages (0%, 1%, 2.5%, and 5%). The used CBP is characterized with a high water absorption of 16.45%, and chemically of 87.95% SiO_2, 9.4% Fe_2O_3, and 2.7% TiO_2. Four mixtures were cast out of the four replacement percentages. Slump flow test was conducted and showed that up to 5% replacement, the CBP had no effect, the measured diameters were (678, 680, 688, and 688) mm. As for the hardened properties, the CBP had a positive effect on the compressive strength at all test ages. The 1% replacement mixture resulted in the highest compressive strength at 7, 28, and 56 days. The individual values are clearly shown in in Figure 2-6 (a). the increase in strength was explained through the pozzolanic reaction and internal curing effect of the powder. The autogenous shrinkage was also monitored. The control mixture (0% CBP) exhibits gradual increase in the shrinkage strain values especially at the first 7 days. Mixtures with 2.5% and 5% yield shrinkage strain values 1/3 of that of the control mixture. The values are graphically presented in Figure 2-6 (b). Moreover, scanning electron microscope investigation was performed. The results showed that the control mixture contains voids more than that in mixture with 1% CBP replacement as shown in Figure 2-7. This is due to the increased amount of hydration products in the CBP mixtures that increases the density and strength of the mixtures (Sun et al., 2014).



(a)

(b)

Figure 2-6 :(a) Compressive strength development (b) autogenous shrinkage development (Sun et al., 2014)



(a) (b)

Figure 2-7: Micrographs of (a) reference SCC (b) 1% CBP SCC (Sun et al., 2014)

A comprehensive study was carried out to evaluate the effect of metakaolin (MK) on the rheology, mechanical properties, and durability of SCC (Sfikas et al., 2014; Badogiannis et al., 2015). A total of nine mixtures were cast, particularly one reference mixture with binding material consisting of cement and limestone powder, and two groups each of four mixtures with MK replacing once cement and in the other group limestone powder (LP) at different replacement levels (6.9%, 10.6%, 14.0%, and 20.0%) and (13.7%, 21.1%, 28.0%, and 40%) for cement and LP respectively. The MK used consisted mostly of SiO_2 and Al_2O_3 that compromised approximately 86.05% of its overall chemical composition and was featured with irregular plate like particle shape. MK, LP, and cement had specific surface area (S.S.A) of 1410 m^2/kg, 1270 m^2/kg, and 700 m^2/kg respectively. Several fresh and hardened concrete tests were conducted, and the results revealed important conclusions highlighted as follows: no optimum content for MK replacing either cement or LP was suggested within the examined replacement ranges. Yet, similar or higher superplasticizer dosages resulted in lower slump flow diameters, higher V-funnel flow times, and low L-box ratios compared to the corresponding reference mixture. The rheological results were attributed to the irregular shape of MK and higher S.S.A. On the other hand, regarding the hardened properties, there was a noticeable improvement in the compressive strength as the MK replacement level increased. The gain in compressive strength was higher at 28 days than at 360 days of age. The rate at which strength development occurred at both testing ages (i.e. 28 and 360 days) was equal for the two replacement cases (cement and LP). Similarly, MK contributed to an increase in the tensile strength values, but with showing low correlation with the compressive strength in the case of MK replacing cement unlike MK replacing LP. Observing the results of the durability tests, MK played a greater and more dominant role in reducing the capillary pore system evaluated through the sorptivity test than the open porosity pores as illustrated in Figure 2-8. In terms of gas permeability, MK lead to lower gas permeability coefficients for high replacement levels regardless of the material being replaced as demonstrated in Figure 2-9. Noteworthy, the best enhancing effect was observed in the chloride penetration resistance of the SCC mixtures, where the improvement was higher than two classes.

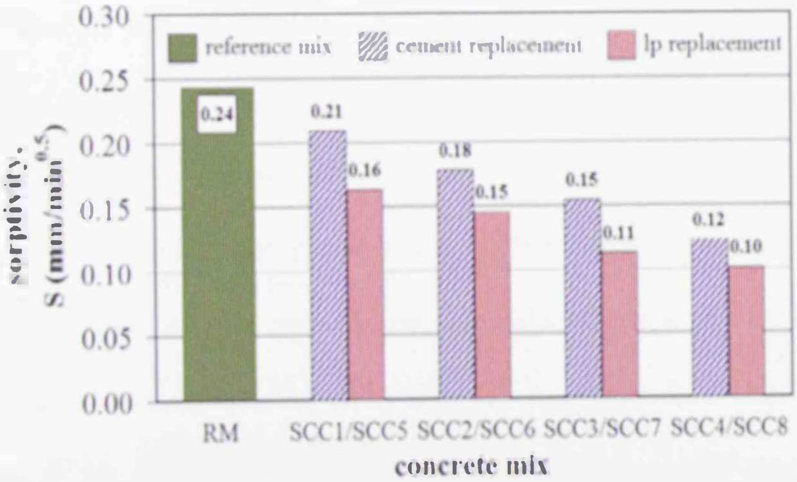


Figure 2-8: Effect of MK on sorptivity (Badogiannis et al., 2015)

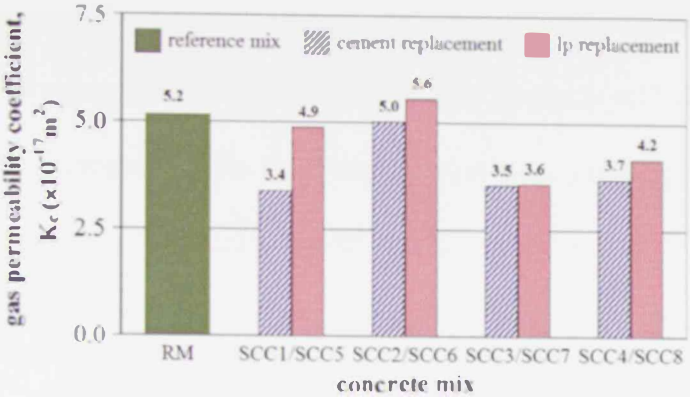
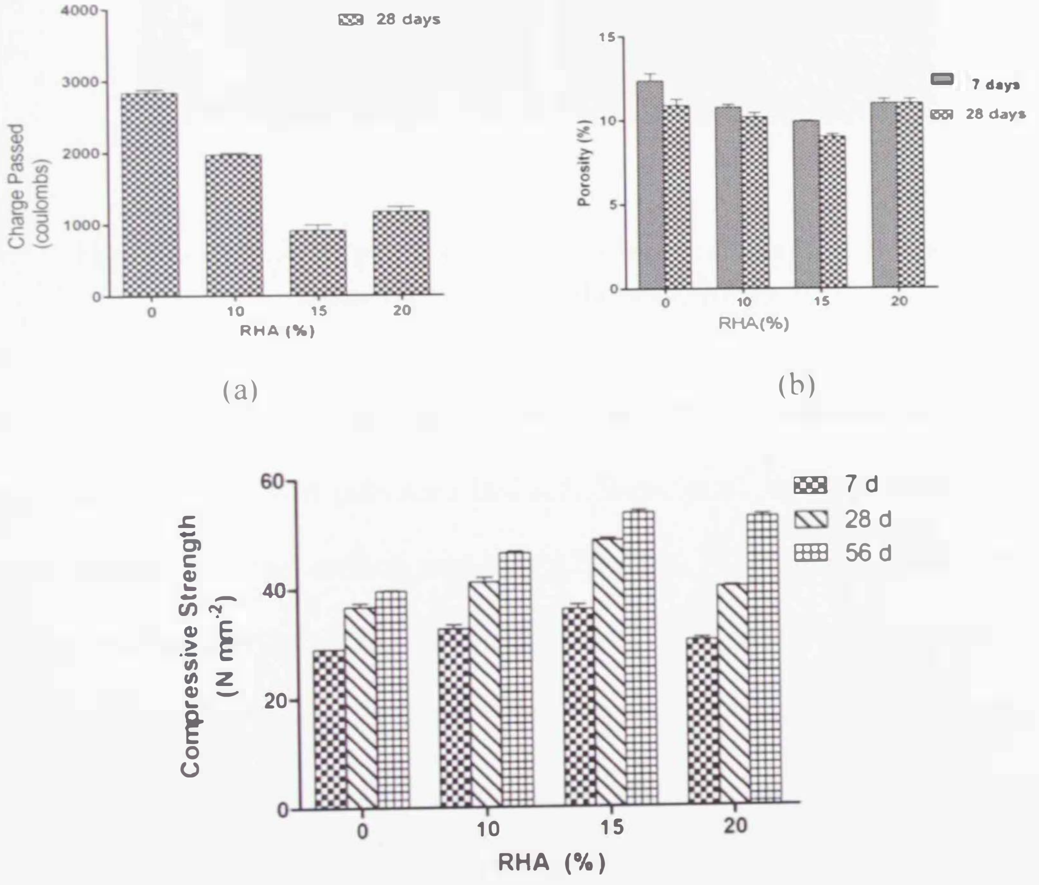


Figure 2-9: Effect of MK on gas permeability (Badogiannis et al., 2015)

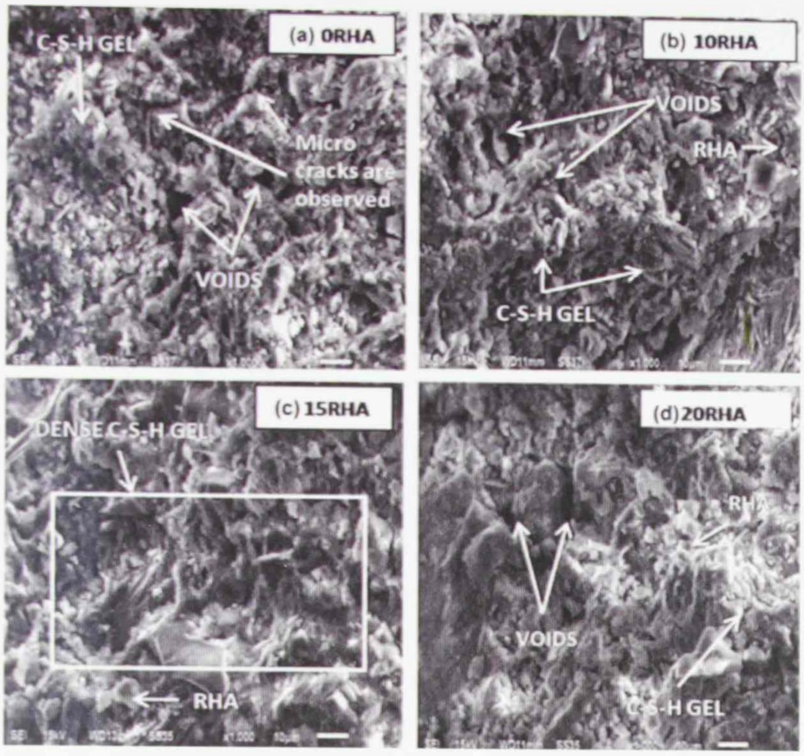
The present study aims at examining the effect of Rice Husk Ash (RHA) on multiple fresh and hardened properties of SCC. RHA is known for its pozzolanic features as the silicate and aluminate oxides make up more than 95% of its chemical composition (Chopra and Siddique, 2015). Three replacement percentages were implemented (i.e. 10%, 15%, and 20%) in addition to a control mixture with zero content of RHA. In all four mixtures the water, binding, and superplasticizer contents were kept constant at 226 kg/m^3, 550 kg/m^3, and 5.5 kg/m^3 respectively. The results of the conducted tests revealed that as the percentage of RHA increases in the mixtures, the flowability and passing ability of the produced mixtures tend to decrease, whereas the viscosity is significantly enhanced. As far as the hardened properties are concerned, both compressive and tensile strengths behave similarly as the highest strength was observed at the level of 15% replacement yielding 25% increase in strength when compared to the control mixture. Additionally, multiple durability tests were executed such as porosity and chloride ion penetration. Mixtures incorporating up to 15% of the RHA showed excellent durability characteristics conforming to the EFNARC's "very low" chloride penetration category and with highly modified pore structure leading to reduced porosity. These results were further confirmed through the obtained SEM images, where the image of the 15% RHA showed very dense structure with the absence of cracks and the C-S-H gel fully spread over the micrograph. The fresh and compressive strength results agree with the conclusions of two other studies conducted using RHA as a cement replacement. Where in (Le and Ludwig, 2016), four replacement mixtures were designed and cast (5%, 10%, 15%, and 20%) in addition to one control mixture. While in (Memon et al., 2011), the authors believed that 10% and 20% would be sufficient for evaluating the influence of RHA.



(a)

(b)

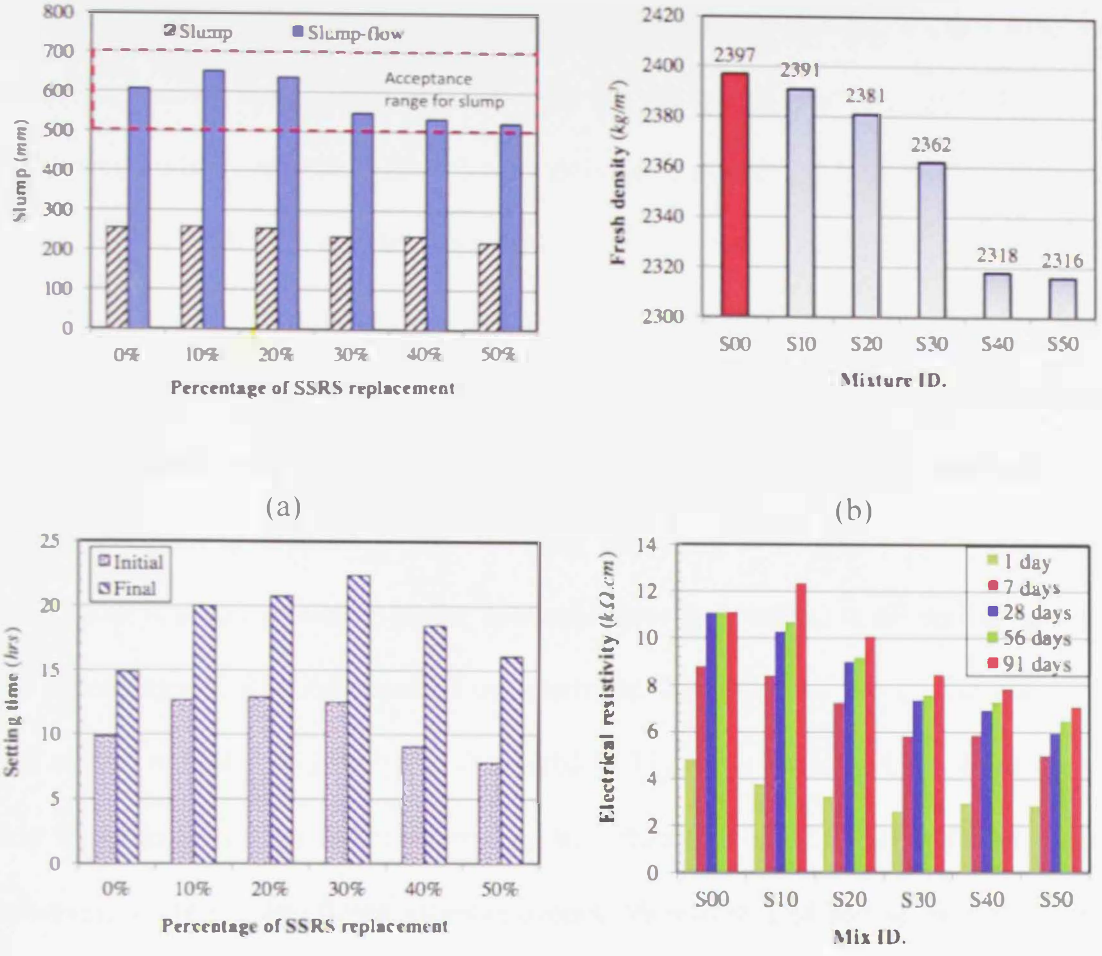
(c)



(d)

Figure 2-10: (a) Charge passed (b) porosity (c) compressive strength (d) SEM images (Chopra and Siddique, 2015)

A recent study intended at evaluating the effect of stainless steel reducing slag (SSRS) on SCC was published in 2015. Sheen et al. used two kinds of SSRS being different in their surface area (i.e. 1766 and 7970 cm^2/g), where one was utilized as filler and the other as a cement substitution. SSRS is a byproduct of the steel manufacturing process, and is discharged during the basic refining practice. It is a glassy granular material similar to ground granulated blast furnace slag in its chemical composition. Six SCC mixtures were prepared where SSRS replaced cement at different levels from 0% to 50% in steps of 10%. The water to powder ratio was maintained at 0.32 for all developed mixtures. The inclusion of SSRS resulted in higher slump flow values up to 20% replacement as shown in Figure 2-11 (a) and an increase in the mixtures' viscosity interpreted through the higher V-funnel flow times. It should be noted that the V-funnel flow times and the T_{500} didn't always change in the same manner. The fresh density of the mixtures was also measured. As the amount of SSRS in the mixtures increased, the fresh density decreased, this is presented in Figure 2-11 (b). This is due to the fact that the powder resulted in an increase in the paste volume thereby led to reduced densities. Another tested fresh property was the setting time. Mixtures containing up to 30% SSRS experienced an increase in the setting time, whereas mixtures containing 40% and 50% SSRS undergo a reduction in the setting time, the trend is clear in Figure 2-11 (c). Regarding the effect of SSRS on the studied hardened properties, the compressive strength was gradually decreased as the percentage of SSRS increased. This was justified by the fact that SSRS is not as good as cement in contributing towards strength development. Therefore, based on this study, SSRS can be used to substitute up to 30% of the cement to produce SCC of Grade 30. Moreover, the UPV test results increased with increasing the curing time but decreased with increasing the replacement percentages of SSRS. The incorporation of 30% SSRS or less yielded UPV values greater than 4.5 km/s indicating excellent quality concrete just after seven days. However, for mixtures containing more than 30% SSRS, it would require at least 90 days to achieve similar values. In regards to the water absorption, the obtained values were the highest at 28 days then got reduced with longer ages attaining the lowest rates at the 30% substitution level. The results of the electrical resistivity test revealed unchanged values for the control mixture after 28 days unlike the rest of the mixtures containing SSRS that continued to increase as obvious from Figure 2-8 (d). Furthermore, the highest values were for the 10% replacement mixture at 91 days of age, which is almost 11% higher than that of the control mixture.



(a) (b)

(c) (d)

Figure 2-11: Effect of slag on (a) slump flow (b) fresh density (c) setting time (d) electrical resistivity (Sheen et al., 2015)

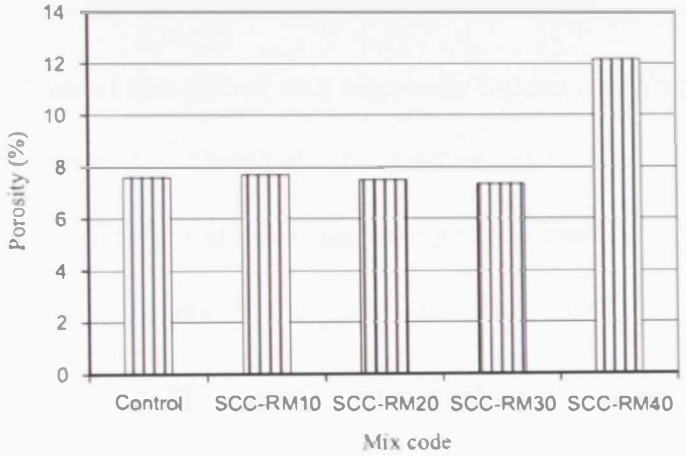
Another waste material that has been lately introduced into the SCC industry is the Red Mud (RM). The used RM is very similar in its chemical composition to Fly Ash (FA) as shown in Table 2-6. Due to the fact that RM has generally a high alkalinity, its disposal can lead to serious environmental problems and hence the need for safe disposal or recycling had arised. In this particular study, Liu and Poon (2016) used RM directly as a replacement for FA. A total of three mortar and five SCC mixtures were designed as summarized in Table 2-7. The mortars consisted of one control containing 500 g of cement, while the remaining two were made of 400 g of cement with the remaining 100 g being replaced once by FA and another time by RM. The mortars were aimed at comparing the pozzolanic reactivity of RM to FA. However, the five concrete mixtures were developed in order to evaluate the effect of replacing FA with RM on the fresh and hardened properties of SCC. The results revealed that RM has a very good pozzolanic activity, in fact the values were very similar to that of FA. Apparently the RM had a high water absorption that led to the use of increased amount of superplasticizers. Hence, the RM slightly decreases the filling and passing abilities but at the same time greatly enhances the segregation resistance. A slight reduction in the hardened density occurred at all curing ages as the percentage of RM increased in the mixtures. The effect of RD on the porosity, and elastic modulus at 28 days is displayed in Figure 2-12 (a) and (c). Its obvious that the porosity of the four mixtures up to 30% replacement is almost equivalent, however, at 40% a significant increase occurs. Moreover, RM had no definite effect on the elastic modulus. Nevertheless, the enhancements in compressive and tensile strengths were highly noticeable at later ages especially at the 30% and 40% replacement levels as presented in Figure 2-12 (b). Finally, the drying shrinkage of all mixtures incorporating RD was lower than that of the control mixture being more profound at higher replacement levels.

Table 2-6: Chemical composition of red mud and fly ash (Liu and Poon, 2016)

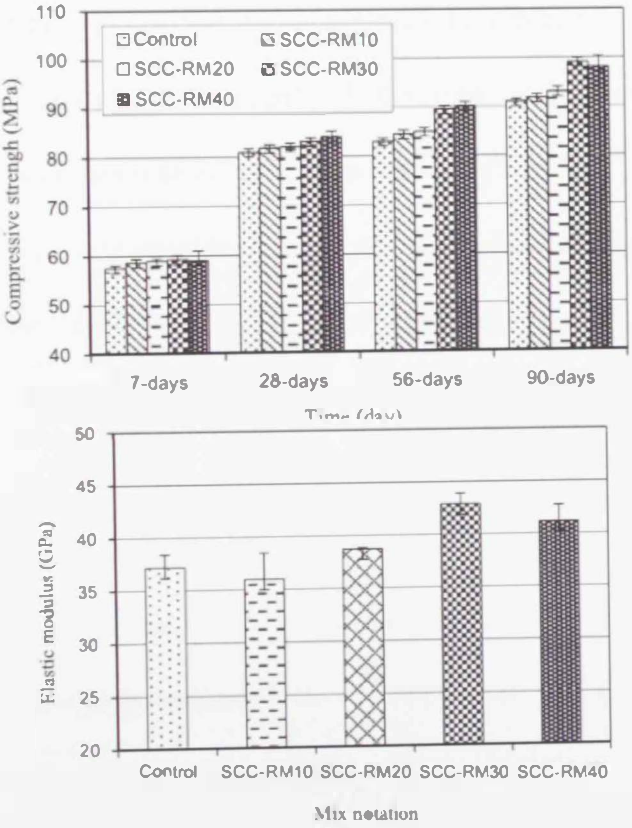
Material (%)	SiO_2	Fe_2O_3	Al_2O_3	TiO_2	CaO	MgO	SO_3	K_2O	Na_2O	P_2O_3	LOI
Fly ash	47.62	7.35	27.4	1.23	8.11	3.55	0.57	0.88	0.87	-	3.90
Red mud	45.76	2.85	40.69	2.03	4.98	0	2.15	0.45	0	1.10	-

Table 2-7: Mix proportions of SCC mixtures (Liu and Poon, 2016)

Mix code	Cement (kg/m^3)	Fly ash (%)	Red mud (%)	Ratio of replacement (%)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	w/c	SP (L/m^3)
Control-II	359	311	0	0	635	872	0.50	5.6
SCC-RM10	359	279.9	31.1	10	635	872	0.50	6.2
SCC-RM20	359	248.8	62.2	20	635	872	0.50	6.6
SCC-RM30	359	217.7	93.4	30	635	872	0.50	7.2
SCC-RM40	359	186.6	124.6	40	635	872	0.50	8.2



(a)



(c)

Figure 2-12: Results of hardened properties (Liu and Poon, 2016)

2.8 Significance of Investigations

The following are the main observations from the previous investigations:

- Some fine materials act as a substitute for viscosity modifying agents, others increase the superplasticizer demand in order to obtain similar flowability values.
- Physical characteristics of fines such as specific surface area, particle shape and, surface texture greatly influence the fresh properties of the produced SCC.
- As the summation of the silicate and aluminate oxides constitute more than 70-80% of the material's chemical composition, it'll have some pozzolanic characteristics contributing towards late strength development.
- Cement hydration takes place at early ages, unlike other materials that inherit latent hydraulic characteristics. These materials undergo prolonged strength development.
- There is no distinct percentage for a material to replace cement, it depends primarily on the materials characteristics. If the optimum percentage is exceeded, negative effects occur such as increase in porosity and strength reduction.
- Some utilized fillers are recycled waste materials that result in SCC mixtures with satisfactory fresh and hardened properties, and hence provide environmentally friendly solutions for waste disposal and reduce the construction cost.

The previous literature did not address the inclusion of CWP as a fine material in producing SCC, thus the aim of this thesis is to thoroughly investigate its feasibility as a SCC component and its influence on the fresh and hardened properties of the produced mixtures.

Chapter 3: Investigation Program

3.1 Introduction

Since self-compacting concrete was first developed in the late 20th century, extensive research took place worldwide to study the possible methods and materials to be implemented in the production of successful SCC mixtures for best performance in the construction industry. SCC properties are the result of modifying the composition of conventional vibrated concrete (CVC). One important modification is the high powder content. Numerous investigations have been conducted to establish reliable materials to be utilized in replacement of cement. These materials will help reduce the carbon footprint imposed on the environment from cement production and hence contribute towards a more environmental and economical concrete production. The aim of this study is to investigate the possible production of SCC incorporating locally available industrial waste material, i.e. ceramic waste powder (CWP). The effect of this waste powder on both the fresh and hardened properties of SCC mixes is evaluated, to identify the optimal content of CWP to be incorporated in SCC mixes yielding the best suitable performance.

During the investigation program of this thesis, several self-compacting concrete mixtures were designed, cast, and tested. The studied SCC mixtures were tested right after mixing while still being plastic, and this stage of the concrete's life time is commonly referred to as the fresh stage. The tests were also extended throughout the hardened stage of concrete at different time intervals (7, 28, 56, and 90 days). It is worth mentioning that the fresh properties of the SCC are what mainly influence the ease of placement and consolidation during construction and at the same time they are considered the main factors that distinguish the SCC from the conventional vibrated concrete (CVC). SCC mixtures are much more fluid than CVC mixtures, and hence they are expected to behave differently. However, it is not sufficient and would not be considered quite significant to say SCC differs in just fluidity. The mixture should inherit other superior properties as well, such as passing ability and stability. Therefore, for evaluating such properties and setting acceptance performance criteria for SCC in general, new testing techniques have been developing since the development of SCC. As for the hardened properties, both SCC and CVC are known to be dense and homogeneous sharing the same engineering properties and durability characteristics and hence the same tests are used for evaluation or assessment. Later in this chapter, section 3.4 is dedicated for discussing the several tests performed to assess the produced SCC and the detailed procedure that was being followed.

3.2 Materials

During the production of SCC mixtures used throughout the experimental phase of this thesis, typical concrete ingredients were utilized in addition to the ceramic waste powder (CWP) as filler and partial replacement for cement. Below is each constituent material and its corresponding properties.

3.2.1 Aggregates

As the maximum nominal size of coarse aggregates is the main parameter affecting the passing ability of the fresh SCC mixtures, ACI-237R-07 suggests it should be one size less than that recommended by ACI 301. Therefore, from Table 3-1, and according to the range of cementitious material content used for the concrete mixtures in this study, the maximum aggregate size to be used is approximately 9.5 mm.

Table 3-1: Recommended maximum aggregate size (ACI-237R-07)

Nominal maximum size (mm)	**Cementitious material content (Kg/m^3)**
37.5	280 to 330
25	310 to 360
19	320 to 375
12.5	350 to 405
9.5	360 to 415

The ratio of fine to coarse aggregates is usually increased to help reduce the inter-particle friction between the coarse aggregate that consumes most of the flowing energy of the paste during placement and hence increase fluidity. Despite this, aggregates cannot be dispensed as they are the main component that contributes to strength, hence they compromise the greatest percentage of the total concrete volume which is about 60 to 80 %. Additionally, a concrete with low aggregate volume may undergo higher drying shrinkage compared to other mixtures prepared with high aggregate volumes (Daczko, 2012). During the production of SCC mixtures, the maximum size of coarse aggregate is recommended by the EFNARC-2005 guidelines not to exceed 12 mm in order to avoid blocking and hence enhance the passing ability. Larger aggregate sizes will also separate easily from smaller particles and the paste content leading to segregation. Nevertheless, mixtures have been produced with aggregate sizes ranging from 10 to 40 mm (Daczko, 2012). ACI-237R-07 suggests that if the coarse aggregate size used is greater than 12.5 mm, then the absolute volume of coarse aggregate should be in the range of 28 to 32 % of the volume of concrete for congested formwork.

The coarse aggregate used in this study is natural crushed stone from Ras Al Khaima (UAE) with nominal size of 10 mm (3/8 in.), a specific gravity of 2.67, and water absorption % of 0.7 was used as coarse aggregate. Two types of fine aggregate were used: crushed natural stone sand from Ras Al Khaima (UAE) with fineness modulus of 0.9 and specific gravity 2.64, and dune sand from Al Ain area (UAE) with fineness modulus of 3.6 and specific gravity 2.63. Sieve analysis was conducted on all aggregates used, and the results are presented in Table 3-2.

Table 3-2: Aggregate sieve analysis

Sieve size (mm)	**Cumulative Passing %**		
	Coarse Aggregate (10 mm)	**Fine Aggregate (Crushed Sand)**	**Fine Aggregate (Dune Sand)**
37.5	100	-	-
19	99.96	-	-
9.5	99.86	-	-
4.75	89.61	99.9	100
2.36	8.12	99.6	100
1.18	-	99.09	100
0.600	-	96.18	99.7
0.300	-	34	99.1
0.150	-	7.14	13.1

3.2.2 Cement

In typical SCC mixtures, the paste content will be greatly relied upon for providing the best fresh properties. The main binding material in the paste is cement. Additional fillers/fine materials were added to the mixtures partially replacing cement: slag and ceramic waste powder. Ordinary Portland cement which conforms to ASTM C150 Type 1 and BS EN 197 CEM I was used. The cement's specific surface area is 380 m^2/kg with specific gravity equal to 3.15 as per the manufacturer data sheet. Chemical composition of the used cement is presented in Table 3-3.

Table 3-3: Chemical analysis of cement (from manufacturer)

Compound	**Weight (%)**
CaO	61.5
SiO_2	21.0
Al_2O_3	6.1
MgO	3.8
Fe_2O_3	3.0
SO_3	2.5
Equiv. Na_2O	0.59
Loss on Ignition	1.6
Insoluble Residue	0.9

3.2.3 Ground Granulated Blast Furnace Slag

Ground granulated blast furnace slag (i.e. slag) was used as a binding material in three of the cast mixtures. It was incorporated as an addition to the cement in order to meet the minimum powder content suggested by the EFNARC-2005 guidelines which is 450 Kg/m^3. Commercially available slag was used for this study conforming to ASTM C989 with a specific surface area of 432 m^2/kg.

3.2.4 Ceramic Waste Powder

Ceramic waste powder (CWP) utilized throughout this study was obtained during the polishing process of final ceramic tiles from "Exeed Industries Companies" in Abu Dhabi, United Arab Emirates. The preliminary raw materials used in manufacturing the ceramic tiles were: feldspar, ball clay, china clay in addition to silica sand.

The ceramic waste powder was delivered in a wet condition with 36% average moisture content. Before the powder was incorporated in the mixtures, it was first dried for 24 hours in an oven at 110°C, then was finely ground using a grinder, where 50% by volume of the particles ranged from 5-10 μm. The dried ground particles were placed in tightly sealed containers to prevent contact with any source of moisture. The specific gravity (SG) was 2.5 and the specific surface area (SSA) measurements using Blaine fineness method (air permeability method) showed CWP to have SSA of 555 m^2/kg.

X-ray florescence (XRF) chemical analysis of CWP was conducted by three different laboratories and the average of the composition of the material is shown in Table 3-4. The XRF shows that CWP mainly consists of silicon and aluminum oxides, where their summation constitutes more than 80 % by mass, in addition to other minor compositions of iron, calcium, magnesium, sodium, and potassium oxides that were detected.

Table 3-4: Chemical composition of CWP by mass%

Main Oxide	**Mass (%)**
SiO_2	68.59
Al_2O_3	57.00
Fe_2O_3	0.80
CaO	1.69
MgO	2.51
Na_2O	4.00
SO_3	0.12
K_2O	1.60

The mineralogical configuration of CWP material was examined using X-ray diffraction (XRD) analysis. The XRD results shown in Figure 3-1 indicated the predominant peaks for quartz (SiO_2) confirming the results of the chemical analysis that revealed the silicon oxide constituted the greatest percentage in the CWP's composition. From Figure 3-1 also, the presence of humps in the parts between 2θ values of 20° and 30° as well as the unleveled graph trend from 2θ values between 0° to 40° indicated the occurrence of some amorphous phase in the CWP material.

The morphology of CWP was observed using scanning electron microscope (SEM) as shown in Figure 3-2. It can be noted from the figure, that the CWP particles exhibited angular shape similar to that of cement particles.

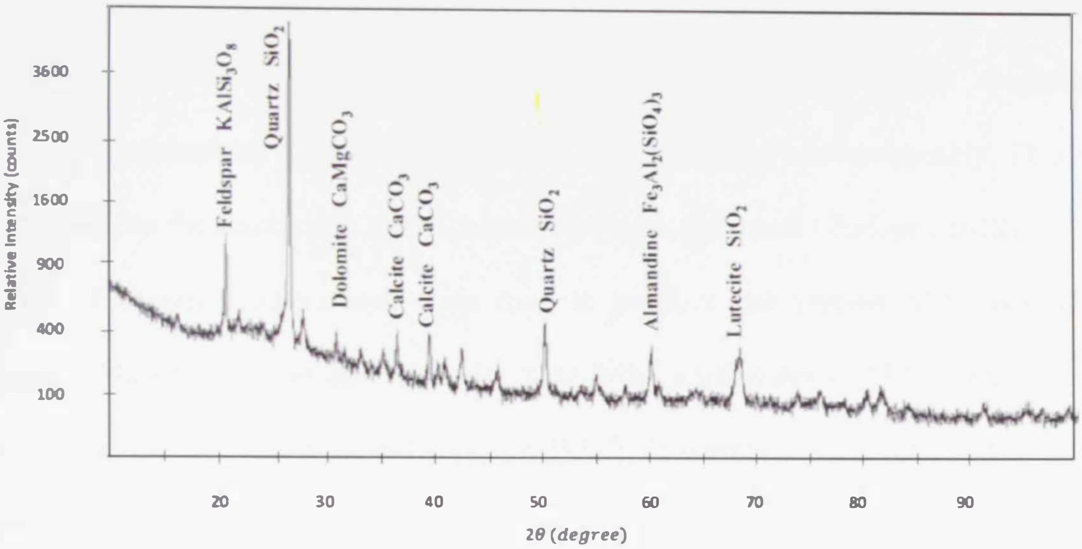


Figure 3-1: XRD pattern of ceramic waste powder

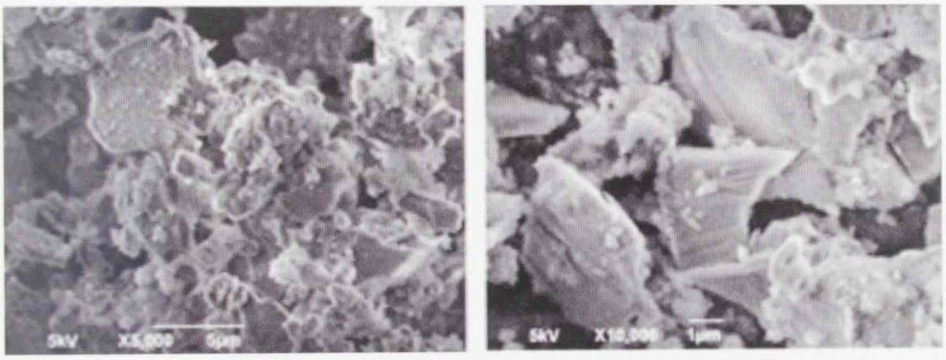


Figure 3-2: SEM of CWP

3.2.5 Admixtures

Admixtures are defined in ASTM C125 as "a material other than water, aggregates, cementitious material, and fiber reinforcement that is used as an ingredient of a cementitious mixture to modify its freshly mixed, setting, or hardened properties and that is added to the batch before or during its mixing". They are used to control specific characteristics of the SCC mixtures intended to be produced.

Several types can also be combined for adjusting various properties concurrently. Admixtures can be either mineral or chemical. Chemical admixtures constitute essential ingredients in concrete in addition to the other typical ingredients, there exists a variety of commercially available types that can be used to produce SCC. But it should be noted that chemical admixtures sharing similar chemical composition obtained from different sources cannot be used interchangeably. This is verified from the results of a study conducted by (Barfield and Ghafoori, 2012). Two types of chemical admixtures were used to produce the studied SCC mixtures namely: Superplasticizer and viscosity modifying admixtures (VMA). Both types were obtained from the chemical company BASF. It is recommended that admixtures are mixed with mixing water. The optimum dosage of these admixtures for yielding the best fresh properties was determined based on trial mixtures. Both types are supplied in the form of a liquid, water soluble compound.

3.2.5.1 Superplasticizers

Superplasticizers are also known as high-range water reducers. This chemical compound enables the production of concrete mixtures with low water/binder ratio maintaining the workability. Or in other words increases the workability without the need for additional water (ASTM C125). A polycarboxylic ether based superplasticizer (Glenium® sky 504) which conforms to Type G in ASTM C494 and Type 2 in ASTM C1107 was used in the study. The amount used varied from 1.28% to 1.7% by weight of the binder content. Its properties as provided by the manufacturer are provided in Table 3-5.

3.2.5.2 Viscosity Modifying Admixtures

Viscosity modifying admixtures are typically incorporated in SCC mixtures to enhance the viscosity providing greater stability while reducing bleeding (Daczko, 2012). One important advantage of the VMA is that they tend to only change the viscosity and not any other property (Łaźniewska-Piekarczyk, 2013). They also help minimize the effect of variations in moisture content, amount of fines and their grain size distribution. The best rheological behavior was recommended by the supplier to be combined with superplasticizers. A high molecular weight synthetic co-polymer viscosity modifying admixture (VMA) (RheoMATRIX ® 110) was used in the preparation of the SCC mixtures studied in this thesis. The dosage varied from 0.29% to 0.33% by weight of the binder content. Properties as provided by the manufacturer are provided in Table 3-5.

Table 3-5: Typical properties of chemical admixtures as obtained from supplier (Manufacturer's datasheet)

	Superplasticizer	**Viscosity modifying admixture**
Appearance	Whitish to straw colored liquid	Brownish liquid
Specific gravity	1.115 at 25°C	1.010 g/cm^3
Chloride content	"chloride free" to EN 934-2	<0.1%
Alkali content (as NaO equivalent)	0.26%	-
PH-value @ 25°C	-	6-9

3.2.6 Water

Potable water was used for mixing and curing of all produced SCC mixtures.

3.3 Concrete Mix Proportions

3.3.1 Mix design Principle and Approach

Concrete mixtures are classified as SCC only when all three fresh requirements are fulfilled (flowability, passing ability, and segregation resistance).

Therefore, in order to achieve the required combined properties, several guidelines should be followed during the mix design process.

- Paste adjustments including the type and proportions of cementitious materials used will influence both the fluidity and viscosity of the produced mixtures. Reducing the water/powder ratio and compensating its effect through the addition of superplasticizers and VMA to maintain a cohesive mixture, all will play a great role towards the production of a successful SCC mixture.
- For enhancing the fluidity of the SCC mixtures, the friction between the coarse aggregates should be reduced. This could be done by increasing the fine to coarse aggregate ratio so that each individual coarse aggregate is fully coated with a layer of mortar for lubrication.

Therefore, if the previous principles are followed, the produced SCC will differ from the conventional concrete in the following main facts:

- Increased fine to coarse aggregate ratio
- Increased paste content.
- Low water/ powder ratio.
- Increased superplasticizer
- Use of viscosity modifying admixtures.

3.3.2 Concrete Mix Proportions

Producing concrete mixtures with high fluidity can be achieved by using a very high water/cement (w/c) ratio. The increase negatively affects the strength in addition to potential influence on the durability. To overcome this, a new classification of concrete has been developed in the late 20th century. This new innovative type of concrete is commonly called self-compacting concrete (SCC). Proper mixture proportions and mixing conditions are of utmost importance in the production of successful SCC mixtures. Three major characteristics should be available in this type of concrete: flowability, passing ability, and segregation resistance. The first property is generally achieved with the incorporation of chemical admixtures such as high range water reducers (HRWR) instead of additional water content. The second property is attained by restricting the nominal maximum size of coarse aggregates to be used depending on the application the designed concrete will be utilized. The segregation resistance is enhanced by either increasing the fines content or the use of VMA. Various fines were used by multiple concrete researchers including inert or reactive ones. VMA enhances the viscosity of the mixtures especially when the fines content is low or when the mixture lacks well graded aggregates. Ideally, acceptable fresh properties for SCC mixtures are achieved with a good combination of well-graded aggregates, HRWR, VMA or, increased powder content. Regarding the hardened properties, the mixture proportioning may vary depending on the property mostly required (Bhattacharya, 2008).

Two groups of mixtures were cast to investigate the addition of ceramic waste powder (CWP) to the mixture and the replacement of cement by CWP. A total of ten mixtures were cast with six mixtures included in the first group, and the remaining four were considered in the second group. In the first group the cement content in the control mixture (A-S-100) was 350 kg/m^3 based on the preliminary mix design, which is below the value recommended by EFNARC-2005 specifications (i.e. powder content $\geq$ 450 kg/m^3). To meet the specifications' requirements, slag was added as filler in the amount of 100 kg/m^3 to fulfil the minimum powder content and to act as a control mixture. Moreover, the incorporation of a commonly used filler i.e. slag attained another important purpose. This allowed for a comparison in judging the performance of SCC mixtures produced with a new material i.e. CWP versus slag. In mixtures (A-S-200 and A-S-300) the amount of slag was gradually increased to 200 and 300 kg/m^3 respectively while maintaining the total powder content at 450 kg/m^3. Similarly, CWP was used in replacement of the slag (i.e. A-C-100, A-C-200 and A-C-300). For this group, the w/cm ratio used was (0.41).

For the second group of mixtures, the initial cement content in the control mixture (R-0) was above the recommended value by EFNARC-2005 specifications without the need of any additional filler, 500 kg/m^3. The cement was partially replaced by the CWP in 20, 40 and 60% which are equivalent to 100, 200 and 300 kg/m^3 respectively (R-100, R-200, and R-300). For this group, the w/cm ratio used was (0.35). The two groups were expected to yield compressive strength in the range of 60 to 80 MPa.

The constituent materials of mixtures were calculated based on trial mixes and conventional concrete mix design method and adjusting mixture proportions according to the requirements of EFNARC specifications of minimum powder content, fine to coarse aggregate ratio, and inclusion of chemical admixtures to produce SCC. The details of the final mixture proportions are as given in Table 3-6 and Table 3-7.

In both groups the minimum replacement level was 20%, this was chosen based on the recommendations of the study conducted recently by (Jackiewicz-Reka et al., 2015), which assessed the utilization of ceramic waste as a replacement of fine aggregate, but the size of the waste used was 0.05 mm, and according to EFNARC

2005 a material of particle size smaller than 0.125 mm is considered as powders or fines. Study concluded that ceramic waste can be used as an effective filler in cement mortars and eventually concretes with rates of addition of at least 20% by mass of the cement.

Table 3-6: Mixture proportions with CWP as cement replacement

Mixture Ingredients	**Mixture Designation**			
	R-0	**R-100**	**R-200**	**R-300**
Cement (kg/m^3)	500	400	300	200
Slag (kg/m^3)	0	0	0	0
CWP (kg/m^3)	0	100	200	300
Water (Liters)	175	175	175	175
Dune Sand (kg/m^3)	479	479	479	479
Crushed Stone (kg/m^3)	392	392	392	392
10-mm aggregates (kg/m^3)	871	871	871	871
Super Plasticizer (kg/m^3)	8.33	8.72	8.33	8.80
VMA (kg/m^3)	1.6	1.6	1.6	1.6
w/cm	0.35	0.35	0.35	0.35

Table 3-7: Mixture proportions with slag and CWP as addition

Mixture Ingredients	**Mixture Designation**					
	Slag Mixtures			**CWP Mixtures**		
	A-S-100	**A-S-200**	**A-S-300**	**A-C-100**	**A-C-200**	**A-C-300**
Cement (kg/m^3)	350	250	150	350	250	150
Slag (kg/m^3)	100	200	300	0	0	0
CWP (kg/m^3)	0	0	0	100	200	300
Water (Liters)	184	184	184	184	192	184
Dune Sand (kg/m^3)	484	482	480.2	484	482	480.2
Crushed Stone (kg/m^3)	484	482	480.2	484	482	480.2
10-mm aggregates. (kg/m^3)	792	771	785.7	792	771	785.7
Super Plasticizer (kg/m^3)	5.75	3	5.75	5.75	4.8	11.15*
VMA (kg/m^3)	1.25	1.25	1.25	1.25	1.25	1.25
w/cm	0.41	0.41	0.41	0.41	0.41	0.41

***high dosage of admixtures was used in this mix due to high air temperature during mixing (40-45°C).**

3.3.3 Procedure of Mixing

EFNARC recommendations for the order of concrete ingredients to be mixed using a forced action mixer were followed. This includes the addition of aggregates and cement to the mixer together. Followed by major portion of mixing water and superplasticizers. Finally, VMA was added with the remaining mixing water. Each of the mixtures was prepared in three batches. All mixing was completed within five minutes, based on EFNARC instruction suggesting a minimum of four minutes. This might be longer than conventional concrete but will efficiently help in fully activating the superplasticizer. The mixing procedure and sequence are summarized in Figure 3-3, and the detailed steps are as follows:

1- Constituent materials were weighed separately for each mixture based on the quantities obtained from the mix design.

2- The weighing process of the ingredients for each mixture took place one day before the mixing, except for cement and admixtures that were freshly weighed on the mixing day.

3- Dry ingredient including both types of aggregates and cementitious materials were first allowed to be mixed for 1 minute.

4- Then approximately 70% of the water content was added to the previously mixed ingredients.

5- The mixture was left for one and a half minute to obtain a uniform mixture with good consistency.

6- The addition of the remaining amount of mixing water and admixtures at later stages will increase the consistency to the required level while avoiding "balling".

7- After two and a half minutes from the start of the mixing, superplasticier mixed in 20% of the water content was added in the mixer.

8- One minute later, VMA was dispensed with the remaining amount of mixing water.

9- The procedure of adding VMA at a later stage is a preferred practice suggested by EFNARC-2005 guidelines.

10- Ingredients were left in the mixer for an additional one and a half minute to ensure all components were efficiently mixed together resulting in a homogeneous fresh concrete.

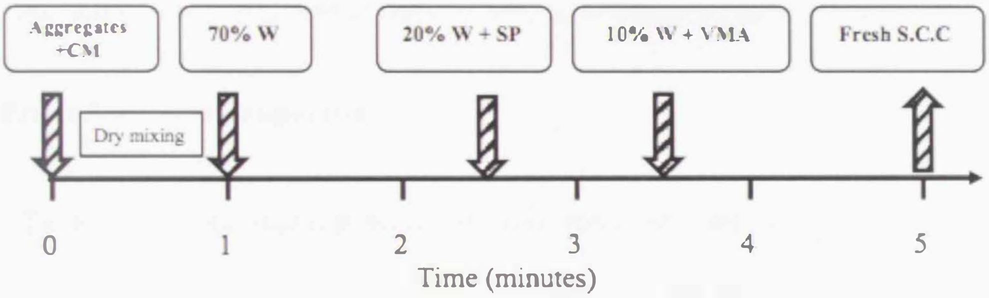


Figure 3-3: Mixing procedure

3.3.4 Order of Conducting Fresh Tests

Upon the completion of mixing, flow property tests of slump flow, J-Ring, L-box, V-funnel, and segregation column were conducted to ensure acceptable flow ability, passing ability, and segregation resistance were obtained. The order in which the fresh tests was conducted was maintained throughout all the ten mixtures.

1. V-funnel
2. L-box
3. J-ring
4. Slump flow

5. GTM segregation column

3.3.5 De-moulding and Curing

After casting, the molded specimens were covered with plastic sheets for 24-48 hours. Mixtures containing cement/CWP were de-molded after 24 hours and then moist cured until the testing age. While mixtures containing slag were de-molded after 48 hours, then moist cured till the testing date.

3.4 Concrete Test Methods

Tests were performed on all ten mixtures both in the fresh and hardened stages. All tests were conducted at the concrete technology lab at UAE university.

3.4.1 Fresh Concrete Properties

Typically, when dealing with flowable materials, the term "rheology" and "workability" appears. Rheology is the scientific investigation of the flow and deformation of a material (Koehler and Fowler, 2004). It is implemented to describe SCC flow properties and considers freshly-mixed concrete as a fluid (Ferraris, 1999). Several models that explain the rheological concrete characteristics exist, and the two most important parameters expressed in these models are: the yield stress; defined as the amount of force required to initiate flow, and the plastic viscosity; defined as the material's internal resistance to flow. Workability can be defined either qualitatively as the ease of placement or quantitatively by rheological parameters (Felekoglu, 2007). For measuring these parameters, there exists several commercial rheometers. But unfortunately, concrete reometers are not available for most concrete researchers, and that is why the need for other performance evaluation methods had engaged (Daczko, 2012). The three common features that characterize SCC mixtures defined by most standards such as the EFNARC specifications, ASTM, and ACI standards, are: filling ability, passing ability, and segregation resistance. Various tests have been established to evaluate these properties in simple ways. The ones conducted during the experimental phase of this thesis are presented in the following sub-sections. Table 3-8 summarizes the SCC fresh properties along with the tests used and the corresponding parameters measured. The recommended values were obtained from the standards followed in the conductance of the test as described in each sub-section. All used apparatuses were first cleaned, and their inner surfaces were dampened before conducting the test.

Table 3-8: Fresh SCC properties, corresponding tests and recommended values (EFNARC, 2005)

Property	Test	Parameter	Recommended values
Filling ability	V-funnel	Tv (seconds)	8-12 (seconds)
	Slump flow	SFD (mm) T50 (seconds)	550-850 (mm) 2-5 (seconds)
Passing ability	J-ring	JRD (mm)	-
	L-box	H2/H1	0.8 – 1.0
Viscosity	V-funnel	Tv (seconds)	8 – 12 (seconds)
Segregation resistance	GTM segregation column	S%	< 15%

3.4.1.1 Filling Ability

This property was evaluated through the slump flow test. The value obtained provides indications on the flowability of freshly cast concrete mixtures in unconfined conditions. It is highly recommended and typically performed for all SCC mixtures. EFNARC 2005 (EN 12350-2) and ASTM C1611 standards were followed while conducting the slump flow test. The main difference between this test and the conventional test described in ASTM C143 is that the flow diameter of concrete is measured rather than the drop in height. The slump flow is a measurement of the horizontal flow of SCC mixtures. It is the average of two spread diameters measured perpendicularly to each other. To carry out the test, simple tools were required, primarily a flat smooth steel square base plate having a minimum diameter of 915 mm as well as the same truncated slump cone used for determining the slump of conventional vibrated concrete. A meter and a stop watch were also needed for flow diameter and T_{50} measurements. The test is shown in Figure 3-4. To start the test, the plate was leveled, dampened and the cone was positioned centrally. Then the concrete was poured into a dampened cone using shovels and scoops. No tamping was done. The cone was then lifted cautiously avoiding any lateral movements or interference with the flow of concrete. The stop watch was immediately started as the cone was raised and stopped when concrete reached the 500 mm circular mark. Time measured was denoted as T_{50}. The maximum concrete circular spread in two perpendicular directions was measured. The average of these two values was computed and denoted as the flow diameter. If the obtained measurement of the two spread perpendicular diameters differs by more than 50 mm, the test should be repeated.

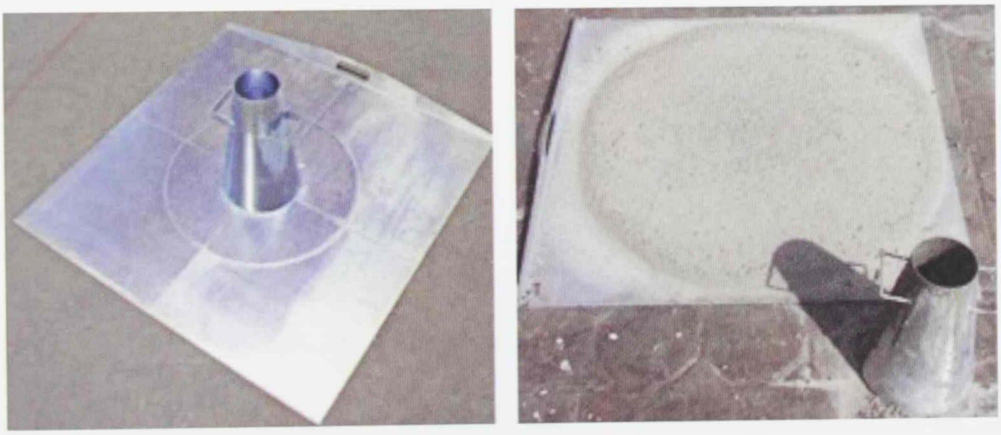


Figure 3-4: Slump flow apparatus of test

3.4.1.2 Passing ability

This property is evaluated through two tests namely the J-ring and the L-box tests. The tests characterize the passing ability of SCC through restricted spaces reinforcing bars.

- **J-Ring**

ASTM C 1621 standard was followed while performing the J-ring test. The test is very similar to the slump flow test but with an additional circular steel ring of 300 mm diameter and 100 mm height. The ring resembles the confinement of steel reinforcing bars. During the test, the J-ring flow diameter is measured in a procedure similar to that followed for determining the slump flow diameter. The freshly mixed concrete is poured in the cone oriented centrically inside the ring in an upright position with the aid of shovels and scoops. The cone is then raised maintaining a vertical movement, while the ring is kept in place for the concrete to spread through the steel bars. If the measurement of two spread perpendicular diameters differs by more than 50 mm, the test should be repeated. The J-ring flow diameter was subtracted from the corresponding slump flow diameter for the same mixture. The difference indicated the passing ability of the concrete. If the difference is less than 25mm, the passing ability is considered "good". While if the difference was greater than 50 mm, then the mixture exhibited a "poor" passing ability through reinforcing bars. Table 3-9 gives the ASTM C6121 blocking assessment. The apparatus used and test are shown in Figure 3-5.

Figure 3-5: J-ring apparatus and test

Table 3-9:J-ring test criteria

Difference Between Slump Flow and J-ring Flow Diameters	Blocking Assessment
0 to 25 mm	No visible blocking
25 to 50 mm	Minimal to noticeable blocking
> 50 mm	Noticeable to extreme blocking

- **L-Box**

The test was conducted to assess the passing ability of the fresh concrete while flowing through congested reinforcements. EFNARC-2005 guidelines were followed in order to perform this test. The apparatus used is a commercially available L-box consisting of two distinct sections i.e. vertical and horizontal as shown in Figure 3-6. The L-box is placed on a leveled horizontal surface, then approximately 15 L of concrete is poured into the vertical section without any tampering or vibration. Concrete is allowed to flow to the horizontal section upon the release of a trap door. As the trap door is released, concrete will pass through 2 re-bars resembling the obstruction of reinforcement in structural members. Concrete is allowed to flow till it reaches the end of the L-box and stops flowing. The ratio (H_2/H_1) is computed by measuring the height of the set concrete at both the beginning (H_1) and the end (H_2) of the horizontal section using a ruler. EFNARC-

2005 suggests a minimum value of 0.80 for the above mentioned ratio. If this ratio goes below 0.8, there is usually a blocking risk for the tested SCC due to the increased viscosity (Kou and Poon, 2009).

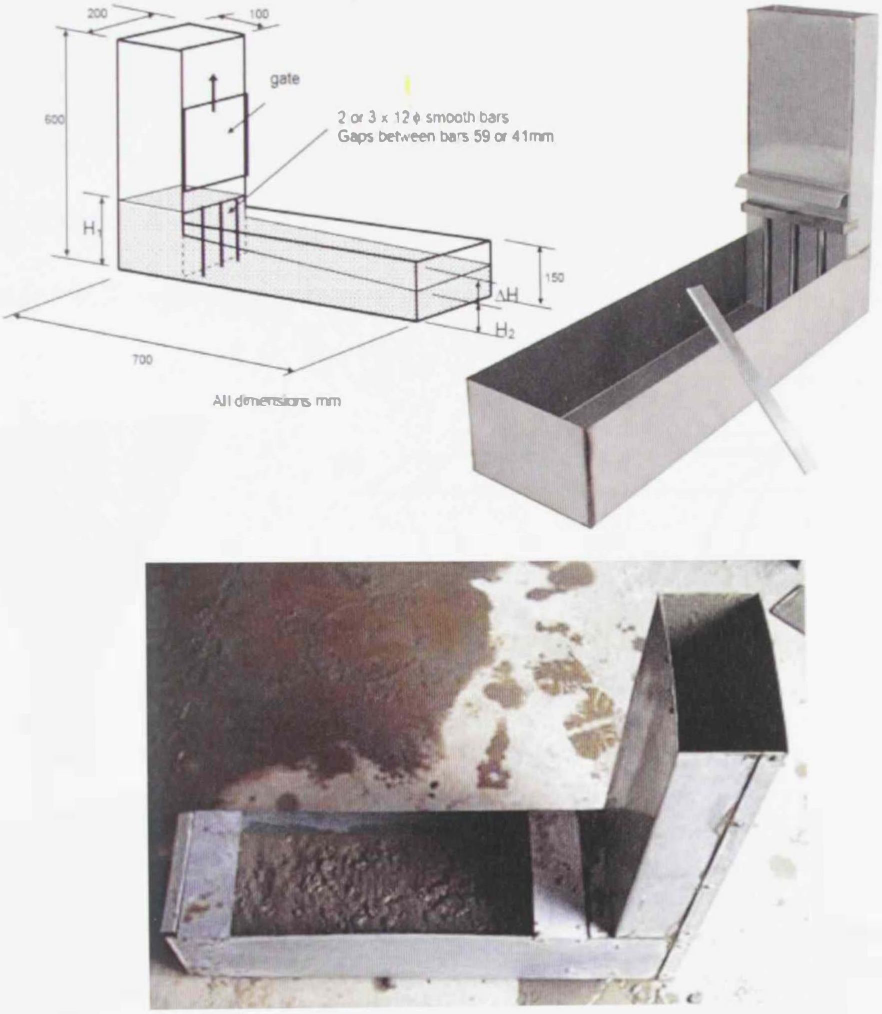


Figure 3-6: L-box apparatus

3.4.1.3 Viscosity

The V-funnel test provides means of evaluating viscosity, and filling ability of SCC for placement in highly congested reinforcement. The test procedure was done in accordance to EFNARC Guidelines. The apparatus is a V-shaped box, the assembly of the test setup is shown in Figure 3-7. Concrete was first poured into the gradually reducing funnel section through the wide opening at the top of the funnel till it's completely full and the surface was leveled with no tamping or rodding. A container was placed right below the funnel opening in order to collect the concrete that passes through the funnel during the test. The hinged gate shown in Figure 3-7is opened and simultaneously the stop watch was started. Time is recorded till it is possible to see the container through the upper funnel opening. The recorded time was denoted as the V-funnel flow time (T_v). It should be noted that this test is only applicable for SCC with aggregate size less than 20 mm.

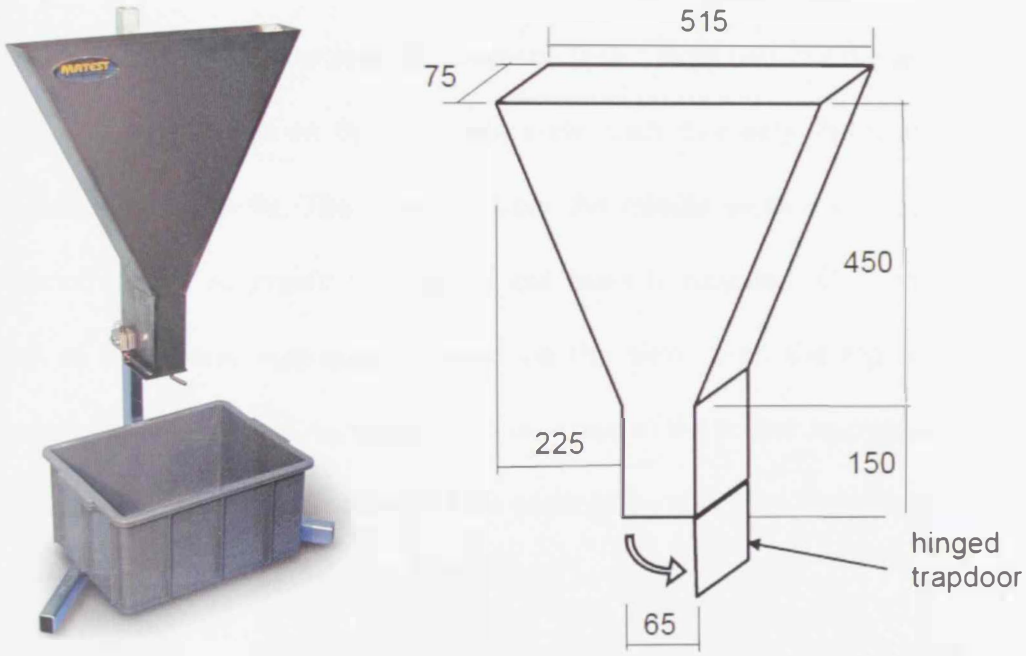


Figure 3-7: V-funnel apparatus

3.4.1.4 Segregation resistance (GTM segregation column)

According to ASTM definitions, the static segregation is "the settlement of coarse aggregates in an undisturbed mass of fresh concrete". Segregation is typically not preferable as it may lead to various problems both in the fresh (i.e. bleeding) and hardened (i.e. durability issues) stages of the concrete. The EFNARC limits the segregation to a maximum of 15 %. This test provides information on potential static segregation of the studied SCC. To perform the test, a portioned plastic column mould was used. This mold is divided into three sections generally named as: top, middle, and bottom sections. The test setup is demonstrated in Figure 3-8. Additionally, a 4.75 mm sieve is needed along with buckets and a weighing balance. A sample of freshly mixed homogeneous SCC was poured into the mould till its completely filled. The mould was left to stand undisturbed by any means of vibration or rodding for 15 minutes. A collector plate is inserted between the top and the middle sections to screed the concrete. The previous step is repeated between the middle and the bottom sections. Concrete collected from both the top and the bottom sections were washed on the 4.75 mm sieve such that only the coarse aggregate remained on the sieve. The concrete from the middle section was discarded. The collected coarse aggregate is weighed and mass is recorded. CA_T represented the mass of the coarse aggregate retained on the sieve from the top section of the concrete mould, while CA_B represented the mass of the coarse aggregate retained on the sieve from the bottom section of the concrete mould. The percentage of potential static segregation (S%) was calculated based on Eq. (1)

$$S = \begin{cases} 2\left[\dfrac{(CA_B - CA_T)}{(CA_B + CA_T)}\right] * 100, if\ CA_B > CA_T \\ 0, if\ CA_B \leq CA_T \end{cases} \qquad \text{Eq. (1)}$$

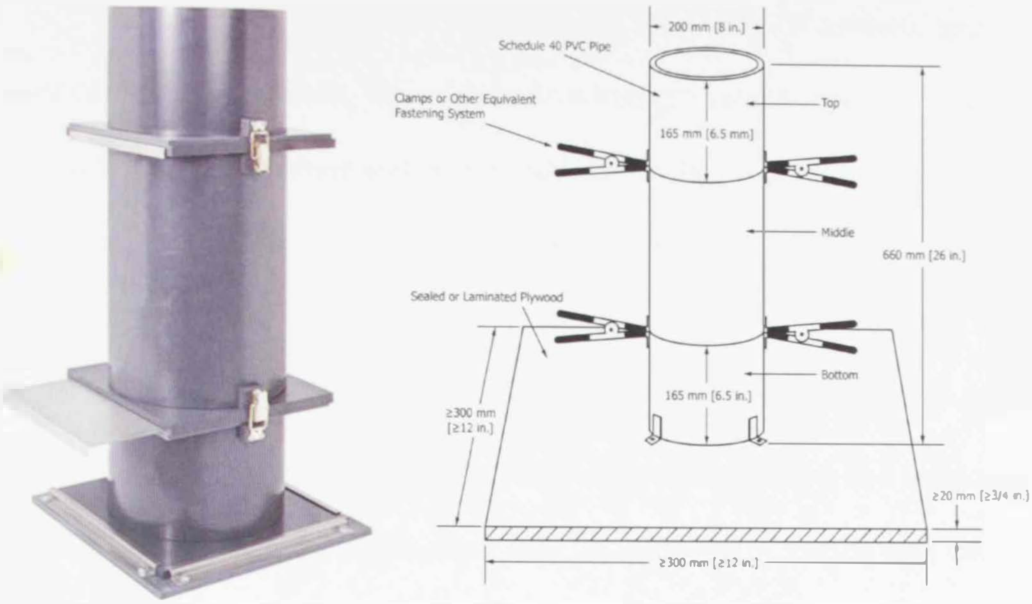


Figure 3-8: GTM segregation column apparatus

3.4.2 Hardened Concrete Properties

In addition to the fresh properties, hardened properties as well should be studied. They are considered as important as the fresh characteristics, as they are retained for the remainder of the life of the concrete. After concrete is removed from the mold and left to cure, it starts to gain its designed strength and durability. Hardened concrete is expected to be strong enough to carry the structural and service loads it is designed for as well as endure all the environmental conditions it might get exposed to. Hardened properties monitored during this study were mainly compressive strength and durability characteristics. Each of the following subsections will review conducted tests and procedure followed.

3.4.2.1 Compressive strength

The compressive strength test measures the ability of concrete specimens to resist compressive stresses. The compressive strength values depend primarily on the w/c ratio, aggregate texture and size, in addition to the properties of the cementitious materials used. The test was performed using WYKEHAM FARRANCE compressive testing machine with a loading capacity of 2000 kN shown in Figure 3-9 in accordance with BS EN 12390. Steel moulds were used and the interior faces were coated with oil for easier de-moulding. All tested specimens were 100 mm cubes that were de-moulded after 24-48 hours of mixing and left to moist cure until test dates. The compressive strength test was performed for all ten mixtures at four different test ages: 7, 28, 56, and 90 days. Specimen's dimensions were checked before conducting the test. During the test, the specimens were centrally aligned on the base plat of the machine in such a way that the finished surface was not loaded. The loading was continued until failure. Three cube specimens were tested at each specified test age and the average values were reported.

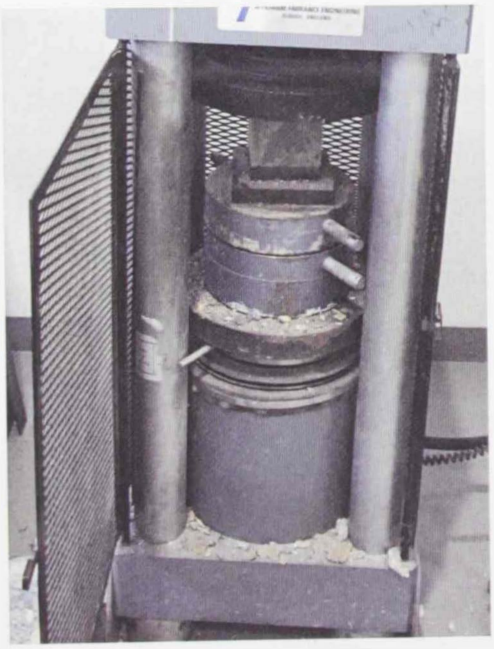


Figure 3-9: Compressive machine test

3.4.2.2 Ultrasonic pulse velocity (UPV)

UPV test was first applied to concrete by Obert in 1940 (Ramachandran and Beaudoin, 2001). It is a non-destructive test used to assess the homogeneity and integrity of concrete, in addition to judging the microstructural development in hardened concrete (Barluenga, Puentes, and Palomar, 2015). In this study, UPV test was conducted in accordance with the principles discussed in ASTM C597 and was performed on 150 mm cube specimens. Direct measurements were done on two cubes at each test age. Transit time (μs) of the impulse travelling from one side of the cube to the other through the tested concrete specimens was recorded. Generally, variation of results increases significantly with deteriorated concrete and with the presence of voids or cracks. Therefore, apparent velocity will be high for direct traversing or non-flaw concrete. Two transducers (transmitter and receiver), connecting wires, cylindrical calibration bar, time measuring device, and gel are required for performing the test. Before conducting the test on the concrete specimens, calibration was carried out. The transducers were positioned tightly along the ends of the calibration bar and the time taken for pulse to travel through the bar was set to 52 μs, to match the standard bar as shown in Figure 3-11 (a).

The transmitter and receiver probes are pressed against the concrete surface, and the time required for the ultrasonic pulse to traverse from transmitter to receiver was recorded. The concrete surface on which the probes was applied should be dried, and cleaned to remove any grits. A schematic diagram of the test is presented in Figure 3-10, and the actual test setup is shown in Figure 3-11(b). Two readings for each tested cube were measured. The pulse velocity was computed knowing the time and distance.

Higher velocity indicates better concrete in terms of uniformity and packing density. The interpretation of the results was based on the general guidelines for concrete quality as a function of the UPV commonly used by concrete researchers (Bilgehan, 2011); (Beycioğlu and Aruntaş, 2014); (Whitehurst, 1951). Table 3-10 shows the relation between pulse velocity and concrete quality.

Table 3-10: Quality of concrete as a function of the UPV (IS:13311 part 1-1992)

Velocity (m/s)	**Quality**
Below 3000	Doubtful
3000-3500	Medium
3500 to 4500	Good
Above 4500	Excellent

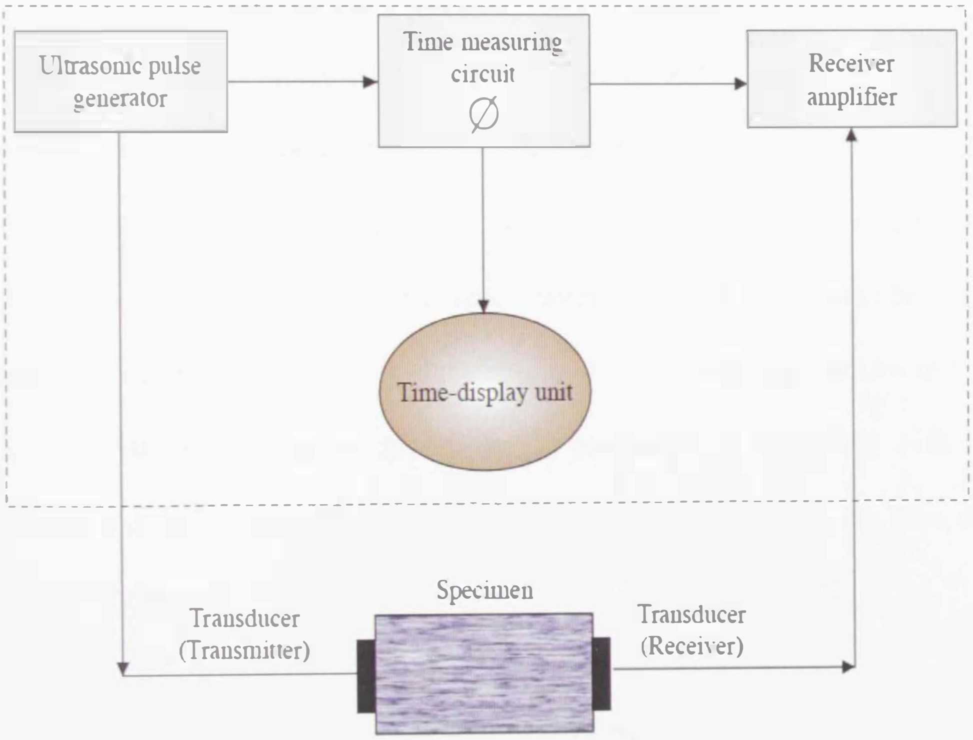


Figure 3-10: Schematic diagram of UPV test (Bilgehan, 2011)

(a) (b)

Figure 3-11: (a) Calibration bar (b) UPV apparatus used

3.4.3 Durability

Durability as stated in EFNARC-2005 guidelines is "the capability of a concrete structure to withstand environmental aggressive situations during its design working life without impairing the required performance". Therefore, good quality SCC is anticipated to resist all kinds of deterioration resulting from either external or internal causes besides its ability to sustain loads. All durability tests were conducted at 28 and 90 days of age to assess the development of durability with age. The durability characteristics of the produced SCC are evaluated using the tests described in the following sub-sections.

3.4.3.1 Rapid chloride permeability test

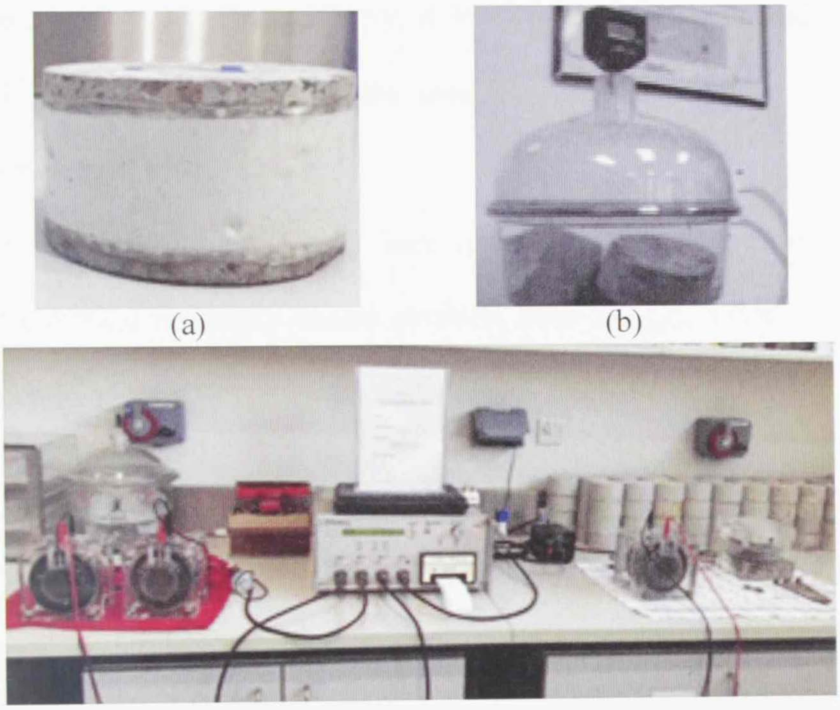
The durability of a concrete structure is greatly influenced by its permeability. A highly permeable concrete is more prone to the ingress of substances; this can lead to serious deleterious effects such as corrosion and loss in structure's integrity. Corrosion is caused by various substances, the most common of which is chloride ions. Corrosion has major negative effects on the serviceability of structures; and hence needs to be controlled. One approach is to limit the amount of soluble chlorides permeating through concrete. Rapid chloride permeability test (RCPT) examines the ability of the concrete to resist chloride ion permeation through concrete by measuring the total charge passed. The amount of charge passing depends on several factors, mainly the porosity of the concrete, and connectivity of the pores.

The test was first adopted in AASHTO T 277 and then was later on adopted by the ASTM C 1202. It is commonly used as it is practically easy and quick. Tested specimens were prepared in accordance with ASTM C1202 and at every test age (28 and 90 days) for each concrete mixture two specimens were tested and the average total charge was recorded. The apparatus used has 4 cells, where each cell accommodates one specimen of dimensions 100 mm in diameter and 50 mm thickness. Specimens were cut from 100 mm diameter cylinders with height 200 mm. The middle discs were selected to maintain homogeneity and avoid the possible variation in the top and bottom portions of the cylinders. To prepare the specimens for the test, the discs were coated along their circumference as shown in Figure 3-12(a), left to cure, and then vacuum saturated. The specimens were left under vacuum for 4 hours, then covered by de-aired water while still under vacuum. The vacuum was maintained for 3 additional hours and then released. The specimens were left under water for 18 ±1 as shown in Figure 3-12(b). Each cell consisted of two compartments where one was filled with sodium chloride solution (3% by mass) and the other was filled with sodium hydroxide solution (0.3 N molarity). A potential difference of 60V DC was maintained across the specimen ends and the total charge was measured at an interval of 15minutes over a period of 6 hours indicating the degree of resistance to chloride ion penetration. The test setup is shown in

Figure 3-12(c). The tested concrete mixtures were judged for the chloride ion permeability based on the charge passed according to ASTM C1202 as given in Table 3-11.

Table 3-11: Chloride ion permeability based on charge passed (ASTM C1202)

Charge passed (coulombs)	Chloride ion penetrability
> 4,000	High
2,000 – 4,000	Moderate
1,000 – 2,000	Low
100 – 1,000	Very low
< 100	Negligible


(a) (b)

(c)

Figure 3-12: RCPT steps; (a) coating. (b) vacuum saturation. (c) test setup

3.4.3.2 Electrical bulk resistivity

Concrete's electrical resistivity is mainly affected by several factors such as pore size and their connectivity as well as the moisture content. Various resistivity tests have been developed to assess the concrete protection against steel corrosion. Different instruments featured with easiness and non-destructiveness are being widely used, one of which is the Giatec RCON test that has been adopted in the study and is demonstrated in Figure 3-13. This electrical resistivity meter was used to measure the electrical resistivity of fully saturated 100 mm concrete cubes.

Concrete specimen was placed between two conductive plates to which fully soaked sponges were attached. Then the meter internally measured the voltage, and when combined with the applied current, resistance was calculated. Then the resistivity is determined using in Eq. (2).

$$\rho = \frac{A}{L} * Z \qquad \text{Eq. (2)}$$

Where ρ [Ω.cm] is the resistivity, A [cm^2] is the cross-sectional area of the specimen, L [cm] is the length of the specimen, and Z [Ω] is the impedance (resistance) measured by the device.

Corrosion protection for steel bars embedded in concrete can be judged through the electrical resistivity values obtained from Eq. (2). Table 3-12 presents the interpretation of the resistivity values as per ACI 222R-01 (2008).

Table 3-12: Corrosion protection based on concrete resistivity (ACI 222R-01, 2008).

Resistivity ($K\Omega.cm$)	**Corrosion protection**
<5	Low
5 – 10	Moderate - Low
10 – 20	High
>20	Very High

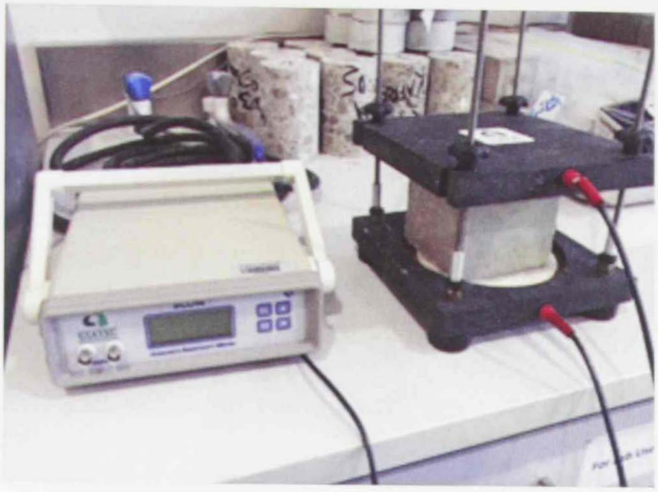


Figure 3-13: Concrete resistivity setup

3.4.3.3 Initial rate of absorption

It is a usual practice to determine the water permeability characteristics when examining the durability properties of hardened concrete. The basic principle of rate of absorption (i.e. sorptivity) was first introduced by Hall in 1977 where he explained that the cumulative absorbed volume per unit area of the inflow surface (m^3/m^2), named i, increases with the square root of the elapsed time as in Eq. (3):

$$i = st^{0.5} \qquad \text{Eq. (3)}$$

The typical sorptivity values for concrete obtained by Hall is presented in Table 3-13:

Table 3-13: Typical sorptivity values for concrete obtained by Hall (Ramachandran and Beaudoin, 2001).

W/C	0.4	0.5	0.6
Sorptivity (mm/min$^{0.5}$)	0.094	0.120	0.170

The sorptivity test was conducted in order to obtain the initial rate of water absorption of the concrete through determining the increase in the mass of a specimen exposed to water from one side over a certain interval of time. The test was done in accordance with ASTM C1585. Used specimens were discs from cast cylinders of 100 mm in diameter and approximately 50 mm in thickness. The preconditioning process followed was placing the discs in an oven at 110 ± 5 °C for about 24 hours before carrying out the test. Then the discs were removed from the oven to cool down to room temperature in a desiccator. Specimens' sides were sealed with vinyl electrician's tape to prevent absorption of water through the sides and to prevent evaporation of internal water. Then the specimens were placed over a metal support inside a container which was filled with tap water to a level of 3 mm above the metal support. The initial mass of the specimens after sealing was recorded. To start the test, the specimen was placed inside the container on the supports in such a way their bottom face was not immersed more than 3 mm inside the water as shown in Figure 3-14. As soon as the specimens came in contact with water, time was recorded using digital stop watch. The water rises through the specimen by capillary suction. The specimen was taken out of the container, surface dried with a towel, and its mass was recorded at intervals of 1, 2, 4, 9, 16, 25, and 30 minutes. Finally, the rate of initial absorption was determined by first calculating the penetration depth from Eq. (6), then plotting the obtained penetration depth against the square root of the elapsed time in a graph. The slope of the graph is the sorptivity (i.e. rate of absorption). While the intercept of the graph is considered to be affected by the surface finish that influences the open porosity of the inflow surface and therefore causes these pores to get filled with water at the beginning of the test (Ramachandran and Beaudoin, 2001).

$$i = \frac{\Delta W}{\gamma \, x \, A} \qquad \text{Eq. (4)}$$

$$i = B + s\sqrt{t} \qquad \text{Eq. (5)}$$

where; i (mm) is the penetration depth,

ΔW (gm) is the change in the specimen's weight. γ (gm/mm^3) is the water density.

A (mm^2) is the cross-sectional area.

B is the equation positive intercept.

s is the rate of absorption (i.e. sorptivity) [mm/min$^{1/2}$].

and t is the exposure time (min).

As per ASTM C1585. the regression coefficient of Eq. (5) shall not be less than 0.98. or else the test must be repeated as then the relation is not strongly linear.

Figure 3-14: Sorptivity test

3.4.3.4 Permeable pores

Porosity and in particular connected pores (i.e. permeable pores) is a significant factor which directly affects the durability of the concrete mixtures (Chopra and Siddique. 2015). The presence of voids is the main cause of concrete deterioration. as it allows the ingress of various aggressive species which adversely affect the durability of concrete. and hence the service life time of concrete. One way to judge the concrete's durability is through assessing the percentage of the pore space. especially the permeable ones.

According to ASTM C125. absorption is defined as "the process by which a liquid is drawn into and tends to fill permeable pores in a porous solid body: also. the increase in mass of a porous solid body resulting from the penetration of a liquid into its permeable pores". The aim of this test was to measure the percentage of connected voids in the hardened concrete. The test was divided into several parts, and was performed on concrete discs obtained from cast concrete cylinders. The specimens were 100 mm in diameter and approximately 50 mm in thickness. All cast concrete mixtures were tested for permeable pores at 28 and 90 days of age. The volume of the specimens had to confirm with the minimum requirements of ASTM C642. Then at each test age, specimens were oven dried for 24 hours at a temperature of 110°C after which they were left to cool down in a desiccator over silica gel till they reach room temperature (25°C). The dry mass of the specimens was recorded and denoted as W_{dry}. The specimens were then immersed in water for a period of 48 hours then their surface-dry mass was determined and denoted as W_{wet}. Then the specimens were boiled under water for 5hours and allowed to naturally cool to room temperature. Their masses were measured and designated as W_{boiled}. Finally, the specimens' mass under water was determined and denoted as $W_{submerged}$. The percentage of permeable pore spaces was calculated as per Eq. (6)

$$\% \text{ of permeable pores} = \frac{W_{boiled} - W_{dry}}{W_{boiled} - W_{submerged}} x100 \qquad \text{Eq. (6)}$$

3.4.4 Drying Shrinkage

During the experimental work of this study, drying shrinkage was assessed. It is mainly caused by the loss of water from the concrete to the atmosphere. Drying shrinkage is relatively slow and takes time (EFNARC, 2005). Typically, in SCC mixtures the volume of aggregates and maximum size are reduced, this reduction is counteracted by an increase in the paste volume leading to an increase in the drying shrinkage (Bhattacharya, 2008). Therefore, drying shrinkage is directly proportional to water/binder ratio and inversely proportional to the aggregate/cement ratio. For each studied mixture, two concrete prisms with square cross-sectional area were cast having dimension of (80 x 80 x 243) mm. Prior to mixing, two steel studs were tightened into the end plates of the steel molds. These studs act as the anchorage points where the hardened concrete prisms were fixed upon in the measuring device. The measured shrinkage was the linear shrinkage in the direction of the longitudinal dimension of the prism. After the prisms were removed from the curing tanks at the age of 14 days, they were left on racks in the laboratory with free circulation of air around the specimens. The length change between the two steel studs was measured using a length comparator. During the measurement, the specimens were placed in the length comparator and gently spun until three reading were taken. The measurements were documented till 150 days (almost 22 weeks) at different time intervals (every two to three days for a week, then the interval was increased to a week until four weeks and then once a month). Three measurements were recorded for each specimen within 10 minutes and the average was calculated.

Ambient conditions in the lab during the test period ranged from 40% to 60% for the relative humidity and 25-35°C for the temperature. The used mold and test setup are shown in Figure 3-15 and Figure 3-16 respectively. Once the length change was calculated, the shrinkage strain at 150 days was calculated using Eq. (7).

$$\text{Shrinkage Strain} = \left[\frac{L_f - L_{14}}{L_o}\right] \qquad \text{Eq. (7)}$$

Where: L_o = the initial length of the prism (243 mm),

L_f = the length at 150 days,

and L_{14} = the length of the prism at 14 days of age (when drying started).

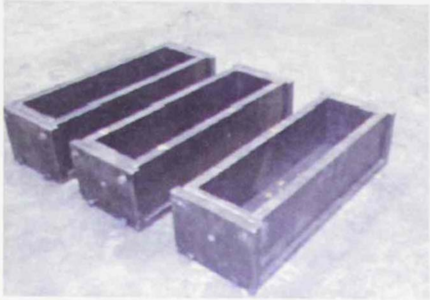


Figure 3-15: Drying shrinkage molds

Figure 3-16: Drying shrinkage test setup

Chapter 4: Results and Discussions

4.1 Introduction

The feasibility of incorporating CWP in SCC mixtures as filler and as partial replacement of cement was judged through studying the performance of the produced ten self-compacting concrete mixtures. The performance of concrete mixtures evaluated through interpreting the results of both the fresh and the hardened tests. During this study, fresh concrete was evaluated by conducting the following tests: slump flow, J-ring, L-box, V-funnel, and segregation resistance. Regarding the hardened concrete, the performance was evaluated through conducting typical hardened concrete tests: compressive strength, ultrasonic pulse velocity, drying shrinkage, and durability tests (i.e. RCPT, resistivity, sorptivity, and permeable pores). The following sections are organized in a way that for any of the performed tests, the results from the addition group mixtures are provided followed by the test results from the replacement group mixtures.

4.2 Fresh Concrete Tests

This section is dedicated for presenting, interpreting, and discussing the fresh concrete test results. Fresh tests were chosen to ascertain the SCC attributes of the mixtures. The tests used were able to determine the filling ability, passing ability, and segregation resistance of the produced mixtures.

4.2.1 Slump flow

Unconfined flowability of the produced SCC mixture was assessed by the slump flow test. The results of the two concrete groups (i.e. addition group and replacement group) are presented in the coming sub-sections. The EFNARC 2005 specifications are shown in Table 4-1 for guidance.

Table 4-1: Classification for slump flow values (EFNARC, 2005)

Class	Slump-flow in mm
SF1	550 to 650
SF2	660 to 750
SF3	760 to 850

4.2.1.1 Addition group

The results of the slump flow test for the addition mixtures are presented in Table 4-2. As the amount of slag/ CWP increased in the mixture (100, 200, and 300 kg/m^3) the obtained slump flow diameter decreased with the exception of mixture A-S-200 where there was no substantial change. However, the decrease was not significant, as for the slag mixtures the decrease in slump flow values was 10%, while the decrease in the slump flow values of the CWP mixtures was 5%.

Table 4-2: Slump flow values of mixtures with slag and CWP as addition

Mixture	Slump flow diameter (mm)
A-S-100	785
A-S-200	795
A-S-300	715
A-C-100	735
A-C-200	715
A-C-300	695

Figure 4-1 illustrates the effect of incorporating slag and CWP on the slump flow of the SCC mixtures. From the figure it can be noticed that as the amount of slag or CWP increased in the mixture, the slump flow diameter decreased. This indicated a reduction in the flowability yet still within the range recommended by the EFNARC-2005 guidelines. All mixtures incorporating CWP were within the second class according to the EFNARC classifications (SF2, as per Table 4-1) which is applicable for many normal applications such as casting of walls and columns maintaining good surface finish characteristics and controlled segregation resistance. On the other hand, as the amount of slag increased, the mixtures showed tendency to move from slump flow class three (SF3, as per Table 4-1) to slump flow class two (SF2, as per Table 4-1). This implies that the set of mixtures containing slag would inherit better surface finish characteristics but the segregation resistance would be harder to control.

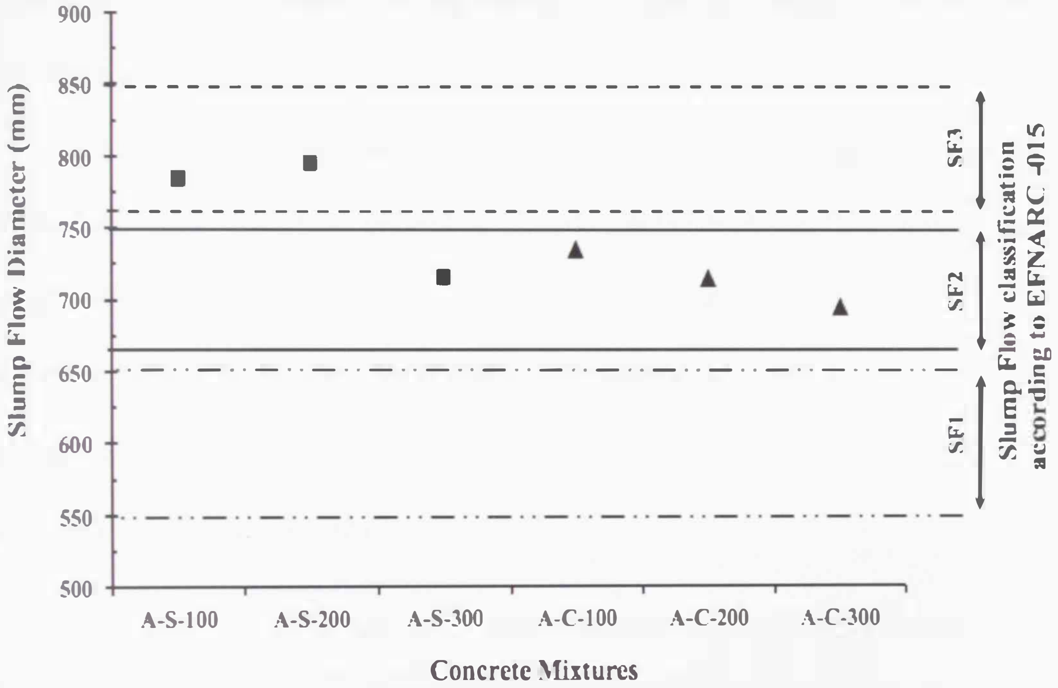


Figure 4-1: Slump flow results of mixtures with slag and CWP as addition

Both the slag and CWP mixtures exhibited similar behavior, as more filler was added to the mixtures, lower slump flow values were obtained. The reduction in the slump flow values can be attributed to the higher water demand due to the increase of SSA of the particles (from 380 m^2/kg for cement to 555 m^2/kg for CWP and 432 m^2/kg for slag). These results confirm with the results revealed by a study conducted to test the self-compacting concrete properties using slag as a partial replacement for aggregates and for cement (Sheen et al., 2015). In the study, the water to cementitious ratio (w/cm) was kept constant at 0.40 and initial amount of cement was 448 kg/m^3. These values are very close to the values used in producing the slag mixtures throughout this study: 450 kg/m^3 of cement and w/cm = 0.41. The study concluded that as the percentage of slag replacing cement increased (i.e. 0%, 10%, 20%, and 30%), the slump flow values obtained were decreased. Moreover, the angular shape of the CWP particles contributed to the reduction in flowability as it is believed to reduce the ability of the mixture to expand, leading to reduced slump flow diameters.

Viscosity of the concrete mixtures can also be judged through the slump flow test by measuring the time in seconds required to achieve 50 cm flow diameter (T_{50}). T_{50} was obtained once the concrete reached the 500 mm circular mark on the steel base plate. Table 4-3 shows the T_{50} values for all the addition group mixtures. All obtained values indicated satisfactory results based on the 2 to 5 seconds range by the EFNARC-2005 guidelines.

Table 4-3: T_{50} results for mixtures with slag and CWP as addition

Mixture	**T_{50} (seconds)**
A-S-100	5.3
A-S-200	2
A-S-300	4
A-C-100	5.34
A-C-200	3.01
A-C-300	4.96

4.2.1.2 Replacement group

The slump flow test was also conducted for the four mixtures in the replacement group and the measured diameters are shown in Table 4-4. It is clear that as the amount of cement being replaced by CWP increased, the slump flow decreased. The highest slump flow diameter recorded was for the control mixture (R-0) at 780 mm. A 7% decline in the slump flow diameter resulted as the amount of CWP in the mixtures increased from 0 to 300 kg/m^3.

Table 4-4: Slump flow of mixtures with CWP as cement replacement

Mixture	Slump flow diameter
R-0	780
R-100	770
R-200	745
R-300	725

Observing the changes in the slump flow diameters in Figure 4-2, it can be concluded that as the CWP replacement level increased, the slump flow values decreased. Despite the reduction, none of the CWP mixtures dropped to the slump flow class one (SF1, as per Table 4-1) which is critical in the presence of highly congested reinforced concrete structures.

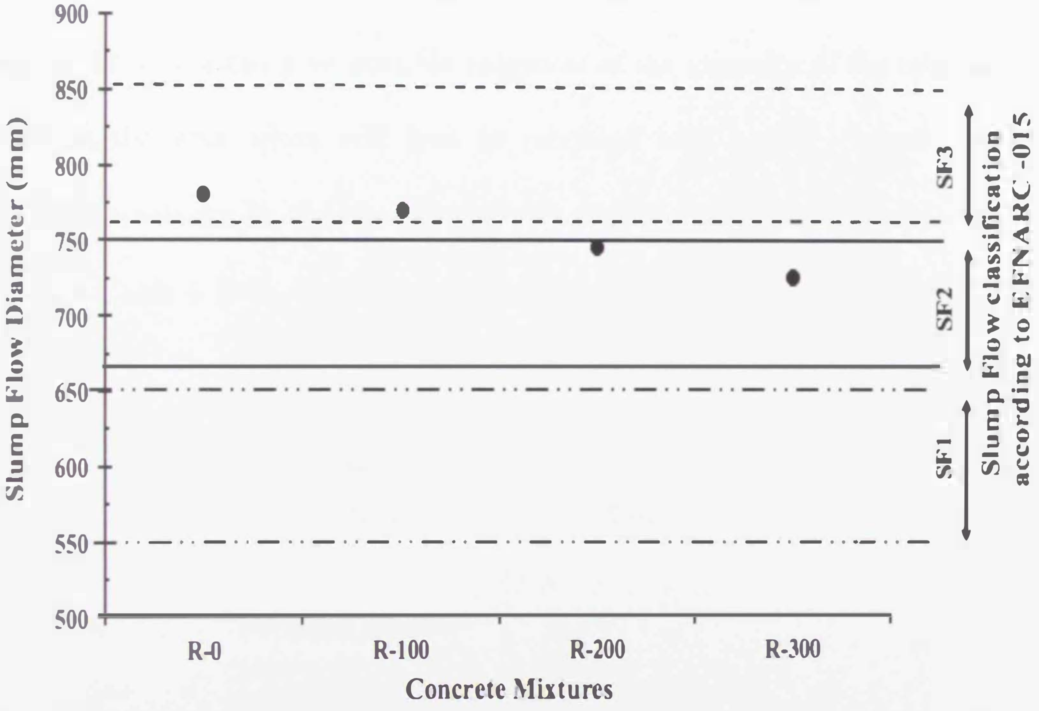


Figure 4-2: Slump flow results of mixtures with CWP as cement replacement

The trend shown in Figure 4-2 is the loss in the flowability of the studied mixtures as the level of CWP replacement increases. This loss is described through a decrease in the slump flow values. Similar results were obtained by Chopra and Siddique. (2015) when using rice husk ash (RHA) as cement replacement. The investigation has reported that there was a decrease in the flow with the increase in RHA content. The relatively higher SSA values of RHA and CWP compared to cement would increase the water demand and accordingly resulted in lower slump flow values (Pande and Makarande , 2013).

Likewise, a study of replacing cement with metakaolin that is characterized with a higher specific area compared to cement with irregular particle shape was conducted by Sfikas et al. (2014). The experimental results showed that as the replacement level increased, the slump flow values decreased.

In addition to the measurement of the slump flow diameter. The time taken for the concrete to completely fill the 500 mm circle on the steel base plate was measured. This time can give possible judgment of the viscosity of the mixture. An increase in the time taken will lead to mixtures with higher viscosity values. Table 4-5 presents the T_{50} values among the set of the replacement mixtures.

Table 4-5: T_{50} results for mixtures with CWP as cement replacement

Mixture	**T_{50} (seconds)**
R-0	2.68
R-100	2.47
R-200	3.24
R-300	4.04

4.2.2 J-ring

The test results will give indications on the passing ability of the produced SCC mixtures. In other words, how the SCC mixtures would function in a restricted environment resembled by the reinforcing bars of the J-ring. The values in Table 4-6 and Table 4-7 are the result of subtracting the obtained J-ring lateral flow diameter from the slump flow diameters obtained previously.

4.2.2.1 Addition group

According to the ASTM standard, the results provide means of determining the passing ability of the tested mixtures. Values in Table 4-6 show slight improvement in the CWP mixtures, as well as deterioration in the passing ability for the group of slag mixtures with the addition amount being increased. Mixtures containing 200 and 300 kg/m^3 of slag exhibited extreme blocking, while mixtures incorporating same amount of CWP experienced no blocking.

Table 4-6: Passing ability for mixtures with slag and CWP as addition

Mixture	Passing ability (mm)
A-S-100	40
A-S-200	70
A-S-300	60
A-C-100	25
A-C-200	20
A-C-300	20

Based on Figure 4-3 all mixtures containing CWP inherit good passing ability indicating no visible blocking. This suggests that these mixtures would perform very good in highly congested reinforced concrete structures or small size sections. A small degree of blocking was evident in the slag mixtures replacing 200 and 300 kg/m^3 of the cement. This could be improved by adjusting the amount of VMAs.

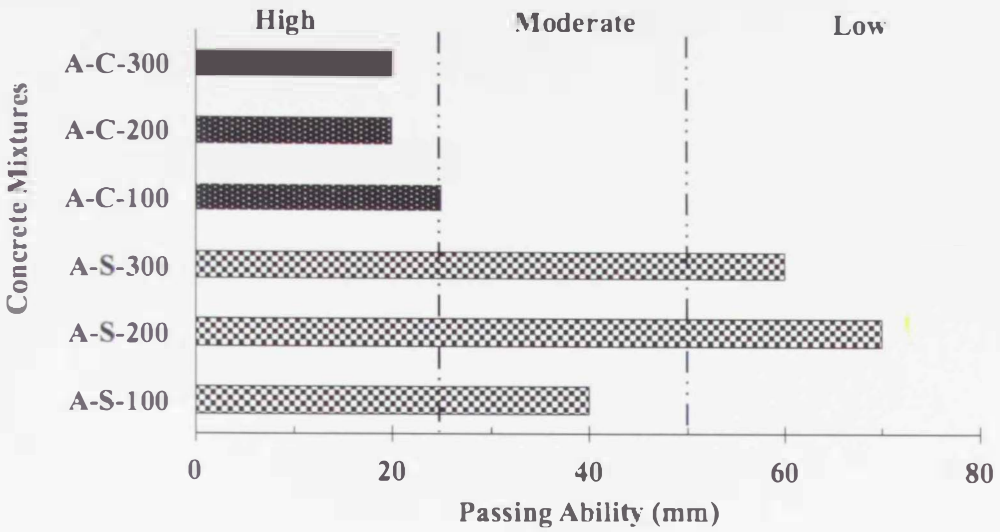


Figure 4-3: Passing ability of mixtures with slag and CWP as addition

4.2.2.2 Replacement group

Values in Table 4-7 revealed there was minimal to noticeable blocking in all mixtures. Mixtures which contained CWP have shown better performance than the control mixture in regards to the passing ability.

Table 4-7: Passing ability of mixtures with CWP as cement replacement

Mixture	Passing ability (mm)
R-0	50
R-100	45
R-200	30
R-300	25

An improvement in the passing ability was observed as the CWP replacement level increased. Figure 4-4 shows that as the CWP content increased, the mixtures exhibited a better passing ability and showed a greater capacity for flowing through congested spaces.

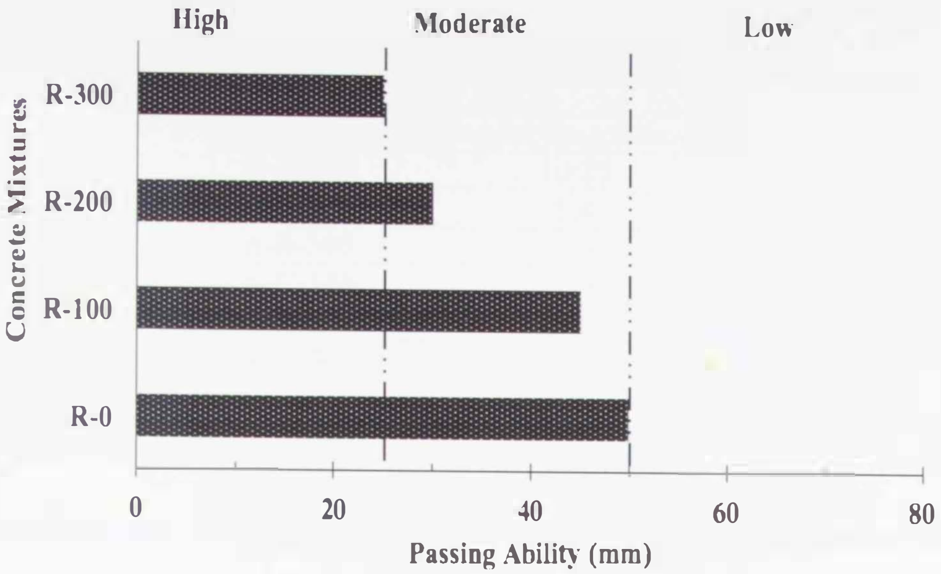


Figure 4-4: Passing ability of mixtures with CWP as cement replacement

4.2.3 V-funnel

The test forces the fresh concrete to flow through small cross sections and bounded spaces, and hence provides indications on the viscosity and filling characteristics of the mixture being tested. The output of the test (i.e. time value) is not directly the viscosity of the mixture but rather the rate of flow. The EFNARC 2005 specifications are shown in Table 4-8. VS represents the viscosity classes expressed by the T_{50}, while VF represents the viscosity classes expressed by the V-funnel time.

Table 4-8: Viscosity classes (EFNARC, 2005)

Class	T_{50} (seconds)	V-funnel time (seconds)
VS1/VF1	≤ 2	≤ 8
VS2/VF2	> 2	9 to 25

4.2.3.1 Addition group

From the results in Table 4-9, it can be noted that all the recorded V-funnel times for the six mixtures are within the range recommended by EFNARC guidelines.

Table 4-9: V-funnel times for mixtures with slag and CWP as addition

Mixture	V-funnel time (seconds)
A-S-100	10.25
A-S-200	5.4
A-S-300	7.9
A-C-100	10.6
A-C-200	6.2
A-C-300	9.69

SCC mixtures displayed acceptable V-funnel performance when they contained both slag and CWP at different amounts. The trend is similar with the addition of slag and CWP as shown in Figure 4-5. At 200 kg/m^3 of either of the addition materials, the recorded time is less than that at 100 kg/m^3 of addition. While at 300 kg/m^3, the recorded time increased but yet remains less than that recorded at 100 kg/m^3.

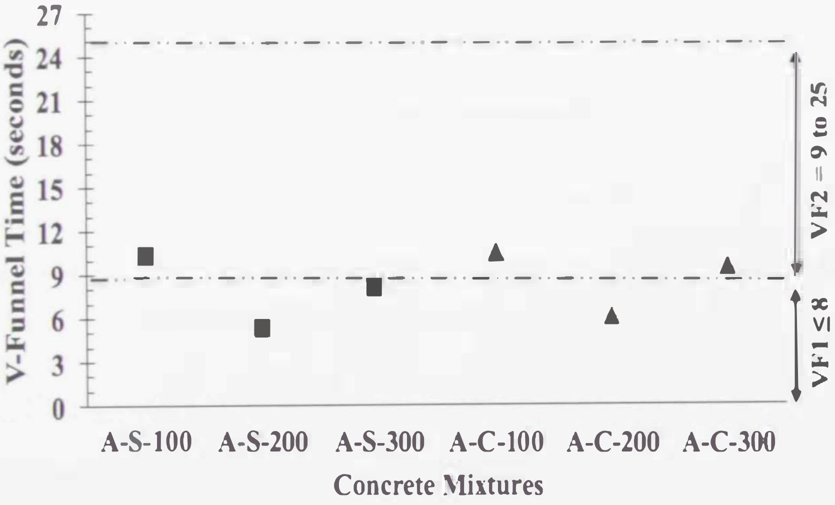
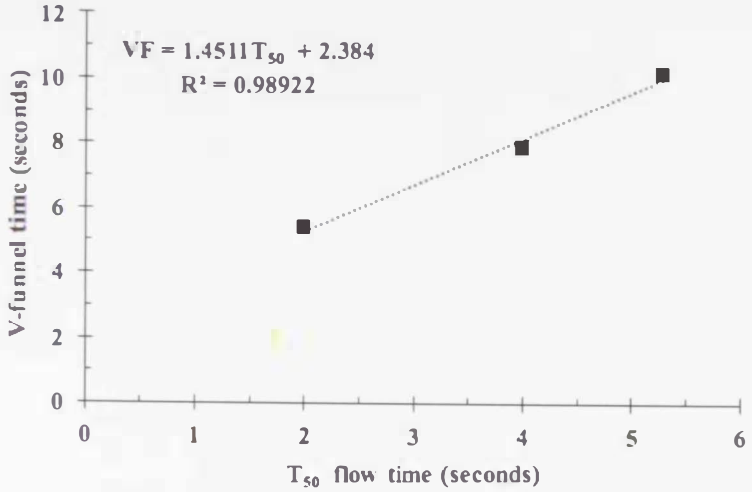
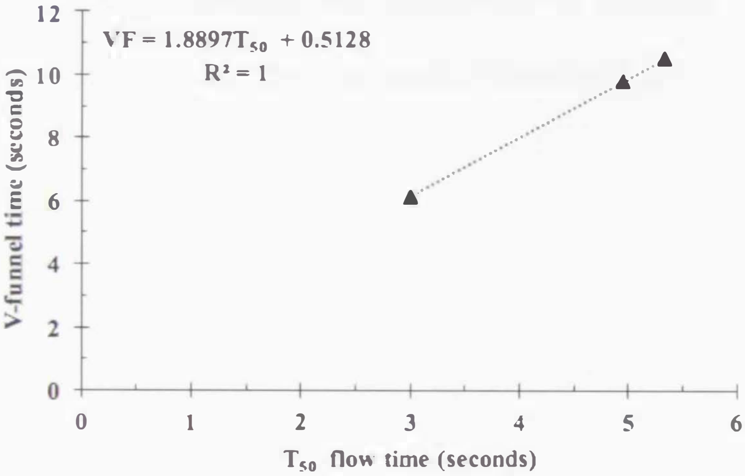


Figure 4-5: V-funnel time for of mixtures with slag and CWP as addition

The results of the V-funnel test are further verified by the very good correlation shown with the T_{50} time measured during performing the slump flow test. The relationship between the two tests is presented in Figure 4-6.



(a)



(b)

Figure 4-6: Correlation between the V-funnel time and the T_{50} in the addition group (a) slag mixtures (b) CWP mixtures

4.2.3.2 Replacement group

The recorded V-funnel times show an increasing trend, indicating a higher viscosity in the replacement mixtures. From Table 4-10, all times obtained correspond to the second viscosity class according to EFNARC specification, this indicates an improvement in the segregation resistance.

Table 4-10: Recorded V-funnel times for mixtures with CWP as cement replacement

Mixture	V-funnel time (seconds)
R-0	10.4
R-100	10.01
R-200	11
R-300	12.82

According to EFNARC-2005 guidelines, the viscosity of the mixtures is not acceptable only if V-funnel time exceeds 25 seconds. In this regard, all concrete mixtures were satisfactory. The V-funnel time shows a distinct tendency to increase as CWP % increases in the mixtures. This implies that the inclusion of CWP led to more viscous concrete and is clear from the results plotted in Figure 4-7.

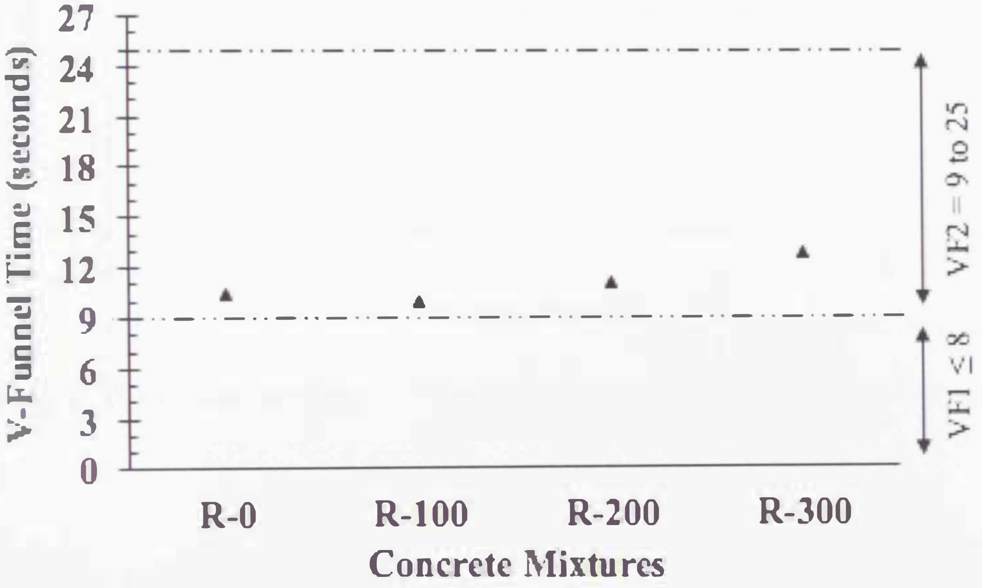


Figure 4-7: V-funnel time for mixtures with CWP as cement replacement

The recorded V-funnel times showed an increasing trend with the increase in CWP replacement level as shown in Figure 4-7. This indicated a higher viscosity of the mixtures with CWP replacement. All the measured V-funnel time correspond to the second viscosity class according to EFNARC specification; this indicated an improvement in the segregation resistance. Hence, the produced replacement mixtures were effective in obtaining stable mixtures with no segregation. According to EFNARC-2005 guidelines, the viscosity of the mixtures is not acceptable only if V-funnel time exceeds 25 seconds. In this regard, all concrete mixtures were satisfactory. As a way of confirming obtained results, the results of the V-funnel test results and the T_{50} time measured during performing the slump flow test are correlated and the results are presented in Figure 4-8.

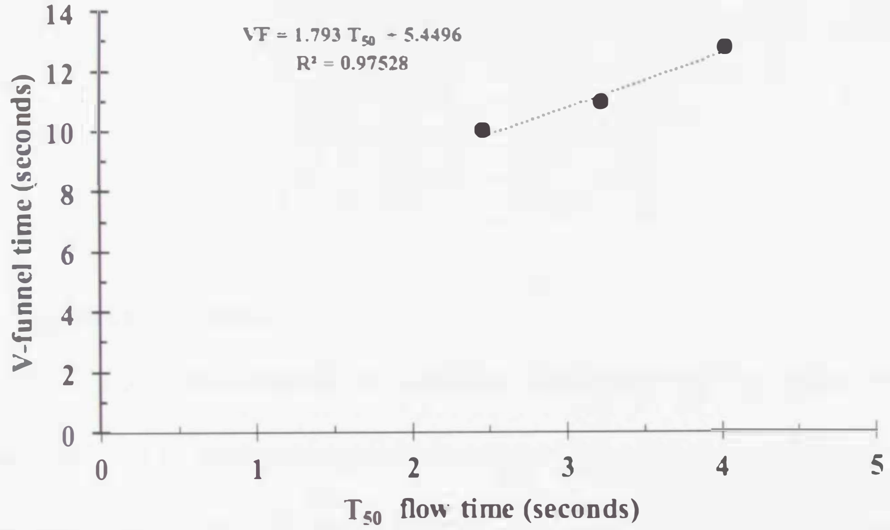


Figure 4-8: Correlation between V-funnel time and T_{50} in the replacement group

4.2.4 L-box

The test is used to evaluate the passing ability of SCC while flowing through small openings like highly congested reinforcements and other obstructions without experiencing blocking or segregation. Despite not being established as a standard; the L-box test is a widely used method for assessing the passing ability of SCC mixtures.

4.2.4.1 Addition group

Table 4-11 illustrates the blocking ratios of the addition group. The results varied from 0.86 to 0.97. Based on EFNARC guidelines, the blocking ratio must be between 0.8 and 1.0, and hence all of the produced SCC mixtures remained within the recommended range. Therefore, all addition mixtures satisfy the fresh behavior requirements related to passing ability.

Table 4-11: L-box ratio for mixtures with slag and CWP as additions

Mixture	L-box ratio
A-S-100	0.978
A-S-200	0.977
A-S-300	0.978
A-C-100	0.88
A-C-200	0.931
A-C-300	0.863

4.2.4.2 Replacement group

Table 4-12 demonstrates the blocking assessment of the replacement group mixtures. All four mixtures exhibited very similar blocking ratios with slight variation less than 1.5 %. The four mixtures showed no signs of blocking. Generally, the EFNARC suggests blocking risk if the blocking ratio is below 0.8. If the blocking ratio is less than 0.8, the viscosity of the mixtures becomes too high which can cause blockage around reinforcement. Based on the results, all replacement mixtures indicated very good passing ability and can be used in applications where flow through congested reinforcement is needed.

Table 4-12: L-box ratio or mixtures with CWP as cement replacement

Mixture	L-box ratio
R-0	0.963
R-100	0.966
R-200	0.977
R-300	0.967

4.2.5 Segregation Resistance

Segregation resistance is the ability of concrete to remain homogenous in composition in fresh state. Segregation is evaluated through the GTM segregation column test. It can be also judged visually during the slump flow test, as when segregation occurs, accumulation of coarse aggregate takes place at the center with the existence of a halo of water around the flowing concrete. The EFNARC 2005 specifications are shown in Table 4-13 with two classifications for the segregation resistance.

Table 4-13: Segregation resistance classes (EFNARC, 2005)

Class	Segregation resistance in %
SR1	≤ 20
SR2	≤ 15

4.2.5.1 Addition group

Table 4-14 presents the segregation % for the addition mixtures. It was obvious that as the addition amount of slag/CWP increased in the mixtures, the segregation % decreased. It should be noted that the set of mixtures containing CWP exhibited very small amounts of segregation even at low addition levels when compared to the slag mixtures. For instance, A-C-100 resulted in 5.61 % segregation which is less than the 6% produced by 300 kg/m^3 addition of slag in the A-S-300 mixture.

Table 4-14: Segregation % or mixtures with slag and CWP as additions

Mixture	Segregation %
A-S-100	18.45
A-S-200	14.63
A-S-300	6
A-C-100	5.61
A-C-200	5.59
A-C-300	1

Figure 4-9 shows that as the addition level of slag/CWP was increased in the mixtures, the segregation resistance was greatly enhanced. This phenomenon is typical when the powder content is generally increased, the viscosity is increased and accordingly results in lower segregation (Liu, 2011). The VMA is normally used to adjust mixtures' viscosity and enhance segregation resistance. Since CWP resulted in significant enhancement of the mixtures viscosity and segregation resistance, the VMA could be eliminated for the mix or its dosage reduced. This will result in more economic and low cost mixtures. Regarding the three mixtures with slag, relatively high segregation percentages were expected from the results of the slump flow test. Both A-S-100 and A-S-200 were assigned SF3 class in the slump flow test which suggests better surface finish with segregation resistance harder to control. All mixtures incorporating CWP were assigned segregation resistance class 2 (SR2, as per Table 4-13). This implied that CWP mixtures could be of great use in vertical applications especially when the flow distance is greater than 5 m.

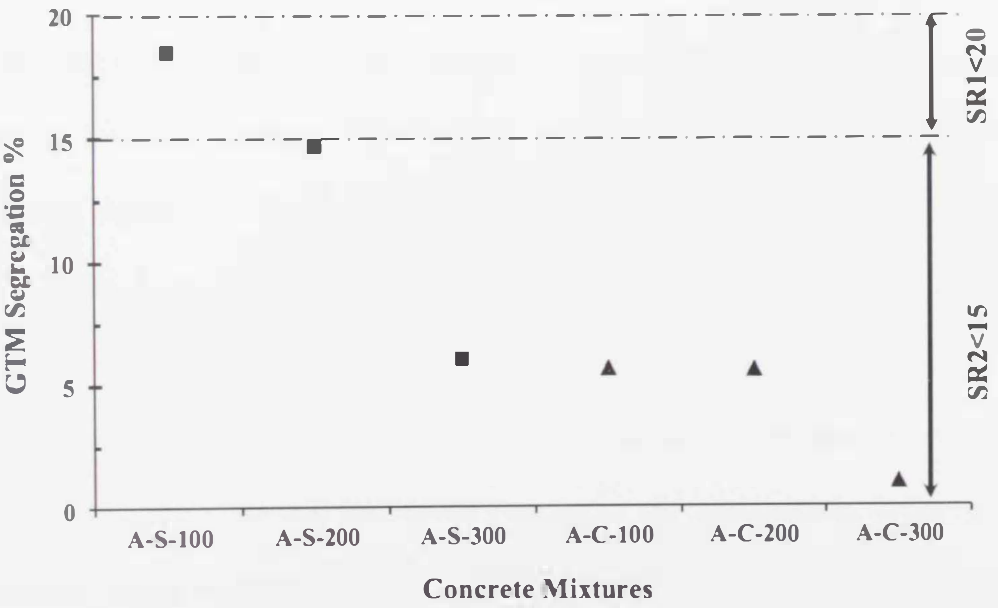


Figure 4-9: Segregation results for mixtures with slag and CWP as addition

4.2.5.2 Replacement group

Table 4-15 presents the segregation percentages of the replacement mixtures. The values indicated an inversely proportional relation between the amount of CWP replacing cement and the segregation percentage. As the CWP level increased in the mixtures, a significant improvement in the segregation resistance took place. This suggested that the introduction of CWP in SCC resulted in mixtures with better cohesiveness characteristics.

Table 4-15: Segregation % for mixtures with CWP as cement replacement

Mixture	Segregation %
R-0	12.49
R-100	8.57
R-200	7.21
R-300	3.44

Figure 4-10 presents the segregation resistance assessment results for the SCC mixtures as predicted by the GTM segregation column test. The results indicated that all of the segregation was below 15% which signified that the SCC mixtures were superior in terms of segregation resistance. Lachemi et al. (2007) related segregation resistance to viscosity, it was stated that higher viscosity can result in lower segregation. This trend is confirmed with the V-funnel test results shown in Figure 4-7. As the amount of CWP increased in the mixtures (from 0 to 300 kg/m^3), the segregation resistance was enhanced by 72.5%. The substantial enhancement in the segregation resistance can be explained by the fact that the water adsorption of the CWP particles may induce suction forces possibly leading to cluster formation. This will lead to an increase in the inter-particle bonds as in the clustering theory enhancing the segregation resistance as in RHA mixtures studied by Le and Ludwig (2016).

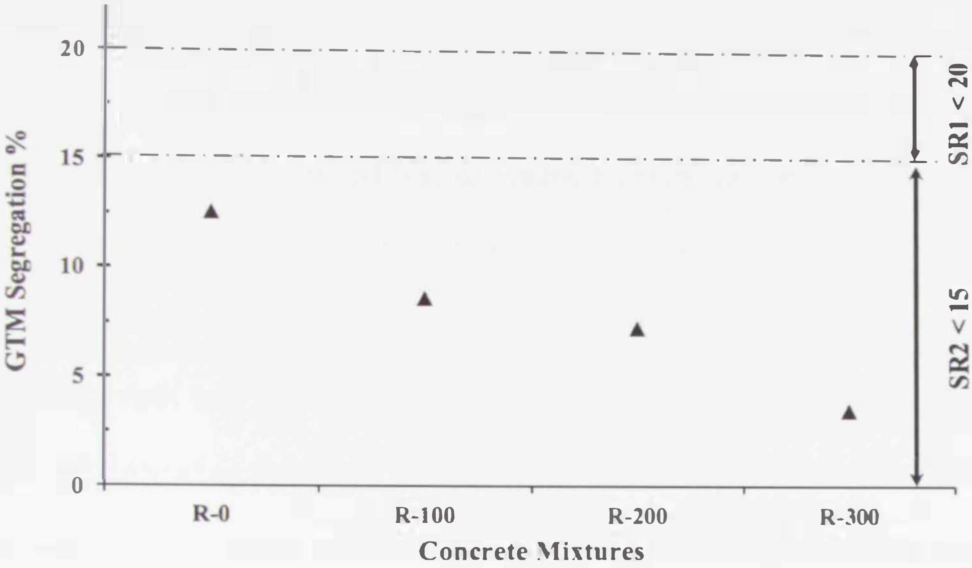


Figure 4-10: Segregation results for the replacement group

4.2.6 Concluding Remarks

Several conclusions were drawn out on the performance of SCC utilizing CWP at the fresh stage. The main findings are summarized below based on the test results discussed earlier:

- The relation between the amount of slag and CWP was inversely proportional to the flowability of the studied SCC mixtures in both the addition and the replacement groups. Both materials reduced the unconfined flow of the SCC mixtures. Despite this adverse effect, all mixtures showed good deformability under their own weight.
- The decrease in flowability was not significant, as the slump flow values decreased only by 10% and 5% in the mixtures with slag and CWP as addition respectively.
- No segregation or bleeding was observed at the periphery of the slump flow.
- Each SCC mixture investigated in this present study exhibited adequate filling ability, as all measured slump flow values ranged from 695 mm to 795 mm.

- J-ring test results indicated that the mixtures prepared in this study achieved adequate passing ability. As the amount of CWP increased in the mixtures, the passing ability was improved (i.e. no visible blocking in A-C-100, A-C-200, A-C300, and R-300 mixtures). Therefore, CWP mixtures are expected to maintain sufficient resistance to segregation around congested reinforcement areas.
- Values greater than 0.96 were achieved by all the replacement mixtures in the L-box test, indicating very good passing ability suggesting that these mixtures were suitable for applications where flow through congested reinforcement is needed.
- Results of V-funnel test were further verified by the very good relation with T_{50} time measured during the slump flow test.
- Column segregation test values varied from 1% to 18.45%, with the lowest being achieved by the highest CWP replacement levels (i.e. A-C-300 = 1%, and R-300 = 3.44%), implying a significant enhancement in the segregation resistance.
- Similar rheological behavior, in terms of viscosity/segregation resistance, was obtained; as amount of CWP increased in the mixtures, the viscosity was increased, and the segregation resistance was greatly enhanced.
- Due to the low specific gravity of CWP compared to cement, mixtures with CWP would contain higher paste volume causing a reduction in the friction between the aggregates and the paste interface, and thus improving the cohesiveness and plasticity, leading to improved SCC flowability characteristics.
- The VMA is normally used to adjust mixtures' viscosity and enhance segregation resistance. Since CWP resulted in significant enhancement of the mixtures viscosity and segregation resistance, the VMA could be eliminated for the mix or its dosage reduced. This will result in more economic and low cost mixtures.

- CWP has potential for producing high-performance self-compacting concrete with satisfactory fresh state properties according to the criteria established by EFNARC-2005 specifications and ASTM standards.

4.3 Hardened Concrete Properties

Mechanical properties such as compressive strength, drying shrinkage, ultrasonic pulse velocity in addition to durability characteristics (sorptivity, RCPT, absorption), and electrical resistivity were evaluated. All findings are presented in the coming subsections.

4.3.1 Compressive Strength

Strength is considered the property most valued by designers and engineers. The compressive strength of concrete is mainly affected by the cement hydration process. Strength is measured at four different test ages (7, 28, 56, and 90 days) in order to account for the changes in the concrete structure. These changes happen due to variations in the hydrated cement paste and the transition zone that are prone to alterations with time and different ambient conditions (Mehta, 1986).

The strength values presented in Table 4-16 and Table 4-18 were obtained by taking the average of three specimens for each concrete mixture at the test age. The variation in the obtained values in the three replicates can be associated to the quality control followed during the casting and testing of the mixtures. According to "Specifications for structural concrete–ACI 301-05", the coefficient of variation (COV) within the test results for batches cast in the laboratory with a "good" class of operation should not exceed 4%. The COV is simply the standard deviation divided by the mean, and it is a measure of the relative variability for a given data set. It helps to judge the reproducibility of measurements on replicates in any test results. The results are presented and discussed as follows:

4.3.1.1 Addition group

Table 4-16 shows the compressive strength values obtained for the addition mixtures. The calculated coefficient of variance of the three strength values the average is presented in Table 4-17. It should be noted that the COV values for all tests ranged from 0.55% to 2.84% which indicated good control.

At 7 days of age, both A-S-100 and A-C-100 achieved the highest measured compressive strength value among the six addition mixtures at 50 MPa. On the other hand, the lowest early age strength was attained by the A-C-300 mixture at 23.1 MPa. As the mixtures undergone prolonged moist curing till the specified test age, the microstructure of concrete started developing and influencing the strength development. This effect was noticed at later ages. The highest 90 days' strength was achieved by the A-S-100 and A-C-100 mixtures at 73 MPa and 73.8 MPa respectively. Compressive strength test was also conducted at 28 and 56 days. The 28 days' strength values are considered as a datum, from which percentage gain in strength at the two later ages (56 and 90 days) was calculated. At 56 days of age, mixtures A-S-100 and A-C-100 continued to achieve similar strength values of 71.9 and 71 MPa respectively. From Table 4-16 and Figure 4-11, the highest percentage gain at 56 days was found to be in mixture A-C-300 (32.6%). Similarly, the same mixture revealed the highest percentage gain at 90 days (47.96%). It is worth mentioning that the percentage gain in the set of CWP mixtures at both 56 and 90 days exceeded that of the mixtures containing slag. The percentage gain at 90 days of age for the slag mixtures and CWP mixtures were (8.9%. 22.0%. 17.6%) and (15.3%. 23.0%. 47.9%) respectively. This could be attributed to the fact that any pozzolanic material are slower in developing strength (Mehta. 1986). and therefore. at later ages. the percentage gain in strength for slag and CWP mixtures considerably higher than those at 28 days of age.

Table 4-16: Average compressive strength for mixtures with slag and CWP as addition

	Test Age	**Mixtures**					
		A-S-100	**A-S-200**	**A-S-300**	**A-C-100**	**A-C-200**	**A-C-300**
Compressive strength (MPa)	**7 Days**	50	33.2	32.4	50	36.6	23.1
	% change at 7D from control	-	-33.6	-35.2	0	-26.8	-53.8
	28 Days	67	50.8	50.3	64	52	39.2
	% change at 28D from control	-	-24.18	-24.93	-4.48	-22.39	-41.49
	56 Days	71.9	58	56.1	71	61.5	52
	% change at 56D from control	-	-19.33	-21.97	-1.25	-14.46	-27.68
	% change at 56D from 28D	7.31	14.17	11.53	10.94	18.27	32.65
	90 Days	73	62	59.2	73.8	64	58
	% change at 90D from control	-	-15.07	-18.90	1.10	-12.33	-20.55
	% change at 90D from 28D	8.96	22.05	17.69	15.31	23.08	47.96

Table 4-17: Coefficient of variance of compressive strength values for mixtures with slag and CWP as addition

Mixtures	Coefficient of variance (%)			
	7 Days	28 Days	56 Days	90 Days
A-S-100	0.90	2.59	1.41	1.37
A-S-200	2.30	1.83	2.59	2.50
A-S-300	2.84	1.52	1.08	2.05
A-C-100	2.65	2.07	0.70	2.74
A-C-200	0.55	1.67	2.44	2.07
A-C-300	2.39	1.47	0.96	2.59

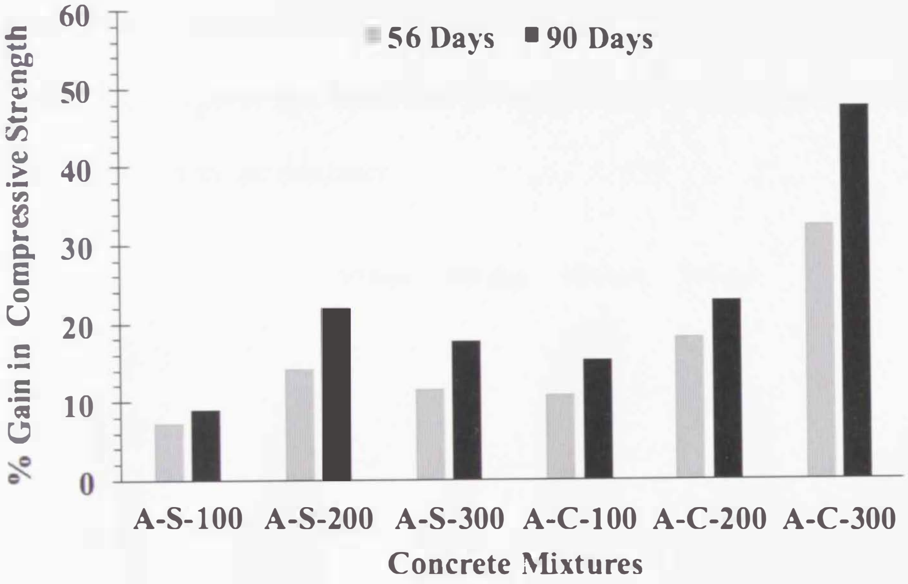


Figure 4-11: Percentage gain in compressive strength

Figure 4-12 illustrates the compressive strength results for the CWP and slag in the addition group. It's obvious that as the addition level increased, the strength values decreased for both materials. This can be attributed to the fact that the cement is being replaced, which is the cementing component responsible for strength development. The high strength obtained at 90 days for CWP can be explained by its physical properties, where its SSA (555 m^2/kg-using Blaine method) is 1.5 times that of cement allowing it to act as a micro-filler. In addition to this, its chemical composition and in particular its high content of SiO_2 and Al_2O_3 contributed in the activity not only as a filler but partially as a binder due to potential pozzolanic characteristics. A pozzolan is defined as "a siliceous and aluminous material which in itself possesses little or no cementitious value but which will in finely divided form and in the presence of moisture chemically react with calcium hydroxide (CH) to form compounds possessing cementitious properties". Consequently, on the contrary of pozzolans, slag is self-cementing, and hence the formation of C-S-H doesn't require CH. Nevertheless, if slag is to be used by itself, the amount and rate of the production of hydrated cementitious products might not be sufficient (Mehta, 1986). This could explain the reduction in compressive strength as the amount of slag highly increased in the mixtures.

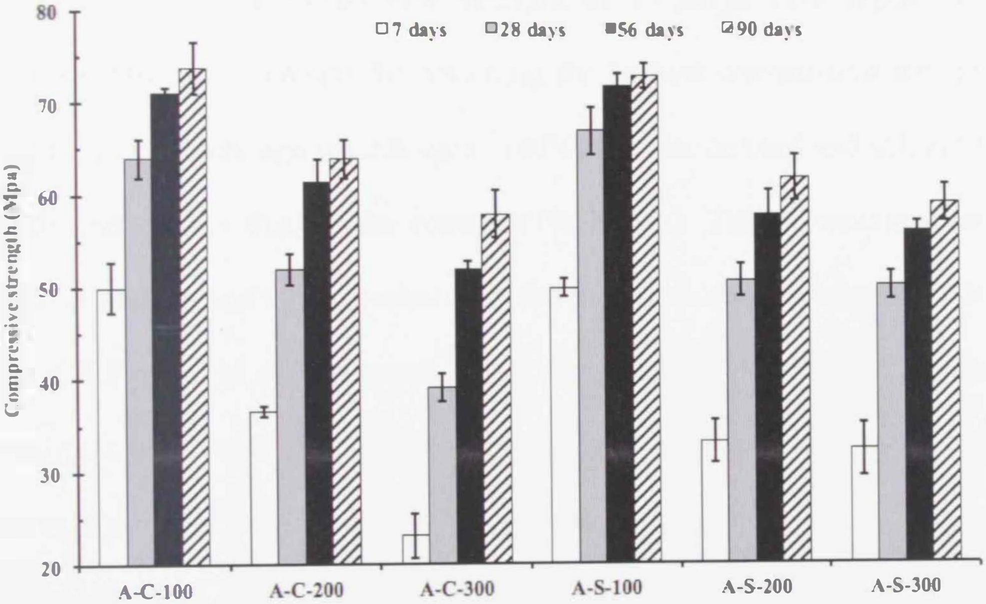


Figure 4-12: Compressive strength for mixtures with slag and CWP as addition

4.3.1.2 Replacement group

Table 4-18 shows the compressive strength values for the replacement mixtures. The calculated coefficient of variance of the three strength values is presented in Table 4-19. The COV values indicated good control. At 7 days of age, the control mixture (R-0) acquired the highest strength, while the remaining three mixtures showed a decreasing trend. After 28 days of age, mixture R-100 achieved the highest strength at 84.3 MPa which is 7% higher than that of the control mixture at the same age. However, the mixture with the least developed strength at 28 days was R-300, the mixture with the highest replacement level. When the mixtures were tested at 56 days, the gain in strength compared to that at 28 days was calculated. Regarding the control mixture, the gain in strength was marginal (3%) compared to the other replacement mixtures (7%, 10%, 9%) respectively. At later ages, the replacement mixtures started to achieve strength values higher than that of the control mixture. For instance, at 90 days, the highest compressive strength measured from this group of mixtures was 94.2 MPa for R-100. The second highest was mixture R-200 with a compressive strength of 90 MPa. This implies that the optimum replacement amount for obtaining the highest compressive strength was 100 kg/m^3 (20%), although the 200 kg/m^3 (40%) can also be used and still achieved a strength higher than that of the control (7% higher). The percentage change in strength at both 56 and 90 days relative to that at 28 days was calculated. At 56 days of age, CWP mixtures demonstrated similar strength gains of average 9%. Likewise, increasing compressive strength was evident between 28- and 90-days of age, however in a higher extent, with an average strength gain of 14%. The high strength gain from 28 to 90 days as opposed to 28 to 56-days curing signifies the CWP was mainly reactive at later ages. It can be concluded that mixtures encompassing CWP experienced relatively high strength gain percentages compared to the control mixture. This suggests that the reactivity of the CWP started at later ages indicating possible pozzolanic characteristics.

Table 4-18: Average compressive strength for mixtures with CWP as cement replacement

	Test Age	Mixtures			
		R-0	**R-100**	**R-200**	**R-300**
Compressive strength (MPa)	**7 Days**	66	61	50.3	41.8
	% change at 7D from control	-	-7.58	-23.79	-36.67
	28 Days	78.3	84.3	77.5	68.7
	% change at 28D from control	-	7.66	-1.02	-12.26
	56 Days	81	91	86	75
	% change at 56D from control	-	12.35	6.17	-7.41
	% change at 56D from 28D	3.45	7.95	10.97	9.17
	90 Days	84	94.2	90	79
	% change at 90D from control	-	12.14	7.14	-5.95
	% change at 90D from 28D	7.28	11.74	16.13	14.99

Table 4-19: Coefficient of variance of compressive strength values for mixtures with CWP as cement replacement

Mixture	Coefficient of variance (%)			
	7 Days	**28 Days**	**56 Days**	**90 Days**
R-0	1.52	1.95	2.47	1.03
R-100	0.00	1.37	1.10	1.11
R-200	3.03	1.94	1.01	0.56
R-300	4.10	3.03	1.33	1.10

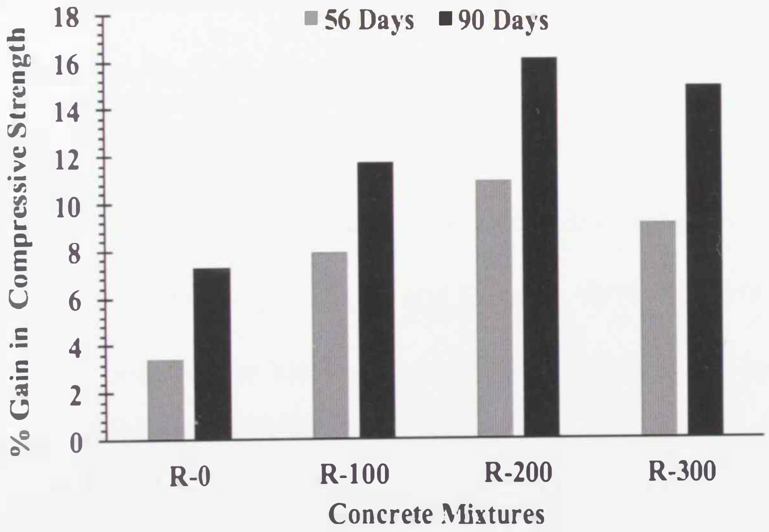


Figure 4-13: Percentage gain in compressive strength

A sufficiently reduced water/cementitious ratio (0.35) compensated by the use of admixtures produced concretes that can have an ultimate compressive strength in excess of 70 MPa. Figure 4-14 shows the strength development among the four replacement mixtures. At 7 days of concrete age, the highest compressive strength value achieved was for mixture R-0 (66 MPa). This strength value is due to the high amount of hydration products produced due to the presence of high cement content. As this amount of cement decreased gradually, the early age strength decreased. After 90 days of age, the mixtures incorporating CWP acquired higher strength values compared to the control mixture (R-0). This trend was maintained up to the replacement level of 200 kg/m^3, after which any additional replacement resulted in strength values lower than that of the control mixture. Here the role of CWP might be better understood not just as filler but also as a binding material enhancing concrete strength. The best performance occurred at the 100 kg/m^3 replacement due to CWP physical nature contributing through a dense packing effect improving the microstructure. Voids are detrimental to strength and hence refinement in the pore system would positively influence the strength. The increase in the strength might be also explained through the nucleation sites (nucleation of CH around the CWP particles) and dilution effect resulting from the inclusion of CWP. The powder resulted in a more homogeneous densely packed concrete mixture due to its pozzolanic reaction and the cement hydration acceleration similar to the effect of RHA observed in another investigation (Le and Ludwig, 2016). Moreover, the high fineness of CWP is believed to allow its particles to increase the reaction with calcium hydroxide (CH) to give more calcium silicate hydrate (C-S-H) resulting in higher compressive strength. On the other hand, the decrease in compressive strength in R-300 might be due to the fact that the amount of silica (from CWP) was too high and the amount of the produced CH as a cement hydration product was most likely insufficient to react with all the available silica and as a result some amount of silica was left without chemical reaction. This trend was similar to the results obtained using RHA as a cement replacement (Chopra and Siddique. 2015)., the measured strength values decreased at 20% replacement. The justification for strength reduction was similar to that explained for the reduction in CWP mixtures as the replacement percentage increased (Chopra and Siddique. 2015).

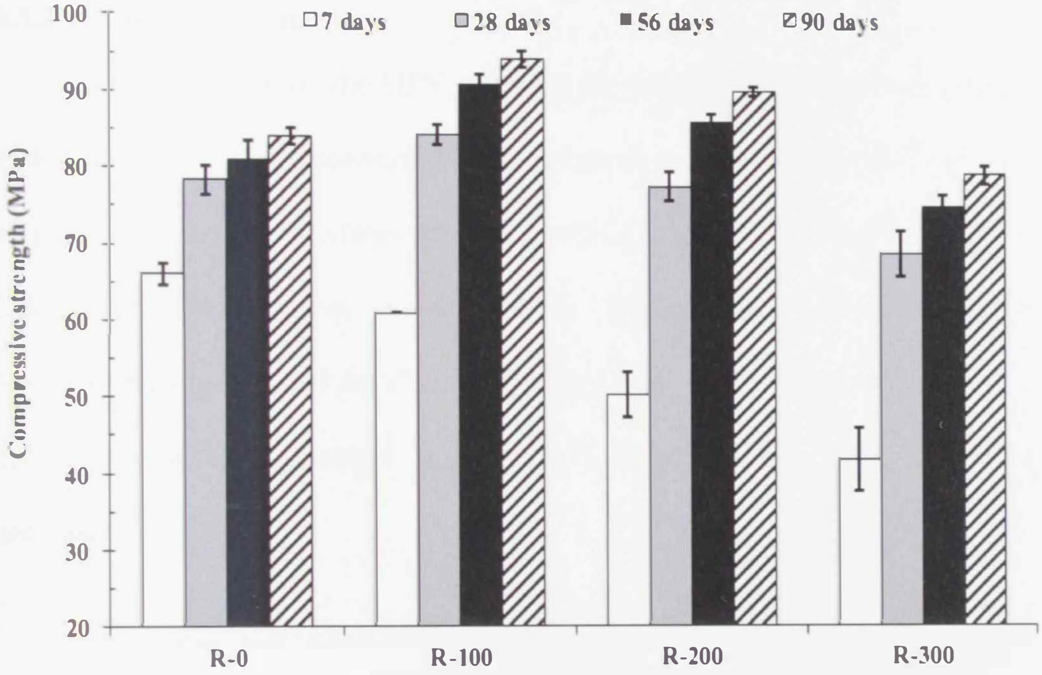


Figure 4-14: Compressive strength for mixtures with CWP as cement replacement

4.3.2 Ultrasonic Pulse Velocity

The UPV test objective was to measure the velocity at which a wave propagates through the hardened cement paste and aggregates providing indications on the tested concrete's homogeneity and integrity. Generally. there had been attempts to associate the pulse velocity data with SCC strength. but unfortunately.

have not been successful (Bzeni and Ihsan, 2013) (Samarin and Dhir, 1984). It was, therefore, recommended that this method was only used for the purpose of quality control. Table 4-20 shows the concrete quality associated with different UPV values.

Table 4-20: Concrete quality as a function of the UPV (IS: 13311 part 1-1992)

Velocity (m/s)	Quality
Below 3000	Doubtful
3000-3500	Medium
3500 to 4500	Good
Above 4500	Excellent

4.3.2.1 Addition group

Table 4-21 shows the UPV values at 28 days and 90 days of age for mixtures with slag and CWP. All measured UPV values were greater than 4500 m/s and thus, all produced concrete mixtures can be classified as excellent. This implies that both CWP and slag mixtures were perfectly homogenous and self- compacted. Noteworthy, when the 90 days' results of the addition group are compared, it shows that as the addition amount of slag/CWP increased, the UPV results slightly decrease.

Table 4-21: UPV results for mixtures with slag and CWP as addition

	Mixtures											
	A-S-100		A-S-200		A-S-300		A-C-100		A-C-200		A-C-300	
Age (Days)	28	90	28	90	28	90	28	90	28	90	28	90
UPV (m/s)	4910	4930	4770	4760	4760	4530	4930	4780	4550	4670	4600	4680
Concrete Quality	Excellent											

4.3.2.2 Replacement group

UPV is affected by the changes in the hardened cement paste such as change in the w/cm ratio. This is better understood by comparing the results of the replacement group to those of the addition group. The UPV values in the replacement group are relatively higher which could be explained by the lower w/cm ratio (0.35) and higher powder content (500 kg/m^3). UPV is related to the density of the constituent materials, and since the density of the mixtures decreased as the CWP percentage increases (specific gravity of CWP is less than that of cement), the UPV values were expected to be lower. This agrees with the results of Uysal and Sumer (2011), where fly ash (FA) was used as a cement replacement (15%, 25%, and 35%). As the amount of FA increased in the mixtures, the measured density was decreased leading to reduced UPV values. Results showed that all SCC produced with CWP had excellent quality according to the classifications. Table 4-22 and Figure 4-15 illustrate the UPV values for the mixtures with CWP as cement replacement at both tested ages (i.e. 28 and 90 days). It could be noted that at 28 days of age, the UPV followed a decreasing trend as the CWP amount increased. On the other hand, at 90 days of age, the reduction was very minimal, as there was not much difference between the mixtures except for mixture R-300 that resulted in a slight decrease in the UPV value. This could be attributed to the fact that with age the microstructure had developed resulting in more compact structure which could be the result of formation of C-S-H due to the late pozzolanic reaction of CWP.

Table 4-22: UPV results for mixtures with CWP as cement replacement

	Mixtures							
	R-0		**R-100**		**R-200**		**R-300**	
Age (Days)	28	90	28	90	28	90	28	90
UPV (m/s)	5020	5090	4930	4990	4750	5020	4780	4900
Concrete Quality	Excellent							

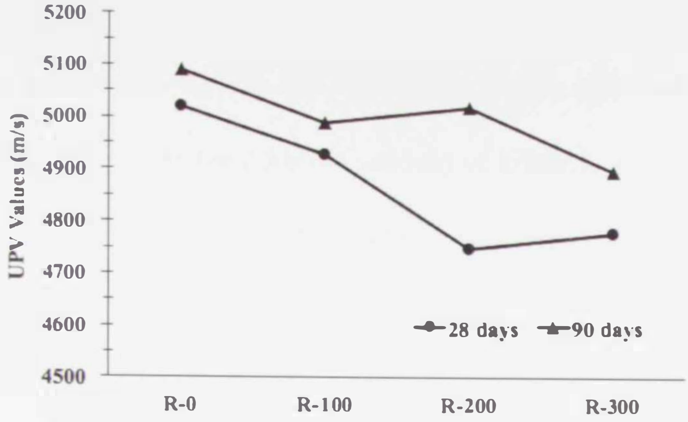


Figure 4-15: UPV results for mixtures with CWP as cement replacement

4.3.3 Electrical Bulk Resistivity

Bulk electrical resistivity of the concrete mixtures at each age were calculated as the average resistivity of three tested cubes. Several factors such as porosity, pore size distribution, connectivity, concrete's moisture content, and ionic mobility in pore solution affect the resistivity of concrete (Shahroodi, 2010). The resistivity test was conducted to assess the possibility of steel corrosion in concrete. It is a non-destructive test conducted by placing electrodes on the specimen surface. This involved at least two electrodes, where one of them could be the reinforcing bar in case of in-situ measurements (Polder, 2001). According to ACI 222R-01 (2008), the corrosion protection level is divided into four categories based on the resistivity value and are presented in Table 4-23.

Table 4-23: Corrosion protection classification based on concrete resistivity (ACI 222R-01, 2008)

Resistivity ($K\Omega.cm$)	**Corrosion protection**
<5	Low
5 – 10	Moderate - Low
10 – 20	High
>20	Very High

4.3.3.1 Addition group

The electrical resistivity of the addition group mixtures is shown in Figure 4-16 and Table 4-24. As the addition amount of either slag or CWP increased. the resistivity is greatly enhanced. All mixtures achieved very high percentage increase at 28 days from the control mixture (A-S-100) varying from 60% for A-S-200 all the way up to 882% for A-C-300. Even at the early curing age of 28 days. all mixtures were classified as "very high" in their corrosion protection. with the exception of A-S-100 with no much difference as it falls in the "high" corrosion protection category. Mixtures incorporating CWP resulted in very high resistivity values compared to mixtures containing slag. For instance. at 28 days of age. mixtures A-C-100 and A-C-200 resulted in a resistivity value almost double that achieved by mixtures A-S-100 and A-S-200. Whereas mixture A-C-300 resulted in even greater enhancement. as its resistivity was about five times higher than that of mixture A-S-300. This trend was also observed at 90 days of age.

Based on the results demonstrated in Figure 4-16 and Table 4-24 and according to ACI 222R-01 (2008). all mixtures at 90 days were classified as "very high" corrosion protection. This could be attributed to the fact that the CWP worked on densifying the microstructure of the concrete and hence reducing the connectivity of pores. This in turn would reduce the possible corrosion rate as the migration of ions decrease with less connected pores. When studying each individual mixture separately. all mixtures exhibited significant increase in its resistivity values with (128%. 135%. 81%) in A-S-100. A-S-200. and A-S-300 respectively and. (144%. 111%. 136%) for A-C-100. A-C-200. and A-C-300 respectively.

Table 4-24: Resistivity results for mixtures with slag and CWP as addition

	Test Age	Mixtures					
		A-S-100	A-S-200	A-S-300	A-C-100	A-C-200	A-C-300
Average Resistivity (kΩ.cm)	**28 Days**	16.68 (12.03)	26.75 (19.58)	37.97 (13.82)	31.94 (19.03)	64.99 (16.11)	163.80 (9.11)
	% increase at 28D from control	-	60.37	127.64	91.49	289.63	882.0
	90 Days	38.18 (17.84)	49.52 (15.86)	68.74 (2.94)	78.06 (5.54)	137.50 (13.11)	387.80 (9.45)
	% increase at 90D from control	-	29.70	80.04	104.45	260.14	915.72
	% increase at 90D from 28D	128.90	135.94	81.04	144.40	111.57	136.75

*** Values in parentheses represent the COV (%) among the three tested cubes**

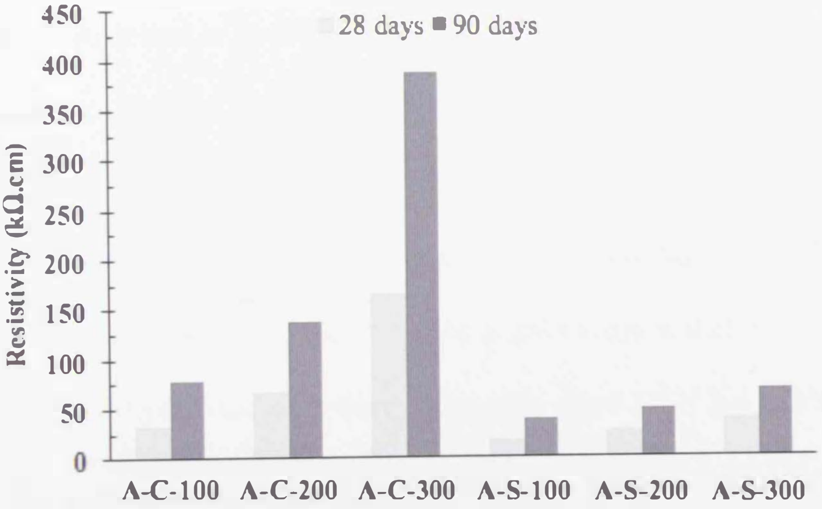


Figure 4-16: Bulk electrical resistivity for mixtures with slag and CWP as addition

4.3.3.2 Replacement group

Figure 4-17 and Table 4-25 represent the total bulk resistivity of the replacement mixtures. Observing the results, the inclusion of CWP significantly increased the resistivity of the mixtures. When the concrete was 28 days old, the incorporation of 100, 200, and 300 kg/m^3 of CWP resulted in an increase in resistivity of 255%, 523%, and 1138% respectively. This enormous increase suggested that CWP had tendency to reduce the interconnected pore network contributing to the reduction of the concrete's conductivity. As time progressed and concrete reached 90 days of age, the resistivity values continued to increase enormously. Therefore, this filler contributed to the refinement of concrete pores and microstructure, thus substantially reduced the permeability, and accordingly resistivity increased. The replacement of 100 kg/m^3 of cement resulted in resistivity values almost three times higher than that of the control mixture. While the inclusion of 200 and 300 kg/m^3 of CWP resulted in resistivity values six and twelve times higher than that of the control mixture respectively. Similarly, this trend was observed at 90 days. The three mixtures containing CWP are classified as "very high" corrosion protection at both ages (i.e. 28 and 90 days). On the other hand, the control mixture at 28 days of age belonged to the "high" corrosion protection category, whereas at 90 days of age it became on the borders of "very high" corrosion protection. This was justified through the relatively high amount of cement used in the mixture (500 kg/m^3). Moreover, the results suggest that the CWP tended to consume calcium hydroxide over time, producing more CSH gel in the concrete due to possible pozzolanic reactions; this decreased the amount of OH^- in the pore solution, reducing the conductivity of the concrete, and consequently contributing to the increase in the electrical resistivity. The measured property was related to the permeability of the concrete in addition to the interconnectivity of the pore network, and hence, as the resistivity increased, it could be concluded that the durability of the tested concrete became better as the penetration of aggressive agents into the concrete was limited.

Table 4-25: Resistivity results for mixtures with CWP as cement replacement

Average Resistivity (kΩ.cm)	**Test Age**	**Mixtures**			
		R-0	**R-100**	**R-200**	**R-300**
	28 Days	12.30 (7.47)	43.67 (13.23)	76.68 (6.35)	152.36 (10.84)
	% increase at 28D from control	-	255.04	523.41	1138.70
	90 Days	21.17 (6.45)	75.86 (13.23)	149.58 (6.35)	277.18 (10.84)
	% increase at 90D from control	-	258.34	606.57	1209.3
	% increase at 90D from 28D	72.11	73.71	95.07	81.92

*** Values in parentheses represent the COV (%) among the three tested cubes.**

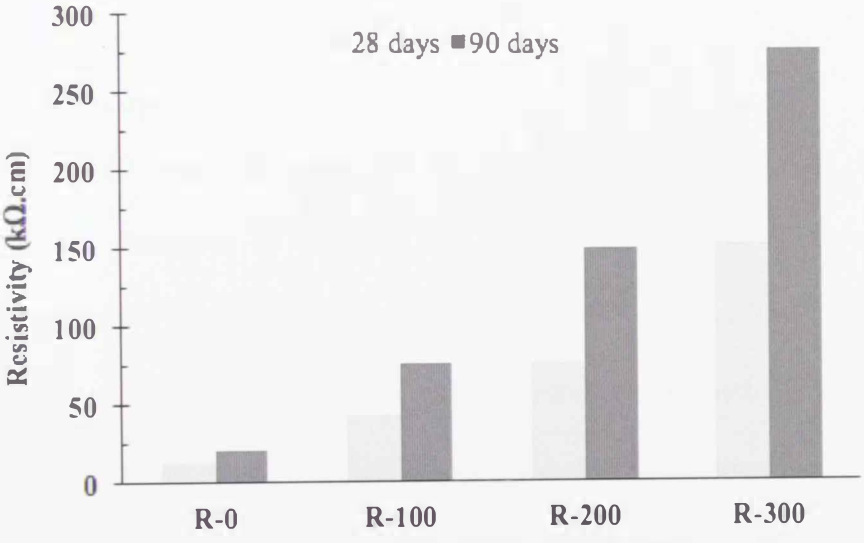


Figure 4-17: Bulk electrical resistivity for mixtures with CWP as cement replacement

4.3.4 Rapid Chloride Permeability

Rapid chloride permeability test (RCPT) is conducted to detect the amount of chloride ions that can permeate through concrete. The chloride-ion permeability is expressed in coulombs. This corresponds to the total amount of electrical charge that passes through the concrete sample during the 6-hour test across a potential difference of 60V DC. There are several concerns regarding the RCPT (Uchoa et al., 2009), one of which is the expected high heat to be generated due to the high voltage applied. For this reason, temperature was monitored throughout the test.

Since the diameter of the discs used was 100 mm and not 95 as specified by the standard, the total charge passed obtained had to be adjusted. Both the total charge and the cross-sectional area are directly related, therefore the adjusted total charge was simply obtained by multiplying the measured total charge by the ratio of the cross-sectional area of the standard to the actual specimen as given in Eq. (8).

$$Q_{95} = Q_{100}\, x\, (\frac{95}{100})^2 \qquad \text{Eq. (8)}$$

4.3.4.1 Addition group

The 28 and 90 days' test results for the resistance to penetration of chloride ions into concrete, measured in terms of the electric charge passed through the specimens in coulombs for the addition mixtures are presented in Table 4-26 and Figure 4-18. It is clear that the general trend was reduction in the total charge passing as the curing age and amount of slag/CWP increased. The main reason behind this was believed to be due to the micro-filling effect taking place as a result of the relatively high S.S.A of slag (432 m^2/kg) and CWP (555 m^2/kg) compared to Portland cement (380 m^2/kg) resulting in a denser matrix. Additionally, Slag/CWP or any filler is theoretically assumed to reduce the size of large permeable pores and decrease the small permeable pores as well that they almost disappear. Consequently, they result in a less porous, denser microstructure and a discontinuous pore system. It is obvious that reduction from the A-S-100 mixture at 28 days in the charge passing of the CWP groups (61%, 84%, 94%) far exceeds those of the slag mixtures (63%, 60%). This clearly indicated that concrete mixtures with CWP performed much better with respect to chloride permeability. An important fact to outline here is that the chloride permeability at 28 days of mixtures with only 100 kg/m^3 addition of CWP achieved chloride permeability lower than the mixture with addition level of 300 kg/m^3 slag. The percentage change from 28 to 90 days in the chloride permeability in the slag mixtures is almost equivalent to those of the CWP at the same addition level with the exception of A-S-200. At 90 days of age, all studied addition mixtures can be classified as "very low" and "negligible" chloride permeability characteristics, with the exception of mixture A-S-100 that fell on the border of the "low" permeability classification (1032 coulombs). This suggested that the designed addition mixtures inherit enhanced characteristics of improved resistance against chloride intrusion. This reduction can be attributed to the increased reactivity of CWP/slag with curing age and change in pore structure as additional C-S-H was produced and hence filling more capillary pores. Moreover, the use of superplasticizers was believed to possibly contribute to the presence of fewer connected voids due to the improved dispersion of fine particles during the mixing stage.

Table 4-26: RCPT results for the addition group

	Test Age	Mixtures					
		A-S-100	A-S-200	A-S-300	A-C-100	A-C-200	A-C-300
Total charge passed (coulomb)	**28 Days**	1680	611	665	651	262	91
	% change at 28D from control	-	-63.63	-60.42	-61.25	-84.40	-94.58
	90 Days	1032	594	269	401	95	39
	% change at 90D from control	-	-42.44	-73.93	-61.14	-90.79	-96.22
	% change at 90D from 28D	-38.57	-2.78	-59.55	-38.40	-63.74	-57.14

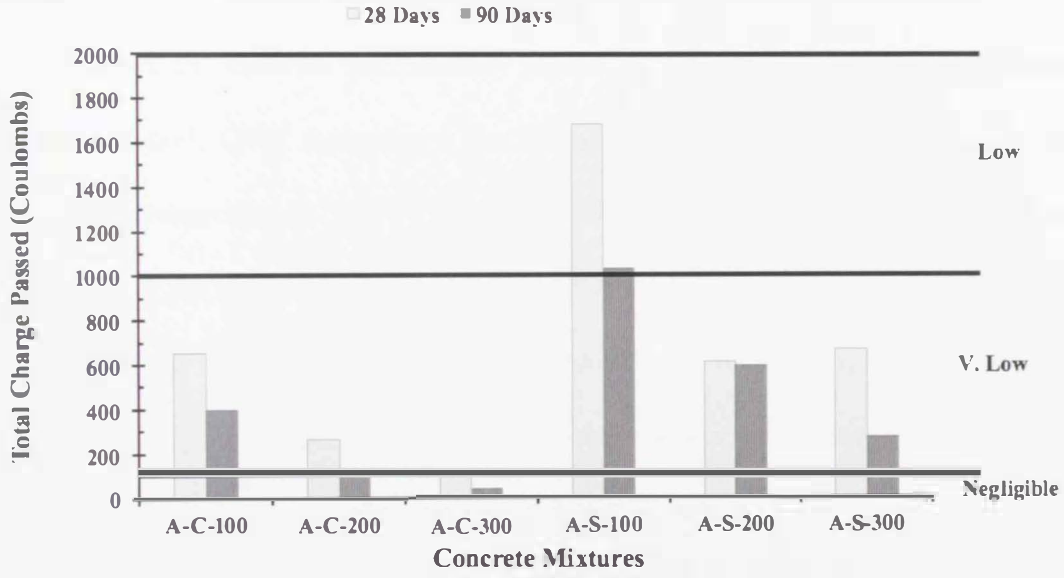


Figure 4-18: RCPT results for the addition group

4.3.4.2 Replacement group

Table 4-27 and Figure 4-19 present the RCPT results for the replacement mixtures at both 28 and 90 days. A tremendous and sharp reduction in the total charge passed in the tested concrete discs was obtained as the amount of CWP replacing cement increased. At the age of 28 days, there appeared to be a considerable difference (96%) between the R-0 mixture with no filler and the R-300 mixture with the highest filler content. The incorporation of CWP had a substantial effect on enhancing the resistance to chloride ion permeability of the concrete mixtures. The chloride permeability actually improved at an order of three classes (from Moderate to negligible) at 28 days when increasing the replacement level of CWP from 0 to 300 kg/m^3 respectively. Even at 28 days of age, the chloride ion permeability in mixtures incorporating CWP were categorized as very low and negligible. This could be attributed to the relatively increased S.S.A of CWP (m^2/kg) resulting in a better densely packed microstructure with fewer connected pores.

Overall, the chloride permeability results at 90 days displayed a significant improvement with CWP replacing a portion of the cementitious materials. As the curing age increased from 28 to 90 days, all CWP mixtures exhibited a reduction of at least 50% in the total charge passing. This could be justified by the change in the pore structure as more C-S-H is being produced and hence a well refined pore structure. The highest reduction from 28 to 90 days was achieved for mixture R-100, this can lead to a conclusion that the use of CWP as low as 100 kg/m^3 replacement was enough to lower chloride ion permeability such that the mixture could be classified as high performance concrete (HPC). It should be taken into consideration that the own porosities of the C-S-H interlayer sheets do not affect the permeability of the hardened concrete, but rather the production of addition of C-S-H resulted in pore size refinement and discontinuity (Mehta, 1986). Applying the ASTM C1202 threshold to the above results, it was found that all the concrete mixtures produced with CWP belonged to "very low" and "negligible" permeability classes. The comparatively very low and negligible amount of charge passing in CWP concrete mixtures at 90 days of age indicated that the migration of aggressive ions is a lot more difficult than in mixtures with cement as the sole binding material. Thus, this gave a good indication that the service life of CWP mixtures would exceed that of concrete with no fillers serving in the same environment.

Table 4-27: RCPT results for mixtures with CWP as cement replacement

Total charge passed (coulomb)	**Test Ages**	**Mixtures**			
		R-0	**R-100**	**R-200**	**R-300**
	28 Days	2707	671	348	94
	% reduction at 28D from control	-	75.2	87.14	96.53
	90 Days	1384	224	170	44
	% reduction at 90D from control	-	83.82	87.7	96.82
	% reduction at 90D from 28D	48.87	66.62	51.15	53.19

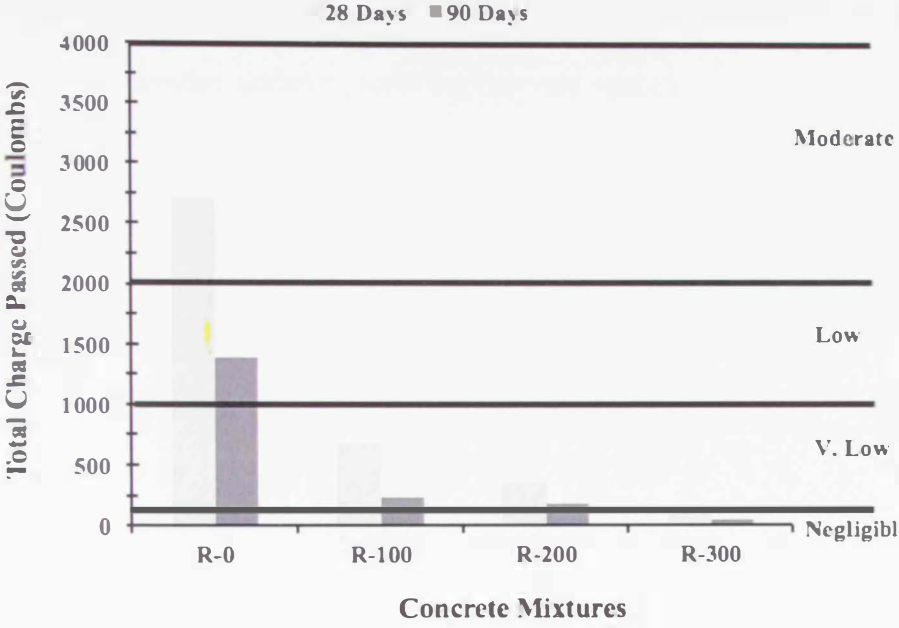


Figure 4-19: RCPT results for mixtures with CWP as cement replacement

4.3.5 Initial Rate of Absorption

Initial rate of absorption (i.e. sorptivity) was also referred to as the rate of capillary absorption. The capillary pores are present in hardened concrete as a result of excess water leaving the concrete after the cement hydration process stops resulting in the formation of the pore system. Therefore, they are the spaces not filled by any of the components of the hydration products. The mechanism of water or any soluble ions entering concrete takes place through these capillary pores. In this test, water enters into the concrete discs through upward capillary suction and only measures the absorption through surface pores.

4.3.5.1 Addition group

Figure 4-20 and Table 4-28 show the initial rate of absorption values at 28 and 90 days of age for the addition mixtures. Generally, the initial rate of absorption values decreased as the slag/CWP content increased in the mixtures at the age of 28 days. This is typical as filler materials are usually used to increase the particle distribution of the powder skeleton, reducing the void spaces.

Table 4-28: Initial rate of absorption results for mixtures with slag and CWP as addition

Initial rate of absorption (mm/min^0.5) at different test ages	Test Age	Mixtures					
		A-S-100	A-S-200	A-S-300	A-C-100	A-C-200	A-C-300
	28Days	0.16	0.13	0.11	0.17	0.16	0.14
	% change at 28D from control	-	-18.75	-31.25	6.25	0.00	-12.5
	90Days	0.11	0.09	0.07	0.08	0.10	0.09
	% change at 90D from control	-	-18.18	-36.36	-27.27	-9.09	-18.18
	% change at 90D from 28D	-31.25	-30.77	-36.36	-52.94	-37.5	-35.71

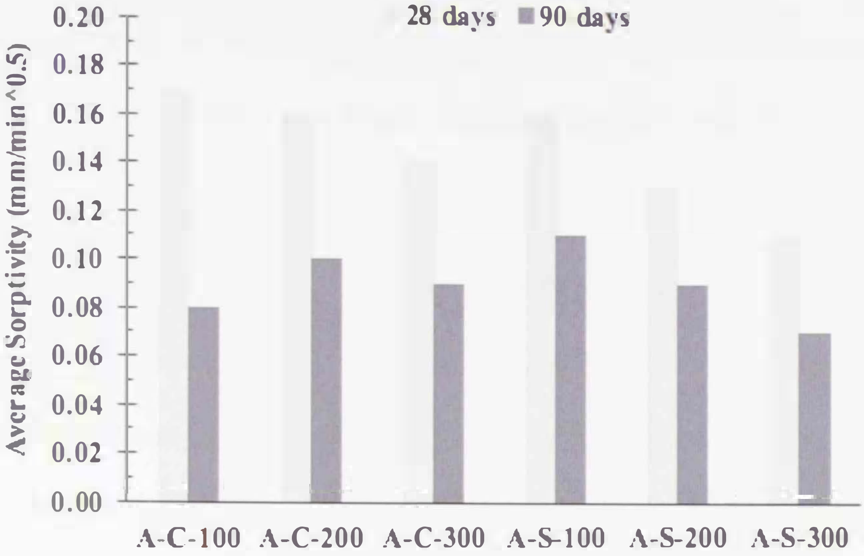


Figure 4-20: Initial rate of absorption for the addition group

The two best performing mixtures at 90 days of age are A-S-300 and A-C-100, they both displayed the lowest initial rate of absorption values at 0.07 and 0.08 (mm/min$^{0.5}$) respectively. A-C-100 mixture also happens to be the lowest among all the CWP. This is believed to be because when the amount of CWP increases in the mixture, the amount of silica (from CWP) is too high and the amount of the produced CH as a cement hydration product is most likely insufficient to react with all the available silica. This results in some voids not filled with hydration products leaving capillary pores.

Observing the percentage changes in the initial rate of absorption from 28 to 90, it can be concluded that all the slag mixtures experience almost the same reduction with an average of 32%. Noteworthy, both the A-C-200 and A-C-300 revealed similar values but with a slight greater reduction (36%). Mixture A-C-100 resulted in the highest percentage reduction from 28 to 90 days among the six tested mixtures (52.9%). This can indicate that the CWP's reactivity takes place at later ages. Moreover, it can also be concluded that the 100 kg/m^3 addition of CWP is the optimum amount to be added in the mixture in order to produce the maximum amount of hydration products and hence, minimum capillary pore volume.

4.3.5.2 Replacement group

Table 4-29 and Figure 4-21 present the initial rate of absorption of the replacement mixtures at two test ages i.e.: 28 and 90 days. The general trend of increasing the amount of CWP replacing a portion of cement is not very clear here. However, as each individual mixture progresses in age, its initial rate of absorption decreases. At the early age of 28 days, the lowest initial rate of absorption was obtained in mixture R-300. This can be due to that fact that CWP's particle size is relatively small compared to cement, and hence, decreases the capillary voids owing to its micro-filling effect. The reduction in initial rate of absorption at 90 days compared to the 28 days is significant in all mixtures. This trend is explained through the modification to the hydration products taking place due to the CWP reaction. The CWP reacts with cement by binding CH with its free silica resulting in the production of non-soluble C-S-H structure. This in turn would produce a more densely packed concrete with reduced water infiltration.

Table 4-29: Initial rate of absorption results for the replacement group

	Test Ages	**Mixtures**			
		R-0	**R-100**	**R-200**	**R-300**
Initial rate of absorption (mm/min^0.5) at different test ages	**28 Days**	0.11	0.10	0.13	0.09
	% change at 28D from control	-	-9.09	18.18	-18.18
	90 Days	0.06	0.08	0.08	0.06
	% change at 90D from control	-	33.33	33.33	0.00
	% change at 90D from 28D	-45.45	-20	-38.46	-33.33

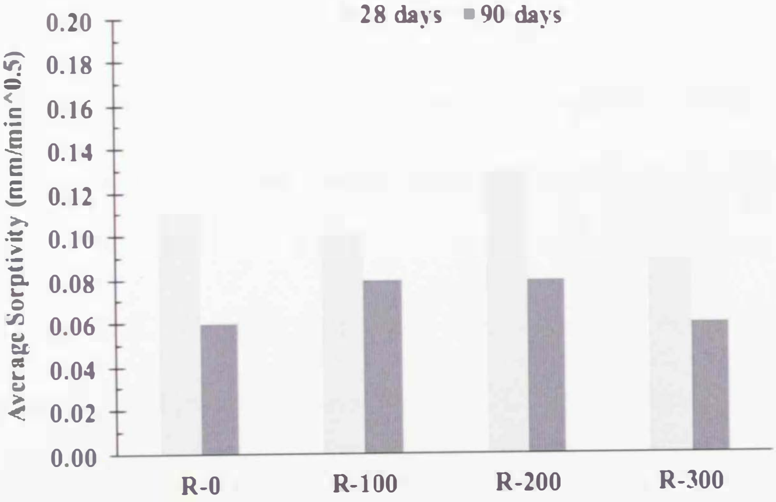


Figure 4-21: Initial rate of absorption for mixtures with CWP as cement replacement

4.3.6 Permeable Pores Test

In addition to the initial rate of absorption, permeable pores test was also conducted. The difference is that the initial rate of absorption uses specimens partially in contact with water from only one side, while the permeable pores test requires the sample to be fully submerged. Therefore, it was expected that permeable pores test will give indication on the average value rather than only the surface pores.

4.3.6.1 Addition group

The permeable pore percentages for the addition group mixtures are presented in Table 4-30. At 28 days of age, slag mixtures experienced a decrease in the volume of permeable pores as the amount of slag in the mixtures increased. This trend was applicable to all slag mixtures excluding A-S-200. Test results of A-S-200 mixture revealed the highest permeable pores among all the addition group mixtures. It should be noted from the RCPT results, that the same mixture also did not undergo a considerable reduction in the chloride permeability from 28 to 90 days similar to the other slag mixtures. This might lead to a conclusion that for this specific mixture some error might had been happen during casting or curing which affected the final pore structure.

Regarding the CWP group mixtures, the volume of permeable pore voids showed a tendency to decrease as the amount of CWP increased, although mixture A-C-300 experienced a 6% marginal reduction compared to the A-C-200 mixture. The decline in the voids could be justified by the relatively high specific surface area of both slag (432 m^2/kg) and CWP (555 m^2/kg) compared to cement (380 m^2/kg). This contributed to the formation of a denser microstructure with lesser amount of pore voids.

The phenomenon of micro-filling effect played a major role in significantly reducing the permeable pore spaces in mixtures A-S-100 and A-C-100. The reduction was calculated to be 28 and 38 % in A-S-100 and A-C-100 respectively as the curing age increased from 28 to 90 days. At early testing age of 28 days, the percentage reduction in permeable pore voids as the amount of slag and CWP increased from 100 to 300 kg/m^3 was almost the same at 40% and 43% respectively.

Table 4-30: Permeable pore test results for mixtures with slag and CWP as addition

Test Age	**Mixtures**					
	A-S-100	**A-S-200**	**A-S-300**	**A-C-100**	**A-C-200**	**A-C-300**
28 Days	5.38	7.68	3.22	5.94	3.13	3.35
90 Days	3.83	4.71	3.48	3.66	3.27	3.03

4.3.6.2 Replacement group

Table 4-31 presents the permeable pore percentage in the replacement mixtures. The volume of voids for the 28-day cured samples decreased with increasing CWP content with the exception of the R-300 mixture showing slight increase. With 200 kg/m^3 (40%) partial replacement of the cementitious materials, CWP provided approximately a 26% decrease in volume of voids. The volume of pores was reduced by CWP's small size and modification to hydration products. Similarly, the volume of voids at the 90-day of age decreased with increasing the amount of CWP in the mixtures. However, there was no measurable reduction in the three mixtures containing CWP from 28 to 90 days. An explanation for the decrease in voids percentage as the replacement amount increased at 90 days was similar to those presented for the 28-day curing results. CWP's small size and high S.S.A caused a physical change through a micro-filling effect and a chemical change by producing additional hydration products that in turn resulted in a better refined pore structure. It is apparent that mixture R-300 developed higher pore volume percentages at 90 days. This observation might be interpreted in a way that as the amount of CWP increased beyond the 200 kg/m^3 (40%), the CWP's own porosity overcame the improvement in the concrete microstructure and thus the permeable voids increased. Also, mixture R-300 may had excessive partial replacement of cementitious materials by CWP to optimize the hydration products volume. Also, the possibility existed that boiling causes pore structure damage or created vapor pressure gradients that were not representative of normal environmental exposures. This suggested that the ASTM term "permeable pore space" is not entirely appropriate for HPC (El Dieb, 1994). Therefore, based on the trend provided at 90 days, it could be concluded that the replacement of cement with 200 kg/m^3 CWP appeared to improve the amount of hydration products through obtaining the most efficient pore structure distribution.

Table 4-31: Permeable pore test results for mixtures with CWP as cement replacement

Test Ages	**Mixtures**			
	R-0	**R-100**	**R-200**	**R-300**
28 Days	3.53	2.86	2.60	2.78
90 Days	3.47	2.84	2.60	3.12

4.3.7 Drying Shrinkage

Shrinkage can be defined as a volumetric time dependent change in concrete due to loss in moisture conditions (Bhattacharya, 2008) or the withdrawal of water from concrete stored in air (Neville, 1998). Emptying of the capillaries causes a loss of water without shrinkage but, once the capillary water has been lost, the removal of adsorbed water takes place and causes shrinkage (Neville, 1998). Concrete usually undergoes shrinkage when there is a difference in the relative humidity of the voids in the concrete pore structure and the surrounding environment the concrete is placed in. As this difference increases, an evaporation process starts taking place for a period of time. The evaporation process depends on several factors: external (i.e. relative humidity and temperature) and internal (i.e. amount of mixing water, size of aggregate, and quantity of cementitious material used) that can affect both the rate and magnitude of shrinkage (Ates, 2010). The temperature and relative humidity readings were monitored throughout the test period and they ranged from 25°C to 35°C and from 40% to 60%.

4.3.7.1 Addition group

The drying shrinkage strains at the age of 150 days is presented in Table 4-32. Mixtures A-S-100 and A-C-100 both resulted in the same shrinkage strain at 150 days (27 mm/mm x 10^{-5}). The percentage difference between the mixtures and the control is negligible with the exception of A-C-200 mixture which experience the highest shrinkage (33 mm/mm x 10^{-5}). Hence, the effect of slag and CWP on the drying shrinkage strain was almost the same with minimal differences. Reviewing the results, there seemed to be no definite trend relating the drying shrinkage strain to the inclusion of either slag or CWP. This could be attributed to the wide range of temperature and humidity measured in the laboratory during the test period. Moreover, by relating the compressive strength, it can be concluded that as strength decreased the drying shrinkage slightly increased.

Table 4-32: 150 Days shrinkage strain values for mixtures with slag and CWP as addition (mm/mm)x10^{-5}

Days	**Mixtures**					
	A-S-100	**A-S-200**	**A-S-300**	**A-C-100**	**A-C-200**	**A-C-300**
150	27	26	30	27	33	28
% change from control	-	-3.7	11.1	0	22.2	3.7

4.3.7.2 Replacement group

Table 4-33 presents the values of shrinkage strain for the replacement group measured at 150 days. As the replacement level increased (20%, 40%, 60%), the shrinkage strain decreased. The minimum shrinkage strain was obtained in mixture R-300 with a reduction of 35% from the strain measured for the control mixture (R-0). A possible mechanism contributing to the reduction of drying shrinkage strain is the refinement in the pore structure due to the presence of CWP. This may have prevented internal moisture evaporation. The refinement is generally related to the shape, pozzolanic reactivity, and micro-filling effect of CWP.

Table 4-33: 150 Days shrinkage strain values for mixtures with CWP as cement replacement (mm/mm)x10^{-5}

Days	**Mixtures**			
	R-0	**R-100**	**R-200**	**R-300**
150	42.5	32.5	29	27.5
%change from control	-	-23.5	-31.8	-35

4.3.8 Concluding Remarks

Multiple conclusions were drawn on the performance of SCC utilizing CWP at the hardened stage. The findings are summarized below based on the test results discussed earlier:

- In the addition group, at the late age of 90 days, mixtures incorporating 100 and 200 kg/m^3 of CWP achieved higher strength values (73.9 and 64 MPa respectively) than those mixtures containing 100 and 200 kg/m^3 of slag (73 and 62 MPa respectively). It is worth mentioning that the gain in CWP mixtures was slower than that for the slag mixtures, this was clear from the calculated percentage gains from 28 to 90 days (8.9% for A-S-100 and 15.3% for A-C-100).

- Optimum replacement amount based on the replacement group for obtaining the highest compressive strength is 100 kg/m^3 (94.2 MPa) but yet the 200 kg/m^3 (90 MPa) is still higher than that of the control (84 MPa), and therefore for economic and environmental reasons, using 200 kg/m^3 replacement is feasible.
- Both groups of mixtures were classified as "Excellent" in terms of UPV results. Despite this, it was noticed that as the amount of slag and CWP increased in the addition mixtures, the obtained UPV values decreased. While in the mixtures with CWP was used as a cement replacement, the same behavior was followed, but it was noticed that the reduction at 90 days was insignificant as the CWP replacement level increased.
- In the addition group, as the amounts of slag and CWP were increased, the measured bulk electrical resistivity was greatly enhanced.
- In the addition group, mixtures incorporating CWP resulted in greater resistivity values compared to mixtures containing slag. At 28 days of age, mixtures A-C-100 resulted in a resistivity value almost double that achieved by mixtures A-S-100 and A-S-200. Whereas mixture A-C-300 resulted in even greater enhancement, as its resistivity was about five times higher than that of mixture A-S-300. This trend was also observed at 90 days of age.
- In the replacement group, mixtures incorporating CWP resulted in concrete with "very high" corrosion protection. The replacement of 100 kg/m^3 of cement resulted in resistivity values almost three times higher than that of the control mixture. While the inclusion of 200 and 300 kg/m^3 of CWP resulted

in resistivity values six and twelve times higher than that of the control mixture respectively.

- Mixtures within the addition group produced with CWP revealed greater resistance to penetration of chloride ions compared to mixtures with slag. The total charge passing through mixture A-C-100 at the age of 90 days was 401 Coulombs which is approximately two and a half times less than the total charge passed through mixture A-S-100 (1032 C).
- The incorporation of CWP in the replacement mixtures had a substantial effect on enhancing the resistance to chloride ion permeability of the concrete mixtures. The chloride permeability actually improved at an order of two classes (from "low" to "negligible") at 90 days when increasing the replacement level of CWP from 0 to 300 kg/m^3.
- From the calculated percentage reduction of the initial rate of absorption from 28 to 90, all the CWP mixtures in the addition group experienced almost the same reduction as the slag mixtures with an average of 36%. This indicated that the CWP's reaction took place at later ages.
- The general trend for the results of the permeable pores test was reduction in the voids percentage as the amount of slag/CWP increased. This was applicable to all mixtures with the exception of mixture A-C-300 in the addition group and mixture R-300 in the replacement group. The results suggested that this relatively high amount of CWP (300kg/m^3) in the mixtures did not contribute much to the pore system. It can also be due to increased porosity as a result of higher CWP content.
- Drying conditioning of specimens for the initial rate of absorption and permeable pores tests could have contributed to the high variability in these

test. Therefore, it can be concluded that the permeable pores test and initial rate of absorption under the performed test conditions were not sensitive enough in detecting changes in concrete mixtures to assess the effect of CWP.

- From the addition group results, there appeared to be no clear relation between the different addition levels of slag and CWP to the 150 days drying shrinkage strain. The drying shrinkage strain difference between the highest and the lowest additions of slag was 11.1%, while it was 3.7% for the CWP mixtures. However, the strain values obtained from the replacement group implied that as the replacement level increased, the shrinkage strain decreased. This was clear from the 35% reduction in drying shrinkage as CWP amount increased from 0 to 300 kg/m^3.

Chapter 5: Performance Evaluation of Concrete Mixtures

5.1 Introduction

The present study aims to investigate the feasibility of using CWP as filler in SCC mixtures. As a final step to fulfill the aim of this experimental investigation is to decide on an optimum amount for CWP to be utilized in SCC mixtures. The experimental results obtained in this investigation showed that CWP amount differs depending on the needed property whether fresh or hardened. Typically, the best suitable mixture is designated when the intended properties of need are met. Since there exists multiple criteria for selection, the best suitable mixture can be identified with the aid of a performance index (PI) approach.

5.2 Performance Index Approach

The performance index (PI) is a management tool that allows multiple sets of information to be compiled into an overall measure. The philosophy behind using performance indices is simple: the method condenses a great deal of information into just one number (Jordan et al., 2001). The performance index method is adopted to facilitate the selection process of the CWP amount to produce the most suitable mixture complying to the multifunctional performance criteria for SCC. For each individual criterion, a weight ranking (C_i) is calculated in such a way that the mixture achieving the best test value in a certain criterion scores 1.00, and the rest of the mixtures' test values are proportioned to that best value, thus their weight ranking will be ≤ 1.00. Eq. (9) represents the calculation of the weight ranking:

$$C_i = \frac{Measured\ performance\ for\ each\ mixture}{Best\ measured\ performance} \qquad \text{Eq. (9)}$$

The second step towards the completion of the PI approach is the computation of a numeric index (R_i). The highest numeric index used in this study is set to 5.00. for each individual mixture, the corresponding numeric index is the product of the previously calculated weight ranking C_i and 5.00 as presented in Eq. (10).

$$R_i = 5\ x\ C_i \qquad \text{Eq. (10)}$$

Finally, based on the required performance criteria, the related R_i are multiplied, and the mixture achieving the highest score is designated the best suitable mixture in terms of the corresponding required multifunctional criteria. This approach can be used to identify mixtures with different performance criteria in the fresh state or hardened state or both.

5.3 Tests Used for the Performance Index Evaluation

For the purpose of evaluation, only certain criteria were chosen. The criteria on which the selection process will be based upon are: flowability, passing ability, and viscosity for the fresh stage, compressive strength and bulk electrical resistivity at 28 days of age for the hardened stage. Although a couple of durability tests were performed (i.e. sorptivity, permeable pores, and RCPT) yet the easiest in terms of sample preparation and the procedure is the resistivity. Moreover, all of the durability tests yielded the same behavior such that as the amount of CWP increased, the durability characteristics were enhanced, and hence the resistivity test was selected to represent the durability tests. Noteworthy, only mixtures containing CWP are included in the PI evaluation (i.e. slag mixtures are excluded).

According to the EFNARC-2005 guidelines, the concrete purchaser should only select those fresh concrete characteristics necessary for the particular SCC application and over specification of both the concrete characteristics and class should be avoided. However, slump flow will usually be required for all SCC mixtures.

Passing ability, viscosity, and segregation resistance will affect the in-situ properties of the hardened concrete but should only be specified if particularly required. Therefore, if the concrete purchaser needs a SCC mixture were no or little reinforcement is present, the passing ability should not be necessarily specified as a requirement, otherwise the J-ring or L-box tests evaluating the passing ability should be conducted. CWP mixtures conforming to such requirements are selected based on PI-1 as shown in Table 5-3. Furthermore, when good surface finish is required in addition to the existence of highly congested reinforcement, viscosity becomes important. PI-2 in Table 5-3 gives an indication on the best CWP mixtures fulfilling this requirement. Finally, if all fresh properties are required combined in a certain application (flowability, viscosity, and passing ability), PI-3 would suggest the mixture that will be best suitable for such function. It should be noted that segregation resistance was not included in the performance index calculations, as all the produced SCC mixtures meet with the requirements suggested by the EFNARC-2005 guidelines and are classified as class SR2 (<20%) implying they are adequate for most applications.

A summary of the best suitable mixtures for certain performance criteria is given in Table 5-1. Tables 5-2 and 5-3 illustrate the weighted ranks and numeric indices for all the CWP mixtures. The individual performance criteria are presented in Table 5-2, while the multifunctional performance criteria are presented in Table 5-3. The shaded cells indicate the mixture that best suites the application with the required performance criteria.

Table 5-1: Selected CWP mixtures for different performance criteria

Performance Criteria	**CWP Mixture**	
	Addition Group	**Replacement Group**
Slump flow	A-C-100	R-0
Slump flow + J-ring	A-C-200	R-300
Slump flow + V-funnel	A-C-200	R-100
Slump flow + J-ring + V-funnel	A-C-200	R-200/R-300
Strength + Slump flow	A-C-100	R-100
Strength + SCC fresh characteristics	A-C-200	R-200
Strength + Durability	A-C-300	R-300
Strength + SCC fresh characteristics + Durability	A-C-300	R-300

From the above analysis it can be concluded that the addition group mixture A-C-200, which includes 200 kg/m^3 CWP, is the best suitable mixture satisfying all fresh properties. While the replacement group, mixture R-300, which included 300 kg/m^3, is the best suitable mixture satisfying all fresh properties.

For strength and all fresh properties, mixture A-C-200, with 200 kg/m^3 CWP, is the most suitable mixture. On the other hand, mixture R-200, with 200 kg/m^3, is the best suitable mixture for strength and all fresh properties.

Mixtures A-C-300 and R-300 with 300 kg/m^3 CWP were found to satisfy all fresh properties, strength, and durability.

It can be concluded that CWP can replace cement with CWP up to 60% by mass and satisfies all fresh properties, strength, and durability.

Table 5-2: Performance indices for individual criteria

Mixture I.D.	Individual Performance Criterion									
	Slump flow		J-ring		V-funnel		Strength (28 days)		Resistivity (28 days)	
	C_i	R_i	C_i	R_i	C_i	R_i	C_i	R_i	C_i	R_i
A-C-100	1.00	5.00	0.80	4.00	0.58	2.92	1.00	5.00	0.20	1.01
A-C-200	0.97	4.86	1.00	5.00	1.00	5.00	0.81	4.34	0.35	1.77
A-C-300	0.95	4.73	1.00	5.00	0.64	3.20	0.61	3.93	1.00	5.00
R-0	1.00	5.00	0.50	2.50	0.96	4.81	0.93	4.46	0.08	0.38
R-100	0.99	4.94	0.56	2.78	1.00	5.00	1.00	5.00	0.27	1.37
R-200	0.96	4.78	0.83	4.17	0.91	4.55	0.92	4.78	0.54	2.70
R-300	0.93	4.65	1.00	5.00	0.78	3.90	0.81	4.19	1.00	5.00

Table 5-3: Performance indices for multifunctional criteria

Mixture I.D.	Multifunctional Performance Criterion						
	PI-1	PI-2	PI-3	PI-4	PI-5	PI-6	PI-7
A-C-100	20.0	14.6	58.4	25.0	292.0	5.05	294.9
A-C-200	24.3	24.3	121.5	21.1	527.3	7.7	933.3
A-C-300	23.7	15.1	75.7	18.6	297.5	19.7	1487.5
R-0	12.5	24.1	60.1	22.3	268.0	1.7	101.8
R-100	13.7	24.7	68.7	24.7	343.5	6.9	470.6
R-200	19.9	21.7	90.7	22.8	433.5	12.9	1170.5
R-300	23.3	18.1	90.7	19.5	380.0	21.0	1900.0

Performance Index (PI)	*Required Performance (s) Criteria*
PI-1	*Slump flow + J-ring*
PI-2	*Slump flow + V-funnel*
PI-3	*Slump flow + J-ring + V-funnel*
PI-4	*Strength + slump flow*
PI-5	*Strength + fresh*
PI-6	*Strength + durability*
PI-7	*Strength + fresh + durability*

Note: Shaded cells represent the mixture that best suits the application with the required performance criteria

Chapter 6: Conclusions and Recommendations

6.1 General

The proposed work shed lights on the feasibility of reusing industrial solid waste materials as a concrete ingredient as a step towards having green and sustainable concrete. This could offer alternative for disposing ceramic waste powder (CWP) in an environmentally friendly way, in addition to increasing people's awareness about the availability of such waste material and encouraging them to develop new ways and ideas for utilizing and reusing CWP effectively in the construction industry. This experimental study implemented CWP as an addition and as replacement to cement. The two produced SCC groups were evaluated for their performance in fresh and hardened stages using multiple tests for each phase. Slump flow, J-ring, L-box, V-funnel, GTM column segregation tests were all performed to assess the fresh stage characteristics. While compressive strength, ultrasonic pulse velocity (UPV), drying shrinkage, electrical bulk resistivity, rapid chloride permeability test (RCPT), initial rate of absorption, and permeable pores tests were all conducted to evaluate the properties of the SCC mixtures in their hardened stage. Finally, a performance index evaluation approach was used at the end of the study to facilitate the identification of the best suitable mixture for a certain performance criterion or multifunctional performance criteria.

The main outcomes of the investigation along with recommendations for future work on the utilization of CWP in the SCC industry are listed in the following sub-sections.

6.2 Conclusions

6.2.1 Fresh Concrete Properties

Several conclusions were drawn out on the performance of SCC utilizing CWP at the fresh stage. The main findings are summarized below based on the test results discussed earlier:

- The relation between the amount of slag and CWP was inversely proportional to the flowability of the studied SCC mixtures in both the addition and the replacement groups. Both materials reduced the unconfined flow of the SCC mixtures. Despite this adverse effect, all mixtures showed good deformability under their own weight.
- The decrease in flowability was not significant, as the slump flow values decreased only by 10% and 5% in the mixtures with slag and CWP as addition respectively.
- No segregation or bleeding was observed at the periphery of the slump flow.
- Each SCC mixture investigated in this present study exhibited adequate filling ability, as all measured slump flow values ranged from 695 mm to 795 mm.
- J-ring test results indicated that the mixtures prepared in this study achieved adequate passing ability. As the amount of CWP increased in the mixtures, the passing ability was improved (i.e. no visible blocking in A-C-100, A-C-200, A-C300, and R-300 mixtures). Therefore, CWP mixtures are expected to maintain sufficient resistance to segregation around congested reinforcement areas.
- Values greater than 0.96 were achieved by all the replacement mixtures in the L-box test, indicating very good passing ability suggesting that these mixtures were suitable for applications where flow through congested reinforcement is needed.

- Results of V-funnel test were further verified by the very good relation with T_{50} time measured during the slump flow test.
- Column segregation test values varied from 1% to 18.45%, with the lowest being achieved by the highest CWP replacement levels (i.e. A-C-300 = 1%, and R-300 = 3.44%), implying a significant enhancement in the segregation resistance.
- Similar rheological behavior, in terms of viscosity/segregation resistance, was obtained; as amount of CWP increased in the mixtures, the viscosity was increased, and the segregation resistance was greatly enhanced.
- Due to the low specific gravity of CWP compared to cement, mixtures with CWP would contain higher paste volume causing a reduction in the friction between the aggregates and the paste interface, and thus improving the cohesiveness and plasticity, leading to improved SCC flowability characteristics.
- The VMA is normally used to adjust mixtures' viscosity and enhance segregation resistance. Since CWP resulted in significant enhancement of the mixtures viscosity and segregation resistance, the VMA could be eliminated for the mix or its dosage reduced. This will result in more economic and low cost mixtures.
- CWP has potential for producing high-performance self-compacting concrete with satisfactory fresh state properties according to the criteria established by EFNARC-2005 specifications and ASTM standards.

6.2.2 Hardened Concrete Properties

- In the addition group, at the late age of 90 days, mixtures incorporating 100 and 200 kg/m^3 of CWP achieved higher strength values (73.9 and 64 MPa respectively) than those mixtures containing 100 and 200 kg/m^3 of slag (73 and 62 MPa respectively). It is worth mentioning that the gain in CWP mixtures was slower than that for the slag mixtures. this was clear from the calculated percentage gains from 28 to 90 days (8.9% for A-S-100 and 15.3% for A-C-100).

- Optimum replacement amount based on the replacement group for obtaining the highest compressive strength is 100 kg/m^3 (94.2 MPa) but yet the 200 kg/m^3 (90 MPa) is still higher than that of the control (84 MPa). and therefore for economic and environmental reasons. using 200 kg/m^3 replacement is feasible.
- Both groups of mixtures were classified as "Excellent" in terms of UPV results. Despite this. it was noticed that as the amount of slag and CWP increased in the addition mixtures. the obtained UPV values decreased. While in the mixtures with CWP was used as a cement replacement. the same behavior was followed. but it was noticed that the reduction at 90 days was insignificant as the CWP replacement level increased.
- In the addition group. as the amounts of slag and CWP were increased. the measured bulk electrical resistivity was greatly enhanced.
- In the addition group. mixtures incorporating CWP resulted in greater resistivity values compared to mixtures containing slag. At 28 days of age. mixtures A-C-100 resulted in a resistivity value almost double that achieved by mixtures A-S-100 and A-S-200. Whereas mixture A-C-300 resulted in even greater enhancement. as its resistivity was about five times higher than that of mixture A-S-300. This trend was also observed at 90 days of age.
- In the replacement group. mixtures incorporating CWP resulted in concrete with "very high" corrosion protection. The replacement of 100 kg/m^3 of cement resulted in resistivity values almost three times higher than that of the

control mixture. While the inclusion of 200 and 300 kg/m^3 of CWP resulted in resistivity values six and twelve times higher than that of the control mixture respectively.

- Mixtures within the addition group produced with CWP revealed greater resistance to penetration of chloride ions compared to mixtures with slag. The total charge passing through mixture A-C-100 at the age of 90 days was 401 Coulombs which is approximately two and a half times less than the total charge passed through mixture A-S-100 (1032 C).
- The incorporation of CWP in the replacement mixtures had a substantial effect on enhancing the resistance to chloride ion permeability of the concrete mixtures. The chloride permeability actually improved at an order of two classes (from "low" to "negligible") at 90 days when increasing the replacement level of CWP from 0 to 300 kg/m^3.
- From the calculated percentage reduction of the initial rate of absorption from 28 to 90, all the CWP mixtures in the addition group experienced almost the same reduction as the slag mixtures with an average of 36%. This indicated that the CWP's reaction took place at later ages.
- The general trend for the results of the permeable pores test was reduction in the voids percentage as the amount of slag/CWP increased. This was applicable to all mixtures with the exception of mixture A-C-300 in the addition group and mixture R-300 in the replacement group. The results suggested that this relatively high amount of CWP (300kg/m^3) in the mixtures did not contribute much to the pore system. It can also be due to increased porosity as a result of higher CWP content.

- Drying conditioning of specimens for the initial rate of absorption and permeable pores tests could have contributed to the high variability in these test. Therefore, it can be concluded that the permeable pores test and initial rate of absorption under the performed test conditions were not sensitive enough in detecting changes in concrete mixtures to assess the effect of CWP.
- From the addition group results, there appeared to be no clear relation between the different addition levels of slag and CWP to the 150 days drying shrinkage strain. The drying shrinkage strain difference between the highest and the lowest additions of slag was 11.1%, while it was 3.7% for the CWP mixtures. However, the strain values obtained from the replacement group implied that as the replacement level increased, the shrinkage strain decreased. This was clear from the 35% reduction in drying shrinkage as CWP amount increased from 0 to 300 kg/m^3.

6.2.3 Performance Index

The used performance index approach was very useful as a tool to identify mixtures for specific performance or multifunctional performance. The main conclusions from the performance index approach are summarized in Table 6-1, that shows the best suitable mixture for the corresponding performance criterion.

Table 6-1: Selected CWP mixtures for different performance criteria

Performance Criteria	**CWP Mixture**	
	Addition Group	**Replacement Group**
Slump flow	A-C-100	R-0
Slump flow + J-ring	A-C-200	R-300
Slump flow + V-funnel	A-C-200	R-100
Slump flow + J-ring + V-funnel	A-C-200	R-200/R-300
Strength + Slump flow	A-C-100	R-100
Strength + SCC fresh characteristics	A-C-200	R-200
Strength + Durability	A-C-300	R-300
Strength + SCC fresh characteristics + Durability	A-C-300	R-300

From the above analysis it can be concluded that the addition group mixture A-C-200, which includes 200 kg/m^3 CWP, is the best suitable mixture satisfying all fresh properties. While the replacement group, mixture R-300, which included 300 kg/m^3, is the best suitable mixture satisfying all fresh properties.

For strength and all fresh properties, mixture A-C-200, with 200 kg/m^3 CWP, is the most suitable mixture. On the other hand, mixture R-200, with 200 kg/m^3, is the best suitable mixture for strength and all fresh properties.

Mixtures A-C-300 and R-300 with 300 kg/m^3 CWP were found to satisfy all fresh properties, strength, and durability.

It can be concluded that CWP can replace cement with CWP up to 60% by mass and satisfies all fresh properties, strength, and durability.

6.3 Recommendations

Based on the conducted investigation and the above conclusions, a number of recommendations are suggested for future studies as a continuation for the use of CWP in self-compacting concrete industry.

- Further work is needed to study the relation between admixtures and CWP.

- The VMA is normally used to adjust mixtures' viscosity and enhance segregation resistance. Since CWP resulted in significant enhancement of the mixtures viscosity and segregation resistance, the VMA could be eliminated for the mix or its dosage reduced. This will result in more economic and low cost mixtures.

- It is relevant to note that the pore structure of CWP, as a main factor influencing the self-compacting properties, has not been studied and interpreted in details.
- Study the effect of increasing the fineness of the CWP and the performance of SCC mixtures.
- Study the effect of CWP on the concrete mixtures' thermal stability and characteristics.

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List of Publications

1. S.T. Aly, A.S. El-Dieb, M.M. Reda Taha, "*Properties of High-Performance Self-Compacting Concrete with Recycled Ceramic Waste Powder*". Accepted in the ACI-KC 4th International Conference and Exhibition: Smart, Green and Durable Structures, Kuwait, 8-10 Nov. 2016.
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