FLEXURAL, SHEAR, AND MECHANICAL BEHAVIOUR OF SELF-CONSOLIDATING RUBBERIZED CONCRETE WITH/WITHOUT STEEL FIBRES

By

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ABSTRACT

This research program focuses on investigating the applicability of using crumb rubber (CR) as a replacement for fine aggregate in developing a novel eco-friendly concrete type suitable for structural applications, especially when self-consolidating concrete (SCC) is used. Four extensive experimental studies have been carried out on both small- and large-scale concrete specimens to accomplish the research objective. The first and second studies aimed to optimize a number of successful self-consolidating rubberized concrete (SCRC) and steel fibre SCRC (SFSCRC) mixtures with maximized percentages of CR and minimized reduction in the stability and strength. The first parametric study included 27 SCRC mixtures developed with different binder contents (500-550 kg/m^3), supplementary cementing materials (SCMs) (metakaolin (MK), fly ash (FA), and ground granulated blast-furnace slag (GGBS)), coarse aggregate sizes (10-20 mm), and entrained air admixture. The second parametric study included 19 SFSCRC mixtures developed with different binder content (550–600 kg/m^3), steel fibre (SF) volume fractions (0.35% and 0.5%), and lengths of SFs (35 and 60 mm). In this study (study 2), another three vibrated rubberized concrete (VRC) and four steel fibre VRC (SFVRC) mixtures were developed for comparison. In both study 1 and 2, the fresh and mechanical properties of the developed mixtures were evaluated using small-scale specimens. The fresh properties included flowability, passing ability, high-range water-reducer admixture (HRWRA) demand, coarse aggregate segregation, and CR distribution. On the other hand, the evaluation of mechanical properties in both study 1 and 2 included compressive strength, splitting tensile strength (STS), flexural strength (FS), modulus of elasticity, impact resistance, ultrasonic

pulse velocity, and acoustic emission measurements. The third and fourth studies evaluated the structural performance (flexural and shear) of large-scale reinforced concrete beams made with SCRC, VRC, SFSCRC, and SFVRC. In these studies, a total of 36 optimized mixtures from study 1 and 2 were selected to cast 36 large-scale reinforced concrete beams to be tested in flexure and shear (24 beams in flexure and 12 beams in shear). The performance of some design codes and empirical equations in predicting the first cracking moment, flexural, and shear capacity of the tested beams was also evaluated in study 3 and 4.

The results showed that using CR in SCRC helped to develop mixtures with improved impact resistance, acoustic absorption capacity, and lower self-weight, but their stability, fresh, and mechanical properties were decreased. However, using higher binder content, different SCMs, and entrained air in SCRC improved their fresh properties and allowed high percentages of CR to be used, successfully. Moreover, MK was found to be the most effective SCMs that could obviously improve the stability and strength of SCRC. Although using SFs in SCRC mixtures negatively affected the fresh properties of the mixtures, they proved to have a significant enhancement on the mixtures' strengths, especially STS, FS, and impact resistance. Since the challenge to optimize mixtures with high flowability and passing ability was not a factor in developing vibrated mixtures, it was possible to develop SFVRC mixtures with higher percentage of CR and SFs. This high combination of CR and SFs provides a new concrete composite with further improvement in ductility, toughness, impact resistance, and with further reduction in self-weight.

The results of the flexural testing conducted in study 3 indicated that increasing the CR appeared to narrow crack widths and improve deformability of SCRC and VRC beams at given load. The safe use of CR in structural applications was found to be 15%. Further increase in the CR content showed a significant reduction in the first cracking moment and ultimate flexural capacity of the tested beams, while the ductility and toughness did not show a confirmed effect for the higher percentages of CR. On the other hand, in SFVRC, the addition of 1% SFs (35 and 60 mm) helped to extend the possible safe content of CR to 35%, achieving successfully semi-lightweight concrete beams with a sufficient capacity, ductility, and toughness for multiple structural applications.

In shear testing conducted in study 4, using CR in SCRC and VRC beams showed a reduction in their shear capacity, post-diagonal cracking resistance, and energy absorption. These reductions could be alleviated by inclusion of SFs. The composite effect of CR and SFs also helped to narrow the developed cracks and change the failure mode from a brittle shear failure to a ductile flexural failure, particularly for SFs volume of 1%. The comparisons between the predictions and the experimental results (obtained from study 3 and 4) indicated that most of the proposed equations can satisfactorily estimate the flexural and shear capacity, but the first cracking moment was overestimated.

PAPERS PUBLISHED FROM THIS RESEARCH

The majority of the results and discussions presented in this dissertation have been published in the following journals and conferences:

Journal Papers

1. **Mohamed K. Ismail** and Assem A. A. Hassan (2017) Use of steel fibers to optimize self-consolidating concrete mixtures containing crumb rubber. *ACI Materials Journal* 114(4): 581-594. (https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=51689714)
2. **Mohamed K. Ismail** and Assem A. A. Hassan An experimental study on flexural behaviour of large-scale concrete beams incorporating crumb rubber and steel fibres. *Engineering Structures* 145: 97–108. (http://www.sciencedirect.com/science/article/pii/S0141029617301712)
3. **Mohamed K. Ismail,** Assem A. A. Hassan and A. Hussein (2017) Structural behaviour of reinforced concrete beams containing crumb rubber and steel fibres. *Magazine of Concrete Research*. (http://www.icevirtuallibrary.com/doi/abs/10.1680/jmacr.16.00525)
4. **Mohamed K. Ismail** and Assem A. A. Hassan (2017) Shear behaviour of large-scale rubberized concrete beams reinforced with steel fibres. *Construction and Building Materials* 140: 43-57. (http://www.sciencedirect.com/science/article/pii/S0950061817302908)

5. **Mohamed K. Ismail** and Assem A. A. Hassan (2017) Impact resistance and mechanical properties of self-consolidating rubberized concrete reinforced with steel fibers. *Journal of Materials in Civil Engineering (ASCE)* 29(1). (http://ascelibrary.org/doi/abs/10.1061/(ASCE)MT.1943-5533.0001731)
6. **Mohamed K. Ismail** and Assem A. A. Hassan (2017) Ductility and cracking behavior of reinforced self-consolidating rubberized concrete beams. *Journal of Materials in Civil Engineering (ASCE)* 29(1). (http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29MT.1943-5533.0001699)
7. **Mohamed K. Ismail** and Assem A. A. Hassan (2016) Impact resistance and acoustic absorption capacity of self-consolidating rubberized concrete. *ACI Materials Journal* 113(06): 725-736. (https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&ID=51689359)
8. **Mohamed K. Ismail** and Assem A. A. Hassan (2016) Use of metakaolin on enhancing the mechanical properties of self-consolidating concrete containing high percentages of crumb rubber. *Journal of Cleaner Production* 125: 282-295. (http://www.sciencedirect.com/science/article/pii/S0959652616301123)
9. **Mohamed K. Ismail**, Mayra T. de Grazia and Assem A. A. Hassan (2016) Behaviour of self-consolidating rubberized concrete under drop-weight impacts. 8th International RILEM Symposium on Self-Compacting Concrete - SCC 2016. RILEM Publications, pp 445-454

10. **Mohamed K. Ismail** and Assem A. A. Hassan (2015) Performance of full-scale self-consolidating rubberized concrete beams in flexure. *ACI Materials Journal* 113(2): 207-218. (https://www.concrete.org/publications/internationalconcreteabstractsportal.aspx?m=details&i=51688640)
11. **Mohamed K. Ismail** and Assem A. A. Hassan (2015) Influence of mixture composition and type of cementitious materials on enhancing the fresh properties and stability of self-consolidating rubberized concrete. *Journal of Materials in Civil Engineering (ASCE)* 28(1). (http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29MT.1943-5533.0001338)

Conference Papers

1. **Mohamed K. Ismail,** Assem A. A. Hassan and Basem H. AbdelAleem "Flexural behaviour of reinforced SCC beams containing recycled crumb rubber." 5th International Structural Specialty Conference, CSCE Conference 2016, London, Ontario, Canada.
2. **Mohamed K. Ismail,** Assem A. A. Hassan and Madolyn A. Lundrigan "Utilization of recycled crumb rubber in structural self-consolidating concrete." 5th International Materials Specialty Conference, CSCE Conference 2016, London, Ontario, Canada.
3. **Mohamed K. Ismail** and Assem A. A. Hassan "Effect of crumb rubber content on structural behaviour of self-consolidating concrete." 8th International RILEM Symposium on Self-Compacting Concrete and 6th North American Conference on Design and Use of Self-Consolidating Concrete 2016, Washington DC, USA.

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5. **Mohamed K. Ismail** and Assem A. A. Hassan "Static and dynamic segregation resistance of self-consolidating rubberized concrete." International Conference on Disaster Management and Civil Engineering 2015, Phuket, Thailand.
6. **Mohamed K. Ismail** and Assem A. A. Hassan "Effect of supplementary cementing materials on fresh properties and stability of self-consolidating rubberized concrete." Proceedings of International Conference on Transportation and Civil Engineering (ICTCE'15) 2015, London, UK.
7. **Mohamed K. Ismail**, Mayra T. de Grazia and Assem A. A. Hassan "Mechanical properties of self-consolidating rubberized concrete with different supplementary cementing materials." Proceedings of International Conference on Transportation and Civil Engineering (ICTCE'15) 2015, London, UK.
8. **Mohamed K. Ismail**, Mayra T. de Grazia and Assem A. A. Hassan "Hardened properties of self-consolidating concrete containing crumb rubber." International Conference on Advances in Structural and Geotechnical Engineering 2015, Hurghada, Egypt.
9. **Mohamed K. Ismail** and Assem A. A. Hassan "Stability of self-consolidating rubberized concrete." International Conference on Advances in Structural and Geotechnical Engineering 2015, Hurghada, Egypt.

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Mohamed K. Ismail

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List of Symbols, Nomenclature or Abbreviations

ACI = American Concrete Institute

AE= Acoustic Emission

AS= Australian Standard

ASTM = American Society for Testing and Materials

BS= British Standards

CR= Crumb Rubber

CSA= Canadian Standards Association

C/F= Coarse-to-Fine Aggregate

EC 2= Eurocode 2

FA= Fly Ash

f_c' = Characteristic Compressive Strength of Concrete (MPa)

FS= Flexural Strength (MPa)

GGBS= Ground Granulated Blast-Furnace Slag

HRWRA= High-Range Water-Reducer Admixture

ITZ= Interfacial Transition Zone

MA= Micro Air

M_{cr}^{exp}= Experimental First Cracking Moment

M_{cr}^{theo}= Theoretical First Cracking Moment Calculated by Design Codes

ME= Modulus of Elasticity

MK= Metakaolin

M_u^{exp}= Experimental Ultimate Moment Capacity

M_u^{theo}= Theoretical Ultimate Moment Capacity Calculated by Design Codes or Empirical Equations

SCC= Self-Consolidating Concrete

SCMs= Supplementary Cementing Materials

SCRC= Self-Consolidating Rubberized Concrete

SFs= Steel Fibres

SFSCRC= Steel Fibre Self-Consolidating Rubberized Concrete

SFVRC= Steel Fibre Vibrated Rubberized Concrete

SR= Segregation Resistance (%)

STS = Splitting Tensile Strength of Concrete (MPa)

T_{50}= Time to Reach 500-mm Slump Flow Diameter (seconds)

T_{50J}= Time to Reach 500-mm J-ring Diameter (seconds)

UPV= Ultrasonic Pulse Velocity (m/s)

VC= Vibrated Concrete

v_{exp}= Experimental Shear Strength of Tested Beams

v_{pred}= Predicted Shear Strength of Tested Beams

VRC= Vibrated Rubberized Concrete

w/b= Water-to-Binder Ratio

1. Introduction

1.1 Background and Research Motivation

Disposal of scrap tyres has become a significant environmental problem worldwide, especially since rubber materials are not easily biodegradable (Sadek and El-Attar, 2014). This issue is getting worse due to the accumulation of millions of discarded vehicle tyres annually (Pelisser et al., 2011; Thomas et al., 2014). Based on 2002 UK statistics, the number of used tyres was estimated to be 37 million annually (Najim and Hall, 2010) and this number continues to increase every year (Martin, 2001). In the United States this number reached up to more than 275 million scrap tyres per year (Papakonstantinou and Tobolski, 2006). Some unacceptable techniques are commonly used to dispose of the worn-out tyres, such as burning or piling up in landfills, which cause serious environmental problems. Burning the discarded tyres releases toxic fumes that can pollute and damage the air, soil, and water (Eldin and Senouci, 1994; Garrick, 2005; Turer, 2012; Sadek and El-Attar, 2014). Similarly, storing the scrap tyres in landfills for a long time may result in many environmental and health problems: the stockpiled tyres provide a breeding medium for mosquitoes and other pests, which can cause several diseases to become widespread (Mohammed et al., 2012; Wang et al., 2013; Sadek and El-Attar, 2014; Thomas et al., 2015). This encourages the research community to evaluate the possible usefulness of waste tyres in multiple applications, attempting to present a safe and clean alternative to re-utilize huge volumes of such problematic waste materials.

Utilizing recycled rubber derived from scrap vehicle tyres in civil engineering applications such as concrete production represents an effective technique for using huge volumes of waste materials safely. This reuse promotes the development of eco-friendly buildings and encourages the concept of sustainable production (Snelson et al., 2009; Ganesan et al, 2013a; Su et al., 2015). In addition, the low density of rubber aggregate compared to a conventional aggregate can contribute to reducing the self-weight of concrete (Batayneh et al., 2008), which helps to reach a more economical design (Najim and Hall, 2010). The use of rubber (as a replacement for fine and/or coarse aggregate) was found to have a positive effect on improving the dynamic properties, strain capacity, ductility, and impact resistance of concrete (Najim and Hall, 2012a; Guo et al., 2014; Ganesan et al., 2013b; Feng et al., 2015; Reda Taha et al., 2008; Al-Tayeb et al., 2013; Gupta et al., 2015). The resistance of concrete to abrasion and freezing-thawing was also enhanced by inclusion of rubber (Gesoğlu et al., 2014; Thomas et al., 2015). The above advantages can be maximized when rubber aggregate is used to develop self-consolidating rubberized concrete (SCRC). The development of SCRC combines the beneficial effects of rubber aggregates and the desired properties of self-consolidating concrete (SCC), such as spreading and filling the formwork under its own weight without applying vibration, which can fix the problem of concrete flowing through congested reinforcements.

However, using waste rubber as a partial replacement for aggregates generally reduced the fresh properties of concrete, especially when SCC was used (Topçu and Bilir, 2009; Güneyisi, 2010). The angular and rough surface of rubber aggregate negatively affected the flowability and passing ability of SCC mixtures (Güneyisi, 2010). In addition, the low density of the rubber makes the particles easy to float toward the surface of freshly mixed SCRC, thus reducing the stability of mixtures (Topçu and Bilir, 2009). The compressive strength, splitting tensile strength (STS), flexural strength (FS), and modulus of elasticity (ME) of concrete were also decreased when the rubber aggregate was used (Batayneh et al., 2008; Reda Taha et al., 2008; Güneyisi, 2010; Al-Tayeb et al., 2012; Najim and Hall, 2012b; Onuaguluchi and Panesar, 2014). This reduction in the mechanical properties with higher percentages of CR could be attributed to (i) the lower modulus of elasticity for rubber particles compared to hardened cement paste (Najim and Hall, 2010; Lijuan et al., 2014), and (ii) the poor strength of the interface between the rubber particles and surrounding mortar (Emiroglu et al., 2007; Onuaguluchi, 2015).

Stability of particles in SCRC mixtures can be improved by adding viscosity-modifying admixtures and/or supplementary cementing materials (SCMs). Metakaolin (MK) is one of the most effective SCMs at improving the viscosity of SCC mixtures, which in turn improves the aggregates' suspension in the mixture and reduces the risk of segregation. In addition, the high pozzolanic reactivity of MK can compensate for the reduction in the mechanical properties of concrete that results from the use of rubber (Madandoust and Mousavi, 2012; Hassan and Mayo, 2014). Using steel fibres (SFs) also can be a potential way to improve the mechanical properties of SCRC, especially the STS and FS of mixtures (Song and Hwang, 2004; Olivito and Zuccarello, 2010; Khaloo et al., 2014). Moreover, the SFs can obviously enhance the toughness, impact resistance, and cracking resistance of concrete (Nataraja et al., 2005; Nia et al., 2012). However, the use of SFs (especially in SCC) increases the inter-particle friction and interference in mixtures, resulting in a high blockage and reduction in the fresh properties of concrete (Khaloo et al., 2014; Ding et al., 2008; Iqbal et al., 2015).

In spite of the potential difficulties on optimizing the fresh properties of SCC incorporating crumb rubber (CR) with/without SFs, developing such composites is increasingly needed in order to produce new types of sustainable concrete with higher ductility, impact resistance, energy absorption, and lower self-weight. For this reason and because there is insufficient data regarding the effect of CR with/without SFs on properties of SCC, this research aimed to investigate the development, mechanical, and structural performance of SCRC and steel fibre self-consolidating rubberized concrete (SFSCRC) mixtures. Vibrated rubberized concrete (VRC) and steel fibre vibrated rubberized concrete (SFVRC) were also included in the experimental program for comparison. Such project presented an attempt to extend the possible applications of waste rubber in the concrete industry.

1.2 Research Objectives and Significance

Although the literature includes several studies that have investigated the effects of using CR as a replacement for fine and coarse aggregate in VRC, there is no sufficient data regarding the fresh properties and strengths of SCRC, especially when different mixture compositions and various SCMs are used. In addition, most of the available research focuses on investigating the behavior of rubberized concrete using small-scale samples (i.e. cubes, cylinders, and prisms), but there is a dearth of studies dealing with the structural behavior of large-scale rubberized concrete elements. The current literature also lacks information about the technical effects of combining SFs and CR on the performance of SCC mixtures, especially when different volumes and sizes of SFs are used.

The research completed in this thesis aimed to develop a number of SCRC mixtures with a maximized percentage of CR and minimized reduction in stability and mechanical properties. Such objective could be achieved by exploiting the beneficial characteristics of different mixture compositions, various SCMs, and SFs to alleviate the reductions in the properties of SCRC due to the addition of CR. This approach safely facilitates the use of high percentages of CR, which in turn contributes to developing new type of green concrete with low strength reductions, high acoustic absorption capacity, superior performance under repeated impact loading, and with further reduced self-weight. In this research, VRC and SFVRC were included for comparison (i.e. the effect of concrete type.). The research also investigated the structural performance of large-scale SCRC, VRC, SFSCRC, and SFVRC beams in flexure and shear. These studies provide information regarding beams' stiffness, ductility, toughness, cracking behaviour, structural capacity, and performance of some design codes and empirical equations. Therefore, this research can greatly contribute to evaluating the applicability of using CR in structural applications.

1.3 Scope of Research

This research included four successive experimental studies conducted on both small- and large-scale concrete specimens. The first and second studies were implemented at the material level (i.e. small-scale specimens such as cylinders and prisms) to evaluate the applicability of involving waste rubber in concrete as a partial replacement for fine aggregate. In the first study, a total of 27 SCRC mixtures were tested. This experimental investigation included different binder contents, SCMs, aggregate sizes, entrained air admixture. The developed mixtures were evaluated in the fresh state based on the self-compactability criteria given by the European Guidelines for Self-Compacting Concrete (2005) and/or the Interim Guidelines for the Use of Self-Consolidating Concrete (2003). On the other hand, the performance of mixtures in the hardened state was assessed by testing the compressive strength, STS, FS, ME, impact resistance (cylinder and beams), and acoustic absorption capacity (acoustic emission (AE) technique and ultrasonic pulse velocity (UPV) test). This study mainly aimed to present some optimized SCRC mixtures with a reduced self-weight and superior properties for structural applications requiring high-impact resistance, energy dissipation, ductility, and acoustic absorption capacity. Similarly, the second study was designed to increase the possible uses of SCRC mixtures in structural applications. In the second study, a total of 26 mixtures were developed using different volumes and lengths of SFs. This study particularly, evaluated the technical benefits that can be achieved by combining CR and SFs, in which the SFs was not exploited only to compensate for CR's adverse effects on strengths of rubberized concrete, but also to further improve the impact energy absorption, ductility, cracking resistance of mixtures. The fresh and hardened properties tests in study 2 were carried out as in study 1.

The third and fourth studies were conducted on some successful mixtures optimized from study 1 and 2, but focused on the influence of rubber on the structural performance of large-scale concrete beams. The third study investigated the behaviour of 24 large-scale reinforced concrete beams in flexure. The effects of changing the CR content, SFs' volume, SFs' length, and concrete type (i.e. SCC and vibrated concrete (VC)) were considered in the third stage. The behaviour of the tested beams was evaluated based on load-deflection response, cracking behaviour, first crack load, ultimate load, ductility, and toughness. The performance of some design codes was evaluated in predicting the flexural capacity and cracking moment of the tested beams. The fourth study investigated the shear behaviour of 12 large-scale reinforced concrete beams made without stirrups. The influence of CR with/without SFs were evaluated on cracking behaviour, shear capacity, post-diagonal cracking resistance, and energy absorption capacity of the tested beams. The results obtained from the conducted experiments were also evaluated against the predictions of shear design models proposed by some of the current design codes and published research.

1.4 Thesis Outline

This thesis consists of eight chapters described as follows:

Chapter 1 addresses the background, motivation, objectives, significance, and scope of the research completed in this thesis.

Chapter 2 presents a review of the literature pertaining to the history of SCC, self-compactability criteria, parameters affect the performance of SCC, effect of waste rubber and/or SFs on properties of VC and SCC. A limited research conducted on studying the effect of waste rubber on the structural performance of large-scale concrete elements is also presented in this chapter.

Chapter 3 describes the experimental program including the used materials, significance and scope of each study, investigated parameters, mixing and casting procedures, description of the cast/tested specimens, curing regimes, and details of the conducted tests.

Chapter 4 discusses the results obtained from the first study which was conducted in the experimental program to optimize the fresh properties, stability, and strength of SCRC using different mixture compositions and various SCMs.

Chapter 5 presents the results and discussions of the findings observed in the second study regarding the use of SFs to optimize SCC mixtures containing CR.

Chapter 6 discusses the results of the third study investigating the flexural performance of large-scale rubberized concrete beams with/without SFs.

Chapter 7 discusses the results of the fourth study evaluating the shear behaviour of large-scale rubberized concrete beams with/without SFs.

Chapter 8 contains the conclusions drawn from the conducted studies and recommendations for future investigations.

1.5 Limitations of Research

All the results obtained from this research were typically affected by the properties of the used materials. Therefore, changing in the physical and/or chemical properties of any of coarse aggregate, fine aggregate, cement, SCMs, admixtures, CR, and SFs can affect the mixtures' properties in the fresh and hardened states. In the structural studies (study 3 and 4), comparative investigations were conducted to evaluate the influence of CR with/without SFs on the shear and flexural performance of reinforced concrete beams neglecting the effect of changing in the beam' size, longitudinal reinforcement ratio, and shear span-to-effective depth ratio. At materials and structural level, all tests were conducted based on the available facilities in Memorial University's labs. However, in some tests such as impact test, using advanced instruments may result in better measurements with further details.

Some important studies such as evaluating the resistance of rubberized concrete to freezing-thawing, abrasion, permeability, carbonation, chloride and sulfate attacks, shrinkage, creep, and fire, were not considered in the conducted experimental program due to time constraints. However, they are strongly recommended for future investigations.

2. Literature Review

2.1 Introduction

The objective of this chapter is to review the available studies in the literature that relate to the scope of the research completed in this thesis. This chapter is divided into three main parts: (i) self-consolidating concrete (SCC) including the overview, criteria of self-compactability, and parameters affect the performance of SCC; (ii) effect of CR on properties of both VC and SCC in terms of fresh, mechanical, and structural performance; and (iii) effect of SFs on fresh and mechanical properties of concrete, in addition to the flexural and shear behaviour of reinforced concrete beams incorporating SFs.

2.2 Self-Consolidating Concrete (SCC)

2.2.1 Overview

The SCC is defined as a special type of concrete which is able to flow and consolidate under its own weight without applying vibration or any external force (RMCAO, 2009). It has also enough flowability and filling ability that allow mixtures to flow through congested reinforcements and fill complex formwork (Said and Nehdi, 2007). Such properties offer many advantages such as (Ouchi et al., 2003; NRMCA, 2004; RMCAO, 2009):

- Faster rate of concrete placement.
- Less labour requirements.
- Surface finishes with high quality.
- High durability and strength.

- A lower level of noise in the construction site.
- Increasing the level of safety in the construction site by minimizing the labour requirement for casting and eliminating the need for mechanical vibration.

The development of SCC was begun in Japan in the late of 1980's, aiming to achieve concrete with high uniformity and full compaction with no vibration. By the early 1990's, Japan had developed SCC that could completely consolidate under its own weight without applying any vibration (Ouchi et al., 2003). After this point, the technology of SCC has received a great attention from several European countries that established a big project in 1996 attempting to develop SCC for practical applications in Europe (Ouchi et al., 2003). During the next several years, they could successfully develop and commercially involve SCC in constructing number of bridges, walls, and tunnels linings (Ouchi et al., 2003). The United States also adopted the use of SCC in multiple applications such as precast concrete industry, flatwork, columns, and walls construction (Hassan, 2008). Currently, SCC is widely used in the construction industry ranging from architectural applications to construction of complex bridges (Ouchi et al., 2003).

2.2.2 Self-Compactability

2.2.2.1 Flowability, Filling Ability, and Viscosity

Flowability is considered one of the most important characteristics of SCC. This property describes the ability of SCC mixture to flow freely under its own weight without applying any external force to fill the formwork completely. According to the European Guidelines for Self-Compacting Concrete (2005), the flowability of SCC mixtures is measured by slump flow test. This test is conducted as a “primary check” to evaluate if the consistency of freshly mixed SCC meets the specifications or not. In this test, the flowability is evaluated by measuring the average diameter of the flow spread of freshly mixed SCC. According to the measured diameter, the European Guidelines for Self-Compacting Concrete (2005) classify the slump flow into three classes, namely SF1 (diameter = 550-560 mm), SF2 (diameter = 660-750 mm), and SF3 (diameter = 760-850 mm). The test procedures and applications suitable for each SCC category are explained in detail elsewhere (The European Guidelines for Self-Compacting Concrete, 2005).

The viscosity of mixtures can be also assessed in the slump flow test by measuring T_{50}, which is defined as the time concrete takes to reach a diameter of 500 mm (as shown in **Figure 2.1**). In addition to the T_{50}, the V-funnel test is also used to evaluate the viscosity of SCC by measuring the time concrete takes to flow out of the V-funnel (see **Figure 2.2**). Based on the T_{50} and V-funnel time, the European Guidelines for Self-Compacting Concrete classify the viscosity of SCC into two classes, namely VS1/VF1 ($T_{50} \leq 2$ seconds, V-funnel flow time $\leq$ 8 seconds) and VS2/VF2 ($T_{50} > 2$ seconds, V-funnel flow time ranging from 9 to 25 seconds). The VS1/VF1 class is characterized by having a good filling ability and self-levelling, but there is a high possibility of bleeding and segregation. The VS2/VF2 class is more likely to experience thixotropic effects, which may help to improve segregation resistance and limit the formwork pressure, but the quality of surface finishes may negatively be affected (The European Guidelines for Self-Compacting Concrete, 2005).

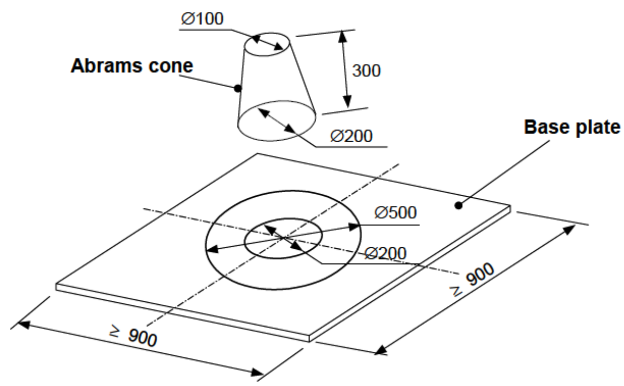


Figure 2.1 Slump flow test setup (dimensions in mm) (TESTING-SCC, 2005)

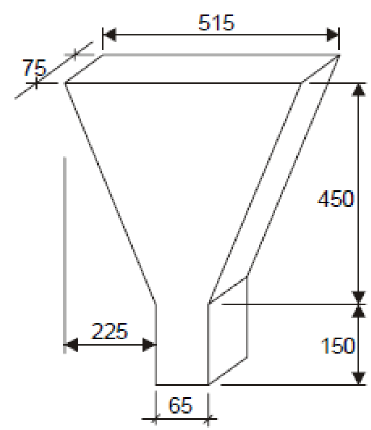


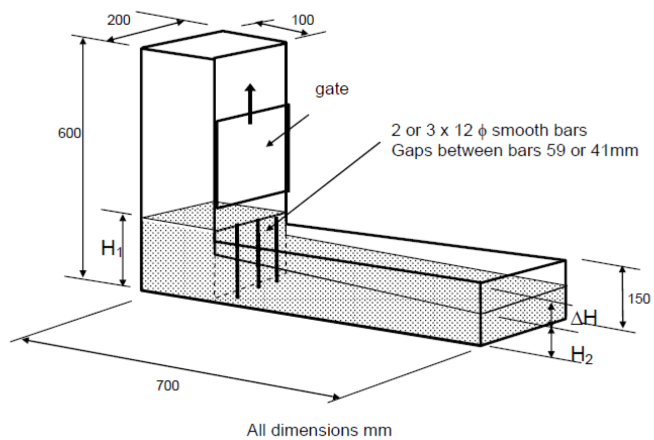
Figure 2.2 V-funnel dimensions in mm (TESTING-SCC, 2005)

2.2.2.2 Passing Ability

Passing ability describes the ability of freshly mixed mixtures to flow through confined and limited spaces without experiencing segregation and blockage (The European Guidelines for Self-Compacting Concrete, 2005). The measured passing ability indicates the possible degree of blockage that may occur in areas with congested reinforcements (Najim and Hall, 2012a). The L-box and J-ring tests (**Figure 2.3**) are used to evaluate the passing ability of SCC. Both tests are explained in detail in the European Guidelines for Self-Compacting

Concrete (2005) and TESTING-SCC (2005). The conformity of the European Guidelines for Self-Compacting Concrete (2005) and the Interim Guidelines for the Use of Self-Consolidating Concrete (2003) accept the passing ability of SCC if the L-box ratio H2/H1 is greater than or equal to 0.75.

(a)



(b)

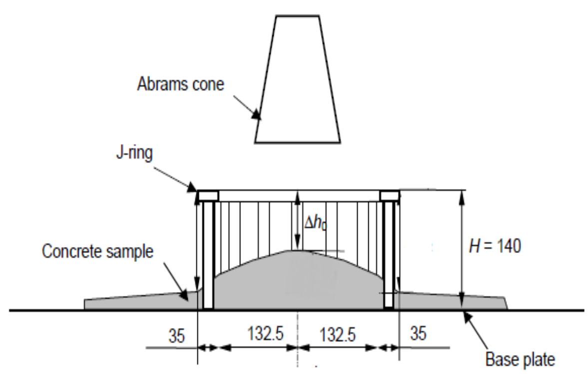


Figure 2.3 Passing ability tests (a) L-box test (The European Guidelines for Self-Compacting Concrete, 2005), (b) J-ring test (TESTING-SCC, 2005)

2.2.2.3 Segregation Resistance

Segregation resistance is defined as the ability of freshly mixed concrete to retain its homogeneity (The European Guidelines for Self-Compacting Concrete, 2005). This means that there is no separation between coarse aggregate and mortar. Segregation occurs when the coarse aggregate tends to accumulate downward under its own weight (in case of normal weight aggregate) or to float toward the surface of concrete (in case of lightweight aggregate). The segregation resistance of SCC is directly affected by the viscosity of its mortar or cement paste. Improving the viscosity of cement paste helps to increase the ability to carry the particles (coarse aggregates) and remain coarse aggregates well suspended and uniformly distributed in mixtures during the fresh state. The European Guidelines for Self-Compacting Concrete (2005) recommend the sieve segregation test to evaluate the segregation resistance of SCC mixtures. According to the test's producers and evaluation criteria, the stability of SCC is considered acceptable when the segregation ratio is less than or equal to 15%.

2.2.3 Parameters Affect the Performance of SCC

2.2.3.1 Chemical Admixtures

Chemical admixtures play an important role in the production of SCC. For example, the use of high range water reducer admixture (HRWRA), which is also known as superplasticizer, is necessary to develop mixtures with adequate flowability while maintaining reasonable water-to-binder (w/b) ratio (Okamura and Ozawa, 1995; Okamura and Ouchi, 1999). The HRWRA gives all cement particles a high negative charge that disperses the particles and reduces the friction (Neville, 1995), thus improving the workability. Using HRWRA also allows SCC to be produced with lower w/b ratio, which helps to increase the strength and durability of concrete (Neville, 1995; Khayat, 1999; Mindess et al., 2003).

Beside the flowability, adjusting the stability of mixtures is considered as a major aspect in the production of SCC. As mention earlier, improving the viscosity of mixtures increases the particle suspension and reduces the risk of segregation (Khayat, 1998; Mindess et al., 2003), and hence provides a better stability. The viscosity can be improved by using viscosity modifying admixtures which improve the cohesion of SCC without a significant change in its fluidity (Hassan, 2008).

Using entrained air admixture can also improve the performance of SCC in terms of flowability and passing ability (Struble and Jiang, 2004; Safiuddin, 2008; Hassan and Mayo, 2014). This is related to that the air bubbles resulted from adding entrained air admixture act as a fine aggregate with high elasticity and low surface friction, which in turn decreases the inter-particle friction and improves the flowability and passing ability (Neville, 1995). In addition, the entrained air admixture reduces the bleeding and increases the resistance of concrete to freezing and thawing (Neville, 1995); however, the mechanical properties may negatively be affected (Hassan and Mayo, 2014).

2.2.3.2 Binder Content and Supplementary Cementing Materials (SCMs)

The development of successful SCC requires high volume of fines to reduce the inter-particle friction and increase the volume of cement paste that provides a smooth flow. The flowability, passing ability, and segregation resistance of mixtures were found to be increased as the binder content increased (Assaad and Khayat, 2005; Nanthagopalan and Santhanam, 2009). However, an excessive content of fines increases the total surface area

(Girish et al., 2010), which consumes high amount of water to get their surfaces wet and hence decreases the fllowability. Increasing the binder content provides a dense microstructure for SCC, which in turn improves the mechanical properties and durability (Girish et al., 2010; Hassan and Mayo, 2014).

The development of SCC is also significantly affected by inclusion of SCMs such as fly ash (FA), ground granulated blast furnace slag (GGBS), silica fume, and metakaolin (MK), which are incorporated in the SCC as a percentage of binder content. Previous investigations reported that adding SCMs to SCC generally improved the filling and passing ability of mixtures (Khayat and Assaad, 2002; Gesoğlu et al., 2009; Hassan and Mayo, 2014). The MK proved to be the most effective SCMs in improving the stability/viscosity and mechanical properties of SCC (Qian and Li, 2001; Hassan et al., 2012; Madandoust and Mousavi, 2012; Hassan and Mayo, 2014). Increasing the mixture viscosity due to inclusion of MK helps to improve the aggregates' suspension in the mixture, prevent coarse aggregate segregation, and keep the mixture homogeneous (Cyr and Mouret 2003). However, developing highly flowable SCC incorporating MK cannot be practically achieved without adding large amounts of HRWRA (Madandoust and Mousavi, 2012).

2.2.3.3 Coarse Aggregate Content and Size

The characteristics of coarse aggregate (shape, content, size, and gradation) have a direct impact on the properties of SCC. Aggregate with rounded and smooth surface gives a higher workability compared to aggregate with angular and rough surface (Neville, 1995).

This is attributed to that for a given aggregate volume, the rounded aggregate has smaller total surface area and lower inter-particle friction (Koehler, 2007) that leave more free cement paste in mixtures and provide a smooth flow. However, the angular aggregate with rough texture forms a greater bond with cement paste, which in turn improves the strength of concrete (Mehta and Monteiro, 1997). The content of coarse aggregate also affects the rheological properties of SCC. From previous studies (Su et al., 2002; Hassan and Mayo, 2014, Khaleel and Razak, 2014), it can be observed that using a lower coarse-to-fine aggregate (C/F) ratio gives a better flowability, filling ability, passing ability, and segregation resistance. These findings may be attributed to that using low content of coarse aggregate leads to reducing the inter-particle friction and the risk of blockage through confined and limited spaces (Koehler, 2007). Other studies (Hu and Wang, 2011; Hassan and Mayo, 2014) reported that for the same coarse aggregate type and volume, increasing the aggregate size decreased the total surface area of aggregate that improved the flowability of SCC (as explained earlier). However, restrictions on maximum aggregate size are needed to meet the requirements of passing ability and segregation resistance (Koehler, 2007; Khaleel and Razak, 2014). The gradation of aggregate has also a significant impact on performance of SCC, in which a well-graded aggregate is considered the optimal choice to develop a successful and economical SCC, while poorly-graded aggregate may experience a lower passing ability and higher risk of segregation (Neuwald, 2004; Khaleel and Razak, 2014).

2.3 Effect of CR on Properties of VC and SCC

2.3.1 Fresh Properties

Many investigations have been conducted to evaluate the influence of rubber replacement on behaviour of VC in both fresh and hardened state. The data available in the literature indicates that inclusion of CR had a negative impact on the workability of VC, which was typically evaluated using slump test. This finding is attributed to the rough and angular surface of rubber particles, which can create high inter-particle friction and increase the resistance of concrete to flow (Reda Taha et al., 2008). These results are generally in agreement with the observed manner by other studies (Fattuhi and Clark, 1996; Khatib and Bayomy, 1999; Nehdi and Khan, 2001; Batayneh et al., 2008). However, the reduction in the workability resulted from adding rubber can be compensated by increasing the dosage of superplasticizer (Youssf et al., 2014). The literature review indicates that concrete made with only CR replacement showed considerably higher workability compared to that incorporated chipped or combined chipped and CR replacement (Khatib and Bayomy, 1999; Khaloo et al., 2008; Reda Taha et al., 2008). Using CR in VC also appeared to increase the air content in mixtures (Reda Taha et al., 2008; Naito et al., 2014). The increase in the air content was related to two possibilities: first, the ability of rubber to entrap air in its rough surface (Reda Taha et al., 2008); and second, the high compressibility of rubber that may create an artificial amount of air, resulting in a misleading measurement (Naito et al., 2014).

Although several investigations have been conducted on using CR as a replacement for fine aggregate in VC, there are limited studies available regarding the development of SCC containing CR. From these studies, it was found that the use of CR appeared generally to decrease the fresh properties of SCC (similar to the CR's effects on VC). Bignozzi and Sandrolini (2006) could produce SCRC with replacements of 0%, 22%, and 33% CR (by fine aggregate volume). They observed that the development of successful SCRC required a higher amount of superplasticizer compared to mixtures with no rubber. This finding agrees with that reported by Güneyisi (2010), who investigated the fresh properties of SCRC incorporating CR in a range of 0%-25%. Güneyisi (2010) also stated that increasing the CR content in SCRC reduced its flowability and passing ability, but adding fly ash to mixtures could alleviate the reduction in the fresh properties resulted from rubber. Other researchers (Topçu and Bilir, 2009) used CR in SCC at contents of 0, 60, 120, and 180 kg/m^3. They observed that increasing the rubber content improves the workability of SCC, but with an increased risk of segregation. The negative effect of CR on the fresh properties of SCC was also confirmed by other few studies (Najim and Hall, 2012a; Karahan et al., 2012; Güneyisi et al, 2016).

2.3.2 Mechanical Properties

By reviewing the available research conducted on CR concrete, it can be observed that increasing the rubber content caused a general reduction in the compressive strength, STS, FS, and ME of mixtures (Bignozzi and Sandrolini, 2006; Batayneh et al., 2008; Topçu and Bilir, 2009; Güneyisi, 2010; Aiello and Leuzzi, 2010; Al-Tayeb et al., 2012; Najim and Hall, 2012b; Karahan et al., 2012; Onuaguluchi et al., 2014; Güneyisi et al, 2016). For example, in VRC, Batayneh et al. (2008) found that using 100% CR replacement (by fine aggregate volume) showed a reduction in the compressive strength reached up to 90%. Similarly, Al-Tayeb et al. (2012) observed that adding 20% CR decreased the compressive strength, STS, and ME by 20%, 16.7%, and 22%, respectively. Other researchers (Onuaguluchi et al. 2014) reported that the addition of 15% CR decreased the compressive strength, STS, and ME by 40%, 35%, and 29.3%, respectively. For SCRC, Karahan et al. (2012) stated that using 30% CR (by fine aggregate volume) showed a reduction the compressive strength, STS, and FS reached up to 53.3%, 22.9%, 35.6%, respectively. Najim and Hall (2012a) also reported a reduction in the compressive strength, STS, and FS of SCRC reached up to 55.4%, 41.9%, and 34.5%, respectively, when 49.5% CR was used. These reductions could be attributed to two reasons: firstly, the significant difference between the stiffness of rubber particles and hardened cement paste (Najim and Hall, 2010; Lijuan et al., 2014); and secondly, the poor strength of the interfacial transition zone (ITZ) between rubber particles and surrounding mortar (Najim and Hall, 2010; Onuaguluchi, 2015). The weaken rubber-cement paste interface allows typically for the development and propagation of microcracks, which can rapidly extend and propagate under loading due to the high differential strain rates between rubber and hardened cement paste (Najim and Hall, 2010).

Researchers have suggested many approaches to alleviate the reduction in mechanical properties of concrete due to the inclusion of rubber aggregates. One of these techniques is the use of SCMs. Guneyisi et al. (2004) investigated the effect of using silica fume on the mechanical properties of VRC mixtures containing CR and/or tyre chips with a replacement of up to 50% by volume. The authors observed that the addition of silica fume could minimize the strength loss, allowing VRC mixtures with up to 15% rubber to be developed with a compressive strength of 40 MPa. Onuaguluchi and Panesar (2014) reported that adding 15% silica fume to VRC can increase the 28-day compressive strength and STS by 32.9% and 32.2%, respectively, compared to mixtures with no silica fume. Similar results were stated by Elchalakani (2015) confirming the beneficial effect of silica fume on improving the ITZ bonding, which minimizes the reduction in concrete strengths due to inclusion of waste rubber. Other researchers suggested that the mechanical properties of rubberized concrete can be enhanced by using chemical pretreatment for the surface of the rubber particles, which improves the adhesion between rubber and cement paste. Previous studies recommended different treatments, such as the use of polyvinyl alcohol, sodium hydroxide (Balaha et al., 2007; Najim and Hall, 2013; Youssf et al., 2014), and sulfur compounds (Chou et al., 2010). However, even after treatment, researchers did not observe a significant enhancement in the compressive and tensile strength of rubberized concrete.

2.3.3 The Usefulness of Rubber in Concrete

Although the mechanical properties of concrete decreased by inclusion of rubber, significant research has reported that reusing waste rubber as an aggregate replacement can be a promising technique to develop concrete with improved dynamic properties and higher ductility. A study performed by Najim and Hall (2012b) stated that using rubber aggregate greatly enhanced the strain capacity of concrete, which in turn decreased the crack mouth opening displacement. In addition, increasing the rubber content showed a significant improvement in the flexural toughness, which had a direct impact on enhancing the concrete's ductility and energy absorption. Najim and Hall (2012b) also found that the damping coefficient of the rubberized concrete at 15% CR increased by 230% compared to concrete with no CR. Guo et al. (2014) reported that using appropriate rubber content could increase the fracture energy and ductility of concrete, but high increase in rubber contents may have adverse effects on the ductility of concrete and its ability to absorb higher energy. Another study by Ganesan et al. (2013b) indicated that the fatigue strength of concrete can be enhanced by adding scrap rubber to the mixture. This finding was also confirmed by Feng et al. (2015), in which the fatigue life of concrete increased as the percentage of rubber increased, achieving the optimal strength when the rubber content reached a replacement of 20% (by fine aggregate volume). Al-Tayeb et al. (2012) investigated the effect of using up to 20% waste rubber as partial replacement for both sand and cement on the impact resistance of VRC beams. The researchers observed that the impact energy for both first crack and failure crack continuously increased as the replacement of sand with fine CR increased, while 10% of rubber powder was shown to be an optimal replacement for cement. Gupta et al. (2015) also reported that replacing the fine aggregate by waste rubber fibre (up to 25% by volume) greatly improved the impact absorption energy of VRC. Reda Taha et al. (2008) observed similar results in VRC beams, in which the CR was used as a replacement for fine aggregate with percentages varying from 0% to 100% in increments of 25% (by volume). This investigation indicated that using 50% CR replacement could achieve the maximum impact energy, while the beams with 75% CR exhibited impact energy mostly equal to the control mixture (CR = 0%).

The durability performance of rubberized concrete was also investigated by a number of researchers. It was found that the addition of waste rubber in concrete showed an improved resistance to abrasion, freezing-thawing action, and acid attack (Richardson et al., 2012; Gesoğlu et al., 2014; Thomas et al., 2014; Thomas et al., 2015; Thomas et al., 2016). These improvements may extend the possible applications for the use of rubberized concrete in cold environments and offshore structures.

Reutilization of CR in concrete mixtures can also play an important role in enhancing the sound absorbance of concrete. Such enhancement provides a promising potential for rubberized concrete to be used in applications, such as eliminating sound transmission through walls, floors, and ceilings. Holmes et al. (2014) investigated the sound absorbance of concrete panels containing CR as a fine aggregate replacement. In this study, VRC mixtures were tested with two volumetric replacement levels of CR (7.5% and 15%) and with different grades following freezing and heating. The researchers stated that the developed mixtures showed a good performance in term of sound absorbance, with no significant effects for freezing and heating. Other investigations (Sukontasukkul, 2009; Pastor et al., 2014) also confirmed the beneficial effect of rubber on improving the sound absorption capacity of concrete, recommending such type of concrete to be used as a sound absorbing barriers in areas with high noise levels.

2.3.4 Use of VRC and SCRC in Large-Scale Structural Members

The current literature includes limited studies investigated the behaviour of intermediate- and large-scale structural elements made with rubberized concrete. Najim and Hall (2014) presented a simple investigation for intermediate-scale reinforced concrete beams containing CR. Eight reinforced concrete beams, two for each mix-VC, VRC, SCC, and SCRC-were cast with dimensions 1700 x 200 x 100 mm. The CR replacement reached up to 14% and 18% of the total aggregate volume for VRC and SCRC, respectively. The authors reported that adding CR decreased the flexural capacity and stiffness of beams. Meanwhile, the deformation capacity and energy absorption were increased with increased percentages of CR. Another study (Sadek and El-Attar 2014) investigated the structural performance of masonry walls under the effect of uniform vertical loading. The constructed walls made from rubber-cement bricks with volume replacements ranging from 0% to 100% for coarse aggregate and from 0% to 50% for fine aggregate. The researchers reported that in addition to the environmental benefits come from involving the waste rubber in such applications, inclusion of rubber in masonry walls generally increased its toughness, deformation capacity, and capability to withstand post-failure loads. Ganesan et al. (2013a) also investigated the effect of replacing 15% of the fine aggregate volume by shredded rubber aggregates on the behaviour of SCRC beam-column joints under monotonic and cyclic load. They observed that the addition of shredded rubber slightly reduced the load-carrying capacity, but the energy absorption capacity, crack resistance, and ductility were improved. Youssf et al. (2015) also observed an improvement in behaviour of rubberized concrete columns under seismic loading. The results showed that adding rubber to concrete column increased its hysteretic damping ratio and energy dissipation with insignificant reduction in the ultimate lateral strength.

2.4 Effect of SFs

2.4.1 Fresh and Mechanical Properties of Concrete

Using SFs in CR concrete can be an effective way to compensate for the reduction in STS and FS resulting from the addition of CR. Moreover, the inclusion of SFs can also improve the flexural toughness, impact strength, ductility, and limit the crack widths in concrete (Song and Hwang, 2004; Nataraja et al., 2005; Olivito and Zuccarello, 2010; Erdem et al., 2011; Nia et al., 2012; Altun and Aktas, 2013; Khaloo et al., 2014). For example, Nia et al. (2012) investigated the mechanical properties and impact resistance of VC mixtures developed with different water-cement ratios and different SF contents. The researchers reported that using 0.5% and 1% SFs appeared to increase the tensile strength by a range of 9%-20% and 30%-62%, respectively, compared to mixtures with no SFs. Also, the impact resistance showed increases reaching up to 3.5 to 10.2 times and 7.2 to 12.4 times in mixtures with 0.5% and 1% SFs, respectively. Nataraja et al. (2005) also studied the effect of SFs with an aspect ratio of 40 on the impact resistance of VC using two different compressive strengths (30 MPa and 50 MPa). The results indicated that using 0.5% SFs showed an improvement in the impact resistance of mixtures with 30 MPa reaching up to 3 to 4 times greater than the control mixture, while this increase was 7 to 10 times in mixtures with a strength of 50 MPa.

However, the addition of SFs has a significant negative effect on the fresh properties of concrete, especially when SCC is used. Khaloo et al. (2014) showed that increasing SFs (20 mm length) higher than 0.5% in SCC mixtures with 600 kg/m3 powder content exhibited unacceptable L-box test results (L-box ratio is less than 0.75). Iqbal et al. (2015) also studied the effect of using up to 1.25% SFs (13 mm length) on the properties of lightweight SCC. The study reported that the addition of SFs appeared to improve the STS and FS of concrete, while the flowability reduced as the volume of SFs increased. No data was provided for the passing ability. The same effect of SFs on the fresh properties of SCC was also noted by other researchers (Ding et al., 2008; Akcay and Tasdemir, 2012).

2.4.2 Shear and Flexural Capacity of Beams

Many studies have been conducted to evaluate the effect of SFs on the shear capacity of reinforced concrete beams (Sharma, 1983; Narayanan and Darwish, 1987; Ashour et al., 1992; Lim and Oh, 1999; Khuntia et al.,1999; Kwak et al, 2002; Meda et al., 2005; Dinh et al., 2010; Ding et al., 2011; Tahenni et al., 2016). The results obtained from the conducted research confirmed the effectiveness of SFs on improving the shear strength of concrete beams. However, the amount of improvement was mainly affected by the volume and length of SFs. For example, Kwak et al. (2002) investigated the shear behavior of 12 SFs-reinforced concrete beams constructed without stirrups having different SFs volumes and shear span-to-depth (a/d) ratios. In this study, the researchers stated that the shear strength, deformation capacity, and cracking behaviour of beams improved as SFs content increased. In addition, using fibres volume of 0.75 changed the failure mode from shear failure (brittle failure) to a combination of shear and flexure failure in beams with a/d = 2, and to a complete flexure failure in beams with a/d = 3. Ding et al. (2011) studied the use of SFs (60 mm length and 0.75 mm diameter) in beams with/without stirrups. They observed that using 20 kg/m^3 of SFs increased the shear strength of beams without stirrups by 17.8% compared to beam with no SFs, while 60 kg/m^3 of SFs caused an increase reached up to 83.4%. It was concluded that such increases can help to partially replace the stirrups and/or increase the stirrups' spacing. Tahenni et al. (2016) also reported that the shear strength of high-strength concrete showed an improvement up to 47% and 88% for a quantity of 0.5% and 3% SFs (35 mm length and 0.54 mm diameter), respectively. Their results also indicated that ductility of beams was significantly increased with the addition of fibres, in which the inclusion of 3% SFs increased the ductility factor by more than twice that of beam with no SFs. Other studies also proved the promising potentials of SFs in improving the flexural behaviour of beams (Henager and Doherty, 1976; Qian and Patnaikuni, 1999; Ashour et al., 2000; Altun et al., 2007; Campione and Mangiavillano, 2008; Hamid et al., 2012; Mertol et al., 2015). Henager and Doherty (1976) reported that inclusion of SFs in reinforced concrete beams appeared to increase the ultimate load capacity, post-cracking stiffness, and limit the crack width and spaces. Qian and Patnaikuni (1999) also stated that beams with SFs exhibited higher post-cracking stiffness, post-peak ductility, larger displacement at failure, and lower crack widths at comparable level of loading compared to beams with no SFs. The addition of SFs also proved to have a beneficial effect on improving the toughness of reinforced concrete beams (Altun et al., 2007; Mertol et al., 2015). These improvements in both shear and flexural behavior are attributed to the ability of SFs to transfer stress across the cracked sections by fibres' bridging mechanism, which provides a residual strength to concrete (Yang et al., 2010; Ding et al., 2012; Ning et al., 2015). Moreover, the fibres' stitching action has an effective role in controlling the development of cracks and limiting the crack openings (Yang et al., 2012; Yoo and Yoon, 2015).

3. Experimental Program

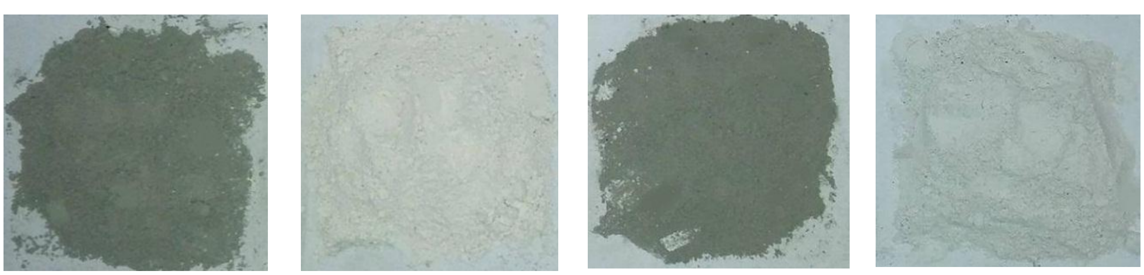
3.1 Introduction

This chapter describes the research methodology including: the properties of the used materials, mixing procedure, specimens type and dimensions, casting and curing techniques, and tests conducted on the developed concrete mixtures in fresh and hardened states. In addition, the details of flexural and shear tests of the large-scale reinforced concrete beams are provided including the beams' dimensions, test setup, application of load, and measurements.

3.2 Materials

3.2.1 Cement and SCMs

Type GU Canadian Portland cement, MK, FA, and GGBS, similar to Type 1 ASTM C150 (2012), ASTM C618 Class N (2012), ASTM C618 Type F (2012), and ASTM C989 (2014), respectively, were used as binders for all developed mixtures. **Figure 3.1** shows the used cement and other SCMs (MK, GGBS, and FA). The chemical and physical properties of the used cement and SCMs are also shown in **Table 3.1**.



Cement MK FA GGBS

Figure 3.1 The used cement and other SCMs

Table 3.1 The chemical and physical properties of the used cement and other SCMs

Chemical properties (%)	Cement	MK	GGBS	FA
SiO_2	19.64	51-53	40.3	52
Al_2O_3	5.48	42-44	8.4	23
Fe_2O_3	2.38	<2.2	0.5	11
FeO	-	-	-	-
TiO_2	-	<3.0	-	-
C	-	-	-	-
Cr_2O_3	-	-	-	-
MnO	-	-	-	-
P_2O_5	-	<0.2	-	-
SrO	-	-	-	-
BaO	-	-	-	-
SO_4	-	<0.5	-	-
CaO	62.44	<0.2	38.71	5
MgO	2.48	<0.1	11.06	-
Na_2O	-	<0.05	-	-
C_3S	52.34	-	-	-
C_2S	16.83	-	-	-
C_3A	10.50	-	-	-
C_4AF	7.24	-	-	-
K_2O	-	<0.40	0.37	-
L.O.I	2.05	<0.50	0.65	-
Physical properties				
Specific gravity	3.15	2.5	2.9	2.38
Blaine fineness (m^2/kg)	410	19000	400	420

3.2.2 Coarse, Fine, and Rubber Aggregates

Natural crushed stones (with a 10 mm and 20 mm maximum size) and natural sand were used for the coarse and fine aggregates, respectively. Each aggregate type had a specific gravity of 2.6 and a water absorption of 1%. In this research, the volume of fine aggregate was partially replaced by a CR aggregate which had a maximum size of 4.75 mm, specific gravity of 0.95, and negligible water absorption. The used aggregates and their gradations are presented in **Figure 3.2**.

(a)

Crushed stone
(coarse aggregate)

Natural sand
(Fine aggregate)

Crumb rubber

(b)

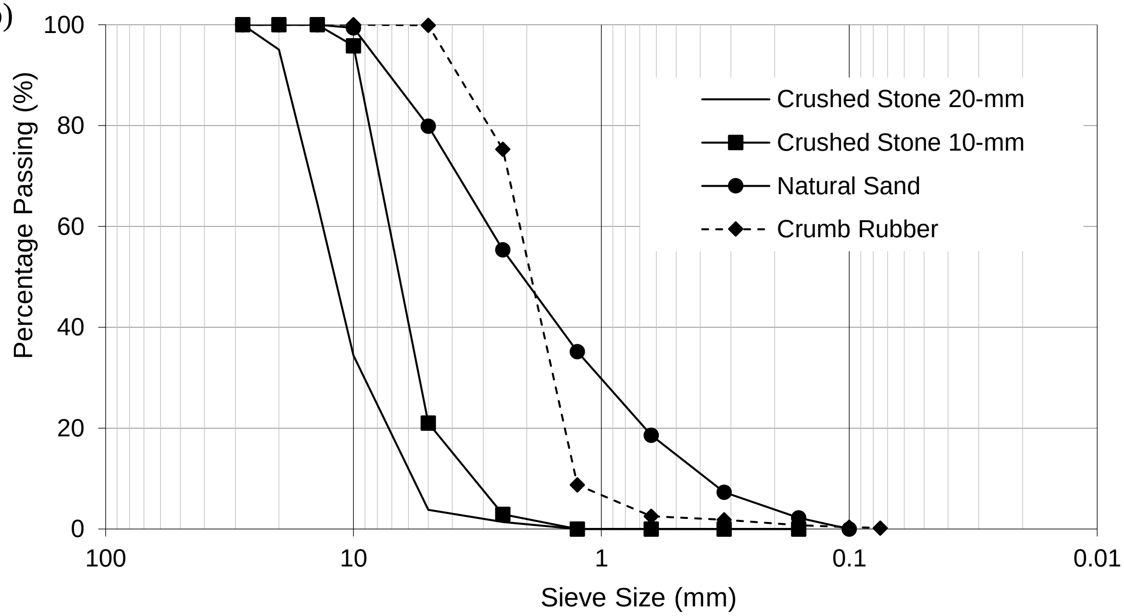


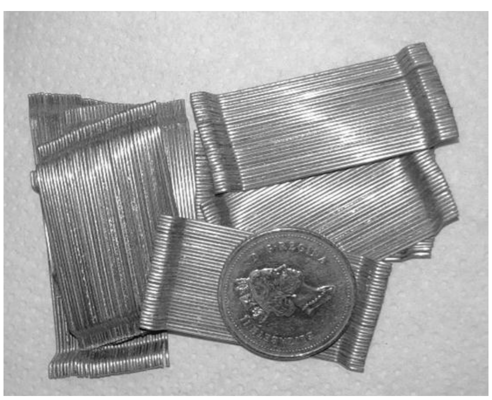
Figure 3.2 The used coarse, fine and crumb rubber aggregates: (a) shape, (b) gradation curves

3.2.3 Chemical Admixtures

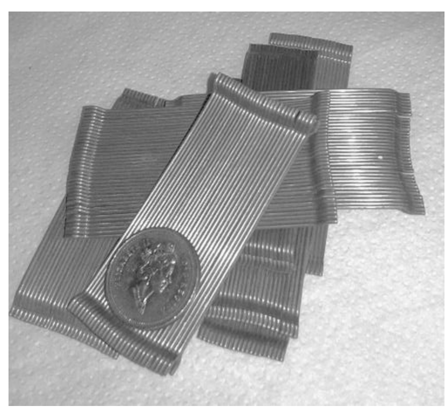
A polycarboxylate-based HRWRA (Glenium 7700) produced by BASF Construction Chemicals was used to achieve the required slump flow/workability of the developed mixtures. This admixture is similar to ASTM C494 Type F with specific gravity, volatile weight, and pH of 1.2, 62%, and 9.5, respectively. MasterAir AE200 entrained air admixture (BASF Construction Chemicals) was used to improve the workability of the developed SCRC mixtures. This admixture meets the requirements of ASTM C260.

3.2.4 Steel Fibres and Steel Rebars

Two types of SFs with hooked-ends (Dramix 3D) were used in the developed mixtures (**Figure 3.3**). The first type had a 35 mm length, 65 aspect ratio, and 0.55 mm diameter, while the second type had a 60 mm length, 65 aspect ratio, and 0.9 mm diameter. Each SFs type had a 1050 MPa tensile strength, 210 GPa Young's modulus, and 7.85 kg/m^3 density. The used SFs were chosen based on the types that are commercially available on the world market. Steel bars with diameters of 10 mm and 25 mm were used in the constructed beams as a transversal and longitudinal reinforcement. All steel bars had an average yield stress of 417 MPa and an average tensile strength of 725 MPa.



Type 1: SF 35-mm length



Type 2: SF 60-mm length

Figure 3.3 The used steel fibres

3.3 Experimental Study 1: Optimizing the Fresh Properties, Stability, and Strength of SCRC Using Different Mixture Compositions and SCMs

3.3.1 Research Significance

This study investigated the fresh properties, mechanical properties, impact resistance, and acoustic absorption capacity of SCRC mixtures developed with different mixture compositions and various SCMs. The current available studies contain some information regarding the properties of VRC; however, research has been limited when it comes to investigating the performance of SCRC mixtures. The review of literature also indicates insufficient information regarding the acoustic characteristics and impact performance of SCRC, especially when high percentages of CR are used. In addition, the optimum percentage of CR in a successful SCRC mixture that improves the impact resistance and/or acoustic absorption is missing from the literature. This study aimed to develop a number of SCRC mixtures with high percentages of CR in order to highlight successful mixtures with maximized impact resistance, acoustic absorption, and minimized reduction in stability and mechanical properties. Developing SCRC with high percentage of CR also contributes to the development of semi-lightweight concrete that can achieve a more economical design of building. In addition, using waste rubber as an aggregate replacement promotes the development of eco-friendly environmentally concrete and encourages the concept of sustainable production which is receiving greater attention nowadays. This investigation can contribute significantly to the enhancement of SCRC performance and will be very useful in developing SCRC with a high potential use in applications that require high-impact resistance and energy dissipation.

3.3.2 Scope of Work (Mixtures Development)

Stage 1- Effect of Percentage of CR on SCRC Mixtures

The main objective of this stage was to obtain the maximum percentage of CR that can be safely used to develop SCRC mixtures with acceptable fresh properties (flowability, passing ability, and stability) according to the limits given by the European Guidelines for Self-Compacting Concrete (2005) and/or the Interim Guidelines for the Use of Self-Consolidating Concrete (2003). In total, eight mixtures were tested in this stage. The percentage of CR varied from 0% to 40% replacement of sand (by volume) (mixtures 1-8). In this investigation, a preliminary trial mixes stage was performed to determine the minimum w/b ratio, the total binder content, and the C/F aggregate ratio that can achieve acceptable SCC flowability without overdosing the HRWRA and with no sign of segregation, especially when crushed stone aggregate was used. The results of the trial mixes stage indicated that a w/b ratio of at least 0.4, a binder content of at least 500 kg/m^3, and a C/F aggregate ratio of 0.7 should be used to obtain SCRC having 650 ± 50 mm slump flow diameter with no visual sign of segregation. Therefore, 0.4 w/b, 500 kg/m^3 total binder content, and 0.7 C/F aggregate ratio were used in all tested mixtures in stage 1. The mixture proportions of SCRCs in this stage are shown in **Table 3.2**.

All mixtures in stage 1 and 2 were developed using a 10 mm crushed stone aggregate. The amount of HRWRA was varied in all tested mixtures to obtain a slump flow diameter of 650 ± 50 mm.

Stage 2- Effect of Binder Content and SCMs on the Fresh Properties, Stability, and Strength of SCRC Mixtures

Owing to the low density of the used rubber, the test results of stage 1 indicated a segregation problem in mixtures containing higher percentages of CR (more than 15%). Moreover, increasing the CR content generally decreased the flowability, passing ability, stability, and strength of all tested mixtures. Therefore, this stage was designed to improve the fresh properties, stability, and strength of SCRC mixtures in order to allow higher percentages of CR to be used safely. This stage investigated the effects of increasing the binder content (from 500 to 550 kg/m^3) and the addition of SCMs (MK, FA, GGBS) on enhancing the stability, fresh properties, and strength of SCRC in thirteen mixtures. All mixtures contained a total binder content of 550 kg/m^3, which was kept constant throughout stage 2 and 3. The thirteen SCRC mixtures were detailed as follows: three mixtures containing no SCMs (mixtures 9-11), four mixtures containing MK (mixtures 12-15), three mixtures containing GGBS (mixtures 16-18), and three mixtures containing FA (mixtures 19-21). The mixtures with SCMs contained 20% MK, 30% GGBS, and 20% FA. The percentages of MK, GGBS, and FA were chosen based on a preliminary trial mixes stage that was carried out on these SCMs to determine their optimal dosage to achieve acceptable fresh properties and a reasonable compressive strength suitable for structural applications. Since the fresh properties were expected to be improved with higher total binder content and the addition of SCMs, the CR replacement level in this stage began at 20% and was increased incrementally until reaching either unacceptable SCC fresh properties (according to the limits given by the European Guidelines for Self-Compacting Concrete 2005 and/or the Interim Guidelines for the Use of Self-Consolidating Concrete 2003) or a compressive strength less than 17 MPa, as this strength will not likely be used in structural applications (Neville, 1995; NRMCA, 2003; Najim and Hall, 2012b). The mixture proportions of SCRCs in this stage are shown in **Table 3.2**.

Stage 3 – Effect of Aggregate Size and Entrained Air on the Fresh Properties, Stability, and Strength of SCRC Containing MK

This stage was designed after obtaining the results of stage 2. The main objective of this stage was to enhance the fresh properties of the mixtures developed in stage 2 in order to allow a higher percentage of CR to be used safely in those mixtures. This stage tested a larger coarse aggregate (20 mm) and evaluated the effect of using entrained air admixture on enhancing the flowability and/or passing ability of SCRC mixtures with higher rubber content (30% to 50%). In total, six SCRC mixtures were tested in this stage: three SCRC mixtures with a larger coarse aggregate size (20 mm) (mixtures 22-24); and the other three SCRC mixtures with entrained air (210 ml/m^3) (mixtures 25-27). It should be mentioned that all tested SCRC mixtures in this stage were categorized as semi-lightweight concrete based on CSA's classification (1850~2150 kg/m^3) (CSA, 2004). The proportions of the developed SCRCs mixtures are shown in **Table 3.2**.

All tested mixtures in the three stages were designated by total binder content, percentage of CR, type of SCM used, and coarse aggregate size or the inclusion of micro air (MA). For example, a mixture using a 550 kg/m^3 binder, 50% CR, MK, and micro air would be labelled as 550C-50CR-MK-MA.

Table 3.2 Mix design for SCRC mixtures of study 1

Mix. #		Mixture	Cement (kg/m^3)	SCM (Type)	SCM (kg/m^3)	C. A. (kg/m^3)	F. A. (kg/m^3)	CR (kg/m^3)	HRWRA (kg/m^3)	Density (kg/m^3)
Stag1: Effect of CR	1	500C-0CR	500	-	-	686.5	980.8	0.0	2.37	2367.3
	2	500C-5CR	500	-	-	686.5	931.7	17.9	2.37	2336.2
	3	500C-10CR	500	-	-	686.5	882.7	35.8	2.37	2305.1
	4	500C-15CR	500	-	-	686.5	833.7	53.8	2.37	2273.9
	5	500C-20CR	500	-	-	686.5	784.6	71.7	2.89	2242.8
	6	500C-25CR	500	-	-	686.5	735.6	89.6	2.89	2211.7
	7	500C-30CR	500	-	-	686.5	686.5	107.5	2.89	2180.6
	8	500C-40CR	500	-	-	686.5	588.5	143.3	3.95	2118.3
Stage 2: Effect of binder content and SCMs	9	550C-20CR	550	-	-	648.1	740.7	67.7	1.84	2226.5
	10	550C-30CR	550	-	-	648.1	648.1	101.5	1.84	2167.8
	11	550C-40CR	550	-	-	648.1	555.5	135.3	2.63	2109.0
	12	550C-20CR-MK	440	MK	110	638.4	729.6	66.7	5.26	2204.7
	13	550C-30CR-MK	440	MK	110	638.4	638.4	100.0	5.26	2146.8
	14	550C-40CR-MK	440	MK	110	638.4	547.2	133.3	6.58	2088.9
	15	550C-50CR-MK	440	MK	110	638.4	456.0	166.6	8.95	2031.0
	16	550C-20CR-GGBS	385	GGBS	165	643.3	735.2	67.2	1.84	2215.7
	17	550C-30CR-GGBS	385	GGBS	165	643.3	643.3	100.7	1.84	2157.3
	18	550C-40CR-GGBS	385	GGBS	165	643.3	551.4	134.3	2.63	2099.0
	19	550C-20CR-FA	440	FA	110	636.0	726.9	66.4	1.84	2199.3
	20	550C-30CR-FA	440	FA	110	636.0	636.0	99.6	1.84	2141.7
	21	550C-40CR-FA	440	FA	110	636.0	545.2	132.8	2.63	2084.0
Stage 3: Effect of aggregate size and entrained air	22	550C-30CR-MK-20	440	MK	110	638.4	638.4	100.0	4.47	2146.8
	23	550C-40CR-MK-20	440	MK	110	638.4	547.2	133.3	5.26	2088.9
	24	550C-50CR-MK-20	440	MK	110	638.4	456.0	166.6	6.32	2031.0
	25	550C-30CR-MK-MA	440	MK	110	638.4	638.4	100.0	5.26	2146.8
	26	550C-40CR-MK-MA	440	MK	110	638.4	547.2	133.3	5.53	2088.9
	27	550C-50CR-MK-MA	440	MK	110	638.4	456.0	166.6	7.89	2031.0

Note: All mixtures have a 0.4 w/b ratio and a 0.7 C/F aggregate ratio; all mixtures with entrained air have a 210 ml/m^3 micro air; C. A. = Coarse aggregates; F. A. = Fine aggregates; and CR = Crumb rubber

3.3.3 Mixing Procedures

1. A rotary mixer with a capacity of 250 liters was used to mix all the developed mixtures. Prior to mixing, the internal surface of mixer was cleaned and wetted.
2. In the first step of mixing, the cement, SCMs (if any), CR (if any), fine, and coarse aggregates were dry mixed for approximately 1.5 minutes.
3. Two thirds of the required amount of water was then added to the dry materials and re-mixed for another 1.5 minutes.
4. The remaining water was first mixed with the required dosage of HRWRA and then added to the mixer and re-mixed for another 2.5 ± 0.5 minutes.
5. Upon achieving the target slump flow diameter for SCC/SCRC, the fresh properties tests were performed according to the used standards.

3.3.4 Casting and Curing Procedures

Different small-scale specimens including cylinders and prisms were cast to evaluate the properties of concrete after hardening (**Figure 3.4a**). The concrete filled those specimens under its own weight without applying an external force or using vibrators. All specimens were then moist-cured in a controlled room temperature of 25 ± 1.5°C for 7 and 28 days before testing (**Figure 3.4b**).

(a)

(b)

Figure 3.4 The developed mixtures (a) the cast- specimens, (b) the moist-curing regime

3.3.5 Fresh Properties Tests

In this study, the time to reach 500 mm slump flow diameter, time to reach 500 mm J-ring diameter (T_{50} and T_{50J}), and the V-funnel time were used to evaluate the mixture viscosity/flowability. These times were accurately measured for all tested SCC/SCRC mixtures using videotape recording device connected to a computer to record the time with up to 0.01 seconds. Slump flow–J-ring diameters and L-box heights were measured for all tested mixtures to evaluate the passing ability of SCC/SCRC. The stability of the mixture was evaluated by measuring the segregation resistance (SR) of SCC/SCRC mixtures which was assessed using a sieve segregation resistance test. All of the aforementioned tests are detailed in the European Guidelines for Self-Compacting Concrete (2005) (**Figure 3.5**). The percentage of the air content in the fresh mixtures was measured by following a procedure given in ASTM C231 (2014). The stability of rubber in the mixture was also evaluated by measuring the distribution of the rubber particles in the mixture visually after splitting a 100 mm diameter x 200 mm height concrete cylinder (**Figure 3.6**). **Figure 3.6** classifies the stability of rubber particles into three cases; namely no segregation (NS), moderate segregation (MS), and heavy segregation (HS).

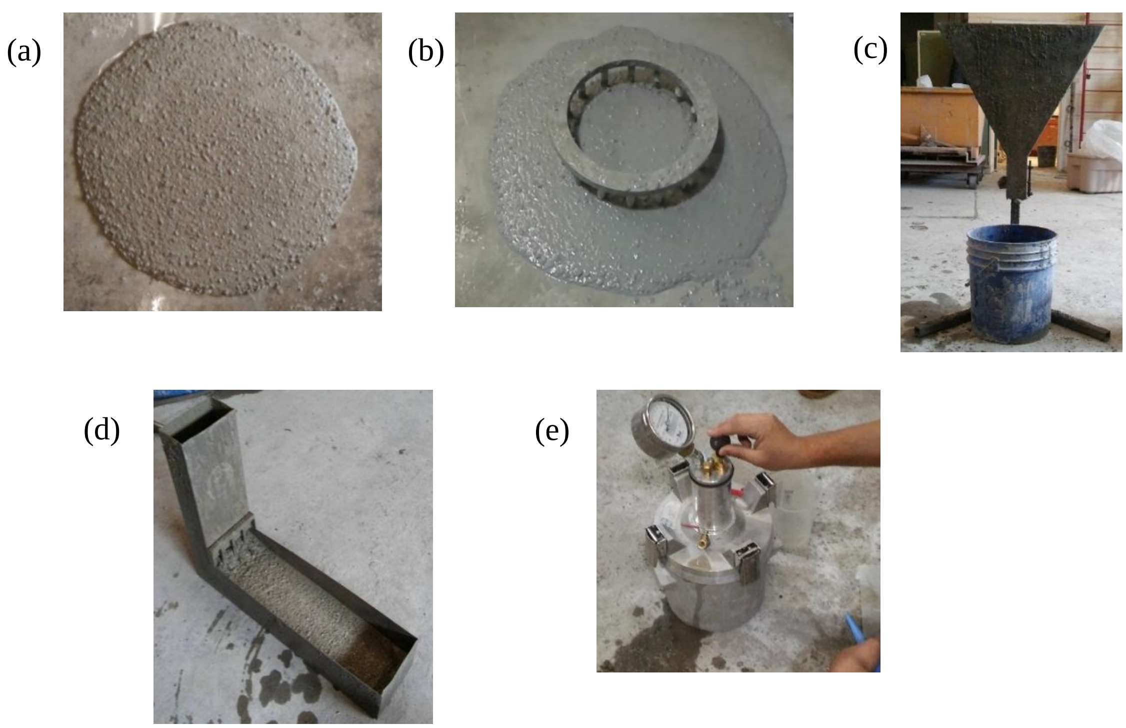


Figure 3.5 Fresh properties tests (a) slump flow, (b) J-ring, (c) V-funnel, (d) L-box, (e) air content

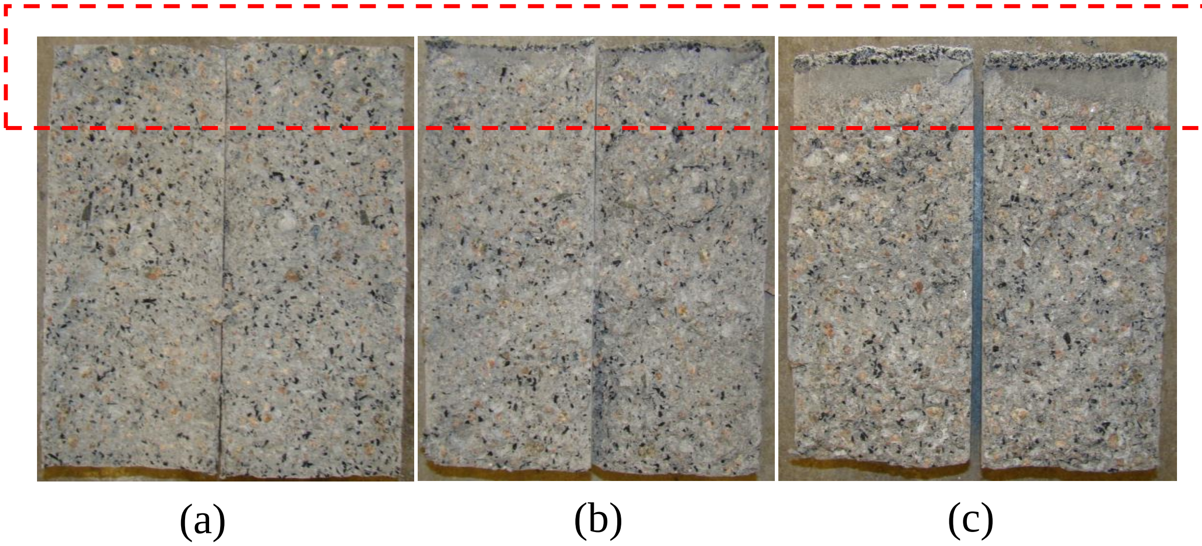


Figure 3.6 Rubber particles stability (a) no segregation (NS), (b) moderate segregation (MS), (c) heavy segregation (HS)

3.3.6 Mechanical Properties Tests

The compressive strength and STS tests were conducted using 100 mm diameter x 200 mm height concrete cylinders, according to ASTM C39 (2014) and C496 (2011), respectively. The FS of 100 mm x 100 mm x 400 mm prisms was measured for all SCC/SCRC mixtures according to ASTM C78 (2010). Also, the modulus of elasticity of all mixtures was tested using 100 mm diameter x 200 mm height cylinders with attached strain gauges. The mechanical properties tests were implemented after the sample had been moist-cured for 7 and 28 days, based on the test age.

3.3.7 Impact Resistance Under Drop-Weight Test

To evaluate the impact resistance of the developed mixtures, a drop-weight test was performed according to the ACI committee 544 proposal (**Figure 3.7a**). The test was performed by dropping a 4.45 kg drop hammer from a height of 457 mm onto a 63.5 mm steel ball located at the centre of the top surface of 150 mm diameter x 63.5 mm thick cylindrical specimens. The number of blows needed to produce the first visible crack (N_1) was recorded to indicate the initial crack resistance. Also, the number of blows needed to cause failure (N_2) was recorded to indicate the ultimate crack resistance.

3.3.8 Impact Resistance Under Flexural Loading

Impact test on beams was performed using three-point loading setup to determine the energy absorption capacity of the developed mixtures under flexural-impact loading (see **Figure 3.7b**). Beams of 100 x 100 x 400 mm were tested with a loading span of 350 mm. The loading was applied by dropping a 4.45 kg drop hammer from a height of 150 mm onto the mid-span of the tested beams. The drop height for this test was chosen based on many trials that have been done to obtain a reasonable drop height that helped to increase the accuracy and the ease of evaluating the impact strength of the tested beams. In this test, it was also very difficult to detect the first visual crack as all beams broke suddenly into two halves. Therefore, only the number of blows to cause failure was recorded to represent the ultimate impact energy.

For both first and second tests, the impact energy (*IE*) was calculated using **Equation (3.1)**:

$$IE = N\,mgh \tag{3.1}$$

Where: N is the number of blows at crack level; m is the mass of the drop hammer (4.45 kg); g is the acceleration due to gravity (9.81 m/s^2); and h is the drop height (150 or 457 mm).

a b

Figure 3.7 Impact tests (a) drop-weight test (ACI-544), (b) flexural loading test

3.3.9 Ultrasonic Pulse Velocity (UPV) Test

In conventional concrete, the UPV test according to ASTM C597 (2009) can be used to evaluate the qualities of the produced mixtures and correlate the pulse velocity with properties of concrete. In these types of concrete, lower readings of pulse velocities can be attributed to possible existing internal defects or air voids. However, in rubberized concrete this test may record lower pulse velocities due to incorporating CR, which may affect the transmission of waves within concrete. Therefore, this study conducted the UPV test on all developed mixture to investigate the effect of using CR aggregate in concrete on the wave behaviour and also to evaluate the correlation between UPV and compressive strength of the tested mixtures. Test setup is shown in **Figure 3.8**.

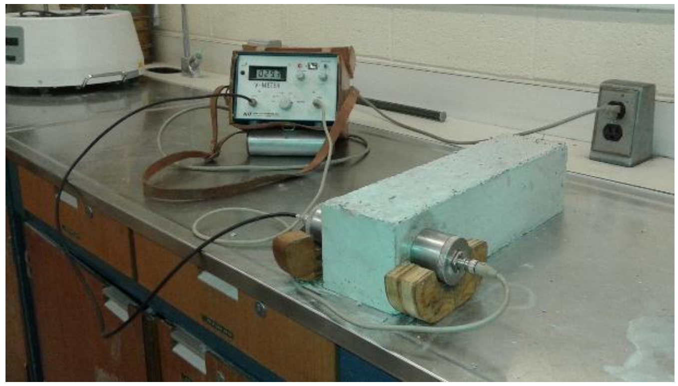


Figure 3.8 UPV test setup

3.3.10 Acoustic Emission Setup

According to ASTM E1316 (2014), a nondestructive test was used to investigate the effect of using CR on the acoustic properties of concrete. The test was conducted on a cylindrical specimen with a 150 mm diameter and 65 mm height. An ultrasonic acoustic wave source was attached to the surface of the tested specimen using a thin layer of gel. On the other side of the tested specimen, a piezoelectric acoustic emission (AE) sensor (Mistras Group R6I-AST sensor, 2005) with integral preamplifier (R6I) was fixed to the specimen using an epoxy adhesive and connected to the AE data acquisition system with AEWin signal processing software (see **Figure 3.9**). At the start of the test, the acoustic wave transmitted from the ultrasonic wave source (sender) to the AE sensor (receiver), passing through the tested SCRC specimen. Different AE signal parameters were measured during the test, including amplitude, energy, counts, rise time, duration, signal strength, absolute energy, and frequency. Since an identical ultrasonic wave was used for all tested specimens (one AE event/hit), the waveform in terms of signal strength and signal energy were chosen to identify the effect of using CR on the wave attenuation, and hence the acoustic absorption capacity of mixtures.

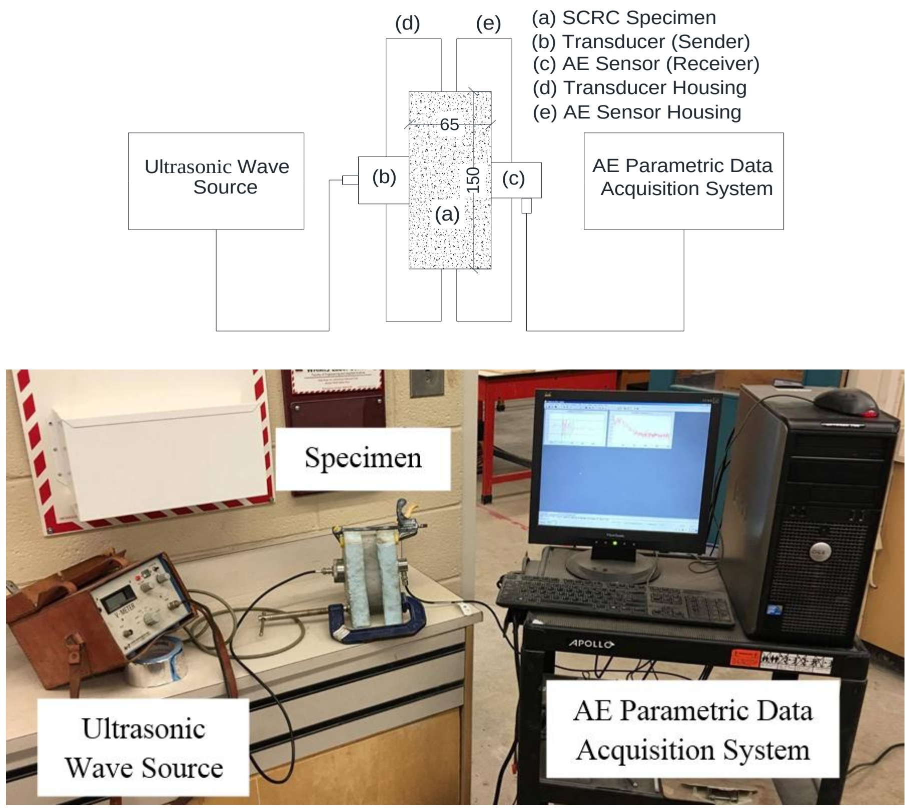


Figure 3.9 Acoustic emission setup

3.4 Experimental Study 2: Use of SFs to Optimize SCC Mixtures Containing CR (Development of SFSCRC)

3.4.1 Research Significance

This study evaluated and optimized the use of SFs in SCRC to compensate for the negative effects of the CR on the tensile and flexural strengths of mixtures, especially when high percentages of CR were used. The experimental work includes VRC and SFVRC mixtures for comparison. The investigation also aimed to maximize the percentage of CR in the developed mixtures, contributing to the development of sustainable semi-lightweight concrete. In addition, combining SFs and CR in concrete can generate types of concrete having superior properties for structural applications that require high impact resistance, energy dissipation, and ductility. The literature review includes limited number of studies that have investigated the effects of SFs on the behaviour of VRC, but there is no data available regarding the impact of combining SFs and CR on the performance of SCC mixtures, especially when different volumes and lengths of SFs are used. Therefore, this research can offer a significant contribution to the development of SFSCRC and SFVRC mixtures with a high potential for structural applications subjected to high-impact loads.

3.4.2 Scope of Work (Mixtures Development)

Trial mixes

The inclusion of CR and SFs in SCC is considered as a significant challenge due to their negative effect on the fresh properties of the mixture. In addition, the low density of the rubber may easily encourage the rubber particles to float toward the concrete surface during mixing, thus increasing the risk of segregation (as explained earlier). Therefore, developing

SCRC containing SFs requires a balanced viscosity to improve the particle suspension and reduce the risk of segregation, as well as achieve the acceptable flowability of SCC without overdosing the HRWRA.

For this reason, a preliminary trial mixes stage was carried out to determine the minimum w/b ratio, the total binder content, C/F aggregate ratio, maximum aggregate size, and the type of SCMs that can achieve balanced viscosity and acceptable fresh properties. The results of the trial mixes stage indicated that at least 0.4 w/b ratio, at least 550 kg/m^3 binder content, 10-mm maximum aggregate size, and 0.7 C/F aggregate ratio should be used to obtain SCC/SCRC/SFSCRC having 700 ± 50 mm slump flow with no visual sign of segregation. FA was also used to increase the flowability of the mixtures in order to avoid using high dosages of HRWRA to compensate for the reduction in the workability due to the addition of CR and SFs. The consistency of SCRC/SFSCRC was adjusted by incorporating MK into the mixture to improve its viscosity, resulting in higher stability for CR particles. Moreover, to obtain SCRC/SFSCRC with adequate mechanical properties, MK was used to compensate for the reduction in the concrete strengths resulting from using high percentages of CR. The MK and FA were used with replacement levels of 20% and 30% (by weight of the binder content, based on the trial mixes), respectively. The amount of HRWRA was varied in all tested mixtures to obtain a slump flow diameter of 700 ± 50 mm. Study 2 was divided into four stages as follows:

Stage 1 – Effect of increasing the CR content on the fresh properties and strengths of SCRC mixtures without SFs

This stage investigated the effect of increasing the CR content (as a replacement of fine aggregate volume) on the fresh and mechanical properties of SCRC without SFs similar to stage 1 in the experimental study 1. It was necessary to conduct this stage to evaluate the effect of the SFs on the fresh and mechanical properties of SCRC, when SCRC mixtures with SFs (stages 2, 3, and 4) were compared to control mixtures (mixtures in stage 1). In addition, this stage was designed to investigate the maximum possible percentage of CR that can be successfully used to develop SCRC mixtures (without SFs) meeting the limits given by the European Guidelines for Self-Compacting Concrete (2005) and/or the Interim Guidelines for the Use of Self-Consolidating Concrete (2003). In total, seven mixtures were tested in this stage. The percentage of CR varied from 0% to 30% replacement of sand (by volume) (mixtures 1-7).

Stage 2– Effect of using SFs on the fresh properties and strengths of SCRC mixtures

The main objective of this stage was to use the SFs to compensate for the reduction in the STS and FS of SCRC caused by using CR. In total, six SFSCRC mixtures were tested in this stage (see **Table 3.3**).

One type of SF (35 mm length, 0.55 mm diameter, and an aspect of 65) with 0.35% fraction volume was used in this stage. With a total binder content of 550 kg/m^3, a maximum of 0.35% fibre volume could be successfully used to develop SFSCRC mixtures. With this type and percentage of SFs, it was hard to develop SFSCRC containing high percentages of CR due to the fast drop of the L-box value with the addition of SFs. Therefore, another part of this stage was designed to evaluate the potential of increasing the binder content (from 550 to 600 kg/m^3) to improve the flowability and passing ability of SFSCRC, in order to allow higher percentages of CR to be used safely.

The tested mixtures in this stage are detailed as follows: a) three SFSCRC mixtures (mixtures 8-10) with varied CR percentage from 0% to 15%, 0.35% fibre volume (SF 35 mm), and binder content of 550 kg/m^3; and b) three SFSCRC mixtures (mixtures 11-13) with a higher binder content of 600 kg/m^3, varied CR percentage from 15% to 25%, and 0.35% fibre volume (SF 35 mm).

Stage 3 - Effect of changing the volume fraction and size of SFs on the fresh properties and strengths of SCRC mixtures

This stage was designed to evaluate the effect of varying the size and volume of SFs on the fresh and mechanical properties of SCRC mixtures. It is worth noting that by increasing the volume of SF (35 mm length) in SCRC mixtures from 0.35% to 0.5%, the binder content was necessarily increased to 600 kg/m^3 in order to achieve acceptable SCRC flowability without overdosing the HRWRA. The tested parameters were evaluated through six SFSCRC mixtures. The first set of SFSCRC mixtures (mixtures 14-16) was developed with varied CR percentage from 0% to 15%, 0.35% fibre volume (60 mm length), and binder content of 550 kg/m^3. The other set of SFSCRC mixtures (mixtures 17-19) was produced with a higher fibre content of 0.5% from SF (35 mm), binder content of 600 kg/m^3, and varied CR percentage from 0% to 15%.

Stage 4 - Effect of increasing the CR content and SF volume fraction on the workability and strengths of VRC mixtures

Since the potential passing ability problems are not a factor in VRC/SFVRC mixtures, seven vibrated concrete mixtures were developed to investigate the possibility of using a higher percentage of CR and SFs. The first three mixtures (mixtures 20-22) investigated the performance of VRC mixtures with maximized percentage of CR (30%, 35%, and 40% by volume of fine aggregate). The other four mixtures (mixtures 23-26) were produced to assess the effect of including higher percentages of 35 mm SF (0.35%, 0.5%, 0.75%, and 1%) on the performance of VRC mixtures. For these mixtures, a constant CR percentage of 35% was chosen. The assessment of a successful mixture in this stage was based on the 28-day compressive strength, in which the target was to produce VRC mixtures with a reasonable strength (most civil infrastructure applications require compressive strength ranges of 28 to 35 MPa) (Zheng et al., 2008). It should be mentioned that the tested SCRC (mixtures 6 to 7), SFSCRC (mixtures 10 to 13, 16, 18, and 19), VRC (mixtures 20 to 22), and SFVRC (mixtures 23 to 26) in this investigation were categorized as semi-lightweight concrete based on CSA's classification (1850~2150 kg/m^3).

The tested mixtures were designated by total binder content, percentage of CR, and either volume, size of SFs used, or VRC (See **Table 3.3**). For example, a mixture using a 550 kg/m^3 binder content, 15% CR, and 0.35% long SFs (60 mm length) would be labelled as 550C-15CR-0.35LSF, and a mixture using a 550 kg/m^3 binder content, 35% CR, 1% short SFs (35 mm length), and VRC would be labelled as 550C-35CR-1SF-VRC.

Table 3.3 Mix design for tested mixtures of study 2

Mix #		Mixture	Cement (kg/m³)	MK (kg/m³)	FA (kg/m³)	C. A. (kg/m³)	F. A. (kg/m³)	CR (kg/m³)	SF (kg/m³)	Density (kg/m³)
Stage 1: Effect of increasing the CR content	1	550C-0CR	275	110	165	620.3	886.1	0.0	-	2246
	2	550C-5CR	275	110	165	620.3	841.8	16.2	-	2207
	3	550C-10CR	275	110	165	620.3	797.5	32.4	-	2163
	4	550C-15CR	275	110	165	620.3	753.2	48.6	-	2128
	5	550C-20CR	275	110	165	620.3	708.9	64.8	-	2094
	6	550C-25CR	275	110	165	620.3	664.6	80.9	-	2041
	7	550C-30CR	275	110	165	620.3	620.3	97.1	-	2006
Stage 2: Effect of using SFs	8	550C-5CR-0.35SF	275	110	165	616.5	836.7	16.1	27.48	2217
	9	550C-10CR-0.35SF	275	110	165	616.5	792.7	32.2	27.48	2177
	10	550C-15CR-0.35SF	275	110	165	616.5	748.6	48.3	27.48	2138
	11	600C-15CR-0.35SF	300	120	180	575.6	698.9	45.1	27.48	2108
	12	600C-20CR-0.35SF	300	120	180	575.6	657.8	60.1	27.48	2076
	13	600C-25CR-0.35SF	300	120	180	575.6	616.7	75.1	27.48	2043
Stage 3: Effect of changing the volume fraction and size of SFs	14	550C-5CR-0.35LSF	275	110	165	616.5	836.7	16.1	27.48	2209
	15	550C-10CR-0.35LSF	275	110	165	616.5	792.7	32.2	27.48	2167
	16	550C-15CR-0.35LSF	275	110	165	616.5	748.6	48.3	27.48	2113
	17	600C-5CR-0.5SF	300	120	180	574.0	779.0	15.0	39.25	2184
	18	600C-10CR-0.5SF	300	120	180	574.0	738.0	30.0	39.25	2133
	19	600C-15CR-0.5SF	300	120	180	574.0	697.0	44.9	39.25	2088
Stage 4: Effect of increasing the CR content and SF volume fraction in VRC	20	550C-30CR-VRC	275	110	165	620.3	620.3	97.1	-	2048
	21	550C-35CR-VRC	275	110	165	620.3	576.0	113.3	-	2014
	22	550C-40CR-VRC	275	110	165	620.3	531.7	129.5	-	1968
	23	550C-35CR-0.35SF -VRC	275	110	165	616.5	572.5	112.6	27.48	2040
	24	550C-35CR-0.5SF-VRC	275	110	165	614.9	571.0	112.3	39.25	2048
	25	550C-35CR-0.75SF-VRC	275	110	165	612.2	568.5	111.9	58.88	2063
	26	550C-35CR-1SF-VRC	275	110	165	609.6	566.0	111.4	78.50	2073

Note: All mixtures have a 0.4 w/b ratio and a 0.7 C/F aggregate ratio; C. A. = Coarse Aggregates; F. A. = Fine Aggregates; CR = Crumb Rubber; MK = Metakaolin; FA = Fly Ash; SF = Steel Fibre (35 mm SF); LSF= Long Steel Fibre (60 mm SF).

3.4.3 Mixing Procedures

All mixing procedures in study 2 were carried out as per study 1. In addition, the separated SFs were added during the dry mixing process to achieve good fibre distribution. It should be noted that prior to the step of adding the SFs, a small amount of the mixture's water was mixed with SFs in order to separate the glued SFs (**Figure 3.3**) into individual fibres in order to avoid the formation of fibres ball in concrete.

3.4.4 Casting and Curing Procedures

For SCC/SCRC/SFSCRC, all casting procedures in study 2 were carried out as per study 1. On the other hand, the VRC/SFVRC specimens were filled in three almost-equal layers and compacted using a vibrating table and then trowel-finished for smooth top surfaces. All mixtures' specimens (SCC, SCRC, SFSCRC, VRC, SFVRC) were exposed to curing condition similar to that of study 1.

3.4.5 Fresh, Mechanical Properties, and Impact Resistance Tests

For SCC/SCRC/SFSCRC, all fresh properties, mechanical properties, and impact resistance tests (drop-weight test, flexural loading test) in study 2 were carried out as per study 1. On the other hand, the workability of VRC/SFVRC mixtures (fresh property) was only evaluated by a slump test, according to ASTM C143 (2015), but the air content, mechanical properties, and impact resistance tests were carried out as per study 1.

3.5 Experimental Study 3: Flexural Performance of Large-Scale Rubberized Concrete Beams with/without SFs

This stage aimed to investigate the flexural behavior of 24 beams that were optimized from the mixtures developed in study 1 and 2.

3.5.1 Research Significance

Reusing waste rubber in concrete is receiving great attention from the research community nowadays, attempting to reduce the environmental pollution and utilize the characteristics of rubber to improve certain properties for concrete. This highlights a need to investigate the applicability of using waste rubber with/without SFs in structural applications, especially when SCC is used. By reviewing the literature, it is obvious that the information concerning the flexural behaviour of large-scale SCC beams containing CR with/without SFs is missing. Therefore, this study was conducted to assess the flexural behaviour of SCRC, VRC, SFSCRC, and SFVRC beams in terms of load-deflection response, stiffness, ductility, toughness, first cracking moment, flexural capacity, and cracking behaviour. The main purpose of the research was to extend the possible applications of CR with/without SFs in the concrete industry. The research also evaluates the performance of code design equations in predicting the cracking moment and flexural capacity against the results obtained from the conducted experiments.

3.5.2 Scope of Work

Mixtures optimized from study 1

A total of 12 concrete mixtures were optimized from study 1 (see **Table 3.4**) to evaluate the effect of CR on the flexural strength and cracking behaviour of beams.

From study 1, it was found that using 500 kg/m^3 binder content and no SCMs allowed for a maximum of 15% CR (mixtures 1–4) to maintain acceptable SCC fresh properties. Increasing this percentage to 20% resulted in a significant reduction in the passing ability (H2/H1 of L-Box) for all mixtures with 500 kg/m^3 binder content. However, when increasing the total binder content from 500 kg/m^3 to 550 kg/m^3 the maximum percentage of CR that maintains acceptable SCC fresh properties increased to 20% (mixtures 5-6). The results also indicated that using MK enhanced the viscosity of tested mixtures and had a direct impact on improving the particle suspension and passing ability, which allowed a higher percentage (up to 30%) of CR to be used safely in SCRC mixtures (mixtures 7-8). Further increase in the percentage of CR in SCRC mixtures with MK from 30% to 40% required the use of entrained air admixture (mixtures 9, 10) in order to improve the flowability and passing ability of mixtures. Considering the type of materials used in this investigation, it was very difficult to develop SCRC mixtures with acceptable SCC fresh properties using more than 40% CR. Therefore, the investigation included developing VRC (mixtures 11-12) in order to compare its performance with that of SCRC. Since the passing ability and segregation are not factors in VRC mixtures, it was possible to reach a maximum percentage of CR of 50%. Using more than 50% CR in VRC mixtures resulted in a very low compressive strength.

Table 3.4 shows the optimized mixtures including a) four SCRC mixtures with binder content of 500 kg/m^3 and CR content varied from 0% to 15% (mixtures 1-4), (b) two SCRC mixtures with binder content of 550 kg/m^3 having 15% and 20% CR (mixtures 5-6); b) two SCRC mixtures with MK having 20% and 30% CR (mixtures 7-8); c) two SCRC mixtures with MK and entrained air admixture (210 ml/m^3) having 30% and 40% CR (mixtures 9-10); and d) two VRC mixtures with MK having 40% and 50% CR (mixtures 11-12). All tested beams were designated by concrete type (whether SCC or VC), binder content, percentage of CR, SCM used, and inclusion of micro air (MA). For example, a beam using SCC, 550 kg/m^3 binder content, 40% CR, MK, and MA would be labelled as SCC-550-40CR-MK-MA, and a beam using VC, 550 kg/m^3 binder content, 50% CR, and MK would be labelled as VC-550-50CR-MK.

Table 3.4 Mix design of beams optimized from study 1

Beam #	Mixture	Cement (kg/m^3)	SCM (Type)	C. A. (kg/m^3)	F. A. (kg/m^3)	CR (kg/m^3)	HRWRA (kg/m^3)	Density (kg/m^3)
B1/1	SCC-500-0CR	500	-	686.5	980.8	0.0	2.37	2367.3
B2/1	SCC-500-5CR	500	-	686.5	931.7	17.9	2.37	2336.2
B3/1	SCC-500C-10CR	500	-	686.5	882.7	35.8	2.37	2305.1
B4/1	SCC-500-15CR	500	-	686.5	833.7	53.8	2.37	2273.9
B5/1	SCC-550-15CR	550	-	648.1	787.0	50.7	1.84	2255.9
B6/1	SCC-550-20CR	550	-	648.1	740.7	67.7	1.84	2226.5
B7/1	SCC-550-20CR-MK	440	MK	638.4	729.6	66.7	5.26	2204.7
B8/1	SCC-550-30CR-MK	440	MK	638.4	638.4	100.0	5.26	2146.8
B9/1	SCC-550-30CR-MK-MA	440	MK	638.4	638.4	100.0	5.26	2146.8
B10/1	SCC-550-40CR-MK-MA	440	MK	638.4	547.2	133.3	5.53	2088.9
B11/1	VC-550-40CR-MK	440	MK	638.4	547.2	133.3	3.50	2088.9
B12/1	VC-550-50CR-MK	440	MK	638.4	456.0	166.6	4.00	2031.0

Note: All mixtures have a 0.4 w/b ratio, a 0.7 C/F aggregate ratio, and a 10-mm maximum aggregate size; C. A. = Coarse aggregates; F. A. = Fine aggregates; CR = Crumb rubber; MK = metakaolin; MA = micro air (210 ml/m^3).

Mixtures optimized from study 2

Twelve mixtures were optimized to cast 12 beams (see **Table 3.5**). These mixtures were divided into two stages. The first stage included a) four SCRC mixtures with CR percentage varied from 0% to 25% (mixtures 1–4) developed to investigate the influence of CR on the flexural behaviour and cracking of SCRC beams; and b) two SFSCRC mixtures with 0.35% SFs (35 mm) having 5% and 15% CR (mixtures 5–6) developed to evaluate the combined effect of CR and SFs on the flexural behaviour and cracking of SCRC beams. It should be noted that all mixtures in this stage (mixtures 1–6) satisfy the self-compactability criteria as per the European Guidelines for Self-Compacting Concrete (2005). Additional increases in the percentage of CR and/or SFs in these mixtures (1–6) dropped the passing ability significantly below the acceptable limits (H2/H1 of L-box ≥ 0.75) given by the conformity of the European Guidelines for Self-Compacting Concrete (2005). Also, it was not possible to use longer fibres (60 mm) in SFSCRC mixtures as its use resulted in high blockage in the L-box, which made it difficult for these mixtures to pass through rebars (as clarified in study 2).

Since the development of vibrated concrete does not require high flowability and passing ability, stage 2 used the vibrated concrete to evaluate the effect of using higher percentages of CR (with/without SFs) and longer fibres on the strength and cracking of the tested beams. In this stage, it was possible to combine a maximum of 35% CR and 1% SFs in the VRC mixtures. Also, varied lengths of SFs (35 mm and 60 mm) could be tested in this stage. The second stage included a) two VRC mixtures with 25% and 35% CR (mixtures 7–8); b) two SFVRC mixtures with 35% CR having 0.35% and 1% SFs (35 mm); and c) two SFVRC mixtures with 35% CR having 0.35% and 1% SFs (60 mm). The maximum percentage of CR (35%) in this stage was chosen based on the 28-day compressive strength, in which additional increase in the CR content resulted in a significant reduction in the compressive strength (as explained in study 2). It should be noted that the VRC mixture with 25% CR was included in this investigation to evaluate the effect of concrete type (i.e., SCRC compared to VRC). The tested beams/mixtures were designated by concrete type (whether SCC or VC), percentage of CR, and volume and size of SFs used (**see Table 3.5**). For example, a beam/mixture using SCC, 15% CR, and 0.35% short SFs (35 mm) would be labelled as SCC-15CR-0.35SF; and a beam/mixture using VC, 35% CR, and 1% long SFs (60 mm) would be labelled as VC-35CR-1LSF.

Table 3.5 Mix design of beams optimized from study 2

Beam /Mix #	Mixture	Cement (kg/m^3)	MK (kg/m^3)	FA (kg/m^3)	C. A. (kg/m^3)	F. A. (kg/m^3)	CR (kg/m^3)	SF (kg/m^3)	Density (kg/m^3)
SCRC/SFSCRC									
B1/2	SCC-0CR	275	110	165	620.3	886.1	0.0	-	2246
B2/2	SCC-5CR	275	110	165	620.3	841.8	16.2	-	2207
B3/2	SCC-15CR	275	110	165	620.3	753.2	48.6	-	2128
B4/2	SCC-25CR	275	110	165	620.3	664.6	80.9	-	2041
B5/2	SCC-5CR-0.35SF	275	110	165	616.5	836.7	16.1	27.48	2217
B6/2	SCC-15CR-0.35SF	275	110	165	616.5	748.6	48.3	27.48	2138
VRC/SFVRC									
B7/2	VC-25CR	275	110	165	620.3	664.6	80.9	-	2048
B8/2	VC-35CR	275	110	165	620.3	576.0	113.3	-	2014
B9/2	VC-35CR-0.35SF	275	110	165	616.5	572.5	112.6	27.48	2040
B10/2	VC-35CR-1SF	275	110	165	609.6	566.0	111.4	78.50	2073
B11/2	VC-35CR-0.35LSF	275	110	165	616.5	572.5	112.6	27.48	2040
B12/2	VC-35CR-1LSF	275	110	165	609.6	566.0	111.4	78.50	2073

Note: All mixtures have a 0.4 w/b ratio, a 0.7 C/F aggregate ratio, and a 10-mm maximum aggregate size; C. A. = Coarse Aggregates; F. A. = Fine Aggregates; CR = Crumb Rubber; MK = Metakaolin; FA = Fly Ash; SF = Steel Fibre; LSF= Long Steel Fibre.

3.5.3 Casting of Specimens

Immediately after mixing, fresh properties tests as well as casting of beams in preassembled wooden forms were carried out. All SCC/SCRC/SFSCRC beams were cast under the own weight of concrete without vibration. On the other hand, the VRC/SFVRC beams were consolidated using electrical vibrators and trowel-finished for smooth top surfaces. Formworks were removed after 24 hours of casting, and the beams were moist-cured for four days and then air-cured until the date of testing. **Figure 3.10** shows the reinforcement and formwork details, pouring concrete, and curing regime (first 4 days) for all tested concrete beams. It should be noted that the specimens which were used to evaluate the compressive strength and STS of beams' mixtures, had been exposed to a condition of curing similar to their tested beams.

a b c

Figure 3.10 Casting of flexural beams (a) reinforcement and formwork details, (b) pouring concrete, (c) curing regime (first 4 days)

3.5.4 Dimensions, Test Setup, and Loading Procedures of the Tested Beams

In total, 24 large-scale beams were constructed to study the effect of CR with/without SFs on the flexural strength and cracking behaviour. **Figure 3.11** shows the dimensions, reinforcement details, test setup, and typical failure mode for all tested concrete beams. All test beams have an identical cross-sectional area of 250 mm x 250 mm, with a total length of 2440 mm, an effective span of 2040 mm, and an effective depth of 197.5 mm. The beams' dimension, loading pattern, shear, and flexural reinforcements were chosen to assure a ductile flexure behaviour. The longitudinal tension reinforcement ratio was kept constant of 2.03%, which consisted of two 25 mm diameter steel bars having a clear concrete cover of 40 mm. The shear span-to-effective depth ratio (a/d) was kept constant of 3.44. The shear reinforcement consisted of 10 diameter closed stirrups spaced at 155 mm, with a constant clear cover of 30 mm.

A hydraulic actuator with a capacity of 500-kN was used to apply a single-point loading onto a steel beam, which distributed the load into two-point loads acting on the beam surface. The mid-span deflection was measured by using a linear variable differential transformer (LVDT) placed at mid-point on the bottom side of the tested beam. At different level of loadings (first crack load, service load level, and ultimate load), the developed cracks were detected with the naked eye and were marked. Then, a crack detection microscope (60x magnification with 0.02 mm least count) was used to accurately measure their widths.

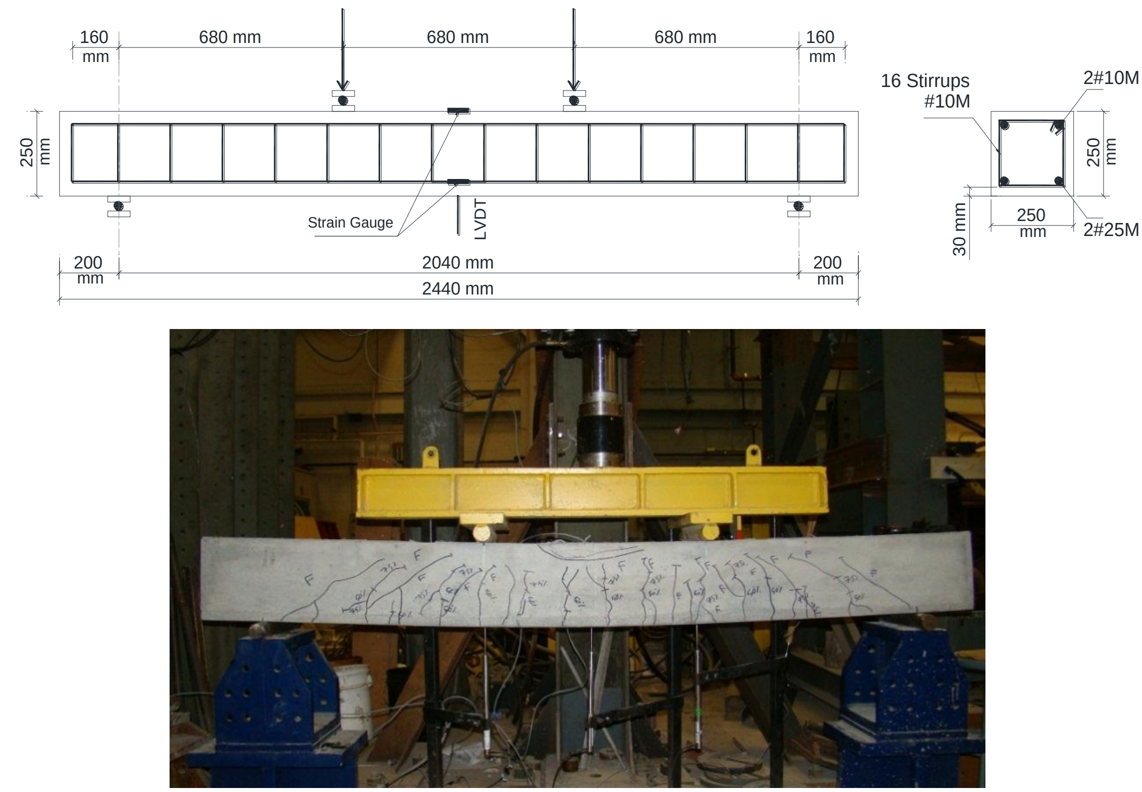


Figure 3.11 Typical test setup, dimensions, reinforcement, and failure mode of tested beams in flexure

3.6 Experimental Study 4: Shear Behaviour of Large-Scale Rubberized Concrete Beams with/without SFs

This stage aimed to investigate the shear behavior of twelve beams that were optimized from the mixtures developed in study 2.

3.6.1 Research Significance

The review of literature indicates that most of the available research has been carried out on small-scale samples and few studies have investigated large-scale testing; but there is no data available regarding the effect of CR with/without SFs on the shear performance of both VC and SCC beams. In addition, evaluating the capability of the proposed equations to predict the shear capacity of rubberized concrete beams with/without SFs is lacking because this type of concrete is a novel material. Therefore, this study was conducted particularly to help understand the shear behaviour and cracking characteristics of SCRC, VRC, SFSCRC, and SFVRC. Such research work can greatly contribute to evaluating the applicability of using CR with/without SFs in structural applications. This study also compares the experimental results with the performance of code design equations and empirical models that are commonly used to predict shear strength of concrete beams

3.6.2 Scope of Work (Concrete Mixtures)

In this part of the research, the shear behaviour of twelve beams made with mixtures listed in **Table 3.5**, was studied. The mixtures were chosen and designated based on the criteria explained in study 3, clause 3.5.1).

3.6.3 Casting of Specimens

All casting and curing procedures in study 4 were carried out as per study 3.

3.6.4 Dimensions, Test Setup, and Loading Procedures of the Tested Beams

A total of twelve beams were constructed with an identical cross section of 250 mm (width) x 250 (height) and total length of 1500 mm (**Figure 3.12**). The longitudinal tension reinforcement ratio was kept constant of 2.03%, which achieved an under-reinforced concrete sections for all tested beams. The longitudinal tension reinforcement consisted of two 25 mm diameter steel bars that were placed with a clear concrete cover of 40 mm in the tension zone, providing an effective depth (d) of 197.5 mm.

According to the scheme of the loading pattern shown in **Figure 3.12**, all the beams were typically tested on a span of 1120 mm under a four-point symmetrical vertical loading condition, showing a constant shear span-to-effective depth (a/d) ratio of 2.5 that ensures a shear failure before bending failure (Kani et al., 1979). The loading was applied gradually through a hydraulic actuator (with capacity of 500-kN) at a single point and then distributed into two-point loads acting on the beam surface. A linear variable differential transformer (LVDT) was used to measure the mid-span deflection of tested beams. The applied load and the beams' mid-span deflection were recorded continuously up to the failure occurrence. At failure, the developed flexural and shear cracks were detected with the naked eye and were marked. Then, a crack detection microscope (60x magnification with 0.02 mm least count) was used to accurately measure their widths.

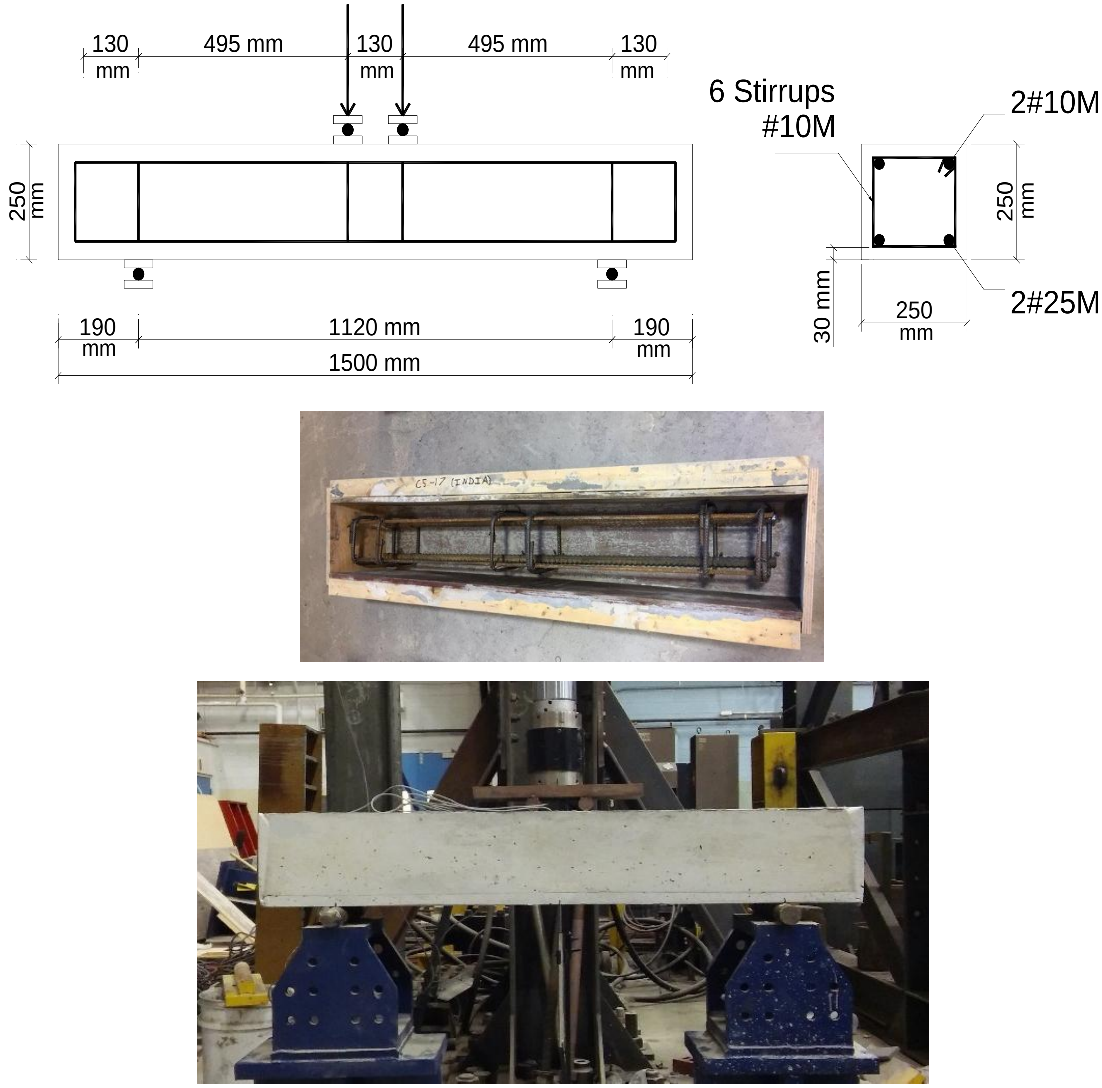


Figure 3.12 Typical test setup, dimensions, and reinforcement of tested beams in shear

4. Discussion of Results from Experimental Study 1: Optimizing the Fresh Properties, Stability, and Strength of SCRC Using Different Mixture Compositions and SCMs

4.1 Introduction

This chapter presents the results and discussion of the experimental work conducted in study 1. The main objective was to develop SCRC mixtures with maximized percentages of CR and minimized reduction in stability and mechanical properties, aiming to highlight a number of successful mixtures with high promising potentials for applications requiring high-impact resistance, energy dissipation, and acoustic absorption capacity. The effects of different percentages of CR (0%-50%), binder contents (500 kg/m^3 and 550 kg/m^3), coarse aggregate sizes (10 mm and 20 mm), SCMs (MK, FA, and GGBS), and entrained air, were studied. The results of the fresh and mechanical tests are presented in **Tables 4.1** and **4.2**, respectively. The results of the impact resistance obtained from the drop-weight and flexural loading tests are listed in **Table 4.3**. **Table 4.4** summarizes the UPV and the acoustic emission measurements for all tested mixtures.

Table 4.1 Fresh properties of tested SCRC mixtures (study 1)

#	Mixture	T_{50} (sec)	T_{50J} (sec)	Slump - J-ring (mm)	L-box H2/H1	V-funnel T_0 (sec)	SR %	CR St.	Air %	HRWRA (kg/m^3)
Stag1: Effect of CR										
1	500C-0CR	1.20	1.97	25	0.89	6.39	2.1	-	1.5	2.37
2	500C-5CR	1.55	2.10	30	0.83	6.95	2.4	NS	2.00	2.37
3	500C-10CR	1.74	2.36	37	0.79	7.57	2.5	NS	2.3	2.37
4	500C-15CR	2.00	2.43	45	0.75	8.75	3.5	NS	4.3	2.37
5	500C-20CR	2.31	2.79	60	0.54	12.5	6.3	MS	4.8	2.89
6	500C-25CR	2.51	3.23	110	0.33	14.6	9.4	HS	6.5	2.89
7	500C-30CR	2.80	5.10	145	0.25	16.2	13.3	HS	5.9	2.89
8	500C-40CR	3.71	6.27	135	0.17	25.2	15.5	HS	6.8	3.95
Stage 2: Effect of binder content and SCMs										
9	550C-20CR	1.54	2.52	50	0.75	6.65	3.0	NS	3.2	1.84
10	550C-30CR	2.08	3.05	65	0.56	10.5	4.2	MS	3.6	1.84
11	550C-40CR	2.31	4.16	70	0.38	17.5	7.1	MS	4.3	2.63
12	550C-20CR-MK	2.57	3.97	30	0.86	8.25	2.1	NS	3.4	5.26
13	550C-30CR-MK	2.86	4.61	40	0.75	13.5	2.9	NS	4.2	5.26
14	550C-40CR-MK	3.12	4.95	50	0.68	18.6	3.1	NS	4.8	6.58
15	550C-50CR-MK	3.26	5.21	65	0.40	19.0	4.0	NS	5.1	8.95
16	550C-20CR-GGBS	1.07	2.35	30	0.80	5.9	1.9	NS	3.2	1.84
17	550C-30CR-GGBS	1.37	2.85	50	0.70	6.3	2.9	NS	5.5	1.84
18	550C-40CR-GGBS	2.1	3.55	70	0.62	10.6	5.2	MS	6.5	2.63
19	550C-20CR-FA	0.99	2.32	45	0.76	5.9	3.1	NS	3.1	1.84
20	550C-30CR-FA	1.46	3.03	65	0.66	9.5	6.3	MS	4.9	1.84
21	550C-40CR-FA	1.94	3.67	70	0.54	15.5	7.3	MS	5.5	2.63
Stage 3: Effect of aggregate size and entrained air										
22	550C-30CR-MK-20	1.62	2.22	50	0.65	8.8	3.3	NS	6	4.47
23	550C-40CR-MK-20	1.75	2.76	50	0.51	11.9	3.5	NS	6.5	5.26
24	550C-50CR-MK-20	2.64	3.78	70	0.38	42	4.3	MS	6.2	6.32
25	550C-30CR-MK-MA	1.53	2.33	5	0.93	5.89	4.8	NS	7.5	5.26
26	550C-40CR-MK-MA	1.74	3.6	10	0.84	9.79	6.3	NS	8	5.53
27	550C-50CR-MK-MA	1.58	4.5	30	0.52	21.9	8.5	MS	8.4	7.89

Table 4.2 Mechanical properties of tested SCRC mixtures (study 1)

Mix	Mixture	7-day f'_c MPa	7-day STS MPa	7-day FS MPa	28-day f'_c MPa	28-day STS MPa	28-day FS MPa	28-day ME GPa
Stag1: Effect of CR								
1	500C-0CR	45.31	3.1	4.86	52.95	4.19	5.78	33.61
2	500C-5CR	40.79	3.04	4.67	44.54	4.16	5.58	31.51
3	500C-10CR	36.63	2.83	4.29	42.09	3.84	5.28	30.78
4	500C-15CR	31.65	2.72	4.14	37.35	3.36	5.01	27.56
5	500C-20CR	25.75	2.41	3.63	30.69	2.89	4.65	23.14
6	500C-25CR	23.92	2.23	3.6	28.83	2.61	4.37	23.01
7	500C-30CR	20.78	2.01	3.29	24.73	2.45	3.96	20.00
8	500C-40CR	15.39	1.65	2.64	17.66	1.82	3.35	15.49
Stage 2: Effect of binder content and SCMs								
9	550C-20CR	26.53	2.52	3.88	32.81	2.98	5.00	24.10
10	550C-30CR	22.92	2.17	3.65	27.05	2.54	4.25	22.03
11	550C-40CR	19.14	1.79	2.92	21.1	2.07	3.85	18.10
12	550C-20CR-MK	45.93	2.84	4.71	47.33	3.32	5.88	30.42
13	550C-30CR-MK	36.83	2.49	4.2	39.83	2.87	4.88	26.25
14	550C-40CR-MK	30.25	2.32	3.69	32.95	2.62	4.29	23.42
15	550C-50CR-MK	20.92	1.84	3.26	22.56	2.08	3.58	19.71
16	550C-20CR-GGBS	26.36	2.34	3.78	34.59	3.12	5.21	26.36
17	550C-30CR-GGBS	25.39	2.15	3.52	30.64	2.66	4.43	23.12
18	550C-40CR-GGBS	18.21	1.88	3.04	20.75	2.21	4.12	18.71
19	550C-20CR-FA	26.90	2.18	3.47	34.15	2.99	4.9	25.61
20	550C-30CR-FA	20.90	2.1	3.12	31.02	2.55	4.34	24.61
21	550C-40CR-FA	17.01	1.72	2.74	20.58	2.24	3.83	17.37
Stage 3: Effect of aggregate size and entrained air								
22	550C-30CR-MK-20	32.77	2.43	3.83	35.63	2.71	4.8	25.54
23	550C-40CR-MK-20	25.10	2.29	2.97	30.26	2.46	4.14	22.55
24	550C-50CR-MK-20	18.11	1.80	3.07	21.25	2.05	3.21	17.71
25	550C-30CR-MK-MA	29.02	2.15	3.34	30.24	2.44	3.87	22.47
26	550C-40CR-MK-MA	23.08	1.85	3.00	25.69	2.11	3.27	21.05
27	550C-50CR-MK-MA	15.34	1.38	2.03	17.16	1.86	2.75	16.22

Table 4.3 Impact test results of tested SCRC mixtures (study 1)

M #	Mixture	Drop Weight Test					Flexural Impact Test	
		No. of blows			IE (J)		No. of blows	IE (J)
		First Crack (N_1)	Failure Crack (N_2)	N_2-N_1	Initial	Failure	Failure	Failure
Stage 1: Effect of CR								
1	500C-0CR	29	30	1	578.4	598.3	8	52.4
2	500C-5CR	33	35	2	658.1	698.0	10	65.5
3	500C-10CR	42	44	2	837.6	877.5	12	78.6
4	500C-15CR	57	60	3	1136.8	1196.6	14	91.6
5	500C-20CR	70	74	4	1396.0	1475.8	15	98.2
6	500C-25CR	80	85	5	1595.5	1695.2	12	78.6
7	500C-30CR	85	90	5	1695.2	1794.9	10	65.5
8	500C-40CR	74	78	4	1475.8	1555.6	9	58.9
Stage 2: Effect of binder content and SCMs								
9	550C-20CR	75	78	3	1495.7	1555.6	16	104.7
10	550C-30CR	88	92	4	1755.0	1834.8	11	72.0
11	550C-40CR	79	83	4	1575.5	1655.3	10	65.5
12	550C-20CR-MK	84	87	3	1675.2	1735.1	18	117.8
13	550C-30CR-MK	95	99	4	1894.6	1974.4	13	85.1
14	550C-40CR-MK	89	92	3	1775.0	1834.8	11	72.0
15	550C-50CR-MK	80	83	3	1595.5	1655.3	10	65.5
16	550C-20CR-GGBS	76	78	2	1515.7	1555.6	15	98.2
17	550C-30CR-GGBS	90	94	4	1794.9	1874.7	11	72.0
18	550C-40CR-GGBS	81	85	4	1615.4	1695.2	10	65.5
19	550C-20CR-FA	79	81	2	1575.5	1615.4	15	98.2
20	550C-30CR-FA	89	92	3	1775.0	1834.8	10	65.5
21	550C-40CR-FA	78	81	3	1555.6	1615.4	10	65.5
Stage 3: Effect of aggregate size and entrained air								
22	550C-30CR-MK-20	86	87	1	1715.1	1735.1	11	72.0
23	550C-40CR-MK-20	83	85	2	1655.3	1695.2	8	58.9
24	550C-50CR-MK-20	74	76	2	1475.8	1515.7	8	52.4
25	550C-30CR-MK-MA	83	85	2	1655.3	1695.2	10	65.5
26	550C-40CR-MK-MA	77	78	1	1535.6	1555.6	9	58.9
27	550C-50CR-MK-MA	69	71	2	1376.1	1416.0	8	52.4

Table 4.4 UPV, signal strength, and signal energy of tested SCRC mixtures (study 1)

Mix. #	Mixture	UPV (m/s)	AE Results	
			Signal Strength (pV.s)	Signal Energy (aJ)
Stage 1: Effect of CR				
1	500C-0CR	4656.2	1.12E+07	1797.0
2	500C-5CR	4450.0	1.07E+07	1717.6
3	500C-10CR	4074.2	9.82E+06	1571.6
4	500C-15CR	3993.2	9.63E+06	1541.2
5	500C-20CR	3567.9	8.60E+06	1374.5
6	500C-25CR	3416.3	7.45E+06	1192.1
7	500C-30CR	3233.1	7.56E+06	1209.5
8	500C-40CR	3092.2	7.23E+06	1156.1
Stage 3: Effect of binder content and SCMs				
9	550C-20CR	3632.4	8.76E+06	1402.4
10	550C-30CR	3322.2	8.01E+06	1282.4
11	550C-40CR	3124.2	7.53E+06	1203.0
12	550C-20CR-MK	4172.8	1.01E+07	1610.7
13	550C-30CR-MK	3745.2	9.03E+06	1443.4
14	550C-40CR-MK	3495.5	7.75E+06	1241.0
15	550C-50CR-MK	3181.9	6.52E+06	1043.2
16	550C-20CR-GGBS	3676.7	8.87E+06	1418.9
17	550C-30CR-GGBS	3536.5	7.71E+06	1233.8
18	550C-40CR-GGBS	3224.5	5.70E+06	911.3
19	550C-20CR-FA	3378.0	8.55E+06	1367.7
20	550C-30CR-FA	3322.2	8.01E+06	1282.3
21	550C-40CR-FA	3140.5	6.15E+06	982.9
Effect of aggregate size and entrained air				
22	550C-30CR-MK-20	3495.5	8.38E+06	1340.7
23	550C-40CR-MK-20	3304.0	6.80E+06	1087.9
24	550C-50CR-MK-20	3140.5	5.87E+06	940.2
25	550C-30CR-MK-MA	3241.8	6.78E+06	1084.7
26	550C-40CR-MK-MA	2941.3	4.91E+06	785.9
27	550C-50CR-MK-MA	2785.1	3.42E+06	547.6

4.2 Fresh Properties of SCRC

4.2.1 Unit weight and Air Content

Owing to the lower density of CR compared to conventional sand, increasing the CR replacement had a direct impact on reducing the unit weight of tested mixtures, as shown in **Figure 4.1**. The addition of 40% CR decreased the unit weight of SCRC mixtures from 2367.3 kg/m^3 to 2118.3 kg/m^3 (10.5% reduction of the total weight) (mixtures 1-8).

Figure 4.1 also shows the effect of increasing the percentage of CR on the air content. A significant increase in the air content can be noticed with increasing the percentage of CR. Increasing the percentage of CR from 0% to 40% (mixtures 1-8) increased the air content from 1.5% to 6.8%. This finding agrees with other studies (Reda Taha et al., 2008; Naito et al., 2013), which indicated a significant increase in the air content with higher percentages of CR. This increase in air content can be attributed to the non-polar nature of rubber particles and their tendency to entrap air in their rough surface texture (Reda Taha et al., 2008). Alternatively, Naito et al. (2014) reported that the increase in the measured air content may come from the high compressibility of rubber particles, which may result in an artificial amount of air measured by the standard ASTM C231 (2014).

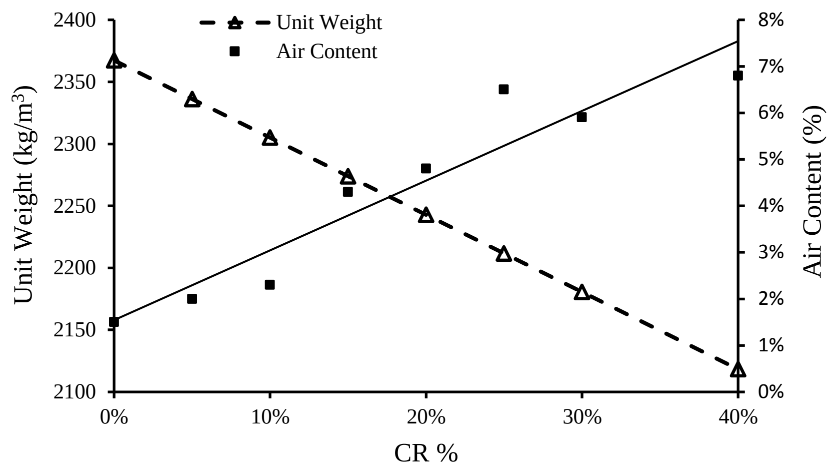


Figure 4.1 Influence of CR replacement on the unit weight and air content of tested SCRC mixtures

4.2.2 HRWRA Demand

The demands of HRWRA for all tested mixtures are presented in **Table 4.1**. It can be seen that the addition of up to 30% CR (mixture 7) did not show a significant increase in the HRWRA demand (to achieve the target slump flow of 650 ± 50). The HRWRA demand, however, appeared to increase when the percentage of CR reached 40%. For example, the addition of 40% CR in mixture 8 (500C-40CR) showed 66.67% increase in the HRWRA demand compared to the control mixture with no CR (mixture 1). The result of increasing the HRWRA demand with high percentages of CR agrees with that reported by other researchers (Güneyisi, 2010).

Table 4.1 also compares mixtures with 500 kg/m^3 to those with 550 kg/m^3 at the same percentage of CR (500C-20CR, 500C-30CR, and 500C-40CR compared to 550C-20CR, 550C-30CR, and 550C-40CR, respectively). As shown, increasing the binder content from 500 kg/m^3 to 550 kg/m^3 decreased the HRWRA demand on average by 35.4%. As the percentage of CR increased from 20% to 30%, the results also showed that at 550 kg/m^3 binder content there was no significant difference in the HRWRA demand but a noticeable increase was observed in the HRWRA demand at 40% CR (mixture 11).

Table 4.1 also shows the results of HRWRA demand for varying percentages of CR in SCRC mixtures incorporating SCMs (MK, GGBS, or FA). The addition of MK showed the greatest increase in the HRWRA demand (compared to the other SCMs) with an average of 274% (mixtures 12-14 vs mixtures 16-18 vs mixtures 19-21). The reason is due to the higher surface area of the MK compared to the replaced cement or other SCMs (Madandoust and Mousavi, 2012). The HRWRA demand in mixtures with MK ranged from 5.26 to 8.95 kg/m^3 as the percentage of CR varied from 20% to 50% (mixtures 12-15). On the other hand, mixtures with GGBS (mixtures 16-18) or FA (mixtures 19-21) showed no difference in HRWRA demand compared to mixtures with no SCMs (mixtures 9-11), when the percentage of CR varied from 20% to 40%.

By comparing each of 550C-30CR-MK-20, 550C-40CR-MK-20, and 550C-50CR-MK-20 (mixtures 22-24) to 550C-30CR-MK, 550C-40CR-MK, and 550C-50CR-MK (mixtures 13-15), respectively, it can be observed that increasing the size of coarse aggregate decreased the amount of HRWRA required to achieve the desired slump flow of 650 ± 50 mm. SCRC mixtures with 20 mm aggregate required an average of 21.49% less HRWRA compared to mixtures with 10 mm aggregate. This could be attributed to that at the same aggregate volume, increasing the coarse aggregate size reduces the total surface area of the coarse aggregate (Neville, 1995), which provides a better workability for a given w/b.

The results also showed the effect of using microair in SCRC mixtures. Only a small amount of entrained air agent, 210 ml/m^3, was used to improve the mixture flowability, as well as maintain acceptable compressive strength. From the results, it can be observed that using entrained air agent (mixtures 25-27) exhibited a 9.3% average reduction in the HRWRA demand compared to the reference mixtures (MK mixtures without entrained air agent, mixtures 13-15), as shown in **Table 4.1**.

4.2.3 Flowability

The results of T_{50}, T_{50J}, and V-funnel time were used to evaluate the flowability of SCRC mixtures. Increasing the percentage of CR appeared to reduce the mixture flowability. **Table 4.1** and **Figure 4.2a** show that the T_{50} increased from 1.2 to 3.71 seconds when the percentage of CR increased from 0% to 40% (mixtures 1-8). The J-ring and V-funnel tests also showed the same effect, in which the T_{50J} and the V-funnel time increased up to 3.18 and 3.94 times, respectively, as the percentage of CR increased from 0% to 40% (mixtures 1-8). **Figure 4.3** shows an optical photo for samples of the used rubber particles. From the figure, it can be observed that the rubber particles have jagged and rough surfaces, which can increase the inter-particle friction in concrete, and thus decaying the flowability of mixtures.

As shown in **Table 4.1** and **Figure 4.2b**, the flowability of SCRC mixtures was considerably enhanced when the binder content increased from 500 kg/m^3 to 550 kg/m^3, which decreased the T_{50}, T_{50J}, and V-funnel times by an average of 32.3%, 27.8%, and

37.5%, respectively (mixtures 9, 10, and 11 compared to mixtures 5, 7, and 8). Such finding may be attributed to that a proper increase in the paste volume leads to a sufficient coating for mixtures' particles and provides an enough lubrication action to achieve a smooth flow (Girish et al., 2010; Chen et al., 2013).

The results also indicated that the viscosity of SCRC greatly increased by adding 20% MK. The T_{50}, T_{50J}, and the V-funnel times increased by an average of 46.5%, 42.6%, and 19.6%, respectively, in MK mixtures (mixtures 12-14) compared to the reference mixtures (mixtures 5, 7, and 8), as shown in **Table 4.1** and **Figure 4.2c**. This results are in agreement with other researchers' findings (Madandoust and Mousavi, 2012; Hassan et al, 2015), as MK has a high surface area and clay nature which contribute to reducing the flowability and increasing the viscosity of SCC mixtures. On the other hand, adding 20% FA or 30% GGBS increased the flowability of SCRC mixtures. The T_{50}, T_{50J}, and the V-funnel times of FA mixtures decreased by an average of 27.2%, 6.8%, and 10.7%, respectively, while with 30% GGBS the times decreased by an average of 24.6%, 9.32%, and 30.3%, respectively, compared to the reference mixtures (mixtures 5, 7, and 8).

The results of the T_{50}, T_{50J}, and V-funnel times of SCRC mixtures indicated an increase in the flowability when the coarse aggregate size increased from 10 mm to 20 mm (see **Table 4.1**, **Figure 4.2d**). For example, the T_{50} and T_{50J} decreased by 35.4% and 41.2% average value, respectively, when the aggregate size changed to 20 mm (mixtures 22-24 compared to mixtures 13-15). These results may be attributed to that for a given aggregate volume, increasing the aggregate size decreases the total surface area of the coarse aggregate

(Neville, 1995; Hassan and Mayo, 2014), which reduces the amount of water required to wet the aggregate surface during mixing (providing more free water in the mixture), and hence improves the flowability of mixture. By comparing mixtures 25-27 to mixtures 13-15, it can be observed that using entrained air also greatly improved the flowability of tested mixtures. The average drop in the T_{50} times in all mixtures with entrained air was 47.4%, while the average drops in the V-funnel times and T_{50J} in the same mixtures were 29.4% and 30.1%, respectively, (**Table 4.1**, **Figure 4.2d**). This finding could be attributed to that the air bubbles resulted from adding air entrainment admixtures act as a fine aggregate with high elasticity and low surface friction, which in turn decreases the particle friction and thus improves flowability (Neville, 1995).

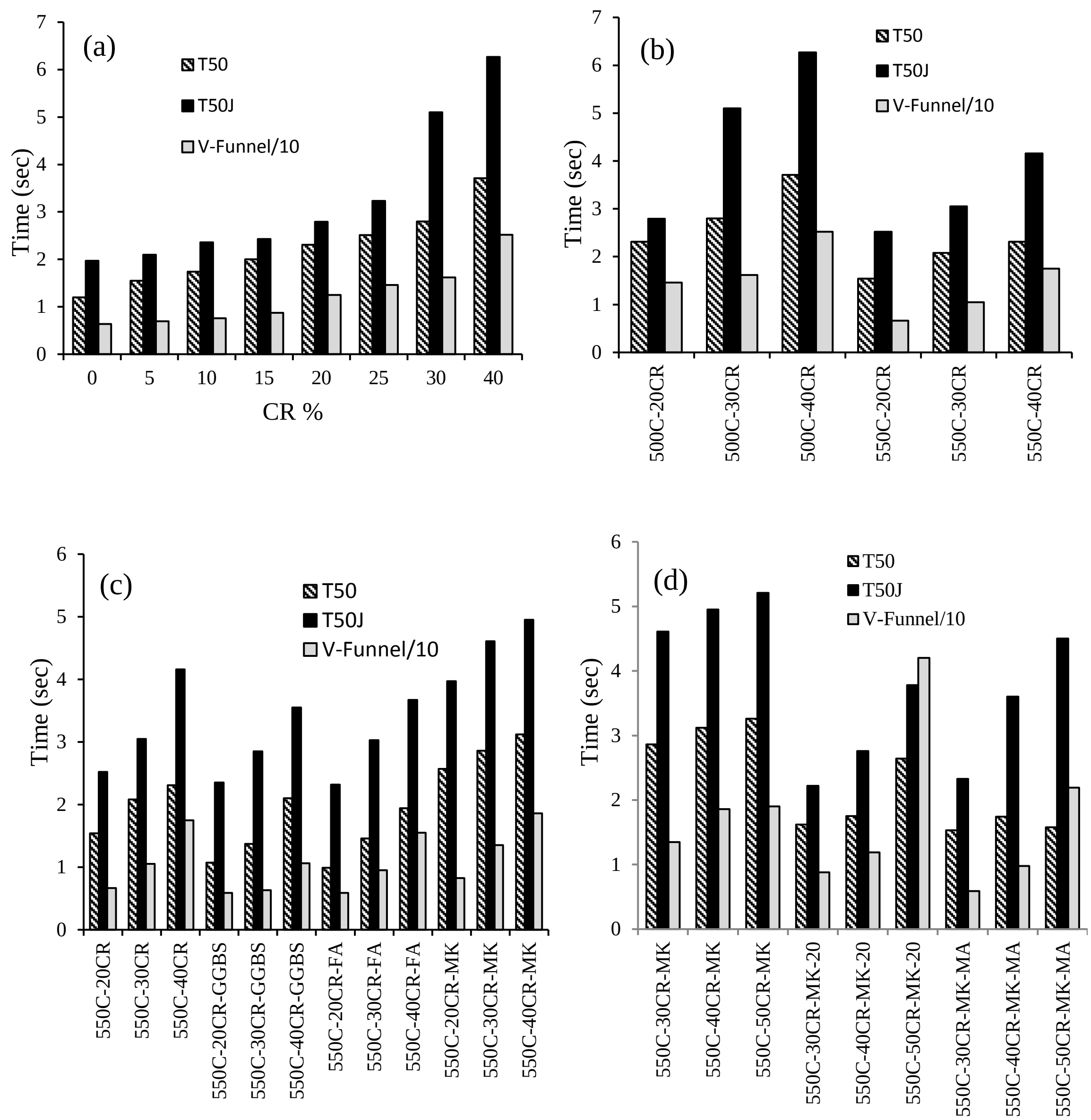


Figure 4.2 T_{50}, T_{50J}, and V-funnel times of the tested SCRC mixtures: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

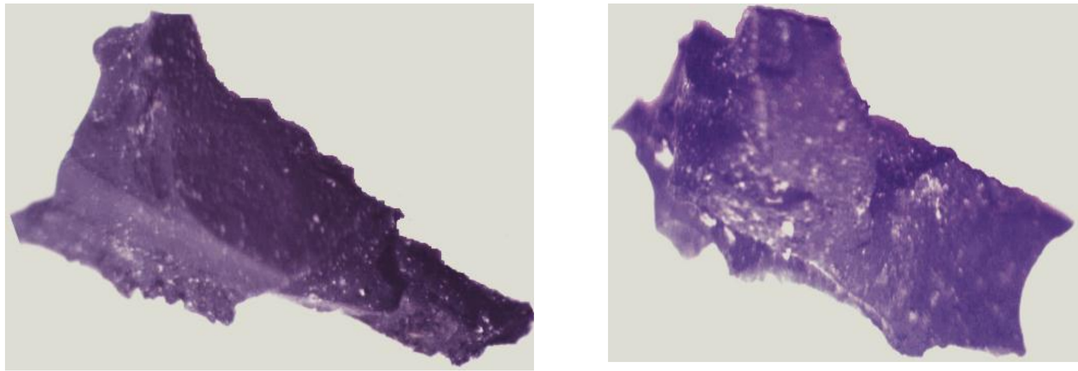


Figure 4.3 Optical microscopy image for a sample of the used rubber particles

4.2.4 Passing Ability

The H2/H1 L-box ratio and the difference between the slump flow and J-ring diameters were used to assess the passing ability of all SCRC mixtures. As seen in **Table 4.1** and **Figure 4.4a**, the addition of CR reduced the passing ability compared to the control mixture (CR = 0). Varying the percentage of CR from 0% to 40% (mixtures 1-8) reduced the L-box ratio by 80.9%. For the same increase in the percentage of CR, the difference between the slump flow and J-ring diameters increased from 25 mm to 135 mm. The reduction of the passing ability due to inclusion of CR could be attributed to the high friction and blocking between the crushed stone aggregate and the rough rubber particles (as shown in **Figure 4.3**). According to the conformity criteria of the European Guidelines for Self-Compacting Concrete (2005), the recommended value of H2/H1 in the L-box test is 0.75 or greater. Similarly, the Interim Guidelines for the Use of Self-Consolidating Concrete (2003) indicate that mixtures with L-box ratio of less than 0.75 (< 0.75) may experience potential problems in casting members with a medium-to-high reinforcement level, medium-to-high element length, and/or low wall thickness. The results of this stage indicated that the tested mixtures with up to 15% CR replacement (mixtures 1-4) showed H2/H1 results close to the value recommended by the two guidelines.

As seen in **Table 4.1** and **Figure 4.4b**, the results of the passing ability showed great improvement due to increasing the binder content from 500 kg/m^3 to 550 kg/m^3, as shown in mixtures 9, 10, and 11 compared to mixtures 5, 7, and 8, respectively. Increasing the binder content showed an average reduction of 40% in the slump flow–J-ring diameter. The L-box ratio also significantly increased in mixtures with high CR replacement, where the values of H2/H1 increased by 195% (on average) as the binder content increased from 500 kg/m^3 to 550 kg/m^3. These enhanced results, however, still do not fulfill the acceptable range for SCC mixtures, as reported in the conformity criteria of the European Guidelines for Self-Compacting Concrete (EFNARC, 2005) and/or the Interim Guidelines for the Use of Self-Consolidating Concrete (2003).

The addition of MK (mixtures 12-14) showed higher L-box values and lower slump flow–J-ring diameter values (see **Table 4.1** and **Figure 4.4c)**, indicating better passing ability. The reduction in the slump flow–J-ring diameter reached up to 35.7% (on average). Also, the H2/H1 ratio of the L-box increased by an average of 42.51% compared to the reference mixtures (mixtures 9-11). This increase in the passing ability could be attributed to the beneficial effect of MK on improving the mixture viscosity (Hassan et al. 2012), which in turn increases the ability of mixture to carry the aggregate particles and flow through the limited spaces of L-box and J-ring devices. This finding is in agreement with what other researchers (Khayat and Assaad, 2002) have reported, in which the passing ability of SCC increased by adding SCMs. In general, the addition of MK allowed the use of up to 30% CR in SCRC mixtures and maintained acceptable fresh properties according to the conformity criteria of the European Guidelines for Self-Compacting Concrete (EFNARC, 2005) and/or the Interim Guidelines for the Use of Self-Consolidating Concrete (2003). The addition of FA and GGBS in SCRC mixtures also showed some improvement in the passing ability of the mixtures (**Table 4.1** and **Figure 4.4c)**. However, this improvement was relatively small compared to that achieved with MK mixtures.

As seen from **Table 4.1** and **Figure 4.4d**, the passing ability of all mixtures decreased when the coarse aggregate size increased from 10 mm to 20 mm. The slump flow–J-ring diameter increased on average by 10.9% when the coarse aggregate size was increased to 20 mm. The L-box ratios also showed an average reduction of 14.4% in mixtures with larger aggregate size compared to smaller aggregate size (mixtures 22-24 compared to mixtures 13-15). This is due to increasing the blockage behind the L-box's and J-ring bars when larger aggregate size was used.

The addition of entrained air appeared to have a significant impact on improving the passing ability of SCRC mixtures (**Table 4.1** and **Figure 4.4d**). The L-box values of mixtures with up to 40% CR began to fall well within the acceptable range when entrained air was used. The beneficial effect of the entrained air on improving the passing ability of SCRC is similar to what Safiuddin (2008) have observed in his study conducted on SCC. The results also showed that the slump flow–J-ring diameter decreased on average by

73.8% when the entrained air was used, confirming the improvement of the passing ability with the addition of entrained air.

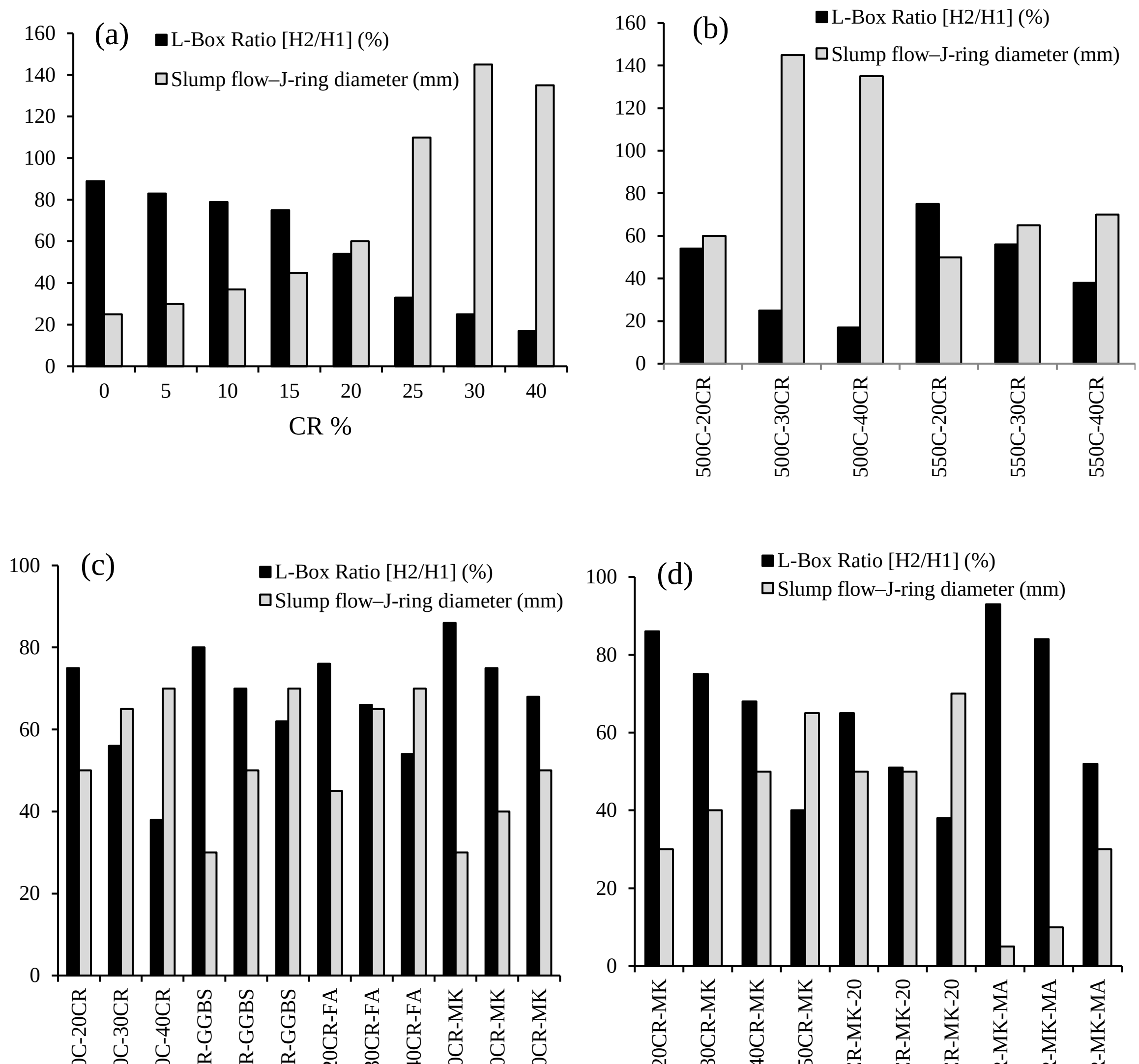


Figure 4.4 Passing ability of the tested SCRC mixtures: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

4.2.5 Segregation Resistance (SR)

The sieve segregation test was used to evaluate the coarse aggregate segregation of all tested mixtures. Also, the stability of rubber particles was evaluated visually. As seen in **Table 4.1** and **Figure 4.5a**, the results of SR indicated that the risk of segregation increased as the percentage of CR increased, similar to other researchers' finding (Topçu and Bilir 2009). Increasing the CR replacement from 0% to 40% (mixtures 1-8) raised the SR up to 7.38 times. The results of SR for 40% CR mixture fell outside the conservative range (SR ≤ 15%) for SCC mixtures, as stated in the European Guidelines for Self-Compacting Concrete (2005). **Table 4.1** also shows that no sign of segregation was observed in the hardened splitted cylinders up to 15% CR replacement (mixture 1-4), but mixtures with 20% CR (mixture 5) showed moderate segregation. Mixtures with 25%, 30%, and 40% CR (mixtures 6-8) appeared to be heavily segregated. This finding is attributed to the low specific gravity of the rubber (0.95), which makes it easy for the rubber to float toward the concrete surface during mixing.

The SR results indicated a lower risk of segregation by an average of 58.3% as the binder content increased from 500 kg/m^3 to 550 kg/m^3 (see **Table 4.1** and **Figure 4.5b)**. In 550 kg/m^3 binder mixtures (mixtures 9-11), the values of SR ranged from 3% to 7.1% and CR varied from 20% to 40%. These results are within the acceptable range of SCC mixtures based on the European Guidelines for Self-Compacting Concrete (2005). Also, the inspection of the hardened splitted cylinders showed that the stability of rubber was enhanced, in which the 20% CR mixtures showed no sign of segregation and the 30% and 40% CR mixtures exhibited a moderate segregation.

The addition of MK enhanced the stability of SCRC mixtures (**Table 4.1** and **Figure 4.5c**). All MK mixtures (mixtures 12-15) had conservative SR values based on the European Guidelines for Self-Compacting Concrete (2005). The percentage of SR ranged from 2.1% to 4% as the percentage of CR varied from 20% to 50% in MK mixtures. The addition of MK also showed no sign of segregation in the hardened splitted cylinders with up to 50% CR replacement. Although the values of SR for GGBS and FA mixtures (mixtures 16-18 and mixtures 19-21, respectively) fell inside the conservative range ($\leq$ 15%), the visual observation of their hardened splitted cylinders showed unsatisfactory results in cases using 30% and 40% CR.

The SR results presented in **Table 4.1** and **Figure 4.5d** also show that using larger coarse aggregate size decreased the stability of SCRC mixtures. The SR values increased on average by 11.4% when using 20 mm aggregate compared to 10 mm (mixtures 22-24 compared to mixtures 13-15). The SCRC mixtures containing 20 mm crushed stone aggregate gave a maximum SR value of 4.3%, which is still acceptable based on the European Guidelines for Self-Compacting Concrete (2005). **Table 4.1** also shows that no sign of segregation was seen in the hardened splitted cylinders for mixtures with 30% and 40% CR replacement, but mixtures with 50% CR showed moderate segregation. It is also observed that the addition of entrained air agent decreased the stability of the mixtures where the SR values showed an increase of 93.7% (on average) compared to the reference mixtures (mixtures 25-27 compared to mixtures 13-15). However, all mixtures containing entrained air in this stage had SR values less than the critical value indicated by the European Guidelines for Self-Compacting Concrete (2005). In the meantime, the visual observation of the rubber distribution in the hardened splitted cylinders showed moderate segregation for mixtures with 50% CR replacement.

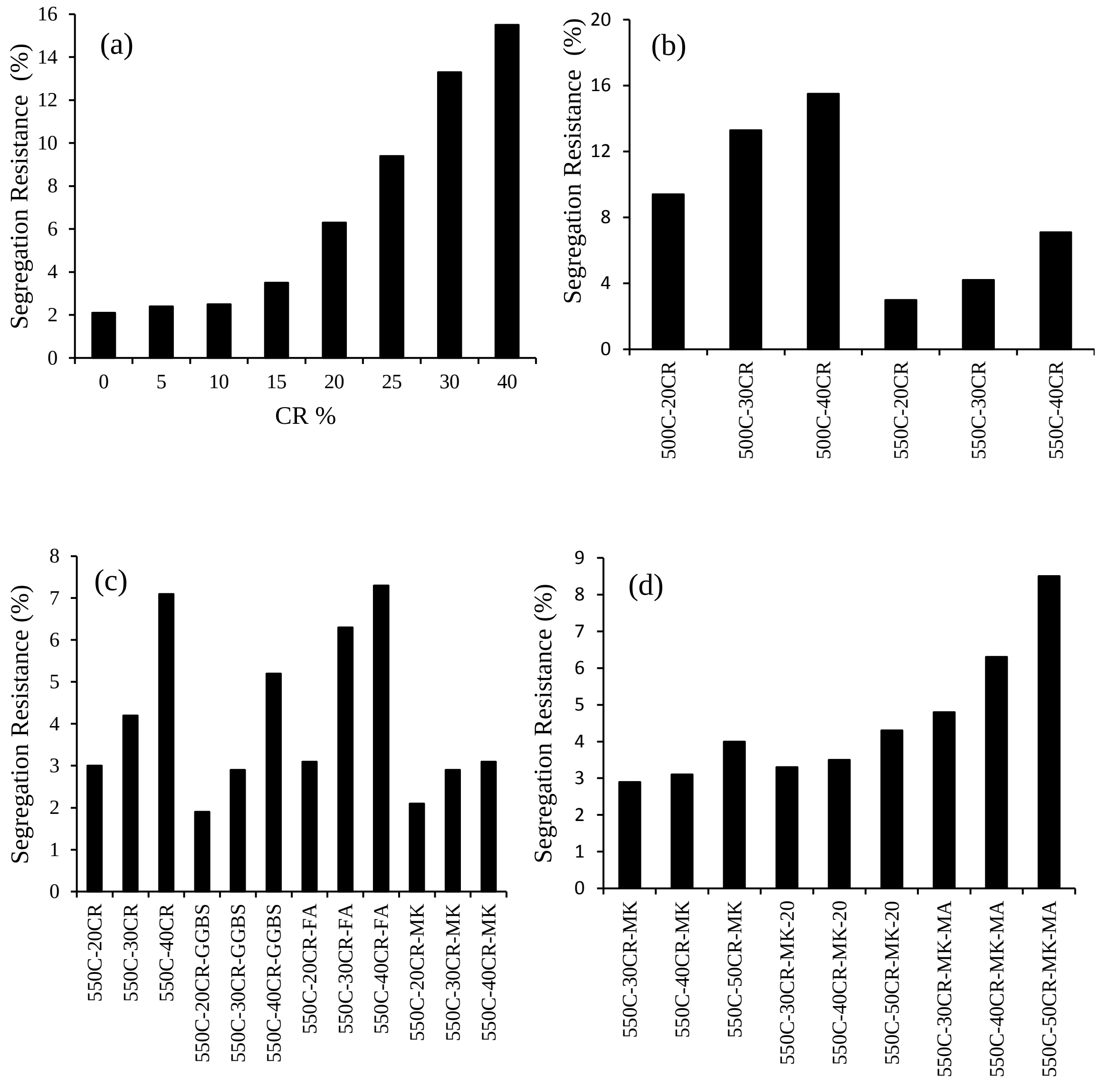


Figure 4.5 Segregation resistance of the tested SCRC mixtures: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

4.2.6 Maximum CR content recommended for SCRC application

Table 4.5 shows the maximum CR contents that can be used safely in the SCRC applications. The recommended maximum contents of CR are based on the results of the fresh properties and stability tests that were conducted and compared with the conformity criteria of the European Guidelines for Self-Compacting Concrete (2005) and/or the Interim Guidelines for the Use of Self-Consolidating Concrete (2003). From the table, it can be concluded that it is possible to use up to 15% CR in SCRC mixtures if a 500 kg/m^3 binder content was used (without SCMs). Further increase the binder content to 550 kg/m^3 (without SCMs or with 20% FA or with 30% GGBS) can increase the possible safe content of CR to 20% (by fine aggregate volume). This percentage can be reached to 30% if a 550 kg/m^3 binder content (incorporating 20% MK) is used in the mixture. Adding microair to MK mixtures can help to increase the maximum percentage of CR that can be used in SCRC mixtures. The SCRC mixtures with MK and microair can be developed with up to 40% CR.

Table 4.5 Maximum CR contents recommended for most SCRC applications

			Max. CR %	Slump flow D_s (mm)	Slump flow T_{50} (sec)	L-box H2/H1	V-funnel T_0 (sec)	SR (%)	CR Stability	f'_c 28-day (MPa)
SCRC without SCMs	Binder content 500 kg/m^3		15	675	2.00	0.75	8.75	3.5	NS	37.35
SCRC without SCMs	Binder content 550 kg/m^3		20	700	1.54	0.75	6.65	3.0	NS	32.81
SCRC with SCMs (550 kg/m^3 binder content)	30% GGBS		20	705	1.07	0.80	5.9	1.9	NS	34.59
SCRC with SCMs (550 kg/m^3 binder content)	20% FA		20	700	0.99	0.76	5.9	3.1	NS	34.15
SCRC with SCMs (550 kg/m^3 binder content)	20% MK	10-mm aggregate	30	620	2.86	0.75	13.5	2.9	NS	39.83
SCRC with SCMs (550 kg/m^3 binder content)	20% MK	10-mm aggregate, MA	40	700	1.74	0.84	9.79	6.3	NS	25.69

Note: All abovementioned values fell inside the acceptable range for SCC recommended by the Interim Guidelines for the Use of Self-Consolidating Concrete (2003) and the conformity criteria of the European Guidelines for Self-Compacting Concrete specification, production, and use.

4.3 Mechanical Properties of SCRC

4.3.1 Compressive Strength

The 7- and 28-day compressive strengths of the tested mixtures are shown in **Table 4.2** and **Figure 4.6**. As seen from mixtures 1–8 (**Figure 4.6a)**, increasing the percentage of CR decreased the 7- and 28-day compressive strengths. Varying the CR from 0% to 40% reduced the 7- and 28-day compressive strength by around 66%. The reduction of the compressive strength with higher percentages of CR may be attributed to the poor strength of the ITZ between the rubber particles and surrounding mortar (Najim and Hall, 2010). **Figure 4.7** shows typical optical microscopy images presenting the rubber-cement interface. From **Figures 4.7a** and **4.7b**, a discontinuity between the CR particles and the surrounding mortar can be observed, thus indicating a poor bonding at the interface, which can contribute to the decay of compressive strength. This observation is similar to other researchers' findings (Emiroglu et al., 2007; Najim and Hall, 2013; Gupta et al., 2015), in which scanning electron microscopy was conducted on the microstructure of the ITZ of rubberized concrete. The reduction of the compressive strength with higher percentages of CR may also be related to the considerable difference between the modulus of elasticity of the rubber particles and the hardened cement paste (Najim and Hall, 2010), which could significantly induce the propagation of microcracks under loading. Moreover, increasing the percentage of CR increased the air content (**Table 4.1**), which in turn led to higher porosity and negatively affected the compressive strength of the mixtures. As shown in **Figure 4.7c**, air voids could be entrapped between rubber particles. This can be due to the non-polar nature of rubber particles and their tendency to entrap air in their rough surface texture (Siddique and Naik, 2004; Reda Taha et al., 2008). However, all tested SCRC mixtures exceeded the minimum 28-day compressive strength for structural concrete (17 MPa) (Neville, 1995), and the mixture with 15% CR (which is the maximum percentage that can be used with 500 kg/m^3 of binder content and no SCMs (see **Table 4.5**)) showed a good 28-day compressive strength of 37.35 MPa.

By comparing mixtures 5, 7, and 8 to mixtures 9, 10, and 11, respectively, it can be noticed that the 7 and 28-day compressive strengths improved as the binder content increased. Increasing the binder content from 500 kg/m^3 to 550 kg/m^3 increased the 7- and 28-day compressive strength, on average, by 12.6% and 11.9%, respectively (**Table 4.2** and **Figure 4.6b**). Increasing the binder content to 550 kg/m^3 also improved the compressive strength of mixture 550C-20CR (the most successful SCRC mixture with 550 kg/m^3 binder and no SCMs (see **Table 4.5**)) by around 10% (see **Table 4.2**). Such observation indicates the possibility of enhancing the adhesion and the ITZ between rubber particles and surrounding mortar by increasing the binder content. This increase may also be attributed to that higher binder content means a greater bulk cementitious mortar content, which may yield greater mixture strength.

Using MK could significantly improve the compressive strength of SCRC mixtures. The 7- and 28-day compressive strengths of mixtures 12–14 increased by an average of 64% and 49.2%, respectively, compared to mixtures 9–11 (with no SCMs) (see **Figure 4.6c**). The addition of MK also greatly improved the 28-day compressive strength of the most successful SCRC mixture incorporating SCMs (550C-30CR-MK) (see **Table 4.5**), increasing it from 27.05 MPa (550C-30CR) to 39.83 MPa (550C-30CR-MK). This improvement in the compressive strength can be attributed to that the higher surface area of MK compared to the replaced cement, which leads to a faster pozzolanic reaction rate (Justice and Kurtis, 2007). In addition, the finer MK particles (compared to the replaced cement) allow for a high filling capacity at aggregate-cement paste interface (Justice and Kurtis, 2007), resulting in a better ITZ. On the other hand, the lower hydration rate of GGBS and FA mixtures (mixtures 16–21) led to a slight increase in the 28-day compressive strengths, reaching an average increase of 5.7% and 5.4%, respectively, compared to mixtures 9-11.

From **Table 4.2** and **Figure 4.6d**, it can be observed that using a larger aggregate size (20 mm) reduced the 7- and 28-day results by 13.8% and 8.2% (on average), respectively, as shown in mixtures 22, 23, and 24 compared to mixtures 13, 14, and 15, respectively. These reductions could be attributed to the increased volume of the ITZ between the coarse aggregate and cement paste with larger aggregate size (Koehler and Fowler, 2007). The ITZ is typically considered the weakest part in the structure of concrete composite because of the wall effect (Scrivener et al., 2004) and accumulating water at aggregate surface (leads to high w/b ratio) due to bleeding (Neville, 1995). These cause a higher porosity and local weakness at the ITZ, and hence make it more susceptible to micro-cracking under loading which can greatly contribute to decaying the mixture's mechanical properties.

As shown in **Table 4.2** and **Figure 4.6d**, for the MK mixtures where CR varied from 30% to 50% (mixtures 25–27), the 7- and 28-day compressive strengths decreased when the entrained air admixture was added. Using entrained air admixture increased the air content by 70% (on average) compared to the reference mixtures (mixtures 13–15). This increase in the air content could consequently increase the porosity of concrete, which in turn decreased the 28-day compressive strength by 23.3% (on average). However, despite the reduction of the mechanical properties with the addition of entrained air, using entrained air admixture greatly enhanced the fresh properties and stability, and allowed up to 40% CR to be used safely in SCRC mixtures with acceptable fresh properties, stability, and strength (see mixture 550C-40CR-MK-MA) (see **Table 4.5**).

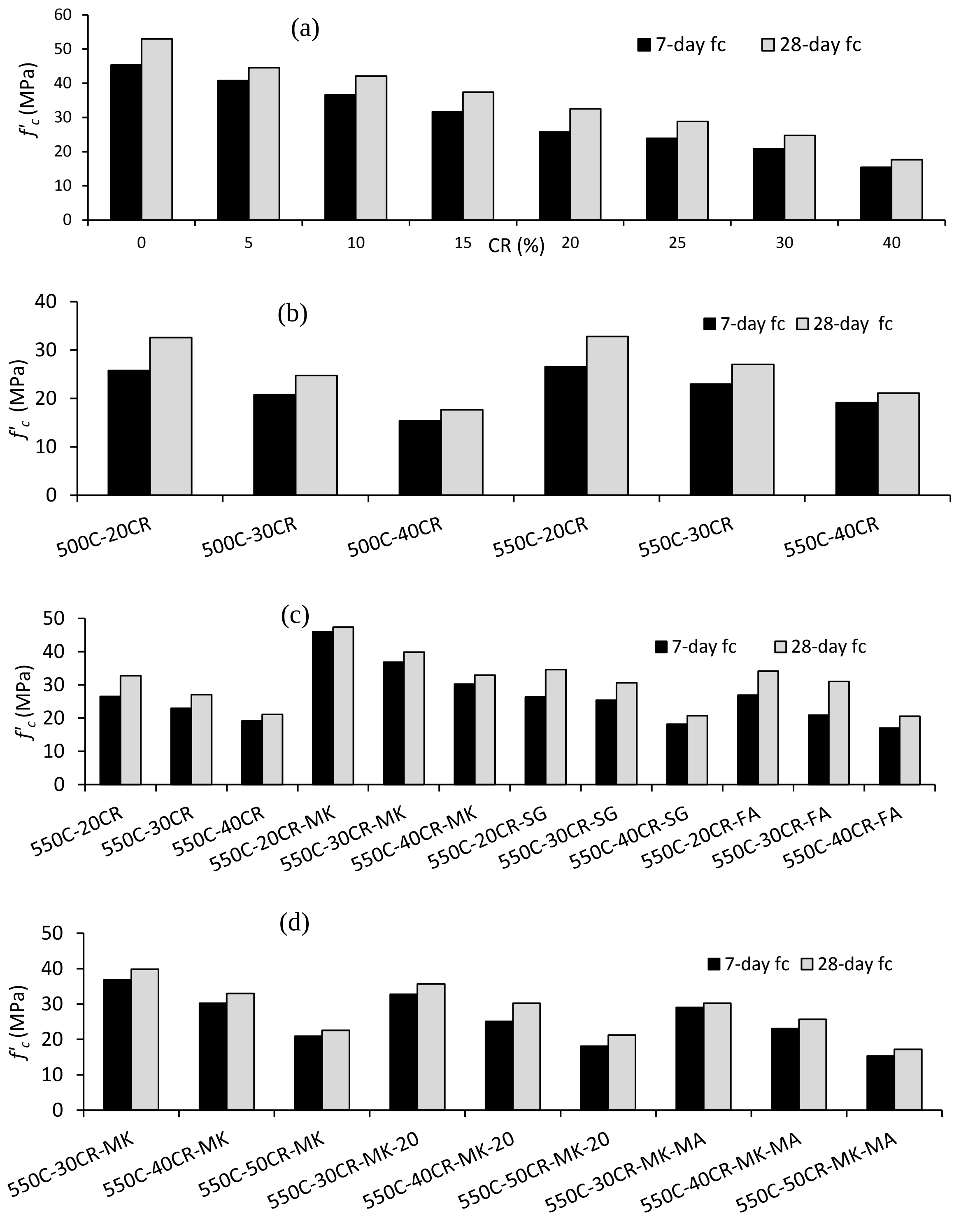


Figure 4.6 Compressive strength of the tested SCRC mixtures: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

(a)

(b)

(c)

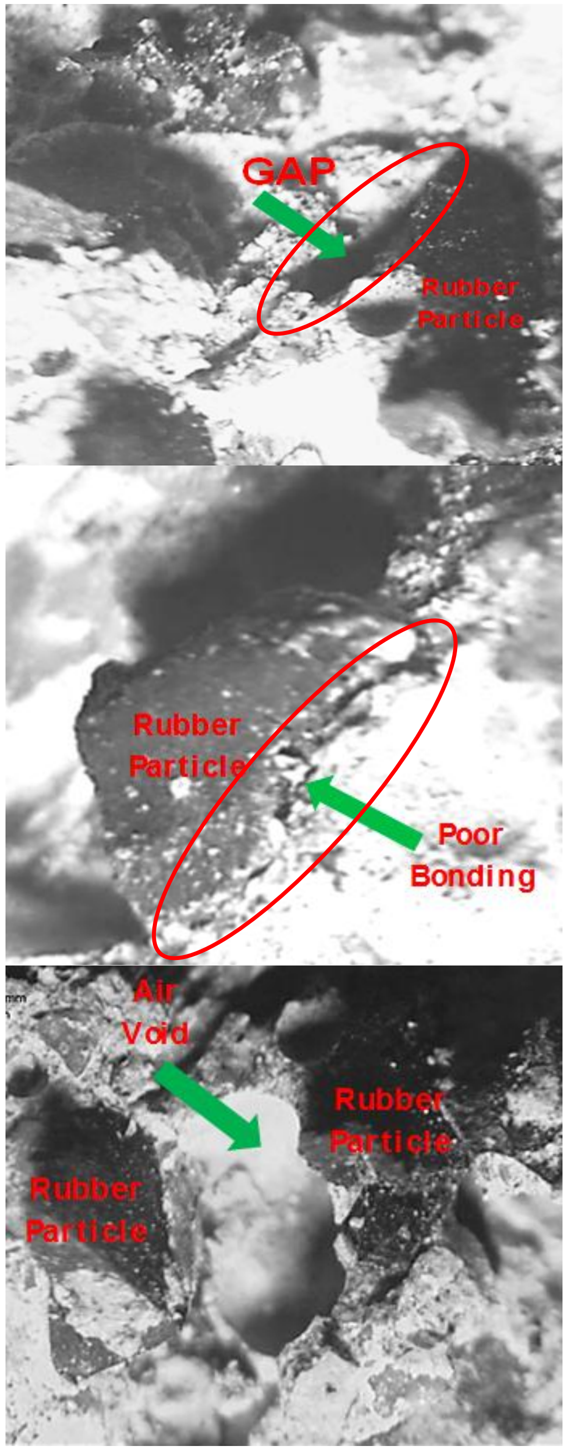


Figure 4.7 Typical optical microscopy image of rubber-cement interface (a) rubber-cement discontinuity, (b) poor bonding between rubber aggregate and mortar, (c) tendency of rubber to entrap air

4.3.2 Splitting Tensile Strength

The results of STS generally have a trend similar to that of the compressive strengths. As shown in **Table 4.2** and **Figure 4.8a**, the STS decreased as a function of the increase in the CR replacement (mixtures 1-8). Increasing the percentage of CR from 0% to 40% reduced the 7- and 28-day STS by 46.8% and 56.6%, respectively. SCRC mixtures with 15% CR (mixtures 4), which contained the maximum percentage of CR for mixtures without SCMs (see **Table 4.5**), showed reductions of 12.3% and 19.8% in the 7- and 28-day STS, respectively. This reduction may be attributed to the same reasons for the reduction of compressive strength with increased percentage of CR.

Looking at mixtures 9, 10 and 11 (**Table 4.2** and **Figure 4.8b**), it can be seen that increasing the binder content from 500 kg/m^3 to 550 kg/m^3 slightly raised the 7- and 28-day STS of these mixtures by an average of 7% compared to mixtures 5, 7, and 8 (with 500 kg/m^3 of binder content). Using MK also showed a positive impact on enhancing the STS of SCRC mixtures. Adding 20% MK in mixtures 12–14 increased the 7- and 28-day STS by an average of 18.5% and 17%, respectively, compared to the reference mixtures (mixtures 9–11) (see **Table 4.2** and **Figure 4.8c**). On the other hand, using GGBS and FA (mixtures 16–21) showed a slight increase in the 28-day STS of around 5.4% and 3% (on average), respectively, compared to the reference mixtures (mixtures 9–11) (see **Table 4.2** and **Figure 4.8c**). SCRC mixtures with 30% CR, which contained the maximum percentage of CR that can be used successfully with MK (see **Table 4.5**), showed an increase of 14.75% and 13% in the 7- and 28-day STS, respectively, compared to the mixture with no SCMs (mixture 10).

Table 4.2 and **Figure 4.8d** show that as the coarse aggregate size increased from 10 mm to 20 mm the 7- and 28-day STS slightly decreased by an average of 2% and 4.4% (mixtures 22-24 compared to mixtures 13-15). The reduction was more pronounced by inclusion of entrained air, in which the 7- and 28-day STS decreased by an average of 19.6% and 15%, respectively, (mixtures 25-27 compared to mixtures 13-15).

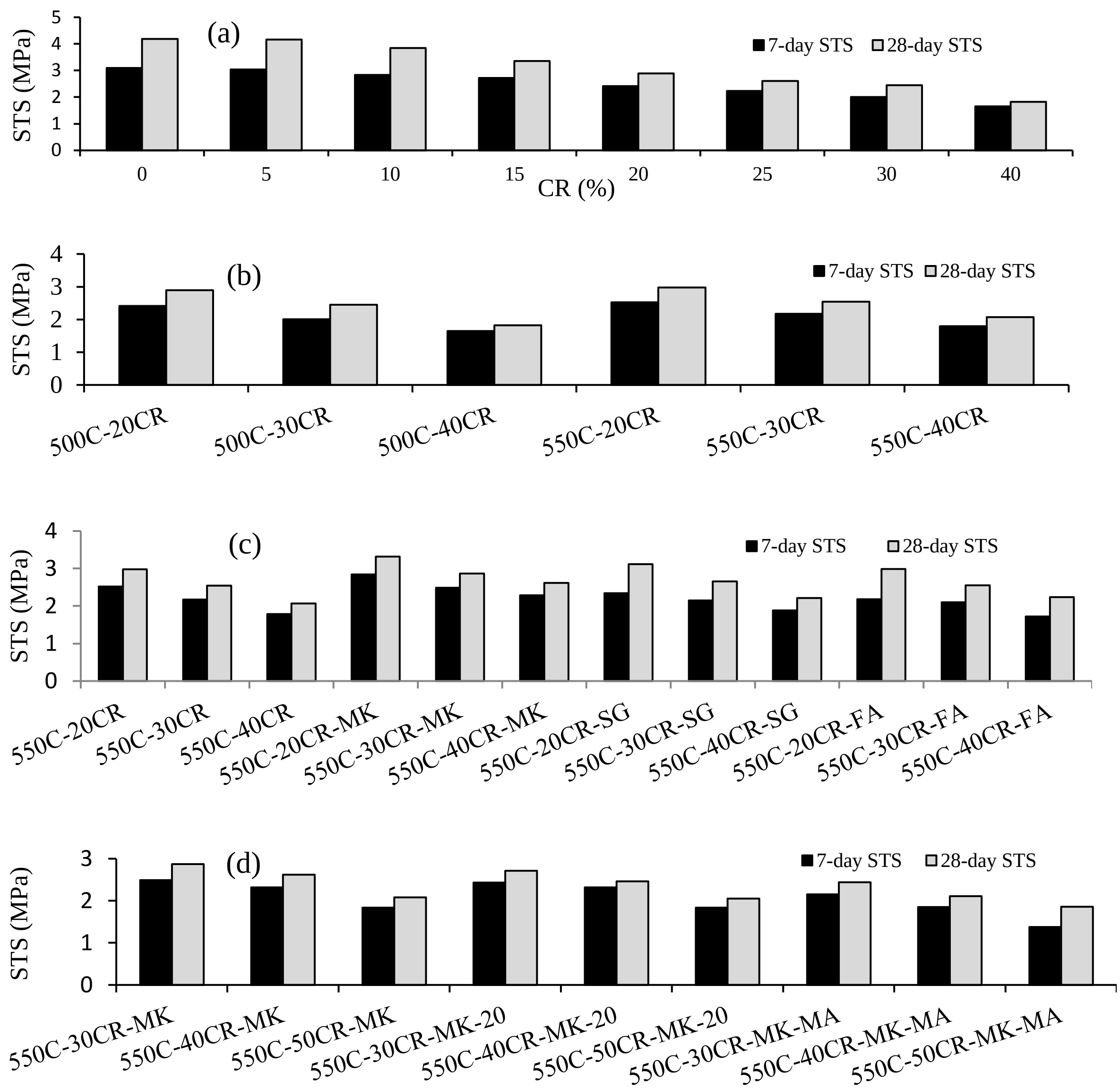


Figure 4.8 Splitting tensile strength of the tested SCRC mixtures: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

4.3.3 Flexural Strength

Table 4.2 and **Figure 4.9** show the four-point flexural strength test results for all tested mixtures, which follow the behaviour of the compressive strength results against the tested parameters. The addition of 40% CR (mixtures 1-8) decreased the 7- and 28-day FS by 45.7% and 41.3%, respectively (**Table 4.2** and **Figure 4.9a)**. Also, the addition of 15% CR in 500C-15CR (the most successful SCRC with a maximum percentage of CR in mixtures without SCMs (see **Table 4.5**)) reduced the 7- and 28-day FS by 14.8% and 13.3%, respectively. The reduction of the ultimate flexural load with increasing the percentage of CR can be explained by the same reasons related to the reduction of the compressive strength and STS, as mentioned above.

Table 4.2 and **Figure 4.9b** indicate that increasing the binder content from 500 kg/m^3 to 550 kg/m^3 (mixtures 9, 10, and 11compared to mixtures 5, 7, and 8, respectively) improved the 7- and 28-day FS by an average of 9.5% and 10%, respectively. Also, increasing the binder content to 550 kg/m^3 increased the 7- and 28-day FS of mixture 550C-20CR (the mixture with the maximum CR percentage when using 550 kg/m^3 of binder (see **Table 4.5**)) by 6.9% and 7.5%, respectively.

The results of the MK mixtures (mixtures 12–14) showed an enhancement in the 7- and 28-day FS of 20.94% and 14.6% (on average), respectively, compared to the reference mixtures (mixtures 9–11). Using 30% GGBS (mixtures 16–18) showed a slight increase in the 28-day FS of around 5.1% (on average) compared to the reference mixtures 9–11 (see **Table 4.2** and **Figure 4.9c**). On the other hand, incorporating 20% FA (mixtures 19–21) showed similar results to those of the reference mixtures (9–11) at 28 days. **Table 4.2** also shows that SCRC mixtures with 30% CR (the most successful SCRC with the maximum CR percentage in MK mixtures (see **Table 4.5**)) had higher values for the 7- and 28-day FS of around 15% compared to mixture 10 (550C-30CR).

As shown in **Table 4.2** and **Figure 4.9d**, the 7- and 28-day FS decreased by an average of 11.3% and 5.2%, respectively, when the coarse aggregate size increased from 10 mm to 20 mm. These reductions reached up to 25.6% and 22.6%, respectively when the entrained air was added.

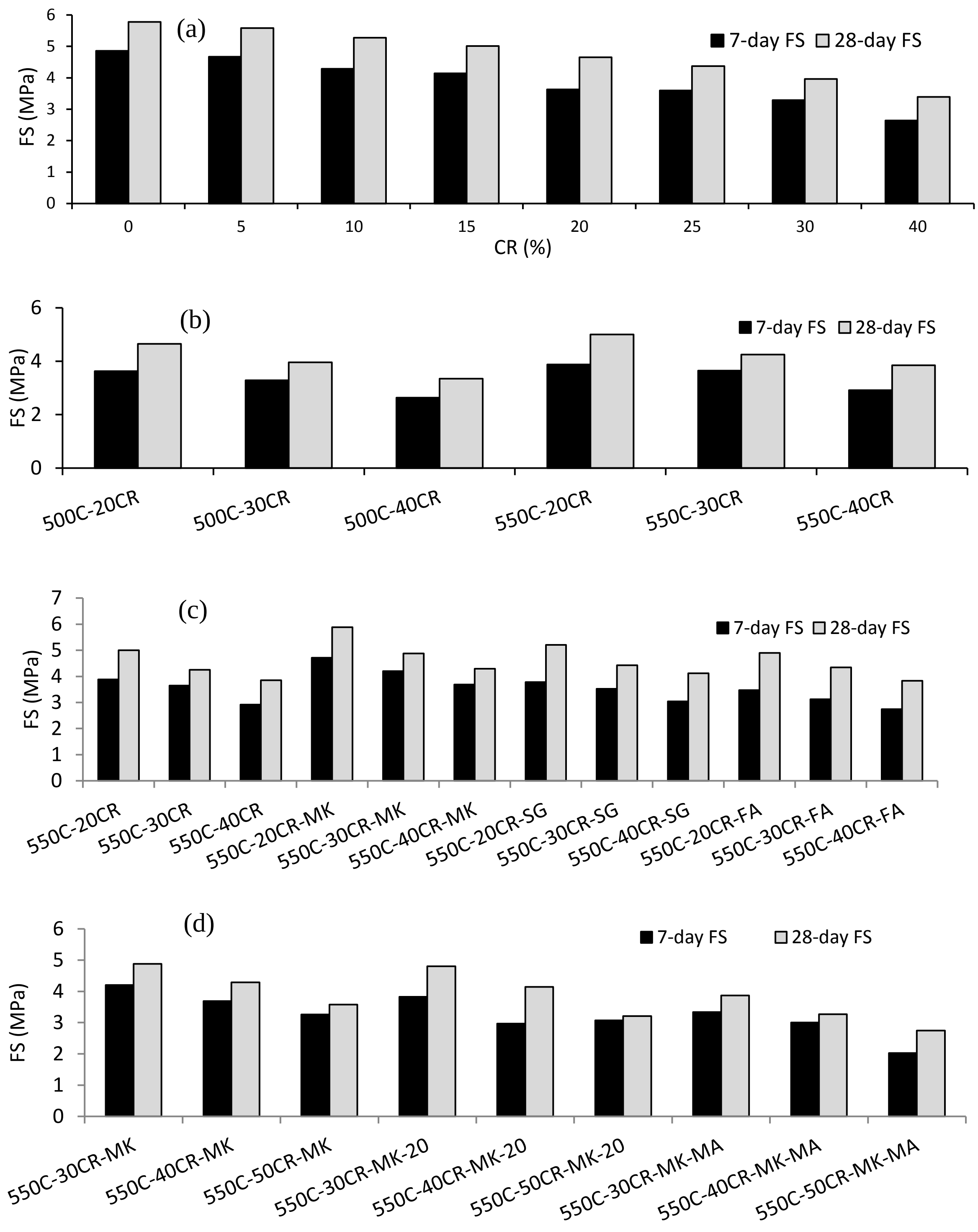


Figure 4.9 Flexural strength of the tested SCRC mixtures: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

4.3.4 Modulus of Elasticity

As seen in **Table 4.2** and **Figure 4.10a** (mixtures 1–8), the ME decreased as the percentage of CR increased in SCRC mixtures. The ME decreased by 6.25% at 5% CR, while at 40% CR the reduction was as much as 53.9%. Mixture 500C-15CR (mixture 4) which is considered the most successful SCRC mixture (with no SCMs) with the highest percentage of CR (15%) (see **Table 4.5**) showed 18% reduction in the ME compared to the control mixture (0% CR). Generally, the ME of SCRC as a composite material is directly related to the stiffness of the aggregates, cement paste, and their bond structure (Evangelista and de Brito, 2006). Therefore, replacing the conventional fine aggregate with a lower-stiffness material such as CR can definitely decrease the overall stiffness/ME of concrete composite. Moreover, the poor strength of the ITZ in mixtures with CR may have encouraged precocious cracking under loading, which could also have reduced the ME.

Improving the strength of cement paste and ITZ due to inclusion of higher binder content and/or MK led to increasing the ME of mixtures similar to the compressive strength. The 28-day ME increased by an average of 10.4% as the binder content increased from 500 kg/m^3 to 550 kg/m^3 (see **Table 4.2** and **Figure 4.10b**, mixture 5, 7, and 8 vs. mixture 9, 10, and 11, respectively). Mixture 550C-20CR (mixture 9), which had the maximum CR percentage in mixtures with 550 kg/m^3 of binder and no SCMs (see **Table 4.5**), also showed an improvement of 4.15% in the 28-day ME when the binder content increased from 500 kg/m^3 to 550 kg/m^3. The results also showed that the inclusion of MK increased the 28-day ME by an average of 24.9%, while the inclusion of GGBS and FA increased the 28-day ME by an average of 5% compared to the reference mixtures (9–11) (see **Table 4.2** and

Figure 4.10c). Mixture 550C-30CR-MK (mixture 13), which had the maximum CR percentage when using MK in SCRC mixtures (see **Table 4.5**), showed an increase of 19.15% in the 28-day ME compared to the mixture with no SCMs (mixture 10).

As shown in **Table 4.2** and **Figure 4.10d**, the 28-day ME decreased by an average of 5.5% and 14.1% when the larger coarse aggregate and entrained air were used, respectively.

4.3.5 Failure mode

All tested samples showed more ductile failure as the percentage of CR increased in the mixture. Increasing the percentage of CR raised the ductility of SCRC and VRC mixtures, which changed the common behaviour of concrete at ultimate loading to non-brittle failure. In addition, CR particles made the failed samples appear to be more cohesive without a noticeable distortion compared to the control mixture (CR% = 0) (see **Figure 4.11**). From **Figure 4.11a**, it can be observed that the compressive strength samples of the control mixture were destroyed with a significant spalling. The splitting tensile strength samples of this mixture were also completely splintered into two halves at the ultimate splitting load. On the other hand, cylinders with CR showed a better geometrical shape with insignificant spalling, very fine cracks, and no splintering/spalling at the ultimate compressive and/or tensile loading (**Figure 4.11b**). This effect was also observed in flexure samples with CR; the failed prisms were not completely broken, but they had a major flexural crack with an average width of 0.5 mm (see **Figure 4.11c** vs **Figure 4.11d**) and the crack width decreased as the CR replacement increased.

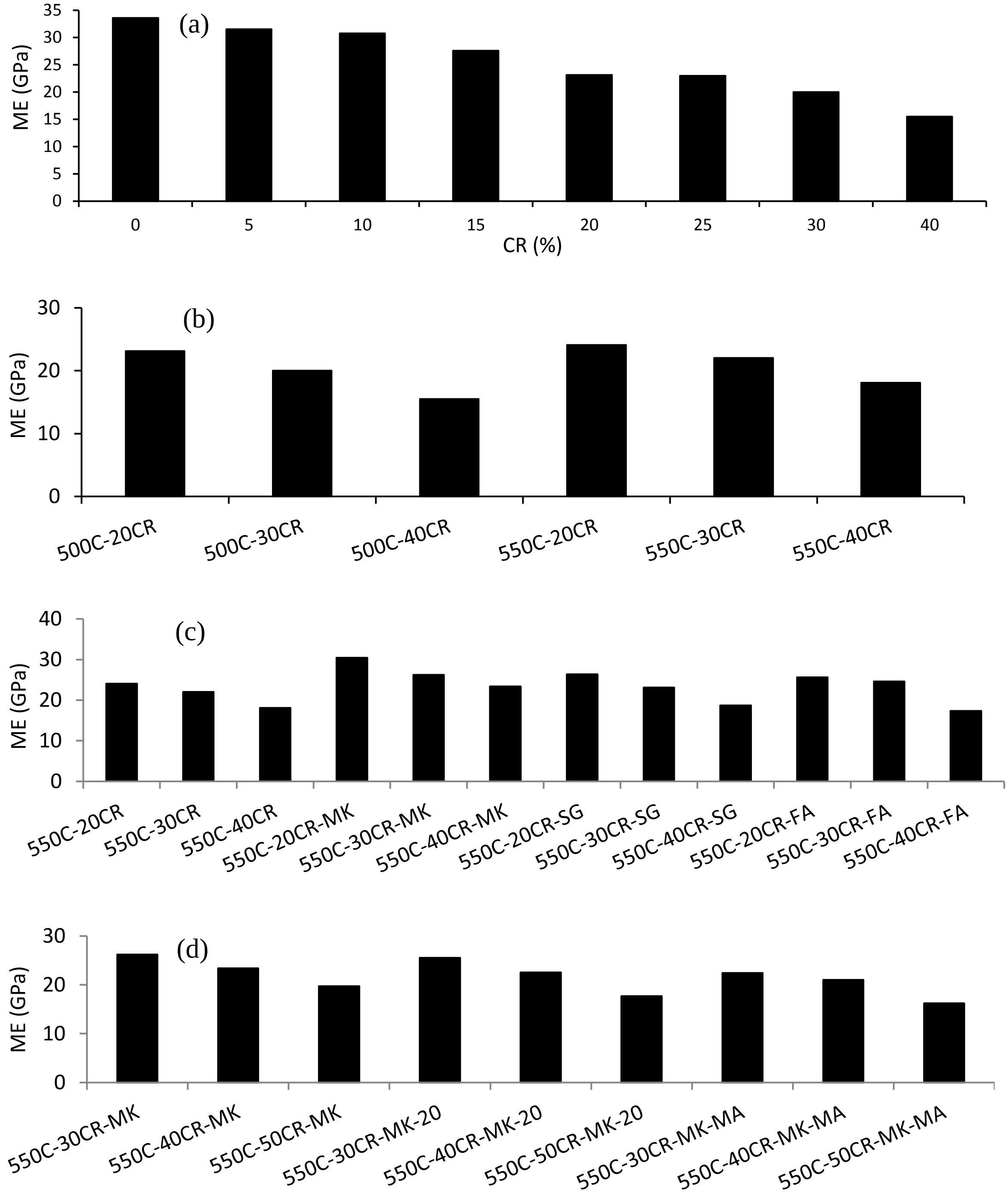


Figure 4.10 Modulus of elasticity of the tested SCRC mixtures: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

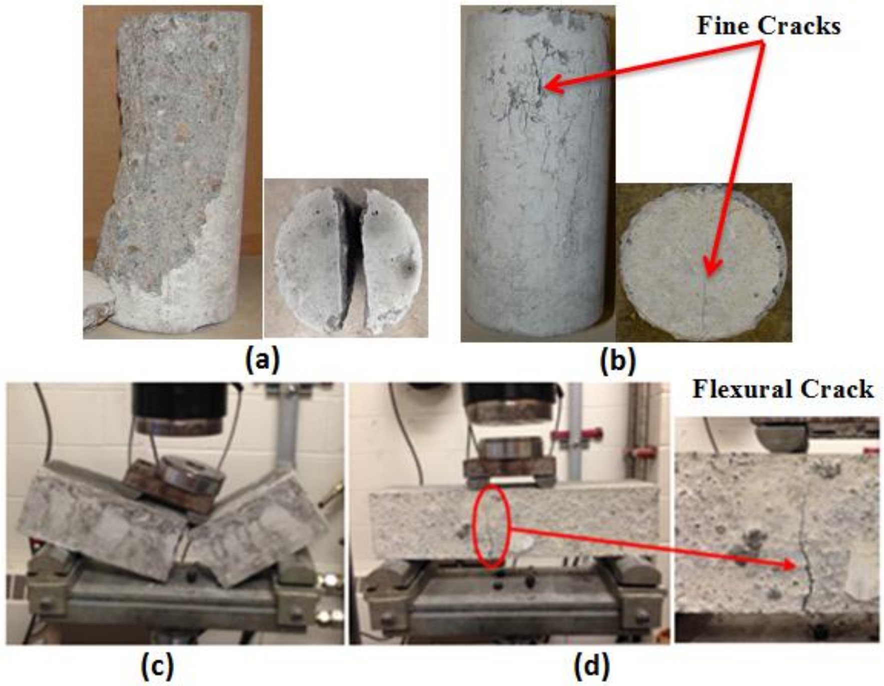


Figure 4.11 Failure pattern of tested samples: (a) control mixture (0% CR) in compressive and STS tests, (b) typical failure mode for mixtures with CR in compressive and STS tests, (c) control mixture (0% CR) in FS test, (d) typical failure mode for mixtures with CR in FS test

4.4 Impact Resistance of SCRC Under Drop-Weight Test

The results of impact resistance under the drop-weight test for all tested mixtures are presented in **Table 4.3** and **Figure 4.12**. It can be observed that using CR showed a general improvement in the impact resistance in terms of numbers of blows required to produce the first visible crack (N_1) and ultimate failure (N_2) of the specimen. The results of mixtures 1–8 (mixtures with 500 kg/m^3 binder and no SCMs) showed that increasing the percentage of CR significantly enhanced the impact resistance up to a replacement level of 30%, in which varying the percentage of CR from 0% to 30% increased N_1 and N_2 by 2.93 and 3 times, respectively, compared to the control mixture (CR= 0%) (**Table 4.3** and **Figure 4.12a**).

Further increase in the percentage of CR (more than 30%) resulted in a lower enhancement in the impact resistance, in which using 40% CR increased N_1 and N_2 by 2.55 and 2.6 times, respectively, compared to the control mixture. Incorporating 15% CR (which is the maximum successful percentage with 500 kg/m^3 of binder content and no SCMs (see **Table 4.5**)) showed an increase in N_1 and N_2 reaching up to 1.97 and 2 times, respectively, higher than the control mixture (500C-0CR). Mixtures 1–8 also show that increasing the CR content had an effect on delaying the crack propagation; the difference between the number of blows for ultimate failure and first crack ($N_2 - N_1$) increased as the percentage of CR increased (**Table 4.3**). This finding indicates a decrease in the brittleness of SCRC mixtures with higher percentages of CR. However, as reported by Reda Taha et al. (2008) who investigated the impact resistance of vibrated concrete containing CR and chipped rubber, using very high rubber content can adversely affect the ductility and energy absorption of the mixture. Very high rubber content can weaken the rubber-cement paste as high strains are generated under loading, which limits the ability of material to absorb energy. In addition, increasing the CR replacement increased the volume of the rubber-cement interface (which was the weakest part in the mixture).

In mixtures with 550 kg/m^3 binder content (mixtures 9-11), increasing the percentage of CR from 20% to 40% showed a trend of results similar to that obtained in mixtures 1-8, in which N_1 and N_2 reached to their maximum values at replacement level of 30%. Mixtures 9, 10 and 11 compared to mixtures 5, 7, and 8 also indicated that increasing the binder content from 500 kg/m^3 to 550 kg/m^3 raised N_1 and N_2 by an average of 5.8% and 4.7%, respectively (see **Table 4.3** and **Figure 4.12b**). SCRC mixtures with 20% CR (which contained the maximum percentage of CR that can be used successfully with 550 kg/m^3 binder content (see **Table 4.5**)) showed a 7% and 5.4% increase in the ultimate absorbed energy of the first and failure crack, respectively.

As shown in **Table 4.3** and **Figure 4.12c,** the results of mixtures 12–15 indicate that the highest improvement in both N_1 and N_2 was found at the addition of 30% CR. Increasing the percentage of CR up to 40% decreased both N_1 and N_2 by 6.3% and 7%, respectively, compared to their values in mixture with 30% CR (mixture 13), while this reduction in N_1 and N_2 reached up to 15.7% and 16.2%, respectively, when 50% CR was used (mixture 15). The results of mixtures 12-14 compared to mixtures 9–11 also showed that using MK can increase the number of blows to produce the initial visible crack and the failure crack by an average of 10.8% and 10%, respectively. Mixture 550C-30CR-MK, which was the most successful SCRC mixture incorporating SCMs (see **Table 4.5**), showed an ultimate absorbed energy of 7.6% higher than a similar mixture without MK (550C-30CR). The results also indicated that using GGBS or FA did not show significant changes in the impact resistance of the tested mixtures; in the meantime, the inclusion of 30% CR appeared to be the optimal replacement level for achieving the highest impact resistance in both GGBS and FA mixtures.

Looking at mixtures 22, 23, and 24 compared to mixtures 13, 14, and 15, respectively, illustrate that increasing the aggregate size from 10 mm to 20 mm reduced the impact resistance of the tested specimens (**Table 4.3** and **Figure 4.12d**). The results showed a reduction in N_1 and N_2 by an average of 7.9% and 9.4%, respectively. This result could be related to increasing volume of the ITZ with larger aggregate size (20 mm) (Koehler and Fowler, 2007), which can have a negative effect on the mechanical properties of the mixture (as explained earlier). **Table 4.3** and **Figure 4.12d** also show that the impact resistance decreased as the air content increased, as shown in mixtures 25–27 compared to the mixtures 13–15. Using entrained air decreased the values of N_1 and N_2 by 13.3% and 14.6% (on average), respectively. By examining mixtures 22-24 and mixtures 25-27, it can be seen that as the percentage of CR increased from 30% to 50% the impact resistance of mixtures exhibited a decreasing trend, confirming the adverse effects of using high contents of rubber on the ability of concrete composite to absorb energy, as explained earlier. However up to 50%, mixtures showed a strong potential for structural applications subjected repeated impact loads.

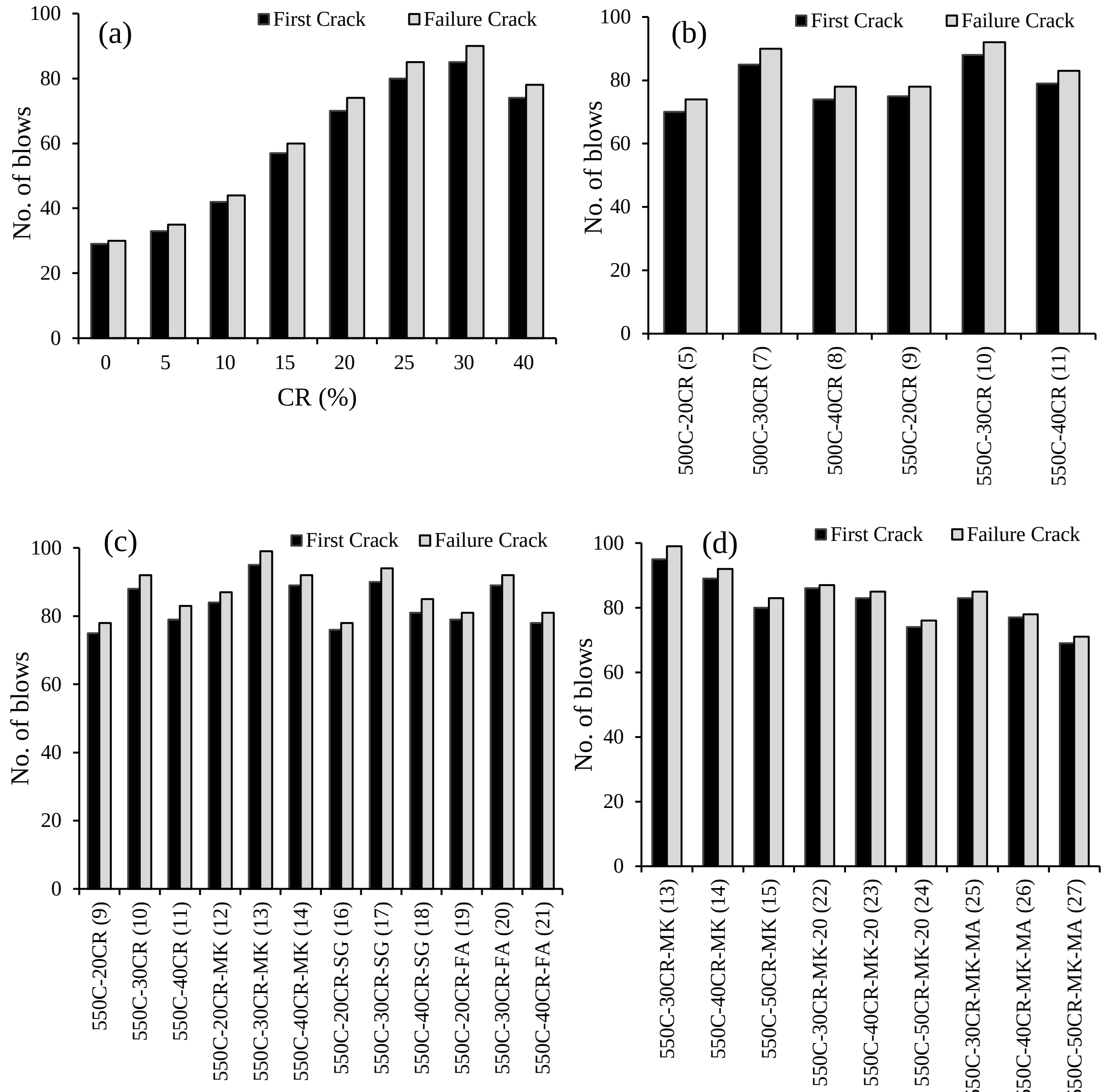


Figure 4.12 Results of impact resistance for SCRC mixtures under drop-weight test: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

4.5 Impact Resistance of SCRC Under Flexural Loading

Table 4.3 and **Figure 4.13** show the results of impact resistance at failure under flexural loading for all tested mixtures. It can be observed that the addition of CR helped to improve the ultimate impact energy. Mixtures 1–8 showed that a replacement level of 20% exhibited the highest improvement in terms of the ultimate absorbed energy of tested beams (**Table 4.3** and **Figure 4.13a**). Increasing the percentage of CR from 0% to 20% increased the impact energy at failure by 87.4%. Further increase in the rubber contents beyond this level showed a reduction in the ultimate impact energy of SCRC beams. However, even with these relatively high rubber contents, the ultimate impact energy is still higher than that of concrete with no CR. For example, using 25%, 30%, and 40% CR showed improvements of 50%, 25%, and 12.4%, respectively, higher than that obtained by the control beam (CR = 0). The mixture with 15% CR (which is the maximum percentage that can be used with a 500 kg/m^3 binder and no SCMs (see **Table 4.5**)) showed an increase in the ultimate impact energy, reaching up to 74.8%, compared to the control mixture (500C-0CR). This increase may be resulted from using the low-stiffness component such as CR, which increased the flexibility of the rubber-cement composite, and thus absorbs an amount of energy. It should be noted that since the flexural-loading test is more affected by the ITZ compared to the cylindrical specimens under the drop-weight test, the results of tested beams showed a lower optimum CR replacement level (20%) compared to the cylindrical specimens under the drop-weight test (30%).

Similarly, the results of mixtures 9-11 and 12-14 also show that replacing higher than 20% of fine aggregate by CR led to a reduction in the ultimate impact energy (**Table 4.3**, **Figure 4.13b**, and **Figure 4.13c**). Increasing the percentage of CR from 20% to 40% decreased the ultimate impact energy by 37.4% in mixtures 9-11 and 38.9% in mixtures 12-14. Comparing mixtures 9, 10, and 11 to mixtures 5, 7, and 8 (**Table 4.3** and **Figure 4.13b**), it can be seen that increasing the binder content from 500 kg/m^3 to 550 kg/m^3 increased the ultimate impact energy by an average of 9.3%. SCRC mixtures with 20% CR (which contained the maximum percentage of CR that can be used successfully with 550 kg/m^3 binder content (see **Table 4.5**)) showed an increase of 6.6% in the absorbed impact energy. Also, by comparing mixtures 12, 13, and 14 to mixtures 9, 10, and 11, respectively, it can be seen that using MK improved the impact energy (**Table 4.3** and **Figure 4.13c**). Mixture 550C-30CR-MK, which represents the most successful SCRC mixture incorporating SCMs (see **Table 4.5**), showed an enhancement in the energy absorption of 18.2%, compared to its counterpart mixture without MK (550C-30CR).

Increasing the percentage of CR from 30% to 50% in mixtures 22-24 and 25-27 decreased the ultimate impact energy by 27.2% and 20%, respectively. Comparing mixtures 22, 23, and 24 to mixtures 13, 14, and 15, respectively, it can be observed that the impact resistance under flexural loading of the tested specimens decreased when the aggregate size increased from 10 mm to 20 mm (**Table 4.3** and **Figure 4.13d**). Also, mixtures 25–27 showed a similar behaviour of the ultimate impact resistance under flexural loading, in which the impact resistance decreased as the air content increased.

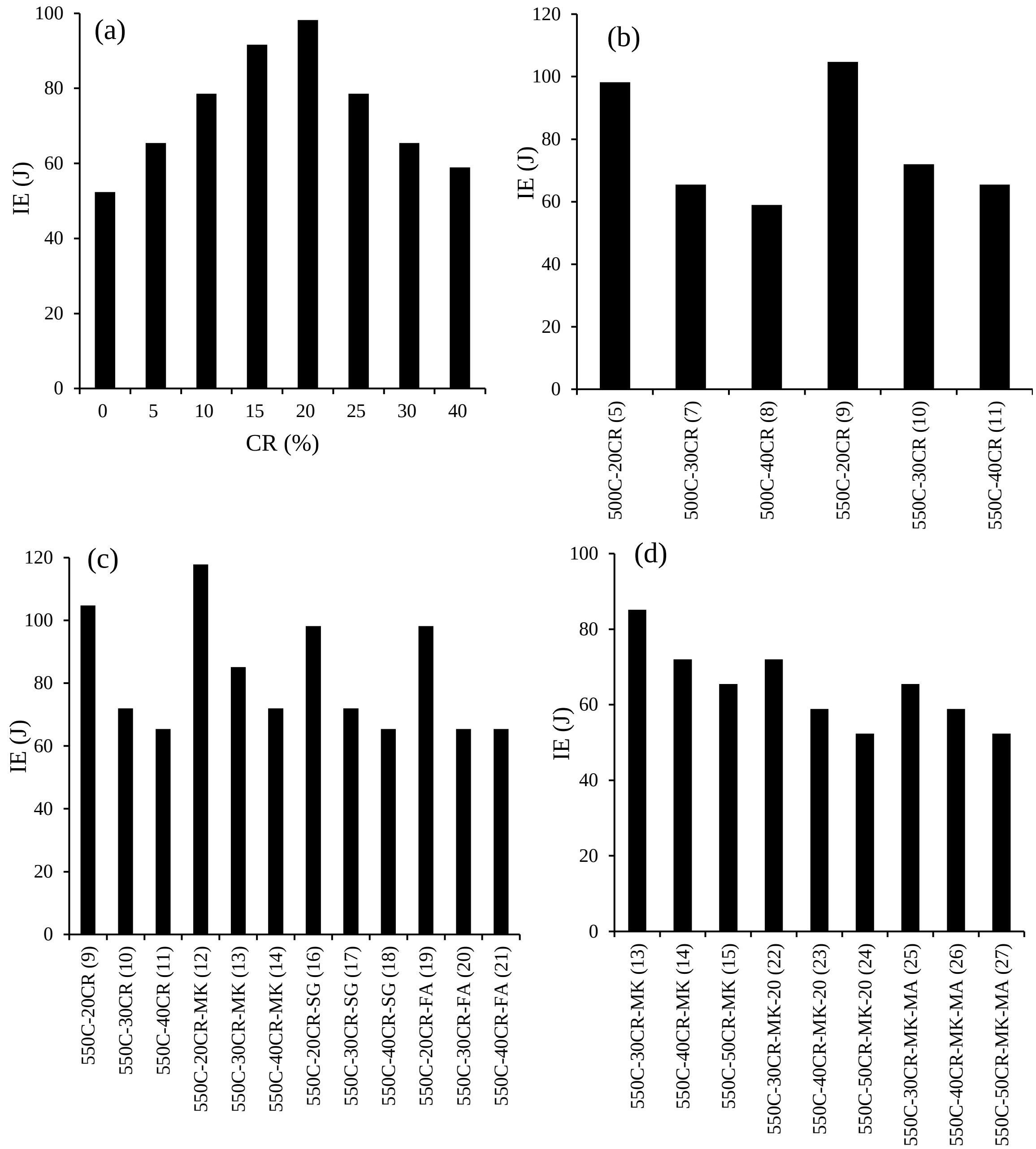


Figure 4.13 Results of impact energy for SCRC mixtures under flexural loading: (a) effect of CR, (b) effect of binder content, (c) effect of SCMs, (d) effect of aggregate size and entrained air

4.6 Ultrasonic Pulse Velocity (UPV)

Figure 4.14 presents the variation of UPV with changing levels of compressive strength, while **Table 4.4** and **Figure 4.15** summarize the measured values of UPV for all tested mixtures. The UPV showed a linear trend of reduction with decreasing levels of the compressive strength, as expected. On the other hand, the results showed that the values of UPV decreased with increased CR content. For example, as shown in mixtures 1–8, at 28 days, varying the CR replacement from 0% to 40% decreased the UPV from 4656 to 3092 m/s. This observation could be attributed to the influence of rubber particles on transmitting the ultrasonic waves. Benazzouk et al. (2007) reported that the velocity of ultrasonic waves in rubber is over 21 times less than that in cement paste. In addition, increasing the air content with higher CR replacement could also contribute to reducing the UPV. Similar behaviour can be observed in the results of mixtures 9-11, 12-15, 16-18, 19-21, 22-24, and 25-27, in which the UPV values decreased as the percentage of CR increased. However, using higher binder content in mixtures 9–11 and/or adding MK in mixtures 12–14 appeared to cause a slight increase in the UPV compared to mixtures 5, 7, and 8. This finding may be related to the improved microstructure of mixtures 9–14, which became denser due to increasing the hydration products in the concrete matrix. Another reason is that the measured air content was lower in mixtures with higher binder content or/and MK, and this lower air content could have reduced the dissipation of the wave velocity through the concrete. Similar behaviour was found in mixtures with entrained air admixtures, in which increasing the air content led to decreasing the UPV (mixtures 25–27 compared to

13–15). By comparing mixtures 22–24 to mixtures 13–15, it can be seen that increasing the aggregate size from 10 mm to 20 mm had an insignificant effect on the UPV.

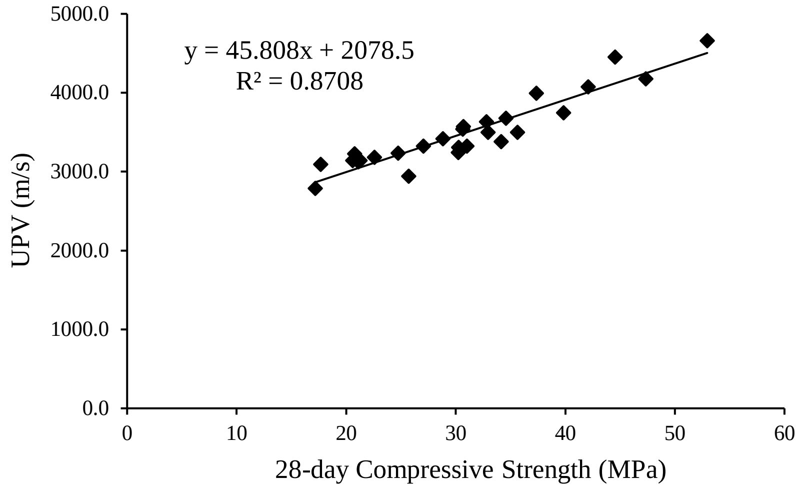


Figure 4.14 Relationship between UPV and 28-day compressive strength

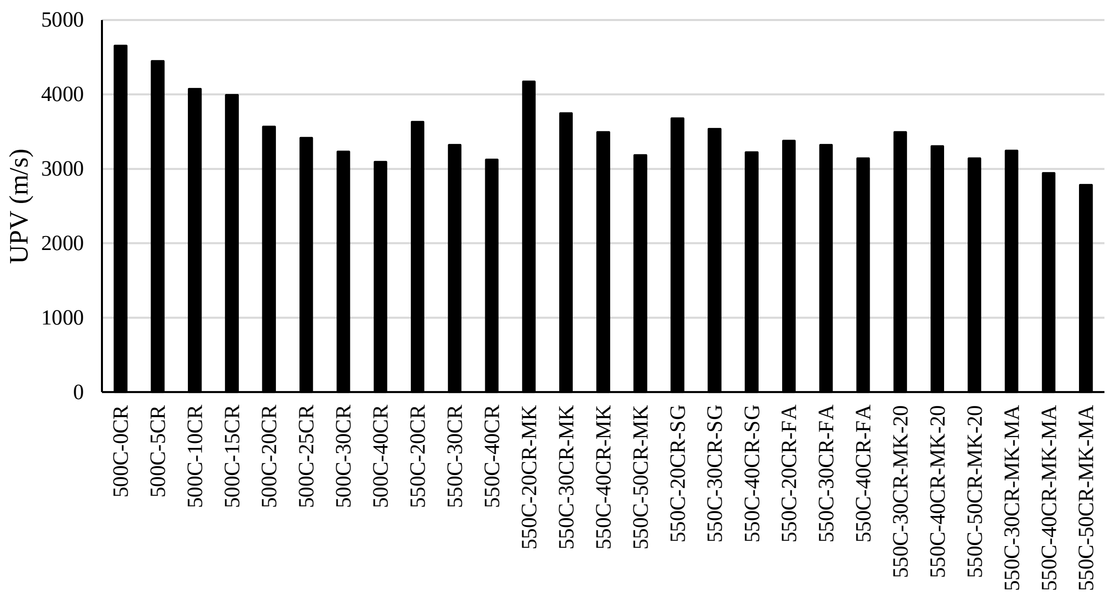


Figure 4.15 UPV of tested mixtures

4.7 Evaluation of Acoustic Properties of Developed Mixtures Using AE Technique

Table 4.4 and **Figure 4.16** show the signal strength and signal energy of all tested mixtures measured by AE technique. It can be seen that increasing the CR replacement level showed a general reduction in the signal strength and energy of all tested mixtures. For instance, in mixtures 1–8 varying the CR from 0% to 40% reduced the signal strength and energy by 35.7%. This finding reflects that incorporating CR in concrete can contribute to the wave attenuation that yields lower values of signal strength and energy. This wave attenuation could be attributed to the reduction of signal amplitude of AE waves as a result of scattering and reflections (Ervin, 2007). As explained earlier, increasing the CR content tends to increase the air content in the mixture, which also could contribute to the wave attenuation. Generally, the reduction of signal strength and signal energy with higher percentages of CR proves the ability of CR to enhance the acoustic absorption of concrete, which provides a promising potential for use in applications of a high level of sound insulation (Benazzouk et al., 2007). The addition of 15% CR (which is the maximum percentage that can be used with a 500 kg/m^3 binder and no SCMs (see **Table 4.5**)) reduced the signal strength and energy by 14.2% compared to the control mixture (500C-0CR).

As explained, increasing the percentage of CR Mixtures with binder content of 550 kg/m^3 (mixtures 9–11) and/or mixtures with MK (mixtures 12–14) showed lower levels of wave attenuation where the AE sensor recorded a slightly higher signal strength and energy compared to mixtures with 500 kg/m^3 binder content and no MK (mixtures 5, 7, and 8). This behaviour reflects that increasing the binder content and/or the addition of MK can contribute to enhancing the acoustic properties of concrete. On the other hand, using GGBS or FA in SCRC mixtures (mixtures 16–21) did not confirm any change in the acoustic properties of the mixtures.

Comparing mixtures 22–24 to mixtures 13–15 shows that the signal strength and energy reduced slightly when the aggregate size increased from 10 mm to 20 mm. Also, comparing mixtures 25–27 to mixtures 13-15 showed that using entrained air increased the wave attenuation, thus reducing the signal strength and energy.

Figure 4.17 shows the relationships between signal strength/signal energy and the 28-day compressive strength for all tested mixtures. It is clear from the figure that the compressive strength can be correlated to each of the signal strength and signal energy. It is also obvious from the figure that increasing the compressive strength of the mixture resulted in a higher acoustic connectivity.

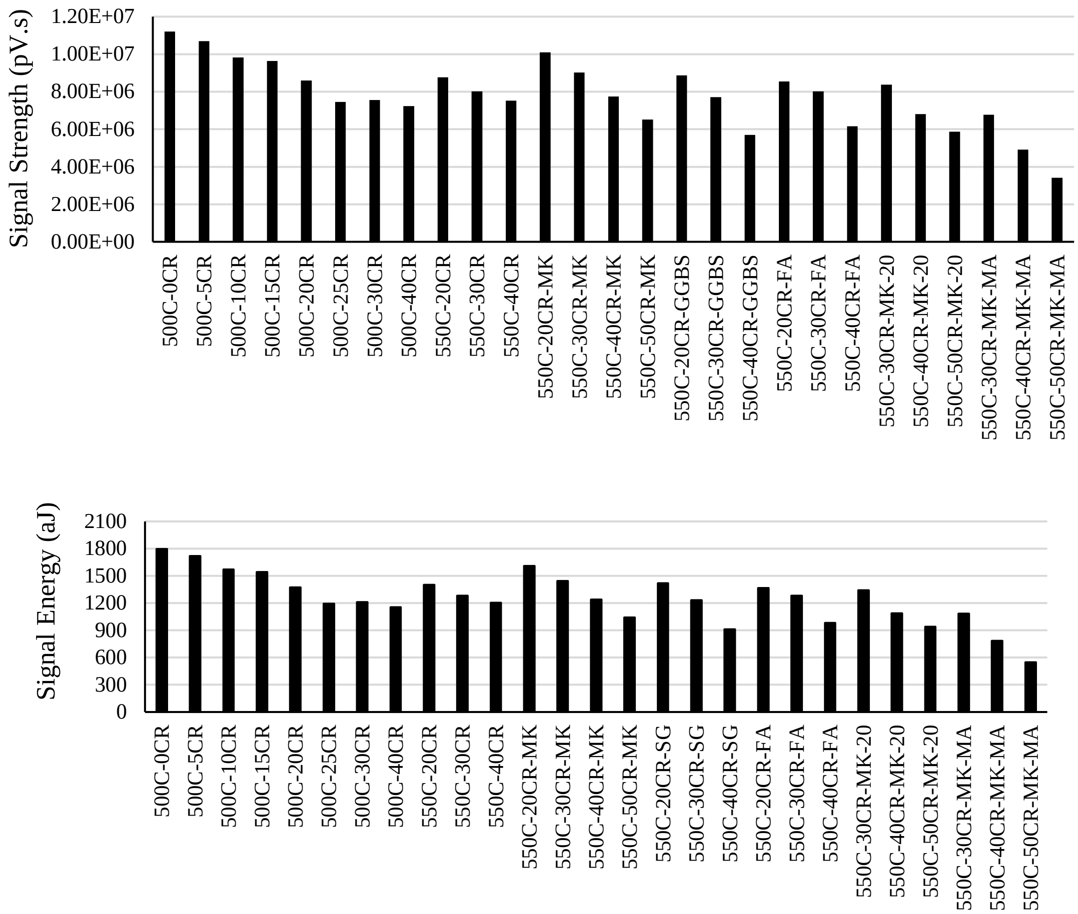


Figure 4.16 Signal strength and signal energy of tested mixtures

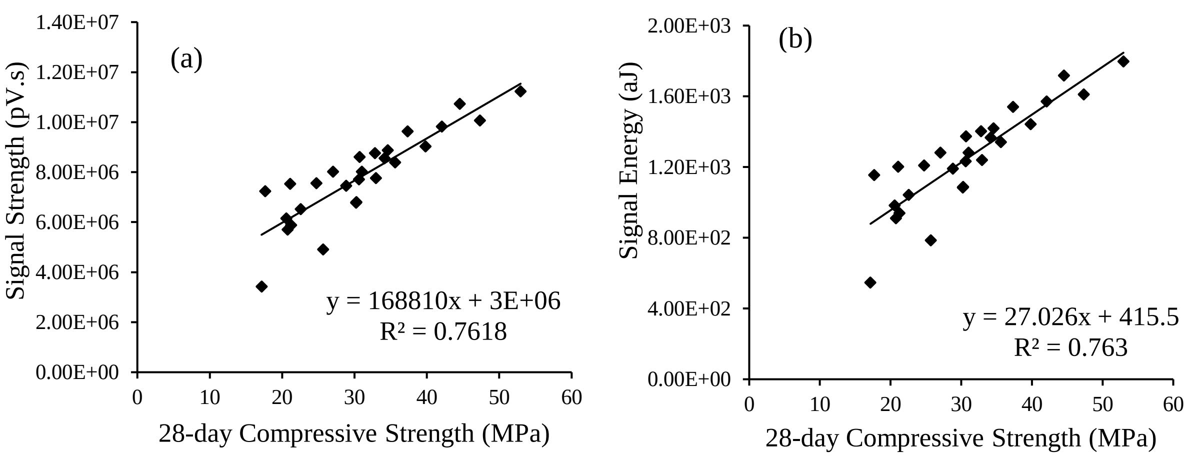


Figure 4.17 Relationship between 28-day compressive strength and (a) signal strength, (b) signal energy

4.8 Evaluation of Using CR in SCC

As seen from the above results, SCRC has a beneficial effect in reducing the self-weight of concrete structure and therefore it is recommended in developing lightweight or semi-lightweight concrete mixtures. This is in addition to the promising potentials of such concrete in applications involving high impact resistance, energy dissipation, and sound absorption. On the other hand, the addition of CR proved to reduce the compressive strength, STS, FS, and fresh properties of SCC mixture. This reduction appeared to be alleviated when using MK and/or higher binder content in the mixture. Therefore, the practitioner should account for the increased cost of the cubic meter of SCRC mixture before making a decision of using this concrete in a specific application.

5. Discussion of Results from Experimental Study 2: Use of SFs to Optimize SCC Mixtures Containing CR (Development of SFSCRC)

5.1 Introduction

The results obtained from the experimental work of the study 2 are presented and discussed in this chapter. Because of the limited information regarding the optimization and development of SFSCRC, the main objective of this study was to exploit the beneficial effect of SFs to develop and optimize SFSCRC mixtures with maximum percentages of CR, acceptable fresh properties, improved STS, FS, and impact resistance. The investigation also included the development of SFVRC for comparison. The experimental test parameters included different percentages of CR (0-40%), binder contents (550-600 kg/m^3), SF volume fractions (0.35-1%), and SF sizes (35 and 60 mm). The results obtained from the fresh and mechanical tests are presented in **Tables 5.1** and **5.2**, respectively. The results of impact resistance under the drop-weight and the flexural loading test for all tested mixtures are listed in **Table 5.3**.

Table 5.1 Fresh properties of tested mixtures (study 2)

Mixture #		Mixture designation	T_{50} (sec)	T_{50J} (sec)	Slump–J-ring (mm)	L-box H2/H1	V-funnel T_0 (sec)	SR %	Air %	Density (kg/m^3)	HRWR (L/m^3)
Stage 1: Effect of increasing the CR content	1	550C-0CR	1.95	2.34	10	0.91	7.01	2.08	1.5	2246	3.43
	2	550C-5CR	2.39	2.77	15	0.88	8.5	2.71	2	2207	3.43
	3	550C-10CR	2.74	3.17	30	0.84	9.51	3.75	2.72	2163	3.75
	4	550C-15CR	2.96	3.4	40	0.82	10.59	5.83	3.1	2128	3.75
	5	550C-20CR	3.14	3.51	45	0.77	10.97	7.50	3.4	2094	3.75
	6	550C-25CR	3.35	3.88	50	0.77	14.3	8.33	4.6	2041	3.75
	7	550C-30CR	3.76	4.232	70	0.75	17.25	8.33	5	2006	4.38
Stage 2: Effect of using SFs	8	550C-5CR-0.35SF	2.62	3.25	40	0.8	9.75	2.92	2.4	2217	4.63
	9	550C-10CR-0.35SF	3.07	3.66	65	0.78	10.65	4.13	3	2177	4.63
	10	550C-15CR-0.35SF	3.31	4.01	80	0.75	12.05	6.04	3.5	2138	4.63
	11	600C-15CR-0.35SF	2.51	2.9	35	0.85	9.8	2.50	3.8	2108	4
	12	600C-20CR-0.35SF	3.03	3.5	40	0.8	12.5	2.50	4.1	2076	4
	13	600C-25CR-0.35SF	3.51	4.27	75	0.75	14.3	4.79	4.5	2043	4
Stage 3: Effect of changing the volume fraction and size of SFs	14	550C-5CR-0.35LSF	2.74	3.96	100	0.35	12.35	2.08	2.7	2209	4.63
	15	550C-10CR-0.35LSF	3.89	4.69	105	0.25	15.04	3.13	3.4	2167	4.63
	16	550C-15CR-0.35LSF	4.06	5.72	130	0.21	16.59	4.17	4.6	2113	4.63
	17	600C-5CR-0.5SF	2.11	2.65	75	0.65	7.19	2.08	3	2184	4.75
	18	600C-10CR-0.5SF	2.52	3.51	100	0.56	9.5	2.50	4.2	2133	4.75
	19	600C-15CR-0.5SF	2.94	3.85	110	0.43	12.25	3.75	5.1	2088	4.75
Stage 4: Effect of increasing the CR content and SF volume fraction in VRC	20	550C-30CR-VRC	-	-	-	-	-	-	3	2048	3.18
	21	550C-35CR-VRC	-	-	-	-	-	-	3.3	2014	3.18
	22	550C-40CR-VRC	-	-	-	-	-	-	4.2	1968	3.18
	23	550C-35CR-0.35SF -VRC	-	-	-	-	-	-	3	2040	3.64
	24	550C-35CR-0.5SF-VRC	-	-	-	-	-	-	3	2048	3.64
	25	550C-35CR-0.75SF-VRC	-	-	-	-	-	-	2.9	2063	3.64
	26	550C-35CR-1SF-VRC	-	-	-	-	-	-	3.1	2073	3.64

Table 5.2 Mechanical properties of tested mixtures (study 2)

Mixture #	Mixture designation	f'_c (MPa)		STS (MPa)		FS (MPa)		ME (GPa)
		7-day	28-day	7-day	28-day	7-day	28-day	28-day
Stage 1: Effect of increasing the CR content								
1	550C-0CR	60.87	75.65	4.01	4.49	5.08	5.74	29.37
2	550C-5CR	48.90	66.72	3.67	4.29	4.73	5.48	27.54
3	550C-10CR	40.09	53.48	3.23	3.90	4.20	5.12	25.71
4	550C-15CR	35.64	44.77	2.96	3.64	3.99	4.82	24.66
5	550C-20CR	31.48	38.40	2.71	3.41	3.64	4.57	21.97
6	550C-25CR	27.57	36.77	2.33	3.00	3.33	4.27	20.02
7	550C-30CR	26.46	31.86	2.20	2.68	3.11	3.92	18.70
Stage 2: Effect of using SFs								
8	550C-5CR-0.35SF	50.46	67.56	4.49	5.27	5.60	6.71	27.95
9	550C-10CR-0.35SF	40.48	54.25	3.97	4.66	5.06	6.11	26.65
10	550C-15CR-0.35SF	35.59	44.94	3.63	4.34	4.61	5.63	25.96
11	600C-15CR-0.35SF	37.12	47.06	4.01	4.61	4.90	6.04	26.03
12	600C-20CR-0.35SF	35.20	45.35	3.65	4.34	4.66	5.76	25.30
13	600C-25CR-0.35SF	30.23	39.90	3.32	4.19	4.38	5.17	22.70
Stage 3: Effect of changing the volume fraction and size of SFs								
14	550C-5CR-0.35LSF	48.58	65.14	4.71	5.57	5.92	7.46	25.76
15	550C-10CR-0.35LSF	38.55	52.43	4.22	4.80	5.43	6.69	24.89
16	550C-15CR-0.35LSF	34.92	43.13	3.83	4.54	4.87	6.00	24.33
17	600C-5CR-0.5SF	51.55	68.53	5.73	6.36	6.61	8.18	29.93
18	600C-10CR-0.5SF	41.64	55.24	5.04	5.48	6.01	7.24	27.86
19	600C-15CR-0.5SF	37.59	48.03	4.51	5.05	5.53	6.75	26.20
Stage 4: Effect of increasing the CR content and SF volume fraction in VRC								
20	550C-30CR-VRC	28.22	33.47	2.32	2.77	3.31	4.21	19.89
21	550C-35CR-VRC	24.99	29.11	2.24	2.55	3.15	4.06	16.57
22	550C-40CR-VRC	20.68	24.71	1.92	2.42	2.98	3.80	14.73
23	550C-35CR-0.35SF -VRC	25.17	29.52	2.55	3.16	3.64	4.87	16.66
24	550C-35CR-0.5SF-VRC	25.56	29.71	3.09	3.56	3.89	5.25	16.95
25	550C-35CR-0.75SF-VRC	26.33	30.74	3.34	3.92	4.83	6.30	17.40
26	550C-35CR-1SF-VRC	26.93	31.08	4.04	4.93	5.28	7.13	17.50

Table 5.3 Results of impact resistance of tested mixtures (study 2)

Mixture #		Mixture designation	Drop-Weight Test					Flexural Impact Loading	
			Number of blows			IE (J)		Number of blows	IE (J) Failure
			N_1	N_2	N_2-N_1	Initial	Failure		
Stage 1: Effect of increasing the CR content	1	550C-0CR	141	143	2	2813	2853	76	498
	2	550C-5CR	153	156	3	3052	3112	92	602
	3	550C-10CR	160	163	3	3192	3252	128	838
	4	550C-15CR	185	190	5	3691	3791	153	1002
	5	550C-20CR	203	209	6	4050	4170	174	1139
	6	550C-25CR	241	248	7	4808	4948	184	1207
	7	550C-30CR	267	273	6	5327	5446	164	1074
Stage 2: Effect of using SFs	8	550C-5CR-0.35SF	337	391	54	6723	7800	252	1650
	9	550C-10CR-0.35SF	380	440	60	7581	8778	283	1853
	10	550C-15CR-0.35SF	470	534	64	9377	10653	314	2056
	11	600C-15CR-0.35SF	546	621	75	10893	12389	346	2266
	12	600C-20CR-0.35SF	570	656	86	11372	13087	416	2724
	13	600C-25CR-0.35SF	634	728	94	12648	14524	464	3038
Stage 3: Effect of changing the volume fraction and size of SFs	14	550C-5CR-0.35LSF	434	496	62	8658	9895	288	1886
	15	550C-10CR-0.35LSF	446	524	78	8898	10454	331	2167
	16	550C-15CR-0.35LSF	502	598	96	10015	11930	398	2606
	17	600C-5CR-0.5SF	547	627	80	10913	12509	554	3628
	18	600C-10CR-0.5SF	586	695	109	11691	13865	611	4001
	19	600C-15CR-0.5SF	656	777	121	13087	15501	776	5081
Stage 4: Effect of increasing the CR content and SF volume fraction in VRC	20	550C-30CR-VRC	281	289	8	5606	5766	165	1080
	21	550C-35CR-VRC	262	269	7	5227	5367	160	1048
	22	550C-40CR-VRC	252	259	7	5027	5167	146	956
	23	550C-35CR-0.35SF -VRC	550	606	56	10973	12090	398	2606
	24	550C-35CR-0.5SF-VRC	615	699	84	12269	13950	594	3890
	25	550C-35CR-0.75SF-VRC	788	896	108	15716	17877	863	5651
	26	550C-35CR-1SF-VRC	922	1078	156	18387	21509	1144	7491

5.2 Summary of Fresh Properties of SCRC

Table 5.1 and **Figure 5.1** show the fresh properties of all SCRC tested mixtures (mixtures 1-7). Similar to SCRC mixtures studied in chapter 4 (experimental study 1), increasing the percentage of CR generally appeared to have a negative effect on the fresh properties of all tested SCRC mixtures. As shown in mixtures 1-7, inclusion of CR content up to 25% showed a slight increase in the HRWRA demand, reaching up to 9.3% compared to the control mixture (percentage of CR = 0%). Further increases in CR content led to increases in the HRWRA demand required to obtain the target flowability (slump flow diameter of 700 ± 50 mm). With the addition of 30% CR in mixture 550C-30CR (mixture 7), the HRWRA dosage was increased by 27.7% compared to the control mixture with no CR (mixture 1). Varying the percentage of CR from 0% to 30% increased the T_{50} and V-funnel times by 1.93 and 2.46 times, respectively, indicating a reduced flowability (**Table 5.1** and **Figure 5.1a**). According to the European Guidelines for Self-Compacting Concrete (2005), the T_{50} and V-funnel time of the control mixture (550C-0CR) meet the limits of VS1/VF1, while those for SCRC mixtures with up to 30% CR meet the limits of VS2/VF2. Both classes have promising potentials for multiple structural applications.

As shown in **Table 5.1** and **Figure 5.1b**, the passing ability also decreased as the CR content increased. Increasing the percentage of CR from 0% to 30% decreased L-box ratio from 0.91 to 0.75 and increased the difference between the slump flow and J-ring diameters from 10 mm to 70 mm. However, all tested SCRC mixtures with up to 30% CR replacement showed an acceptable passing ability as per the European Guidelines for Self-Compacting

Concrete (2005) and the Interim Guidelines for the Use of Self-Consolidating Concrete (2003) (H2/H1 ≥ 0.75).

The sieve segregation test showed a decay in the stability of mixtures with increases in the CR (**Table 5.1** and **Figure 5.1c**), in which a 30% replacement level resulted in an SR value 3.33 times greater than mixture with no CR. However, all mixtures with up to 30% CR did not exceed the acceptable limit (SR ≤ 15%) for SCC mixtures, as recommended by the European Guidelines for Self-Compacting Concrete (2005). In addition to the SR test, this study visually evaluated the stability of rubber particles by investigating the distribution of CR particles along hardened splitted cylinders. As mentioned earlier, the low density of the rubber may decrease the stability of mixtures and make it easy for the rubber to float toward the concrete surface during mixing. From **Figure 5.2**, it can be seen that mixtures with up to 30% CR appeared to have a good distribution of CR particles, indicating the effect of the mixture's viscosity on improving particle suspension.

Increasing the percentage of CR from 0% to 30% also raised the measured air content from 1.5% to 5%, as shown in **Table 5.1**. This can be related to the same reasons explained in the chapter 4 (clause 4.2.1).

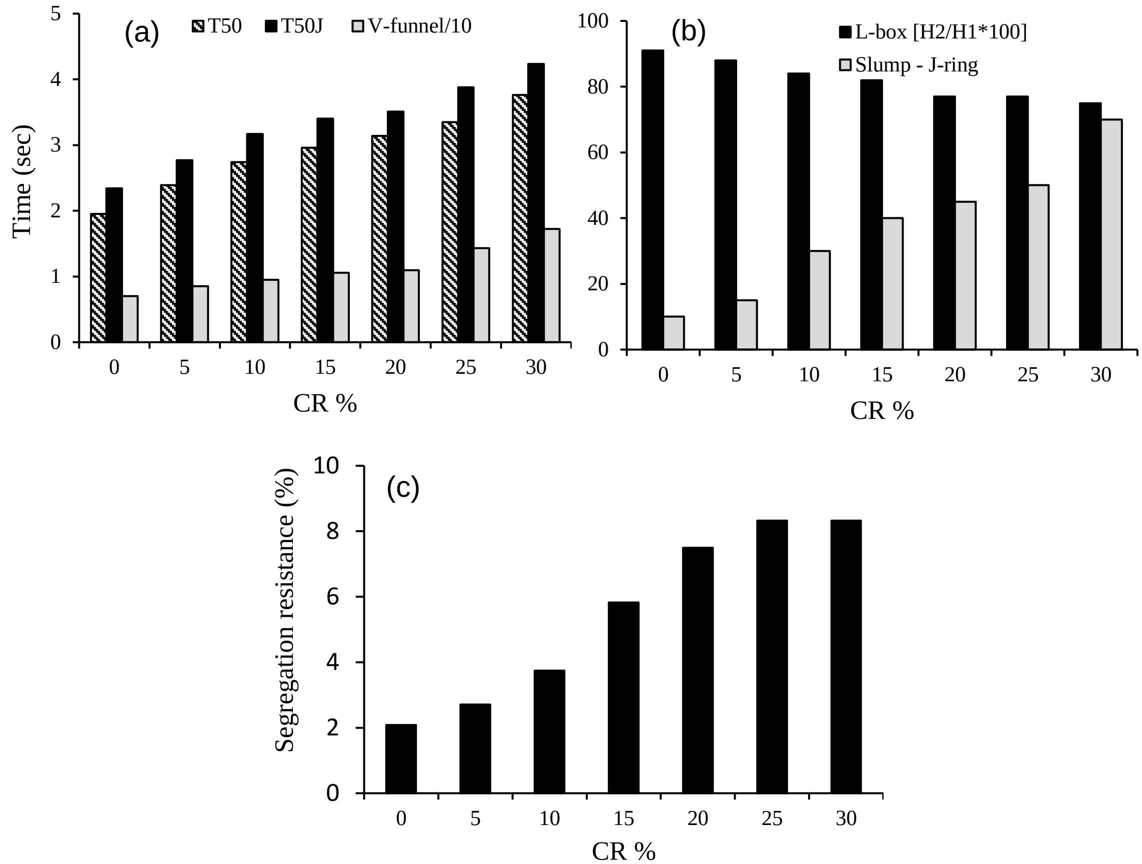


Figure 5.1 Effect of CR replacement on the fresh properties of the tested SCRC mixtures (mixtures 1–7): (a) flowability, (b) passing ability, (c) segregation resistance

5% CR **15% CR** **30% CR**

Figure 5.2 Distribution of CR particles

5.3 Fresh Properties of SFSCRC

5.3.1 HRWRA

Table 5.1 presents the HRWRA demands required to achieve the target slump flow of 700 ± 50 mm for tested SFSCRC mixtures. By comparing mixtures 8, 9, and 10 to mixtures 2, 3, and 4, respectively, it can be seen that the addition of SFs caused an increase in the required HRWRA. Inclusion of 0.35% SFs raised the HRWRA demand by 27.3% (on average). The results also showed that increasing the binder content could decrease the HRWRA demand required to achieve the target slump flow. This effect can be seen by comparing mixture 11 to mixture 10, in which increasing the binder content from 550 kg/m^3 to 600 kg/m^3 reduced the HRWRA demand by 13.6%.

In mixtures 14, 15, and 16 compared to mixtures 8, 9, and 10, respectively, it can be observed that increasing the size of fibres did not show a significant change in the amount of HRWRA required to achieve the desired slump flow. Mixtures with both 35 mm and 60 mm SFs could be developed by adding similar amount of HRWRA of 4.63 l/m^3. On the other hand, using a higher volume of fibre (0.5% instead of 0.35%) required more HRWRA to achieve the target slump flow. As shown in mixture 19 compared to mixture 11, increasing the SFs from 0.35% to 0.5% (for 35 mm SFs) raised the dosage of HRWRA from 4 l/m^3 to 4.75 l/m^3.

5.3.2 Flowability

The flowability of SFSCRC mixtures were evaluated using T_{50}, T_{50J}, and V-funnel time. As shown in **Table 5.1** and **Figure 5.3a**, the flowability of SCRC decreased by adding SFs.

By examining mixtures 8, 9, and 10 compared to mixtures 2, 3, and 4, respectively, it can be observed that adding 0.35% SFs increased the T_{50}, T_{50J}, and the V-funnel times by an average of 11.2%, 16.9%, and 13.5%, respectively. This reduction in the flowability of SFSCRC could be attributed to the increased inter-particle friction and interference occurred between SFs, CR particles, and coarse aggregate, which caused a decay in the smoothness of the mixture's flow.

Increasing the binder content from 550 kg/m^3 (mixture 10) to 600 kg/m^3 (mixture 11) noticeably improved the flowability of SFSCRC mixtures (see **Table 5.1** and **Figure 5.3a)**, which reduced the T_{50}, T_{50J}, and V-funnel times by an average of 24.2%, 27.7%, and 18.7%, respectively. Mixtures (8-13) achieved the flowability characteristics of the VS2/VF2 class of mixtures given by the European Guidelines for Self-Compacting Concrete, thus expanding their possible applications.

The results of the T_{50}, T_{50J}, and V-funnel time showed that the flowability of SFSCRC mixtures decreased as the length of fibres increased (**Table 5.1** and **Figure 5.3b**). The T_{50}, T_{50J}, and V-funnel times increased by 17.9%, 30.9%, and 35.2% (on average), respectively, when the length of SFs increased from 35 mm to 60 mm (mixtures 14, 15, and 16 compared to mixtures 8, 9, and 10). The results also indicated that increasing the volume of fibres reduced the flowability of mixtures. Mixture 19 compared to mixture 11 shows increases in the T_{50}, T_{50J}, and V-funnel times reached up to 17.1%, 32.8%, 25%, respectively (**Table 5.1** and **Figure 5.3b**), when the volume of SFs increased from 0.35% to 0.5%. The reason can be due to increasing the inter-particle friction and interference experienced as the volume or length of fibres increased, which in turn limited the fluidity of mixture. From the results, it is clear that the J-ring and V-funnel tests were more affected by increased fibre length and/or higher volumes of SFs. This effect may be attributed to that in both tests the concrete should flow through confined and limited spaces. Therefore, high interference and blockage due to fibres can definitely increase the time concrete takes to flow.

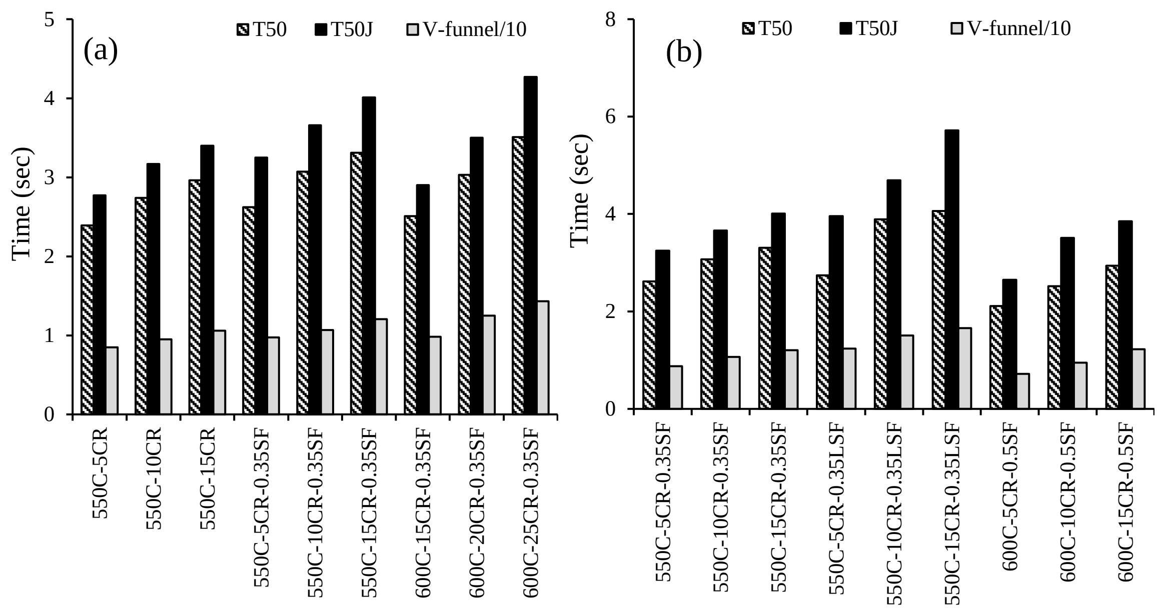


Figure 5.3 Flowability of the tested SFSCRC mixtures: (a) effect of SFs, (b) effect of the volume fraction and size of SFs

5.3.3 Passing Ability

The passing ability of all tested mixtures was assessed by measuring the L-box (H2/H1) ratio and the difference between the slump flow and J-ring diameters. The addition of SFs generally reduced the passing ability of SCRC mixtures, as shown in **Table 5.1** and **Figure 5.4a**. By comparing mixtures 8, 9, and 10 to mixtures 2, 3, and 4, respectively, it can be observed that including 0.35% SFs increased the difference between the slump flow and J-ring diameters up to 2.28 times (on average), while the results of the L-box test showed an average reduction of 8.3%. The drop in the passing ability of SFSCRC mixtures is attributed to the high friction and interference between SFs, CR, and coarse aggregates, which caused a blockage at the vertical steel bars in both L-box and J-ring devices. It is worth noting that using 550 kg/m^3 binder content helped to develop SFSCRC mixtures having 0.35% SFs and up to 15% CR, while further increasing the CR content showed higher blockage in the L-box test, which made it difficult for mixtures to pass through rebars.

Increasing the binder content showed an enhancement in the passing ability, allowing higher percentages of CR to be used. Increasing the binder content from 550 kg/m^3 to 600 kg/m^3 led to an average reduction of 56.3% in the slump flow–J-ring diameter. The L-box ratio also increased from 0.75 to 0.85 when the binder content increased from 550 kg/m^3 to 600 kg/m^3, as shown in mixture 11 compared to mixture 10. Using 600 kg/m^3 binder content allowed up to 25% CR and 0.35% SFs to be combined in SFSCRC mixtures and maintained acceptable fresh properties (**Table 5.1** and **Figure 5.4a**).

As presented in **Table 5.1** and **Figure 5.4b**, the passing ability of SFSCRC mixtures significantly decreased when the fibres' length increased from 35 mm to 60 mm. In mixtures with 60 mm SFs (mixtures 14, 15, and 16) the L-box ratios decreased by an average of 65.4% compared to mixtures with 35 mm SFs (mixtures 8, 9, and 10). The slump flow–J-ring diameter also increased by an average of 91.34% when 60 mm SFs were used. This may be attributed to the fact that the length of fibres (60 mm) exceeded the spacing between the reinforcement of the L-box and J-ring, which are 41 mm and 58.9 mm, respectively. Similarly, increasing the volume of SFs from 0.35% to 0.5% (for 35 mm SFs) showed a reduction in the passing ability of mixtures. The L-box test had a reduction of up to 49.4%, as shown in mixture 19 compared to mixture 11. The slump flow–J-ring also rose from 35 mm to 110 mm as the SFs volume fraction increased from 0.35% to 0.5%.

It is important to note that although all mixtures in this stage achieved the required flowability and filling ability for SCC class of VS2/VF2, none of them fulfilled the acceptable passing ability ratio of 0.75, as given by the SCC standards. Therefore, according to the Interim Guidelines for the Use of Self-Consolidating Concrete (2003), these mixtures have a potential problem for the use in structural applications that have a medium-to-high level of reinforcement, medium-to-high element length, low wall thickness, and/or mixtures cast using low placement energy.

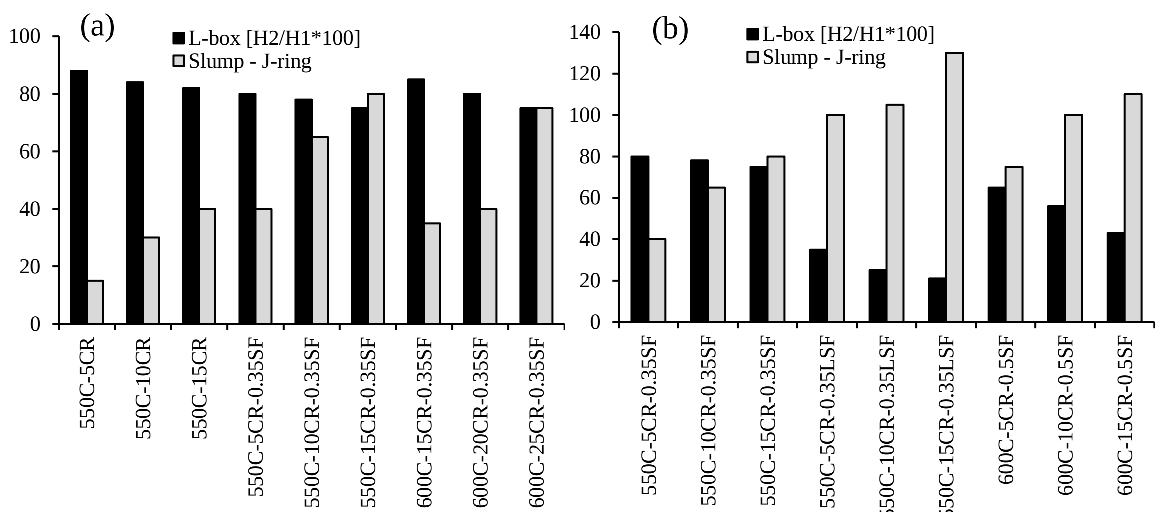


Figure 5.4 Passing ability of the tested SFSCRC mixtures: (a) effect of SFs, (b) effect of the volume fraction and size of SFs

5.3.4 Segregation Resistance (SR)

The sieve segregation test was used to evaluate the coarse aggregate segregation of all tested SFSCRC mixtures. Comparing mixtures 8, 9, and 10 to mixtures 2, 3, and 4, respectively, it can be seen that adding SFs to SCRC had a negative impact on the stability of mixtures. Using 0.35% SFs exhibited an average increase of 7.2% in the SR results, as shown in **Table 5.1** and **Figure 5.5a**. However, all developed mixtures had SR values within the acceptable range (≤ 15%) given by the European Guidelines for Self-Compacting Concrete (2005). Also, **Figure 5.6** shows a well distribution for SFs along the cross-section of broken sample, which indicates a proper homogeneity of the mixture.

The results also showed that increasing the binder content considerably enhanced the stability of SFSCRC mixtures (see **Table 5.1** and **Figure 5.5a)**. As the binder content increased from 550 kg/m^3 in mixture 10 to 600 kg/m^3 in mixture 11 the SR values decreased by an average of 58.6%.

The results of the sieve segregation test indicated that using longer fibres decreased the SR results (**Table 5.1** and **Figure 5.5b**). In mixtures with 60 mm SFs (mixtures 14, 15, and 16) the SR values reduced by an average of 27.94% compared to mixtures containing 35 mm SFs (mixtures 8, 9, and 10). On the other hand, increasing the volume of fibres from 0.35% to 0.5% increased the SR. Changing the volume of SFs from 0.35% to 0.5% heightened the SR values from 2.5% to 3.75%, as shown in mixture 11 compared to mixture 19 (see **Table 5.1** and **Figure 5.5b**).

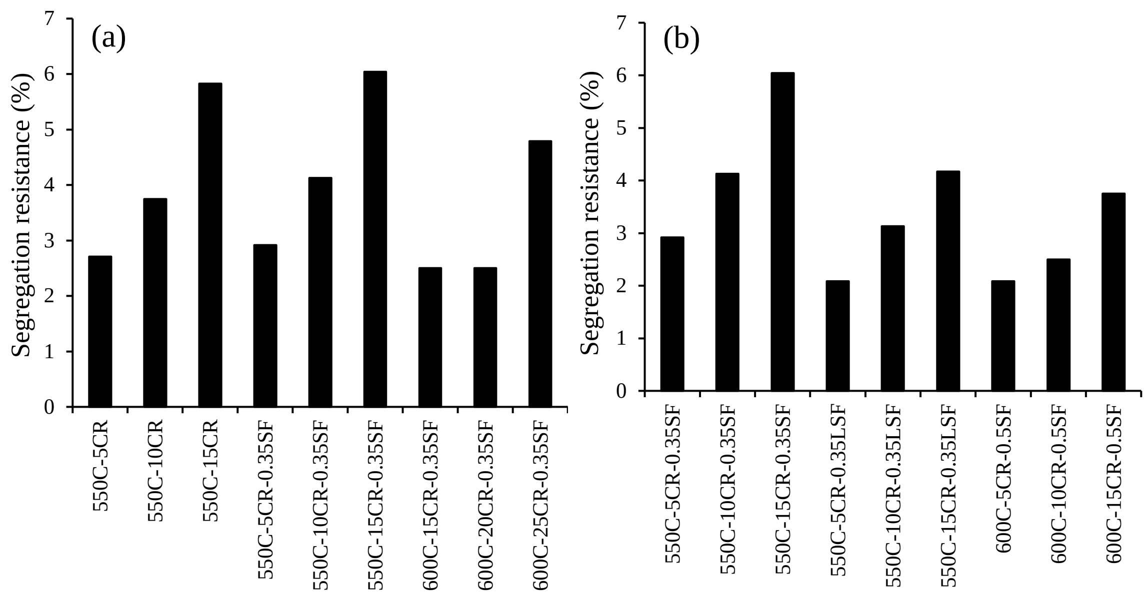


Figure 5.5 Segregation resistance of the tested SFSCRC mixtures: (a) effect of SFs, (b) effect of the volume fraction and size of SFs

Figure 5.6 Distribution of SFs across the fracture surface

5.3.5 Effect of Increasing The CR Content and SFs Volume Fraction On VRC Mixtures' Workability

Table 5.1 and **Figure 5.7** show that both CR and SFs negatively affected the workability of vibrated concrete mixtures due to high inter-particle friction and interference, as explained earlier in SCRC and SFSCRC mixtures. By examining mixtures 20, 21, and 22, it can be observed that at a constant HRWRA of 3.18 l/m^3, varying the percentage of CR from 30% to 40% reduced the slump from 190 mm to 145 mm, respectively. Similarly, with a constant HRWRA of 3.18 l/m^3, increasing the SFs volume from 0.35% to 1% decreased the slump values by 56%, as shown in mixtures 23 to 26.

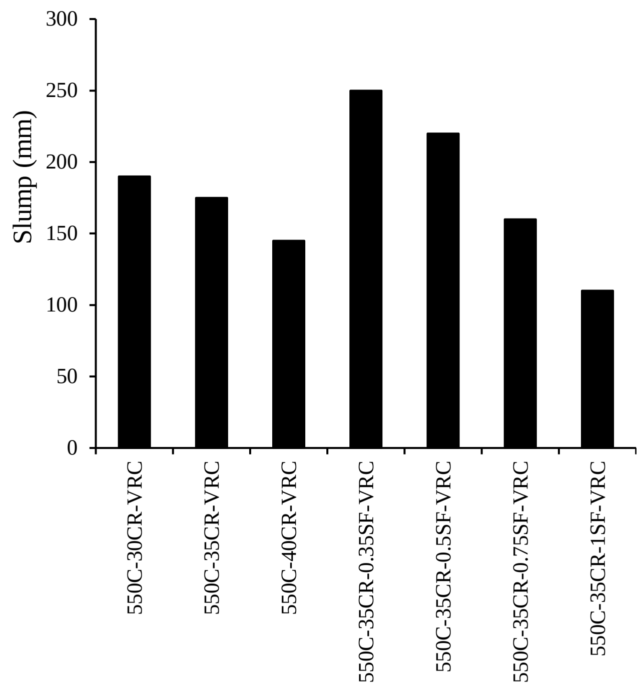


Figure 5.7 Workability of VRC and SFVRC

5.4 Summary of Mechanical Properties of SCRC

Table 5.2 and **Figure 5.8** show the mechanical properties of tested SCRC mixtures. The results obtained in this study (study 2) confirmed the negative impact of CR on the mechanical properties of SCRC mixtures similar to the experimental results of study 1 (chapter 4). As shown in mixtures 1-7, the 7- and 28-day compressive strength decreased as the percentage of CR increased. Increasing the CR from 0% to 30% showed a decrease in the 7- and 28-day compressive strengths reaching up to 56.5% and 57.9%, respectively (**Table 5.2** and **Figure 5.8a**). It is worth noting that although the compressive strengths obviously decreased with an increase in the CR content, mixtures with up to 15% CR could be developed with a compressive strength of almost 45 MPa. In addition, mixtures with up to 30% CR achieved adequate strength (31.86 MPa) for multiple structural applications.

Table 5.2 and **Figures 5.8b** and **5.8c** also shows that the STS and FS decreased as the percentage of CR increased. Varying the percentage of CR from 0% to 30% reduced the 7- and 28-day STS by 45.1% and 40.3%, respectively. Similarly, the reductions in FS reached up to 38.8% and 31.7% at 7- and 28-day, respectively, when the percentage of CR increased from 0% to 30%. The ME also decreased as the percentage of CR increased (**Table 5.2**). This reduction reached up to 6.2% at 5% CR, while at 30% CR the reduction was as much as 36.3%.

It should be noted that the reduction in compressive strength, STS, FS, and ME is attributed to the same reasons stated in the study 1, which briefly are: (a) the poor strength of the rubber-mortar interface, (b) the significant difference between the stiffness of the rubber particles and the hardened cement paste, and (c) increasing the air content (leading to higher porosity) in mixtures with increases in the CR content.

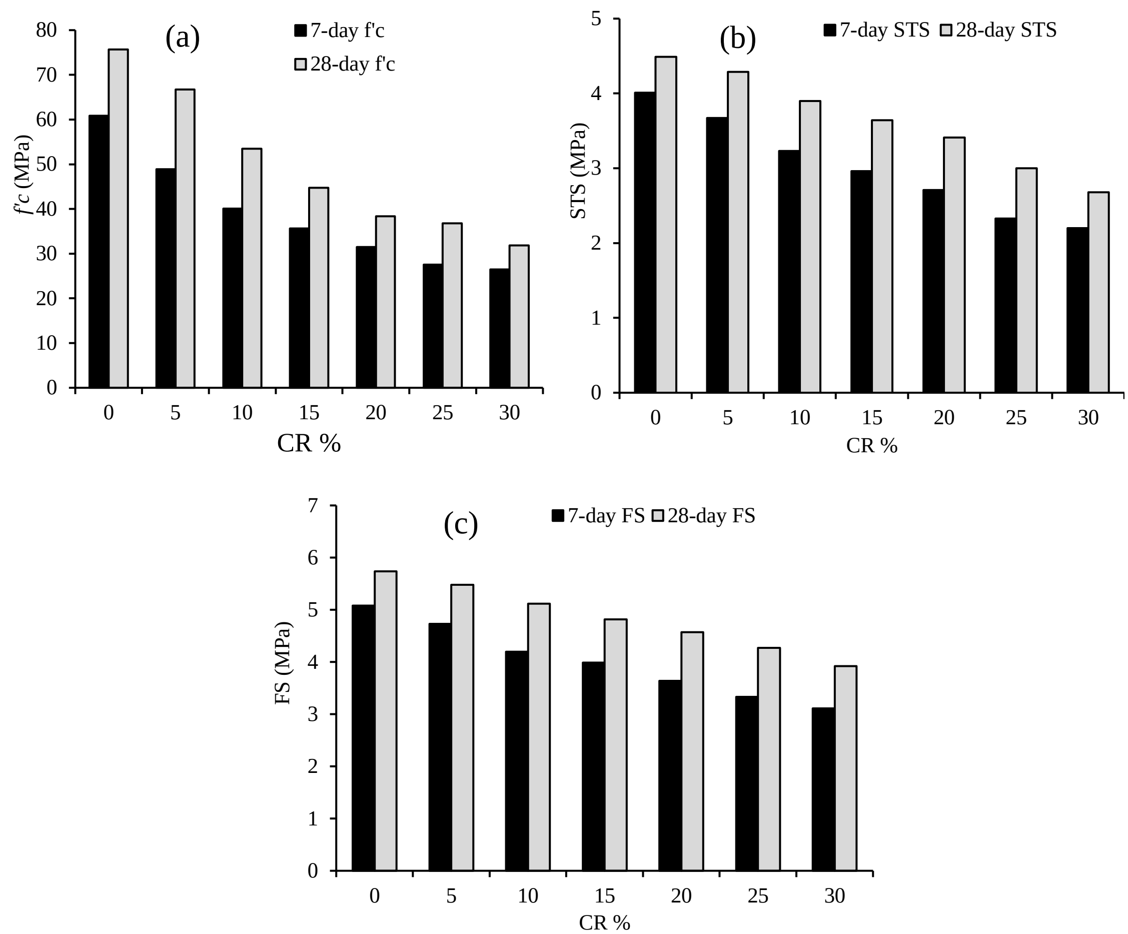


Figure 5.8 Mechanical properties of the tested SCRC mixtures: (a) compressive strength, (b) STS, (c) FS

5.5 Summary of Impact Resistance of SCRC

The results of impact resistance confirmed the beneficial effect of CR on enhancing the impact resistance of concrete (in both drop-weight and flexural loading tests), similar to the research's findings in study 1 (chapter 4). **Table 5.3** and **Figure 5.9** show the results of the drop-weight test for all SCRC tested mixtures. In mixtures 1-7, it can be seen that using CR generally improved the impact resistance of tested mixtures in terms of the number of blows required to cause the first visible crack (N_1) and ultimate failure (N_2) of the specimen.

Increasing the percentage of CR from 0% to 30% increased N1 and N2 by 1.89 and 1.91 times. This increase could be attributed to the low stiffness of the rubber particles, which in turn increases the flexibility of the rubber-cement composite and considerably enhances its energy absorption compared to concrete with no CR (as explained in study 1). Also similar to study 1, increasing the CR content was found to improve the post-cracking resistance and the ductility of mixtures; as shown, the difference between the number of blows for ultimate failure and first crack (N_2 - N_1) increased as the percentage of CR increased (see **Table 5.3**).

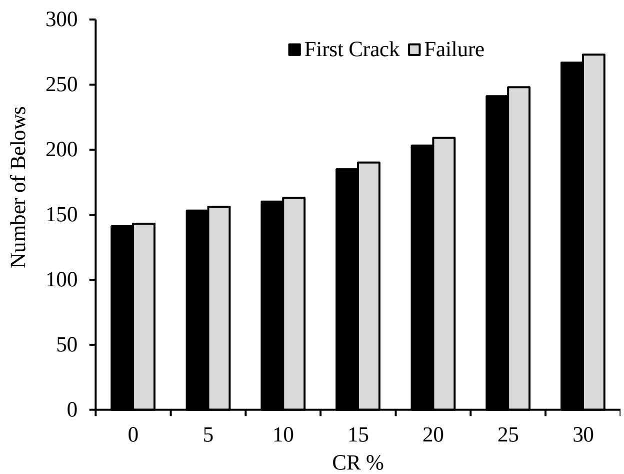


Figure 5.9 Results of impact resistance for the cylindrical specimens under the drop-weight test

Table 5.3 and **Figure 5.10** show the results of all tested mixtures at failure under flexural impact loading. It can be seen that adding CR to concrete helped to improve its ultimate impact energy (similar to study 1). Results of mixtures 1-7 indicated that a replacement level of 25% appeared to have the optimal effect on improving the ultimate impact energy of concrete. This value is close to the optimal value obtained from study 1 (which was 20%). Increasing the percentage of CR from 0% to 25% increased the ultimate impact energy at failure by 2.42 times. Meanwhile, using 30% CR exhibited a relatively lower enhancement of 2.16 times higher than that obtained by the control beam (CR = 0). It should be noted that the results of the tested beams showed a lower optimum CR replacement level (25%) compared to the cylindrical specimens under the drop-weight test (30%), and this observation is similar to what obtained from study 1 (chapter 4). This finding may be related to that increasing the percentage of CR increases the poor-strength ITZ in the mixture, which may encourage higher propagation for cracks due to tensile stress in beams under flexural-loading test compared to cylindrical specimens under the drop-weight test.

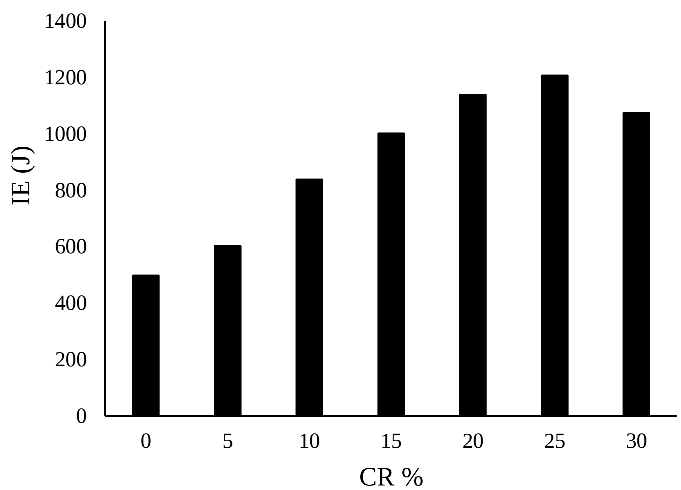


Figure 5.10 Results of impact resistance for the beams under the flexural loading test

5.6 Mechanical Properties of SFSCRC

5.6.1 Compressive Strength

The 7- and 28-day compressive strengths of the tested mixtures are shown in **Table 5.2** and **Figure 5.11**. By comparing mixtures 8, 9, and 10 to mixtures 2, 3, and 4, it can be seen that using SFs with a volume of 0.35% (35 mm length) did not show a considerable effect on the 7- and 28-day compressive strength, in which the increase of compressive strengths in both ages reached a maximum value of 3.2% (see **Table 5.2** and **Figure 5.11a**). Similar behavior was noticed in mixture 19 compared to mixture 11, in which increasing the SF volume from 0.35% to 0.5% resulted in negligible increases in the compressive strength, reaching up to 1.3% and 2% after 7 and 28 days, respectively (see **Table 5.2** and **Figure 5.11b**). These results are in agreement with other researchers' observations (Olivito and Zuccarello, 2010; Atis and Karahan, 2009), in which the compressive strength of normal concrete was unaffected by the addition of SFs.

Table 5.2 and **Figure 5.11a** also show that increasing the binder content from 550 kg/m^3 to 600 kg/m^3 (mixture 10 compared to mixture 11) slightly improved the 7- and 28-day compressive strength on average by 4.3% and 4.7%, respectively. By examining mixtures 14, 15, and 16 compared to mixtures 8, 9, and 10, respectively, it can be seen that increasing the length of SFs from 35 mm to 60 mm showed a slight negative impact on the compressive strength of the developed mixtures, as shown in **Table 5.2** and **Figure 5.11b**. This behavior may be due to increasing the measured air content in mixtures with long SFs (see **Table 5.1**), which in turn causes a reduction in the compressive strengths.

The results also showed that VRC mixtures seemed to exhibit higher compressive strengths compared to SCRC mixtures. This finding can be seen by comparing the results of mixture 20 (VRC) to its counterpart, mixture 7 (SCRC). This increase reached up to 6.7% and 5.1% in the 7- and 28-day compressive strengths, respectively. This may be attributed to the fact that the VRC mixtures entrapped less air than the SCRC mixtures (see **Table 5.1**). Increasing the CR content in VRC mixtures from 30% to 40% reduced the 7- and 28-day compressive strength by 26.7% and 26.2%, respectively. This finding can be explained by the same reasons related to the reduction of the compressive strength in SCRC mixtures.

Increasing the percentage of SFs (35 mm length) in SFVRC had a slight impact on improving the compressive strengths, as seen in **Table 5.2** and **Figure 5.11c**. Varying the SF volume from 0% (mixture 21) to 1% (mixture 26) raised the 7- and 28-day compressive strength by 7.8% and 6.8%, respectively. It is worth noting that mixtures 20-26 contributed to developing SFVRC mixtures with a density of less than 2150 kg/m^3, which are categorized as semi-lightweight concretes based on the CSA's (2004) classification (1850~2150 kg/m^3).

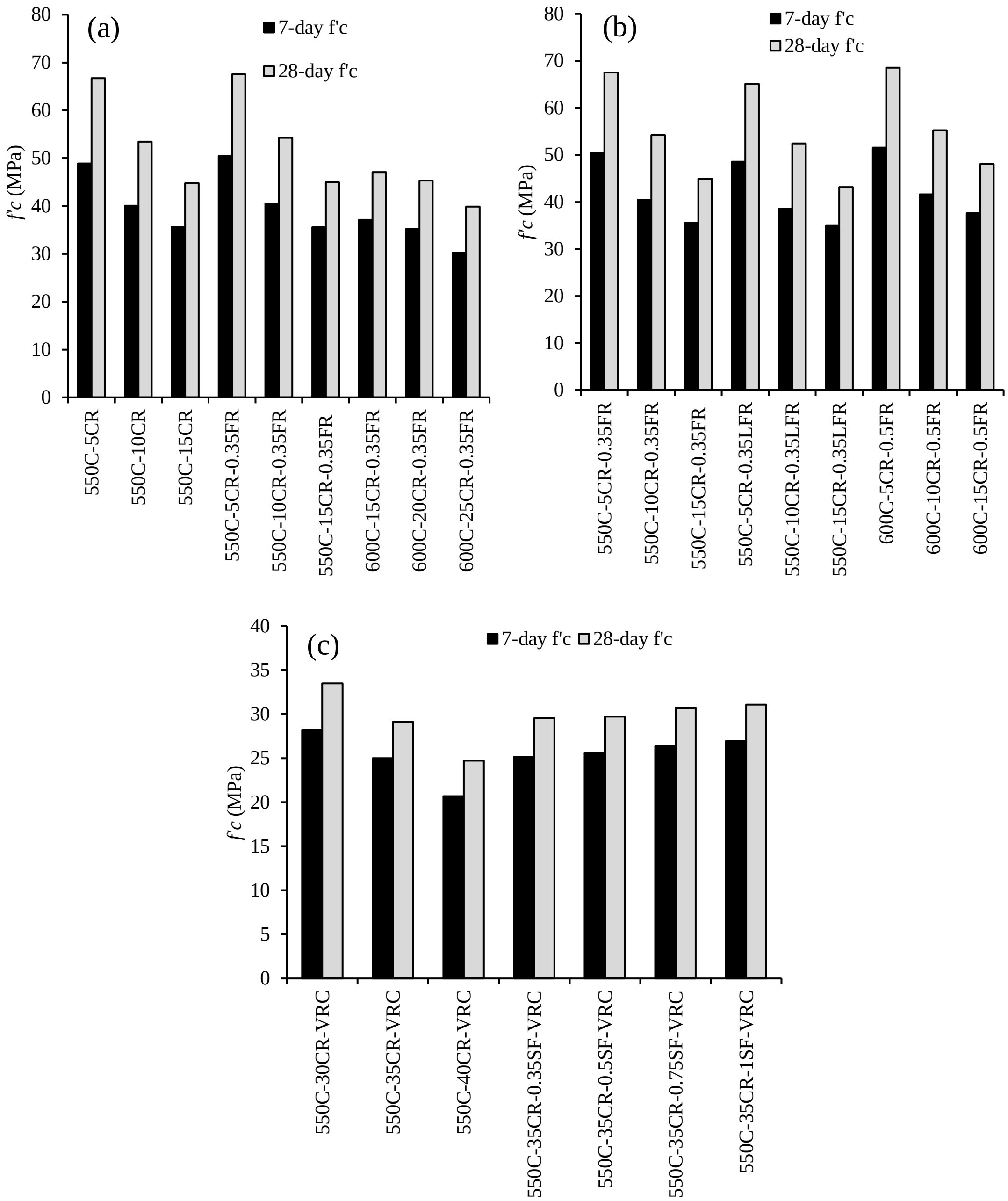


Figure 5.11 The 7- and 28-day compressive strengths: (a) effect of 0.35% SF (35 mm length) on SCRC, (b) effect of fibres' length and volume on SCRC, (c) effect of CR and SFs on VRC

5.6.2 Splitting Tensile and Flexural Strengths

The STS and FS results for all tested mixtures are shown in **Table 5.2** and **Figures 5.12** and **5.13**. By looking at mixtures 8, 9, and 10 compared to mixtures 2, 3, and 4, respectively, it can be observed that using 0.35% SFs (35 mm length) noticeably increased the STS and FS of the developed mixtures, as seen in **Figures 5.12a** and **5.13a**. For these mixtures, the inclusion of SFs appeared to improve the 7- and 28-day STS by an average of 22.6% and 20.5%, respectively, while the 7- and 28-day FS increased by 18.1% and 19.5% (on average), respectively. These increases could be attributed to the fact that SFs act as crack arrestors, which in turn restrict the development of cracks and also help to transfer the stress across crack's faces using the bridging effect. This compensates for the inherent weakness of concrete against tensile stress. It is worth noting that adding 0.35% SFs (35 mm length) to SCRC mixtures can completely compensate for the reduction in the 7- and 28-day STS and FS that resulted from adding 10% CR. Moreover, comparing mixture 19 to mixture 11 shows that increasing the volume of fibres from 0.35% to 0.5% enhanced the 7- and 28-day STS by 12.4% and 9.5%, respectively (see **Table 5.2** and **Figure 5.12b**), while the 7- and 28-day FS were improved by 12.9% and 11.8%, respectively, as seen in **Table 5.2** and **Figure 5.13b**.

Increasing the binder content from 550 kg/m^3 to 600 kg/m^3 (mixture 10 compared to mixture 11) enhanced the 7- and 28-day STS, on average, by 10.5% and 6.2%, respectively, as shown in **Table 5.2** and **Figure 5.12a**. The 7- and 28-day FS were also improved by increasing the binder content; using 600 kg/m^3 instead of 550 kg/m^3 enhanced the 7- and 28-day FS by an average of 6.2% and 7.3%, respectively (see **Table 5.2** and **Figure 5.13a**).

As seen in mixtures 14, 15, and 16 compared to mixtures 8, 9, and 10, respectively, increasing the length of fibres (from 35 mm to 60 mm) showed a slight improvement in the 7- and 28-day STS by an average of 5.6% and 4.4%, respectively (see **Table 5.2** and **Figure 5.12b**). When the length of fibres was increased from 35 mm to 60 mm, the 7- and 28-day FS increased, on average, by 6.2% and 9.1%, respectively (see **Table 5.2** and **Figure 5.13b**). The increased STS and FS may be related to the fact that increasing the length of fibres allowed a greater bond between the concrete and fibres to develop, which increases the pullout strength of fibres and constrains the micro-cracks propagation, thus heightening the tensile strength of concrete, as observed by other researchers (Mohammadi et al., 2009; Ghernouti et al., 2015).

As shown in **Table 5.2**, by comparing mixture 20 to mixture 7, it can be seen that VRC mixtures exhibited increased strengths compared to SCRC mixtures with the same CR content (30%) (similar to the compressive strength results). These increases reached up to 5.5% and 3.4% in the 7- and 28-day STS, respectively, and up to 6.4% and 7.4% in the 7- and 28-day FS, respectively. The results also showed that varying the percentage of CR in VRC from 30% to 40% reduced the 7- and 28-day STS by 17.2% and 12.6%, respectively, while the 7- and 28-day FS decreased by 10% and 9.7%, respectively (see **Table 5.2** and **Figures 5.12c** and **5.13c**).

The addition of SFs significantly enhanced the STS and FS of VRC mixtures, as seen in **Table 5.2** and **Figures 5.12c** and **5.13c**. Increasing the SF volume from 0% in mixture 21 to 1% in mixture 26 greatly increased the 7- and 28-day STS by 80.4% and 93.3%, respectively, while the 7- and 28-day FS were improved by 67.6% and 75.6%, respectively, indicating the effectiveness of SFs in compensating for the reduction in the STS and SF of SCRC (due to the addition of CR). It is important to note that the VRC mixture with 1% SFs (mixture 26) showed comparable strength results to those of the SCRC mixture with no CR (mixture 1), indicating a complete recovery from the reduction of STS and FS due to adding 35% CR.

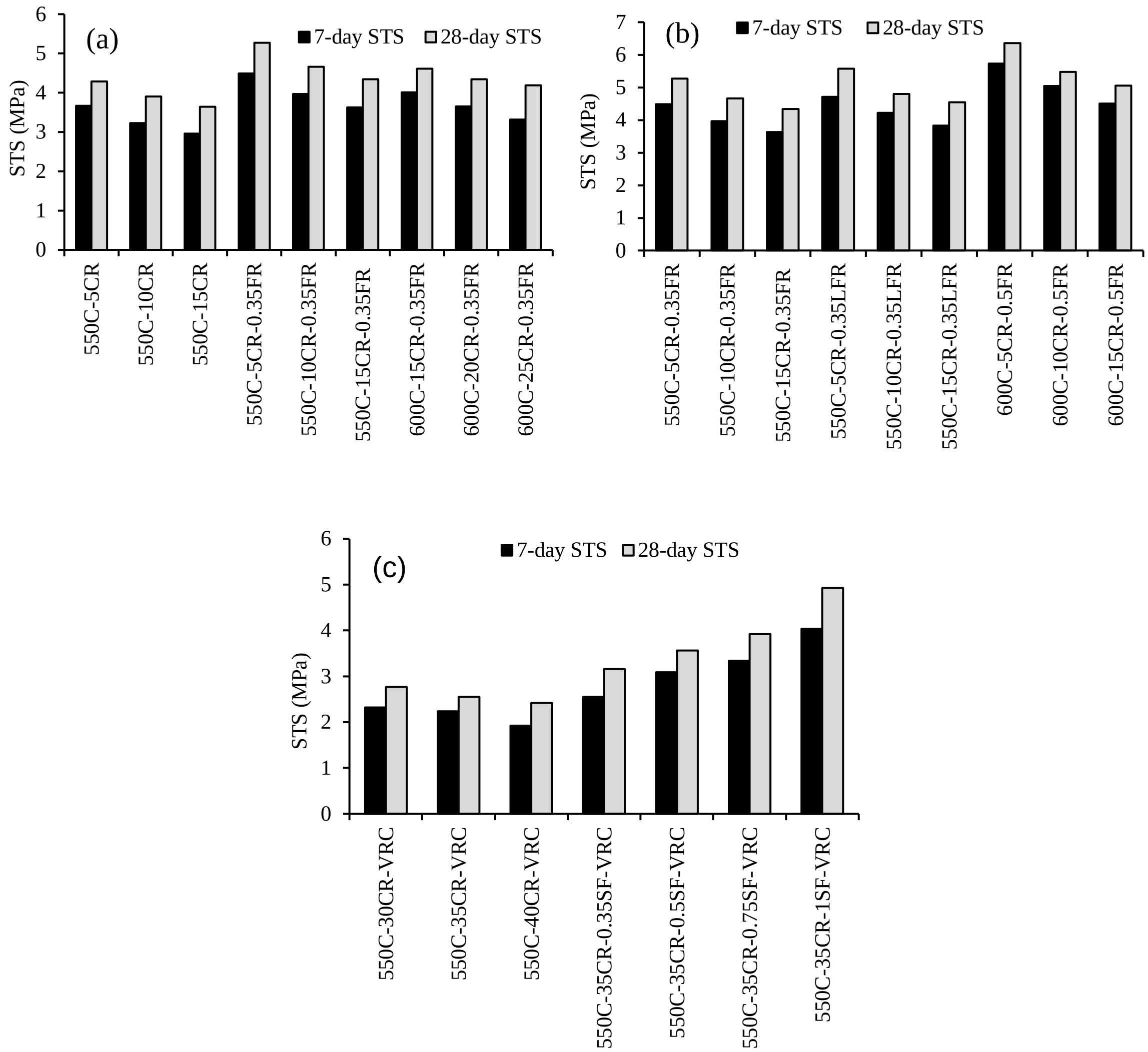


Figure 5.12 The 7- and 28-day STS: (a) effect of 0.35% SF (35 mm length) on SCRC, (b) effect of fibres' length and volume on SCRC, (c) effect of CR and SFs on VRC

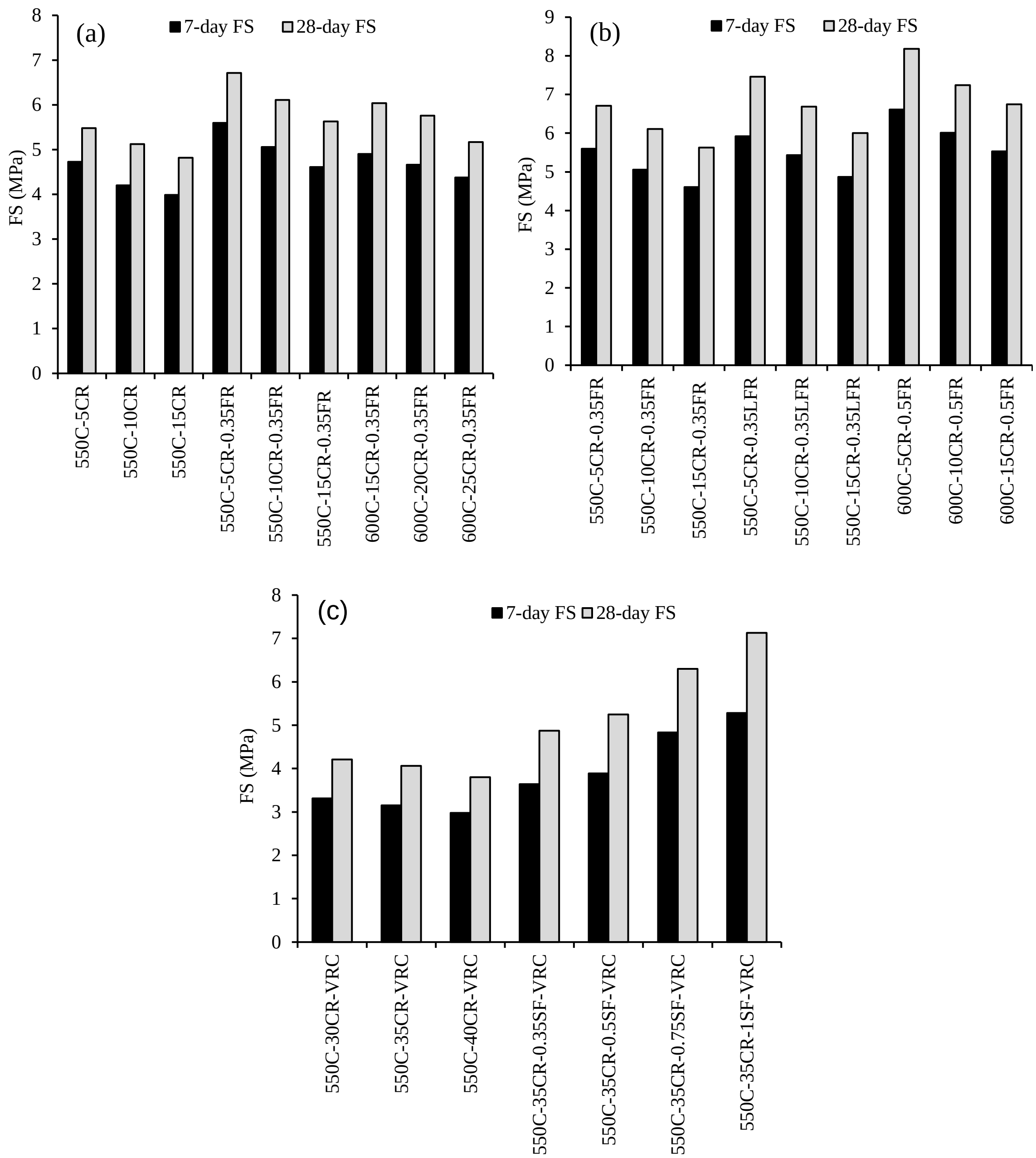


Figure 5.13 The 7- and 28-day FS: (a) effect of 0.35% SF (35 mm length) on SCRC, (b) effect of fibres' length and volume on SCRC, (c) effect of CR and SFs on VRC

5.6.3 Modulus of Elasticity

The ME results for all tested mixtures are presented in **Table 5.2**. Results of mixtures 8, 9, and 10 compared to mixtures 2, 3, and 4, repectively, indicated no significant impact for the addition of SFs on the ME of tested mixtures. This finding is in agreement with what other researchers have found (Altun and Aktas 2013, Iqbal et al. 2015), in which using SFs showed inconsiderable variation in the ME of concrete mixtures. Similar behavior was observed when the SF volume increased from 0.35% (mixture 11) to 0.5% (mixture 19), in which no noticeable difference in the ME values.

From **Table 5.2**, it can be also seen that using a higher binder content of 600 kg/m^3 in mixture 11 showed a value of ME similar to that obtained in mixture 10 with 550 kg/m^3, indicating insignificant effects on improving the ME for the additional quantity of binder content (50 kg/m^3).

The ME results slightly decreased as the length of the used SFs increased from 35 mm to 60 mm, as shown in mixtures 14, 15, and 16 compared to mixtures 8, 9, and 10, respectively. The average reduction was 6.9%, and this reduction can be attributed to the same reasons for the reduction of compressive strength with increased length of SFs.

By evaluating the results of VRC (mixture 20) vs. SCRC (mixture 7), it can be seen that the measured ME was slightly higher in VRC compared to SCRC mixtures by 6.4%. This may be related to the decreased entapped air in VRC, as explained earlier. For mixtures 20-23, increasing the CR percentage from 30% to 40% reduced the ME by 25.9%. On the other hand, in VRC mixtures with 35% CR, increasing the SF volume from 0% to 1% exhibited a slight increase in the ME, reaching up to 5.6%, as shown in mixtures 23-26 in **Table 5.2**.

5.7 Impact Resistance of SFSCRC under Drop-Weight Test

The results of impact resistance under the drop-weight test for all tested mixtures are shown in **Table 5.3** and **Figure 5.14**. By examining each of mixtures 8, 9, and 10 compared to mixtures 2, 3, and 4 (**Table 5.3** and **Figure 5.14a**), respectively, it can be seen that using 0.35% SFs (35 mm length) raised N_1 and N_2 by an average of 2.37 and 2.68 times, respectively. This increase resulted from the beneficial effect of SFs on arresting the cracks induced due to impact loading. The difference between N_2 and N_1 also showed higher increases with the inclusion of SFs, indicating a significant enhancement in the post-cracking resistance and ductility performance of concrete. Mixture 10, which contained the maximum possible combination of CR and SFs that can be used successfully with 550 kg/m^3 binder content, showed an increase of 3.33 and 3.73 times in the absorbed energy at the first and failure cracks, respectively, compared to the mixture with no CR and SFs (mixture 1). Similar behavior was observed in comparing mixture 19 to mixture 11, where increasing the SF volume from 0.35% to 0.5% led to a noticeable improvement in the energy absorption and ductility of the tested mixtures.

Increasing the binder content from 550 kg/m^3 in mixture 10 to 600 kg/m^3 in mixture 11 appeared to have a positive effect on enhancing the impact resistance of SFSCRC mixtures, in which the total energy required to break the tested specimens of mixture 11 increased by 16.3% compared to that obtained from mixture 10.

As shown in **Table 5.3** and **Figure 5.14b**, by looking at the results of mixtures 14-16 vs. mixtures 8-10, it can be seen that increasing the length of SFs exhibited relatively higher impact strength. The number of blows to produce the initial visible crack and the failure crack were increased by an average of 17.7% and 19%, respectively, when the length of SFs increased from 35 mm to 60 mm. This may be attributed to the higher bond strength of long SFs (60 mm), which may play a more effective role in arresting the cracks than obtained by using small fibres (35 mm).

The drop-weight impact test showed a comparable performance for VRC and SCRC mixtures (see **Table 5.3**), in which mixtures 7 and 20 (both with 30% CR and 550 kg/m^3 binder content) were almost failed at almost the same level of impact energy. The results of VRC mixtures (mixtures 20-22) also indicated that increasing the percentage of CR higher than 30% exhibited a reduction in the values of N_2 and N_1, as shown in **Table 5.3** and **Figure 5.14c**. This may be attributed to that at high rubber content, the increased volume of ITZ and the high differential strain between the rubber particles and the hardened cement paste can limit the ability of concrete to absorb more energy.

Using higher combinations of CR and SFs in SFVRC mixtures contributed to developing a concrete with promising capabilities to endure high impact energy. In mixtures with 35% CR, inclusion of 0.35% SFs (35 mm length) (mixture 23) improved the impact resistance of the mixture by 2.25 times, while the addition of 1% SFs increased the energy required to break the tested specimens by 4 times (mixture 26) compared to the mixture with no SFs (mixture 21) (See **Table 5.3** and **Figure 5.14c**). The results also showed that combining 35% CR and 1% SFs greatly increased the difference between N_1 and N_2 and improved the impact resistance of concrete by 7.54 times compared to mixtures with no CR and SFs (mixture 26 compared to mixture 1). Such improvement indicates the possibility of exploiting the beneficial interaction between SFs and CR to develop types of concrete with a strong potential for structural applications that are subjected to high-impact loads. Other studies (Ganesan et al. 2013b, Guo et al. 2014) also showed that the benefits of combining CR and SFs extend to improve the fracture toughness, fracture energy, and fatigue life of concrete. For example, Ganesan et al. (2013b) reported that inclusion of 15% CR (by fine aggregate volume) increased the fatigue strength by 12.9%, while combining 15% CR and 0.75 SFs raised the fatigue strength by 53%, compared to control mixture (mixture with no CR or/and SFs).

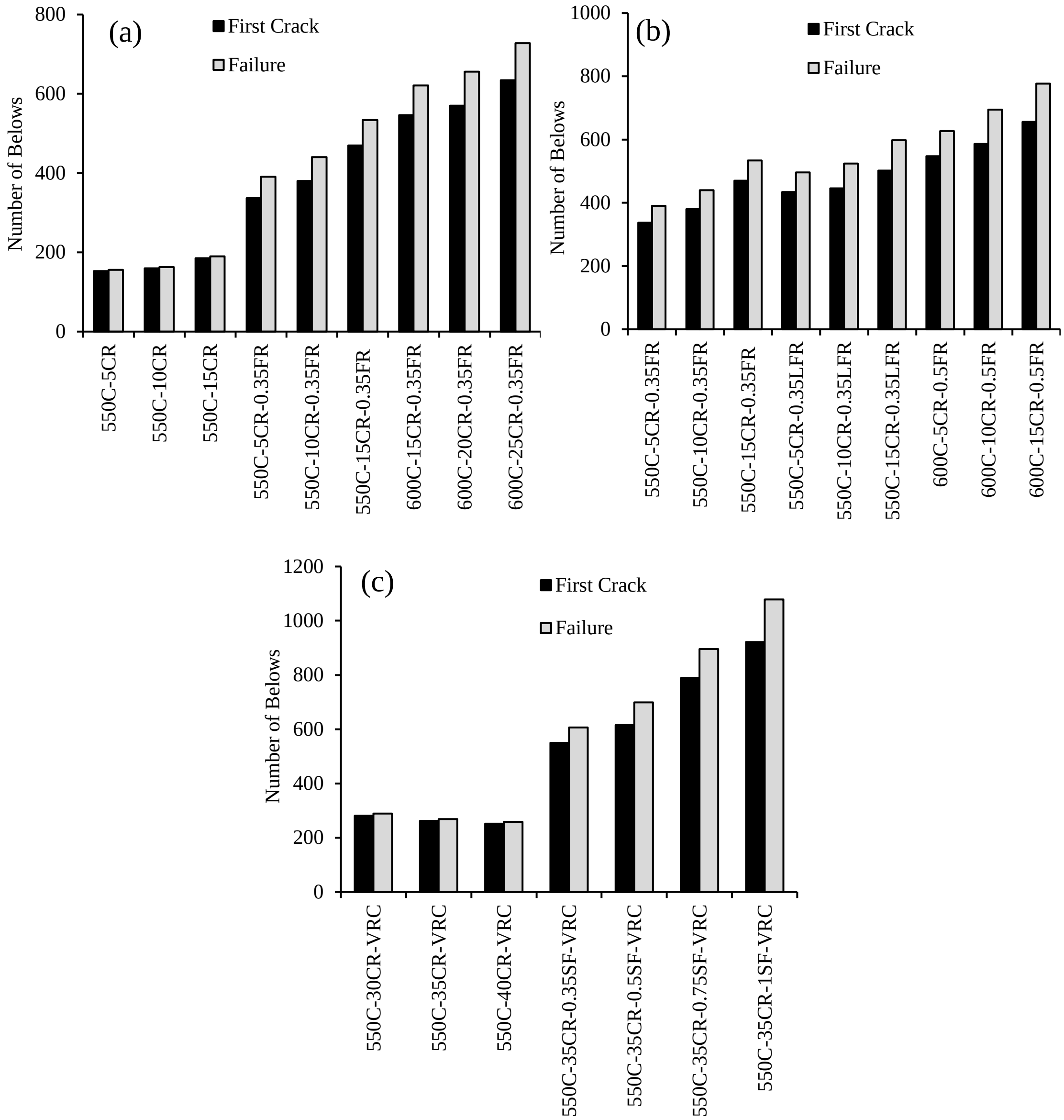
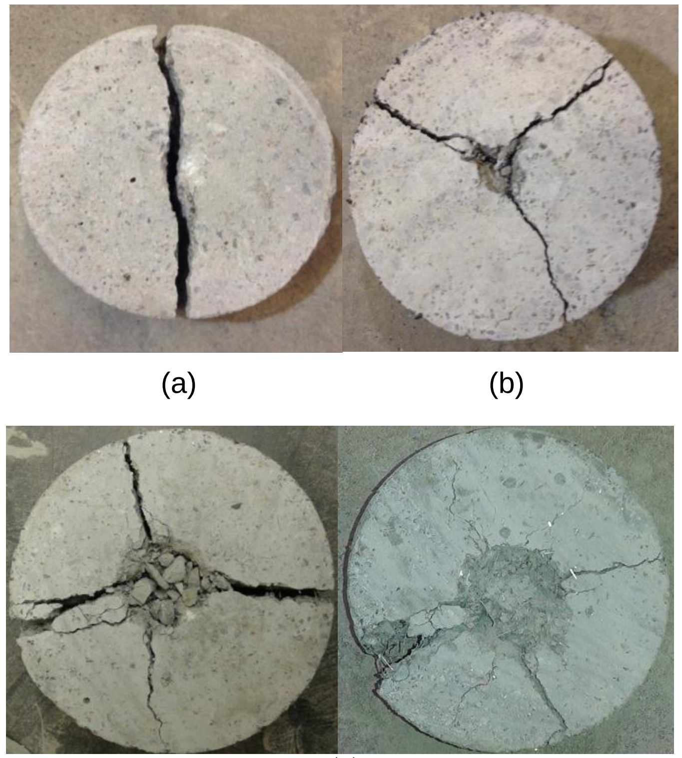


Figure 5.14 Results of impact resistance for the cylindrical specimens under drop-weight test: (a) effect of 0.35% SF (35 mm length) on SCRC, (b) effect of fibres' length and volume on SCRC, (c) effect of CR and SFs on VRC

By examining the failure pattern of the tested specimens in **Figure 5.15**, it can be observed that the failure crack pattern changed from a single large crack, as in the control mixture (CR = 0) (**Figure 5.15a**), to three or more cracks in mixtures with CR (**Figure 5.15b**), and/or a group of narrow cracks in mixtures with a combination of high percentages of CR and SFs (**Figure 5.15c**). This indicates that the beneficial effects of CR replacement and/or SF volume on enhancing the ductility and performance of concrete under impact loading.



(a) (b)

(c)

Figure 5.15 Failure patterns: (a) plain specimen, (b) specimen with CR, (c) specimen with CR and SFs

5.8 Impact Resistance under Flexural Loading

Table 5.3 shows the results of all tested mixtures at failure under flexural impact loading. By comparing mixtures 8, 9, and 10 to mixtures 2, 3, and 4, it can be seen that using 0.35% SFs (35 mm length) showed an increase in the ultimate impact energy of tested beams by an average of 2.33 times. Mixture 10, which contained the maximum possible combination of CR and SFs that can be used successfully with 550 kg/m^3 binder content, showed a 4.13 times increase in the ultimate absorbed energy compared to mixture 1 with no CR and no

SFs. Similarly, comparing mixture 19 and 11, it was found that increasing the SF volume from 0.35% to 0.5% improved the ultimate impact energy by 2.24 times.

Increasing the binder content from 550 kg/m^3 to 600 kg/m^3 (mixture 10 compared to mixture 11) increased the ultimate impact energy by an average of 10.2%, as shown in **Table 5.3**. Similar to the drop-weight test, comparing mixtures 14-16 to mixtures 8-10 showed that increasing the length of SFs from 35 mm to 60 mm improved the ultimate impact energy by 19.3 (on average), as shown in **Table 5.3**.

Results in **Table 5.3** indicated that no significant effect for concrete type on the results of ultimate impact energy. VRC beams made with 35% CR and 550 kg/m^3 binder content (mixture 20) showed behavior under flexural impact loading similar to that observed in its counterpart SCRC beams (mixture 7). The results also showed that in VRC mixtures, increasing the percentage of CR from 30% to 40% reduced the energy absorption of tested specimen by 11.5%. This behavior is attributed to the same reasons related to the reduction of the ultimate impact energy of tested mixtures under the drop-weight test.

Using 35% CR and SFs varied from 0.35% to 1% in SFVRC greatly improved the performance of concrete under flexural impact loading. Mixtures with 35% CR and 0.35% SFs showed an enhancement in the ultimate impact energy of 2.49 times, while increasing the SFs up to 1% helped to heighten the ultimate impact energy by 7.15 times. Comparing the mixture with maximum combination of CR and SFs (mixture 26) to the mixture with no CR and no SFs (mixture 1) showed a great improvement in the impact energy, reaching up to 15 times due to the addition of 35% CR and 1% SFs. These results indicate a very strong potential for combining CR and SFs in concrete in order to develop types of concrete with superior performance under flexural impact loading.

5.9 Evaluating the Results of SCRC and SFSCRC in the Light of the Recent Published Research

Table 5.4 shows a summary for the available studies conducted on SCRC and SFSCRC. Unlike these available studies, the research conducted in study 2 was characterized by addressing knowledge gaps in the area of development and optimization of SCRC using SFs. In addition, this research project attempted to identify a new technology to compensate for the reductions of STS and FS resulted from the addition of CR. As seen in **Table 5.4**, Studies 1-6 (Bignozzi and Sandrolini, 2006; Topçu and Bilir, 2009; Güneyisi et al., 2016; Najim and Hall, 2012a; Güneyisi, 2010; Karahan et al., 2012) focused on developing SCRC without considering the use of SFs. However, by looking closely at the results obtained in studies 1-4 (Bignozzi and Sandrolini, 2006; Topçu and Bilir, 2009; Güneyisi et al., 2016; Najim and Hall, 2012a), it can be observed that these studies missed to evaluate the passing ability of the developed mixtures by L-box test, which represents the most challenging obstacle in developing SCRC, as shown in the present work (study 1 and 2) and reported by other researchers (Güneyisi, 2010; Karahan et al., 2012). Such lacking in the results highlights a concern that those mixtures may not fulfill the criteria of self-compactability given by the European Guidelines for Self-Compacting Concrete (2005) and the Interim Guielines for the Use of Self-Consolidating Concrete (2003). Further testing was performed in studies 5-6 (Güneyisi, 2010; Karahan et al., 2012), in which the L-box was conducted to assess the passing ability. In study 5 (Güneyisi, 2010), SCRC could be developed successfully with up to 25% CR, achieving a compressive strength of 21 MPa and a density of 2066 kg/m^3. However, high dosage of HRWRA (13.75 kg/m^3) was used in the development of these mixtures which may increase the risk of segregation, especially for the low-density CR particles. In contrast, in the present work, less amounts of HRWRA (4.38 L/m^3) were used to develop SCRC mixtures containing 30% CR with a relatively higher compressive strength of 31.86 MPa and a lower density of 2006 (mixture 7). Mixtures 1-7 in the present work also appeared to have higher compressive strengths than those obtained in studies 1-6 (see **Table 5.4**), although higher w/b ratio (0.4) was used. This finding may be attributed to the use of MK in the developed mixtures which has a high impact on improving the compressive strength (Madandoust and Mousavi, 2012; Hassan et al., 2015). The experimental work in study 7 (Ganesan et al., 2013a) and 8 (Ganesan et al., 2013b) investigated the behavior of SCRC incorporating SFs under cyclic and fatigue loading using beam-column joints and prisms. These studies, however, used limited number of mixtures (as shown in **Table 5.4**) and focused only on the structural and mechanical behavior of SCRC without discussing the fresh properties and the development of the tested mixtures.

Table 5.4 Summary for the available studies conducted on SCRC and SFSCRC

Study	Mixtures' variables			Rubber % (by fine aggregate volume)	Steel fibres		Unit weight kg/m^3	HRWRA kg/m^3	Remarks on fresh properties	Mechanical properties MPa		
	w/b	C/F	binder		Length (mm)	Volume (%)				f'_c	STS	FS
1. Bignozzi and Sandrolini (2006)	0.34	0.63	566	0	-		2364	4.75	Only slump and J-ring diameters are provided.	33	-	-
				22.2			2224	5.49		24.7	-	-
				33.3			2153	6.51		20.2	-	-
2. Topçu and Bilir (2009)	0.32	0.46	530	-	-		2340	10.6	No data for passing ability. Segregation was observed in mixture of 60, 120, and 180 kg/m^3 CR	49.7	-	-
		0.46		-						37.5	-	-
		0.48		-						28	-	-
		0.49		-						16.9	-	-
3. Güneyisi et al. (2016)	0.35	1	520	0	-		2344	3.4	Passing ability was not evaluated.	62.8	-	-
				5			2314	3.6		53.5	-	-
				10			2283	3.9		49.7	-	-
				15			2253	4.2		44.6	-	-
				20			2223	4.4		36.6	-	-
				25			2192	4.7		31.2	-	-
4. Najim and Hall (2012a)	0.37	1	472	0	-		2408	9	L-box test was not conducted.	56	4.3	8.4
				16.5						37	3.1	7.4
				33						32	3.4	7.1
				49.5						25	2.5	5.5
5. Güneyisi (2010)	0.35	1.05	550	0	-		2319	6.05	Segregation test was not conducted.	42	-	-
				5			2267	6.16		41	-	-
				15			2164	6.99		33	-	-
				25			2066	13.75		21	-	-
6. Karahan et al. (2012)	0.32	0.96	500	0	-		2284.3	2.8	Segregation test was not conducted.	45.2	3.5	5.9
				10			2228.2	3		35.6	3.3	5.4
				20			2172.2	3.2		31.2	3.1	4.8
				30			2116.4	3.6		21.1	2.7	3.8
7. Ganesan et al. (2013a)	0.412	1	600	0	-		2488.9	5.83	Segregation test was not conducted.	52.89	3.21	6.48
	0.427			15	-		2103.7	7.8		41.04	2.83	5.65
	0.427			15	30-mm Crimped	0.5	2162.9	7.8		48.22	3.11	7.14
8. Ganesan et al. (2013b)	0.37	0.8	522	0	-		2312	8.35	Segregation test was not conducted.	58.86	-	5.65
	0.38			15	-		2317.4	8.66		54.83	-	6.48
	0.38			20	-		2317.4	8.71		51.1	-	6.2
	0.38			15	30-mm Crimped	0.5	2356.6	9.08		56.58	-	7.14
	0.38			15	30-mm Crimped	0.75	2376.4	9.14		58.2	-	7.65

6. Discussion of Results from Experimental Study 3: Flexural Performance of Large-Scale Rubberized Concrete Beams with/without SFs

6.1 Introduction

This chapter addresses the knowledge gaps in the area of full-scale testing for SCRC, VRC, SFSCRC, and SFVRC beams. The behaviour of the tested beams was evaluated based on load-deflection response, cracking behavior, first crack load, ultimate load, ductility, and toughness. The performance of some code design equations was evaluated in predicting the cracking moment and flexural capacity of the tested beams. The tested beams were developed with varied percentages of CR (0% to 50%), different SFs volume fractions (0%, 0.35%, and 1%), and different SFs lengths (35 mm and 60 mm). **Table 6.1** summarizes the fresh properties, 28-day compressive strength, and STS of the tested 24 beams' mixtures. **Tables 6.2** and **6.3** present the results obtained from the flexural tests.

Table 6.1 Fresh and mechanical properties of tested beams' mixtures (study 3)

Mixtures optimized from study 1								
Beam /Mix #	Mixture designation	T_{50} (sec)	V-funnel (T_0) (sec)	L-box ratio H2/H1	Air %	HRWR (L/m^3)	f'_c (MPa)	STS (MPa)
SCRC mixtures								
B1/1	SCC-500-0CR	1.20	6.39	0.89	1.5	2.37	50.2	3.87
B2/1	SCC-500-5CR	1.55	6.95	0.83	2.00	2.37	43.0	3.23
B3/1	SCC-500C-10CR	1.74	7.57	0.79	2.3	2.37	41.8	2.94
B4/1	SCC-500-15CR	2.00	8.75	0.75	4.3	2.37	35.3	2.67
B5/1	SCC-550-15CR	1.32	5.97	0.76	3.5	1.84	37.6	2.73
B6/1	SCC-550-20CR	1.54	6.65	0.75	3.2	1.84	32.8	2.49
B7/1	SCC-550-20CR-MK	2.57	8.25	0.86	3.4	5.26	40.8	2.69
B8/1	SCC-550-30CR-MK	2.86	13.5	0.75	4.2	5.26	34.8	2.36
B9/1	SCC-550-30CR-MK-MA	1.53	5.89	0.93	7.5	5.26	30.2	2.27
B10/1	SCC-550-40CR-MK-MA	1.74	9.79	0.84	8	5.53	26.4	1.84
VRC mixtures								
Beam /Mix #	Mixture designation	Slump (mm)			Air %	HRWR (L/m^3)	f'_c (MPa)	STS (MPa)
B11/1	VC-550-40CR-MK	95			4.5	3.50	28.9	2.22
B12/1	VC-550-50CR-MK	80			6.1	4.00	22.4	1.74
Beam /Mix #	Mixture designation	T_{50} (sec)	V-funnel (T_0) (sec)	L-box ratio H2/H1	Air %	HRWR (L/m^3)	f'_c (MPa)	STS (MPa)
Mixtures optimized from study 2								
SCRC/SFSCRC mixtures								
B1/2	SCC-0CR	1.95	7.01	0.91	1.5	3.43	65.61	3.98
B2/2	SCC-5CR	2.39	8.5	0.88	2.0	3.43	58.44	3.72
B3/2	SCC-15CR	2.96	10.59	0.82	3.1	3.75	48.35	3.34
B4/2	SCC-25CR	3.35	14.3	0.77	4.6	3.75	38.35	2.75
B5/2	SCC-5CR-0.35SF	2.62	9.75	0.8	2.4	4.63	59.15	4.36
B6/2	SCC-15CR-0.35SF	3.31	12.05	0.75	3.5	4.63	49.45	3.86
VRC/SFVRC mixtures								
Beam /Mix #	Mixture designation	Slump (mm)			Air %	HRWR (L/m^3)	f'_c (MPa)	STS (MPa)
B7/2	VC-25CR	180			3	3.18	40.26	2.83
B8/2	VC-35CR	145			3.3	3.18	29.73	2.51
B9/2	VC-35CR-0.35SF	185			3	3.64	31.10	3.24
B10/2	VC-35CR-1SF	85			3.1	3.64	32.38	4.40
B11/2	VC-35CR-0.35LSF	170			3.2	3.64	30.71	3.38
B12/2	VC-35CR-1LSF	80			3.4	3.64	31.51	4.73

Table 6.2 Results of the flexure test for beams optimized from study 1

Beam #	Load capacity (kN)		Deflection (mm)		Ductility	Toughness kN.m	Cracking	
							at services load	at failure load
	First crack	Failure/ peak	Yield	Ultimate			Max. width	Max. width
B1/1	32.8	250.0	13.00	42.00	3.23	8.37	0.24	5.0
B2/1	25.3	251.1	12.20	43.80	3.59	8.68	0.22	4.0
B3/1	22.8	249.2	13.10	39.70	3.03	7.78	0.20	3.5
B4/1	21.4	243.3	13.00	39.10	3.01	7.54	0.19	3.0
B5/1	22.0	246.6	13.00	31.80	2.45	5.90	0.23	3.7
B6/1	18.2	243.2	13.20	42.80	3.24	8.16	0.21	3.3
B7/1	20.8	245.0	12.90	26.20	2.03	4.50	0.26	3.0
B8/1	17.2	228.0	13.90	31.10	2.24	5.11	0.23	2.8
B9/1	16.5	219.0	12.00	24.20	2.02	4.02	0.26	2.5
B10/1	13.9	203.6	12.80	21.10	1.65	2.76	0.24	2.0
B11/1	14.8	205.7	13.80	23.10	1.67	3.10	0.26	2.1
B12/1	14.0	197.5	13.90	25.20	1.81	3.32	0.26	2.0

Table 6.3 Results of the flexure test for beams optimized from study 2

Beam #	Load capacity (kN)		Deflection (mm)		Ductility	Toughness kN.m	Cracking	
							at services load	at failure load
	First crack	Failure/ peak	Yield	Ultimate			Max. width	Max. width
B1/2	32.88	296.12	11.6	36.90	3.18	8.59	0.26	3.5
B2/2	29.80	286.91	11.5	38.00	3.30	8.63	0.24	3.2
B3/2	25.30	266.75	11.5	37.20	3.23	7.81	0.20	2.5
B4/2	20.66	247.82	11.7	34.10	2.91	6.72	0.20	2.3
B5/2	33.50	298.93	11.8	41.65	3.53	9.93	0.18	3.5
B6/2	27.90	277.97	12.0	40.40	3.37	9.14	0.15	3.0
B7/2	21.88	255.29	11.7	31.40	2.68	6.20	0.20	2.1
B8/2	18.11	231.27	12.7	22.50	1.77	3.56	0.24	2.0
B9/2	19.98	243.12	12.5	28.00	2.24	5.22	0.20	2.8
B10/2	24.11	263.08	12.8	38.75	3.04	8.37	0.13	3.2
B11/2	19.57	241.50	12.7	27.20	2.14	4.96	0.20	2.6
B12/2	23.26	254.94	12.9	36.95	2.86	7.59	0.15	2.9

6.2 Flexural Behaviour

6.2.1 Load-Deflection Characteristics

Figure 6.1 presents the load-central deflection responses of the tested beams that were optimized from study 1 (B1/1-B12/1). Looking closely at the curves of B1/1-B12/1, it can be observed that up to the first crack load, the curves appear to be linear with higher stiffness. Beyond this limit of loading, the slope of the curves gradually decreases that indicates lower stiffness due to formation of micro-cracks. After additional application of load, the longitudinal reinforcement started to yield. During the lifetime between the first crack load and the load that caused steel yielding, the slope of the load-deflection curves changed many times due to multiple cracking. Further increasing the applied load finally caused the concrete crushed in the compression zone and beams to fail. Then, the applied load started to decrease gradually until a sudden drop happened. All plots present a typical ductile mode of failure, normally called tension failure, in which the steel bars in tension side yielded before the failure occurrence (as confirmed from the steel strain gauges). The load-deflection curves show that the flexural stiffness (the slope of the load-central deflection curve) of the tested beams decreased as the CR content increased. However, this decrease was not clear in beams with 0%–15% CR (B1/1-B4/1) (**Figure 6.1a**) and was more pronounced in beams with higher percentages of CR (more than 20%) (see **Figures 6.1b**, **6.1c**, **6.1d**, and **6.1d**). This reduction in stiffness could be attributed to the low modulus of elasticity of rubber particles compared to the replaced fine aggregate, which in turn decreased the overall stiffness of the tested the beams.

The SCRC beams optimized from study 2 (B1/2-B4/2 and B7/2-B8/2) showed load-central deflection responses similar to that of B1/1-B12/1 (see **Figures 6.2a** and **6.2b**). However, the reduction in the stiffness of beams with increasing the CR content from 0% to 15% appeared to be more pronounced, as shown in B1/2-B3/2 compared to B1/1-B4/1 (**Figure 6.1a vs Figure 6.2a)**. By looking at B1/1-B4/1 and B1/2-B3/2, it can be observed that the tested beams showed comparable ultimate deformation in the range of 0%~15% CR. Further increase in the CR (more than 15%) showed inconsistent effect on the deformation capacity of beams. The beams optimized from study 1 (B5/1-B12/1) exhibited an increase in the ultimate deformation as the CR increased (B6/1 vs B5/1, B8/1 vs B7/1, and B12/1 vs B11/1), indicating an improvement in the ductility of post-peak stage. On the other hand, increasing the CR content to 25% and 35% in B4/2 and B7/2-B8/2 (beams optimized from study 2) appeared to limit the deformation capacity of beams. Such behaviour highlights the need for a further research to understand the effect of CR on the deformability of beams, especially when high percentage of CR is used. **Figure 6.2b** also shows that changing the concrete type (VRC compared to SCRC) did not show a significant impact on the flexural stiffness and ultimate deformation of tested beams (as shown in B7/2 compared to B4/2, respectively).

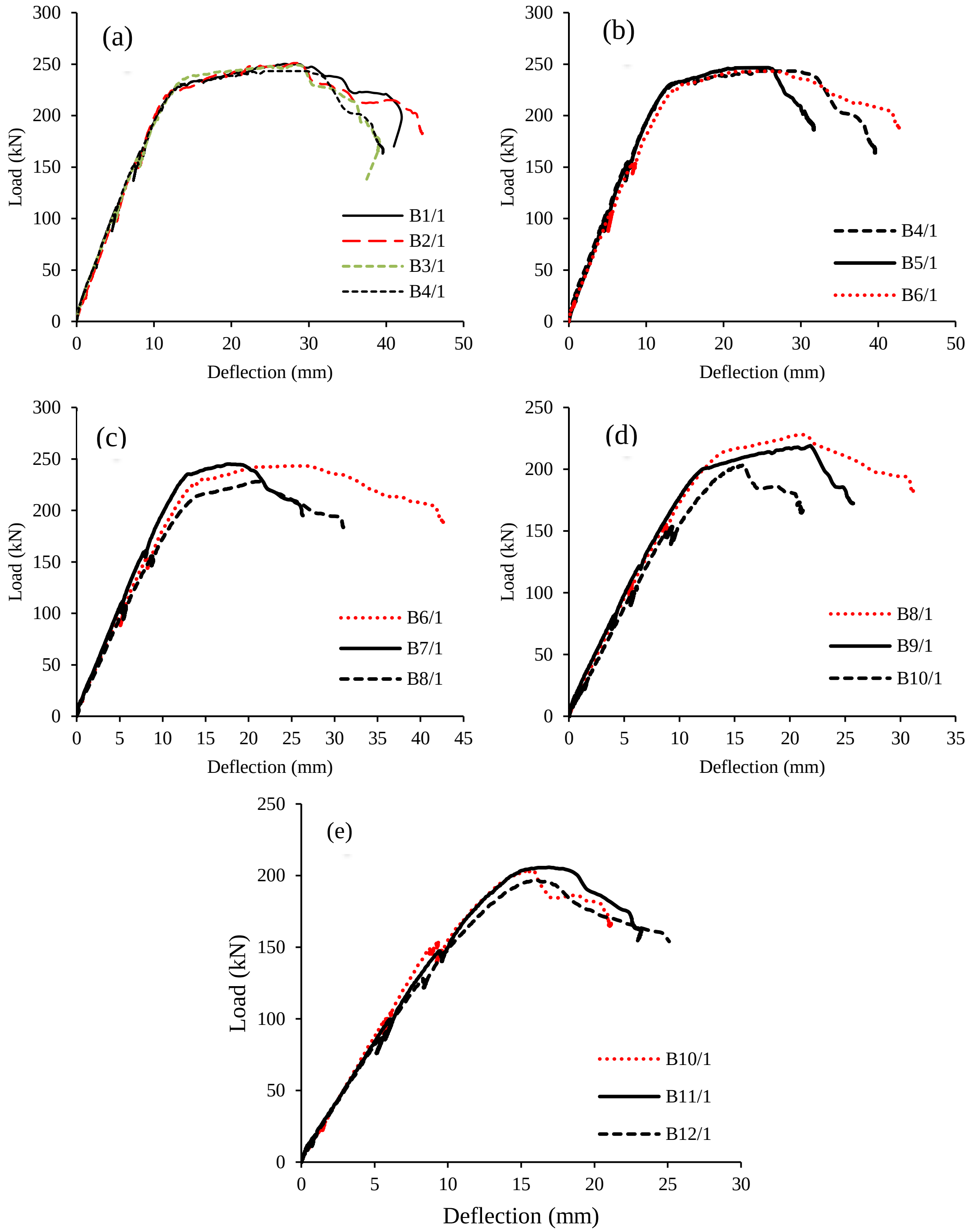


Figure 6.1 Experimental load-central deflection responses of beams optimized from study 1

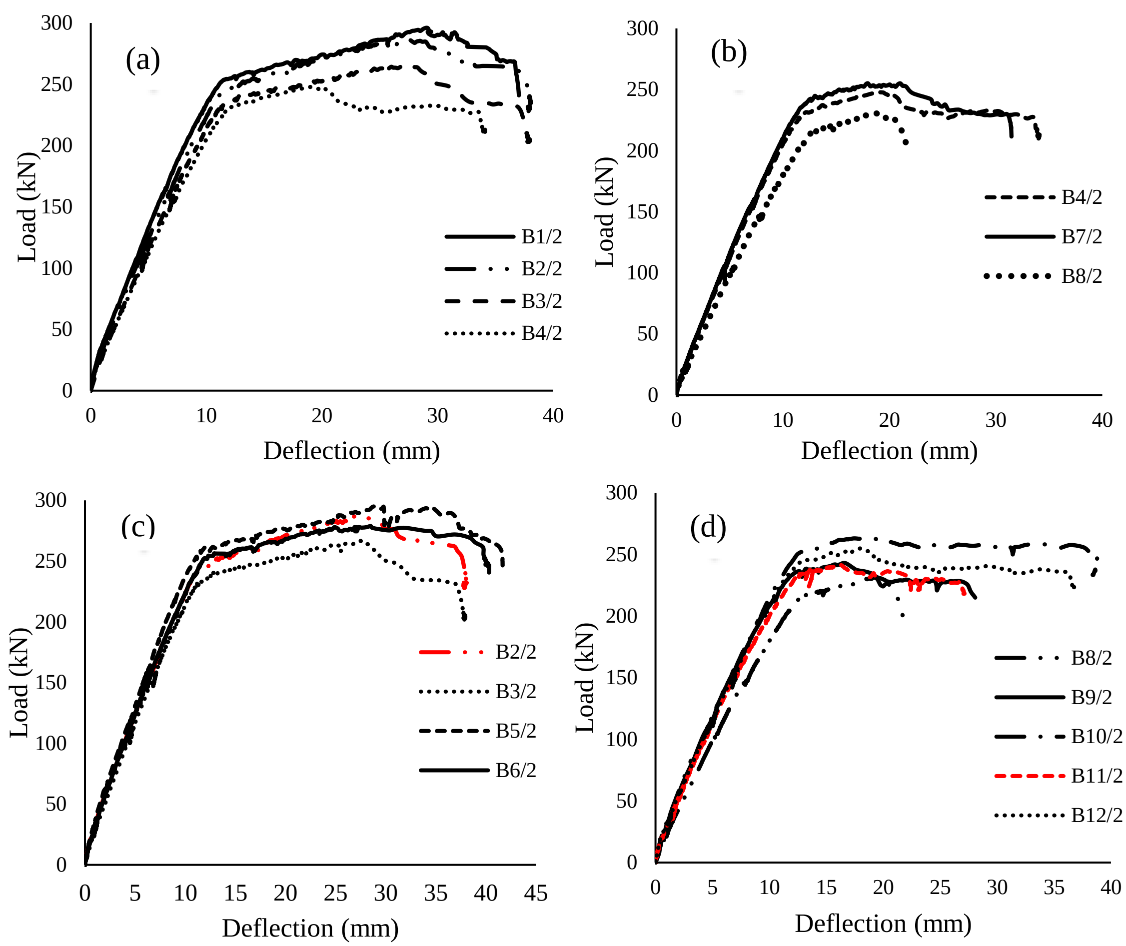


Figure 6.2 Experimental load-central deflection responses of beams optimized from study 2

Using 0.35% SFs (35 mm) appeared to increase the flexural stiffness of the tested beams, as shown in B5/2, B6/2, and B9/2 compared to B2/2, B3/2, and B8/2, respectively (**Figures 6.2c** and **6.2d**). Such finding is attributed to the stitching action of fibres that limits the cracks' opening and their propagation. The ultimate deformation capacity of tested beams also increased by inclusion of SFs, thus indicating a more ductile behaviour compared to their counterpart beams with no SFs. Higher volume of fibres (1%) led to a further cracking control at comparable load, higher beams' stiffness, and helped the beams to experience larger ultimate deflections (B10/2 compared to B8/2) prior to the failure. By comparing

B11/2 to B9/2 and B12/2 to B10/2, it can be seen that using longer SFs (60 mm) showed comparable a stiffness and ultimate deformation capacity with that of short SFs (35 mm), as shown in **Figure 6.2d**.

6.2.2 Cracking Behaviour

Figures 6.3 and **6.4** show the crack pattern including widths and numbers for all tested beams. **Tables 6.2** and **6.3** also present the maximum crack width of each tested beam at service and failure load. In this study, 40% of the estimated failure load was taken as a customary service load level, which is in agreement with the assumption given by Gholamreza et al. (2009). From the results, it can be observed that increasing the percentage of CR generally showed a reduction in the maximum crack width of tested beams at both service and failure load. For example, increasing the percentage of CR from 0% to 15% (beams with comparable ultimate deflection) reduced the maximum crack width from 5 to 3 mm in B1/1-B4/1 and from 3.5 to 2.5 mm in B1/2-B3/2. Such results may be attributed to decaying the tensile strength of concrete as the CR increased, which may allow for developing larger number of visual and tiny cracks instead of continuous widening of one localized crack, thus reducing the overall cracks' widths. By looking at VRC compared to SCRC beams (B7/2 compared to B4/2), it can be seen that the type of concrete did not have a significant effect on the cracking behaviour of beams (see **Figure 6.4 and Table 6.3**).

By examining the effect of SFs, it can be observed that all beams with SFs at service load showed narrower maximum crack widths compared to beams with no SFs. The reason is due to the role of SFs in stitching the developed cracks and delay their propagation and widening for given load. However, at failure stage the SFs beams exhibited larger cracks' number and/or widths than that exhibited by beams with no SFs. This could be attributed to that the presence of SFs allowed the beams to experience large deformations and load-carrying capacity prior to failure, as shown in **Figures 6.2c** and **6.2d**, which contributed to developing higher number and/or wider cracks. For example, in SFSCRC beams, using 0.35% SFs (35 mm) with 5% and 10% CR (B5/2 and B6/2, respectively) decreased the maximum crack width at service load to 0.18 and 0.15 mm, respectively, compared to 0.24 and 0.2 mm in beams with no SFs (B2/2–B3/2), respectively. On the other hand, these maximum crack widths reached at failure to 3.5 and 3 mm in B5/2 and B6/2, respectively, compared to 3.2 and 2.5 mm in B2/2 and B3/2, respectively. A similar effect for SFs was confirmed in SFVRC beams (B9/2 and B10/2 compared to B8/2). Beams with 60 mm SFs exhibited similar cracking behaviour to that with 35 mm SFs, as shown in B11/2-B12/2 compared to B9/2-B10/2.

As per serviceability, the design codes assume some limitations for the maximum allowable crack width at service load in order to fix problems with long-term durability. From **Tables 6.2** and **6.3**, it can be seen that the measured maximum crack width at service load for all tested beams were less than the critical crack width for the exterior exposure condition given by CSA (2004) (0.33 mm), ACI 318 (1995) (0.33 mm), and BS 8110 (1997) (0.3 mm). In addition, the measured crack widths satisfied the limit of 0.3 mm maximum crack width assumed by ACI 224R (2001) and CEB-FIP (1990) with respect to specific exposure classes. This finding may extend the possible applications of rubberized concrete with/without SFs to be used safely in specified exterior-exposed structures.

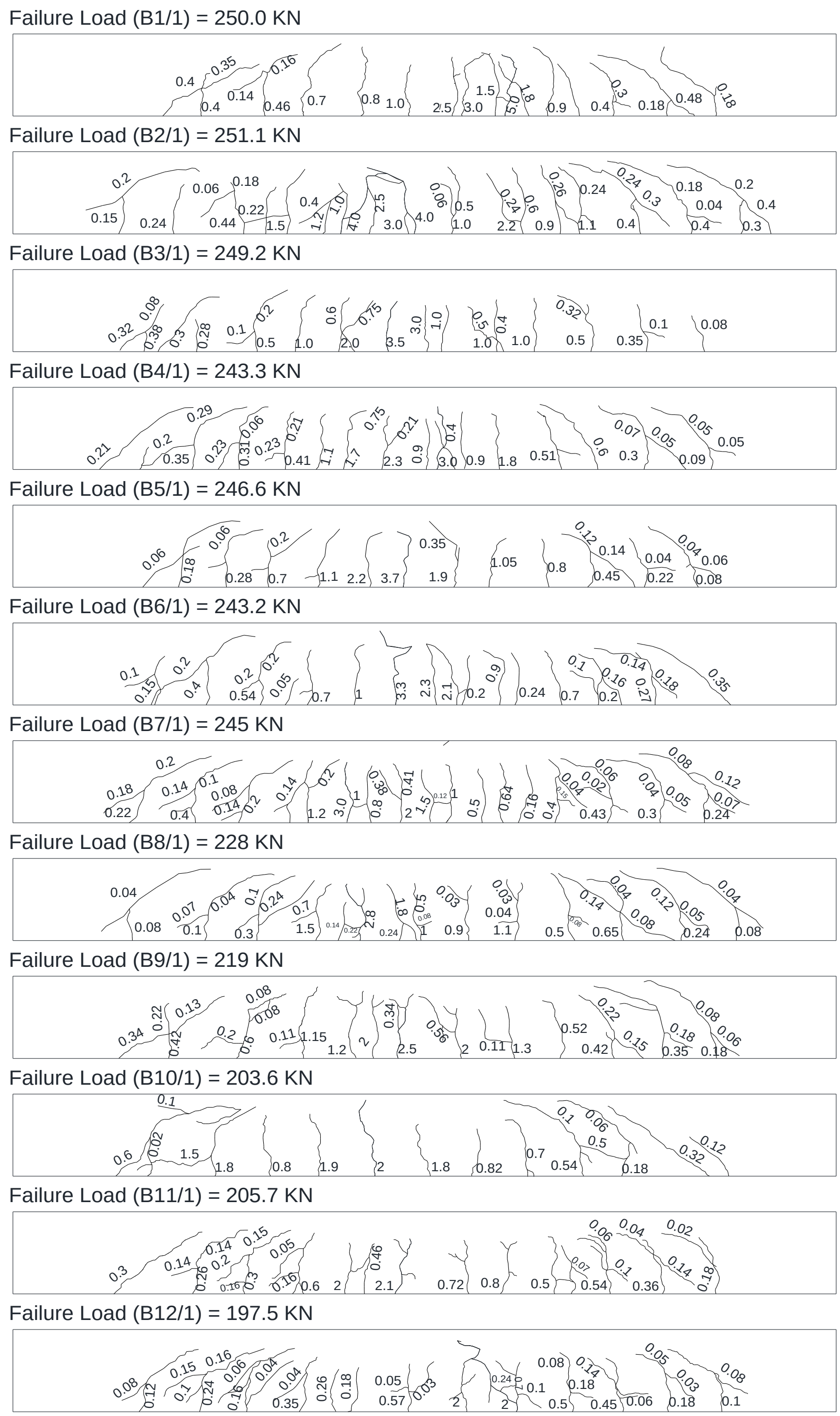


Figure 6.3 Failure crack patterns of tested beams optimized from study 1 (crack width in mm)

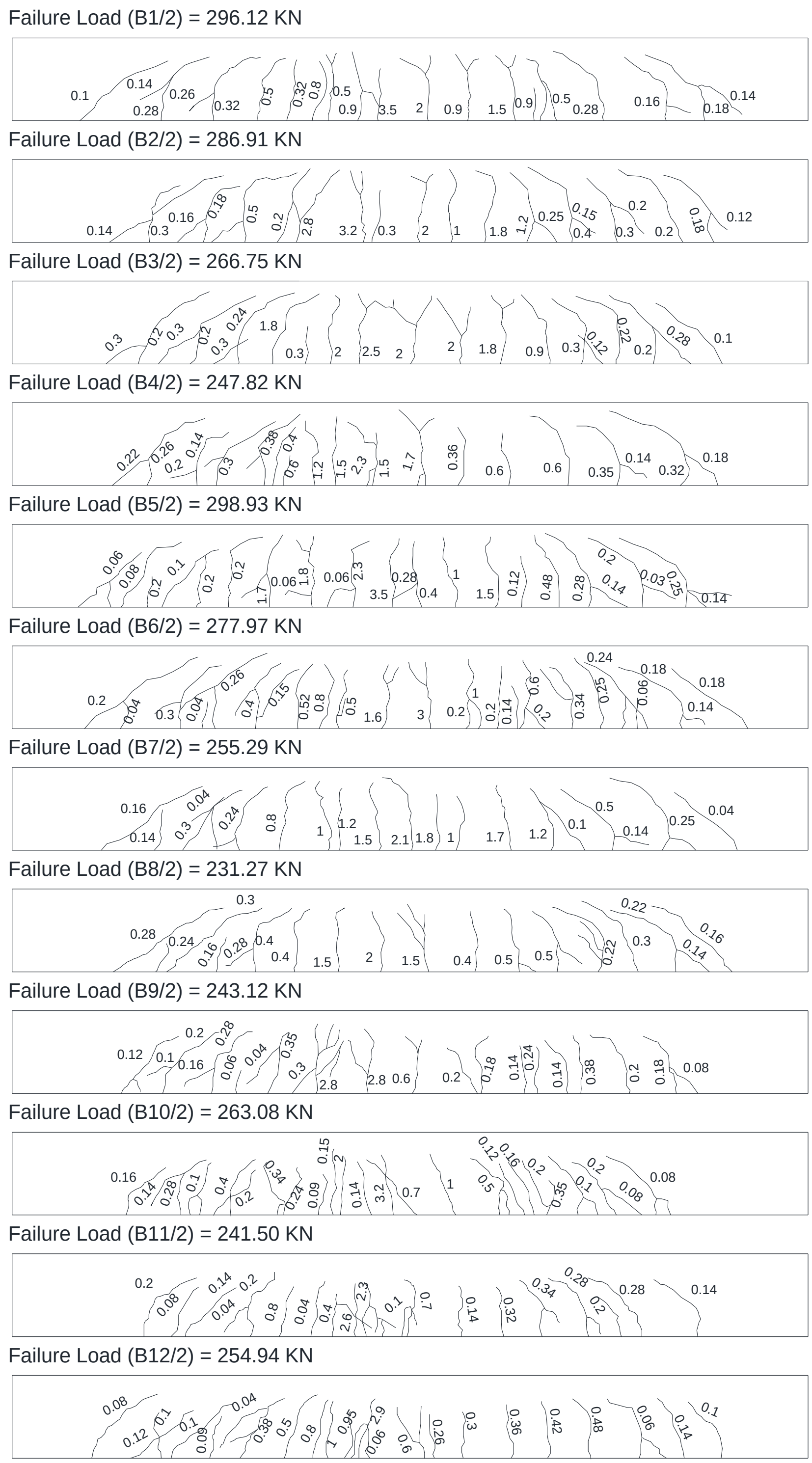


Figure 6.4 Failure crack patterns of tested beams optimized from study 2 (crack width in mm)

6.2.3 Experimental and Theoretical Bending Moment Capacity

6.2.3.1 SCRC and VRC Beams

Figures 6.5a and **6.5b** present the experimental ultimate moment capacity (M_u^{exp}) of all tested beams. The results showed that increasing the CR content generally reduced the M_u^{exp} in all tested beams. By examining both sets of beams (B1/1-B12/1 and B1/2-B12/2), it can be observed that increasing the percentage of CR from 0% to 15% decreased the M_u^{exp} by an average of 6.3% (in B1/1-B4/1 and B1/2-B3/2), reaching about 93.7% (on average) of that reached by the control beams (with no CR). This decrease seemed to be more pronounced at high percentage of CR. For example, increasing the percentage of CR by increment of 10% in VRC beams (from 25% in B7/2 to 35% in B8/2) decreased the M_u^{exp} by 9.4%. Such finding may be attributed to the fact that increasing the CR increases the volume of the weakened rubber-mortar interface in concrete composite, which significantly decayed the ability of beam to sustain higher load. Comparing VRC to SCRC (B7/2 compared to B4/2) showed insignificant effect for the concrete type, in which both beams had comparable flexural capacity. It is worth noting that mixtures of beams with CR content varied from 30% to 50% (in B8/1-B12/1) and from 15% to 35% (in B3/2-B12/2) achieved densities within the range of 1850 to 2150 kg/m^3, which is classified as a semi-lightweight concrete according to the CSA (2004).

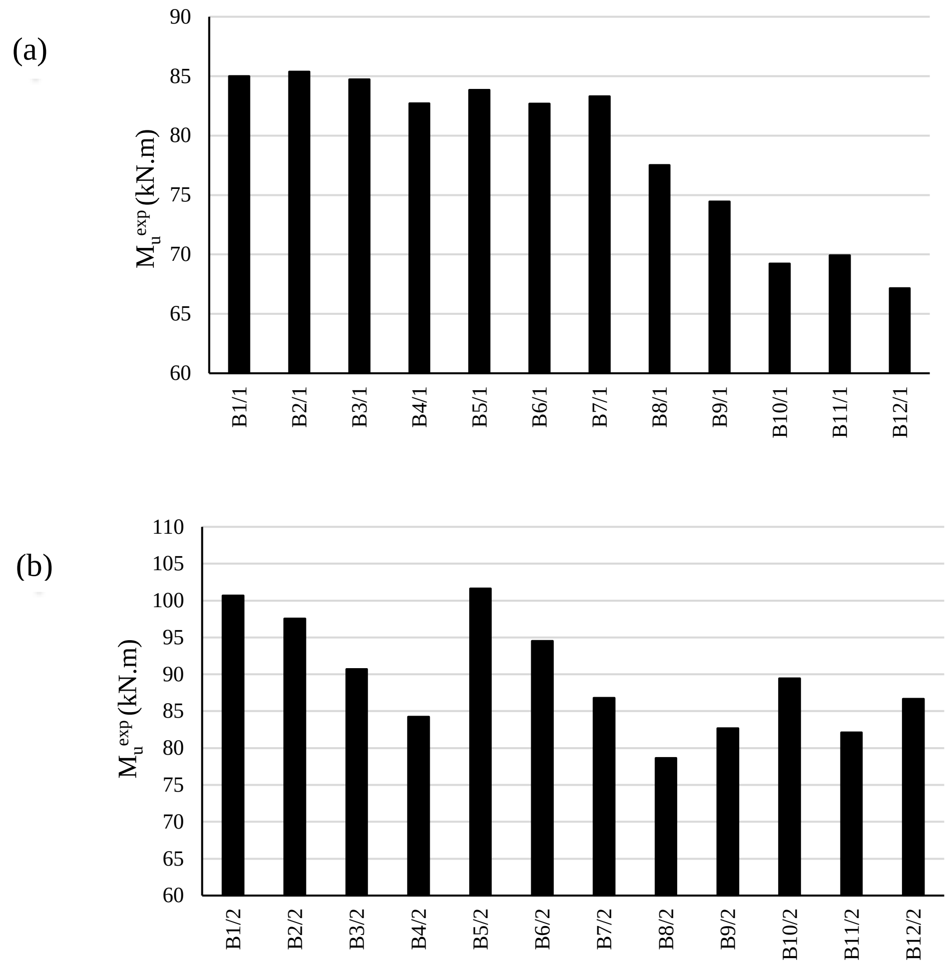
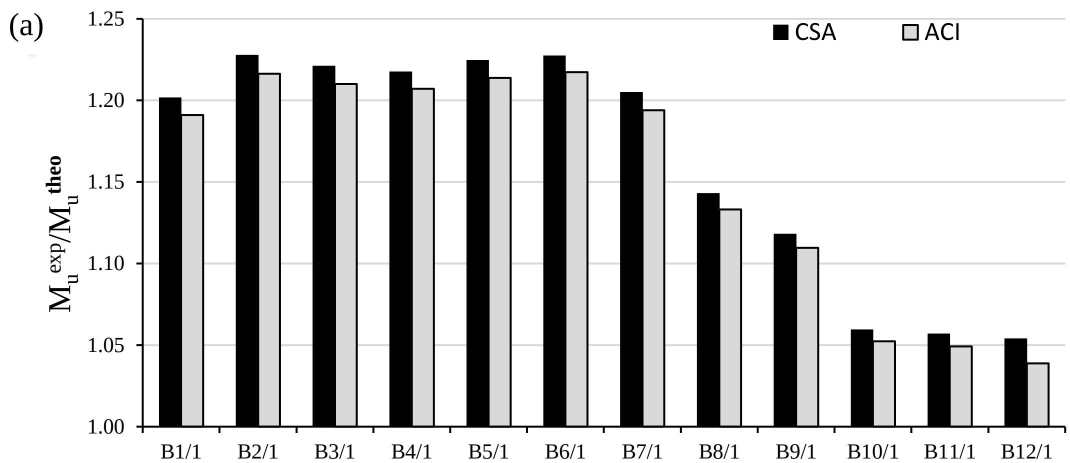


Figure 6.5 Ultimate moment capacity (a) beams optimized from study 1, (b) beams optimized from study 2

In this study, the M_u^{exp}. of each tested beam were compared to the theoretical design moments (M_u^{theo}.) predicted using the rectangular stress block analysis, as recommended by CSA (2004) and ACI 318 (2008). As shown in **Figures 6.6a** and **6.6b**, the comparison showed that the CSA (2004) and ACI 318 (2008) underestimated the flexural capacity of the tested beams by a range of 4%-32%. Increasing the CR content appeared generally to decrease the value of M_u^{exp}/M_u^{theo}, which indicates a lower margin of safety with the inclusion of CR. Such finding is attributed to the fact that the proposed approaches are established for conventional concrete with no CR, and hence further research is required to include the effect of CR on flexural capacity of beams.



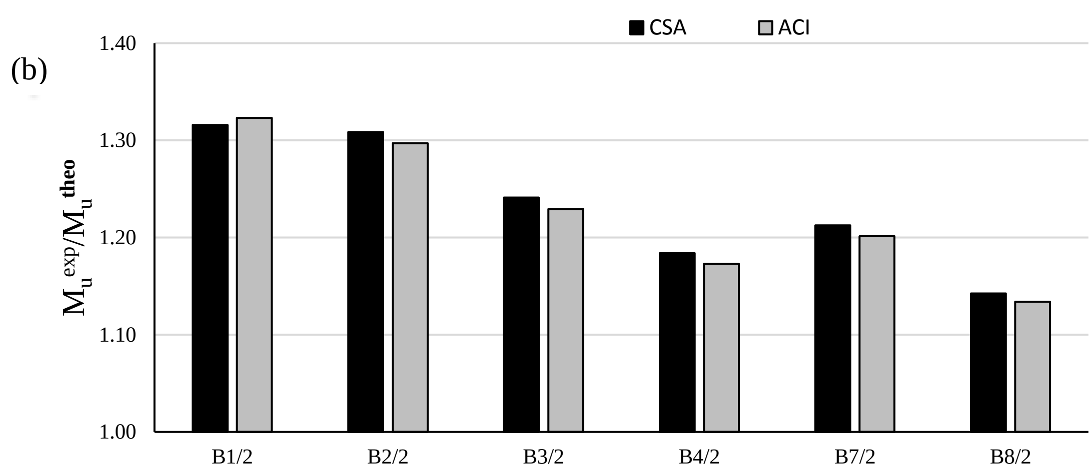


Figure 6.6 The ratio between the experimental ultimate moment to that predicted for SCRC and VRC beams (a) beams optimized from study 1, (b) beams optimized from study 2

6.2.3.2 SFSCRC and SFVRC Beams

From **Figure 6.5b**, it can be seen that using 0.35% SFs (35 mm) slightly improved the flexural capacity of the tested beams. Adding SFs to SCRC beams with 5% and 10% CR (B5/2-B6/2) increased the M_u^{exp} by an average of 4.2% compared to beams with no SFs (B2/2-B3/2), achieving a flexural capacity of 100.9% and 93.9% of that reached by the control beam (B1/2), respectively. In SFVRC beam (B9/2-B10/2), adding 0.35% and 1% SFs (35 mm) exhibited around 5% and 13.75% increase in the M_u^{exp} compared to beam with no SFs (B8/2). These increases in the M_u^{exp} in those beams (B9/2-B10/2) with high percentage of CR (35%) contributed to the development of semi-lightweight beams (with a density of 2040 and 2073 kg/m^3, respectively) with a flexural capacity of 82.1% and 88.8% of that reached by beams with no CR, respectively. Using 60 mm SFs with volumes of 0.35% and 1% (B11/2 and B12/2, respectively) improved the flexural capacity by 4.4% and 10.2%, respectively. These improvements in the flexural capacity are due to the fibres' contribution in transferring the tensile stress across the cracks by the bridging mechanism, as explained before.

A method developed by Henager and Doherty (1976) was used to calculate the M_u^{theo} for beams with fibres. This method is derived based on the rectangular stress block analysis of the ACI but takes into account the contribution of SFs in the tension zone. The basic design assumptions of the proposed model are presented in clause 3.2.2 of ACI 544.4R (1999). **Figure 6.7** shows the M_u^{exp}/M_u^{theo} ratio for each SFs beam. From the figure, it can be seen that the proposed model predicted the ultimate moment reasonably well, in which the

M_u^{exp}/M_u^{theo} ratio ranged from 1.14 to 1.27. However, similar to beams without SFs, increasing the percentage of CR seemed to reduce the safety's margin of the proposed model, as shown in B5/2-B6/2 when the percentage of CR increased from 5% to 15%.

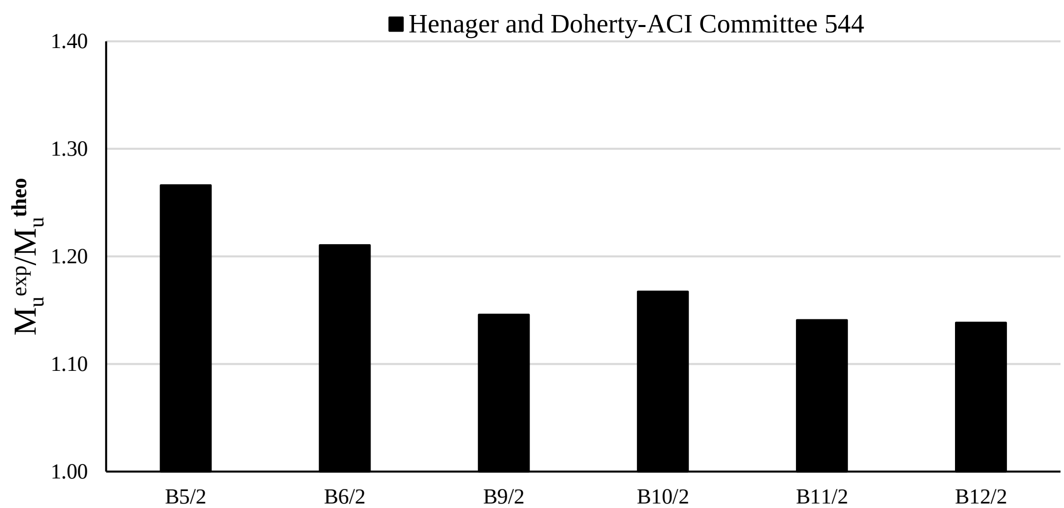


Figure 6.7 The ratio between the experimental ultimate moment to that predicted for SFSCRC and SFVRC beams (optimized from study 2)

6.2.4 Ductility

Ductility ratio (μ) of tested beams is defined in terms of $\mu = \delta_u / \delta_y$, where δ_u is the ultimate experimental deflection value and δ_y is the experimental deflection at yielding. The ductility ratios of all beams are presented in **Tables 6.2** and **6.3** and **Figure 6.8 (a** and **b)**. Beams with up to 15% CR showed a comparable ductility, in which the μ of B1/1-B4/1 and B1/2-B3/2 ranged from 3.23 to 3.01 and from 3.18 to 3.23, respectively, when the percentage of CR increased from 0% to 15%. It should be noted that in both sets of beams (B1/1-B4/1 and B1/2-B3/2), the highest ductility ratio was found in beams with 5% CR

(B2/1 and B2/2). Previous studies have stated that the members with a displacement ductility in the range of 3 to 5 achieve adequate ductility suitable for structural members subjected to large displacements, such as those in the areas of seismic activities (Ashour, 2000; Teo et al., 2006; Gunasekaran et al., 2013). Beams optimized from study 1 (B5/1-B12/1) showed that the ductility enhancement continued as the percentage of CR increased (B6/1 vs B5/1, B8/1 vs B7/1, and B12/1 vs B11/1), but these beams exhibited lower ductility ratios compared to beam with no CR, except B6/1 (incorporating 20% CR) (see **Figure 6.8a**). On the other hand, beams optimized from study 2 (B4/2 and B7/2-B8/2) showed a continuous decay in the ductility of beams when the percentage of CR increased to 25% and 35% (see **Figure 6.8b**). Such results indicate unconfirmed effect for the high percentages of CR on beams' ductility, thus highlighting a need for further investigations. Generally, however, the lower ductility ratios obtained at high percentage of CR (more than 20% in B7/1-B12/1 and/or more than 15% in B4/2 and B7/2-B8/2) may be related to the weakened concrete at the compression zone due to the poor bonding between the CR and the surrounding mortar, which limited the beams' ability to experience higher loading beyond the yielding point. The results also indicate that the SCRC beam (B4/2) had a ductility ratio 8.6% higher than that of the VRC beam counterpart (B7/2).

The inclusion of SFs allowed the beams to experience more deformations prior to the failure, which in turn increased the ductility ratio of tested beams. As shown in **Figure 6.8b**, using 0.35% SFs (35 mm) in B5/2 and B6/2 (SFSCRC beams) raised the μ by an average of 5.7% compared to their SCRC counterparts beams with no SFs (B2/2-B3/2), achieving a ductility of 1.11 and 1.06 times, respectively, as much as the control beam. The improvement in the ductility reached up to 26.6% in VRC beam with 35% CR when 0.35% SFs (35 mm) was used (B9/2 compared to B8/2). Further increase in the volume of SFs exhibited more improvements in the ductility of beams, in which adding 1% SFs (35 mm) to beam with 35% CR increased the ductility by 71.8% (see B10/2 compared to B8/2), reaching to around 96% of the ductility of the control beam. Such behavior is attributed to the bridging mechanism of SFs, which allowed the beams to endure higher ultimate loading and undergo large deformation beyond the yielding point, as explained earlier. Increasing the length of fibres to 60 mm also improved the ductility of tested beams, but with slightly less values compared to SFs of 35 mm length, as shown in B11/2-B12/2 compared to B5/2-B6/2 (see **Table 6.3** and **Figure 6.8b**).

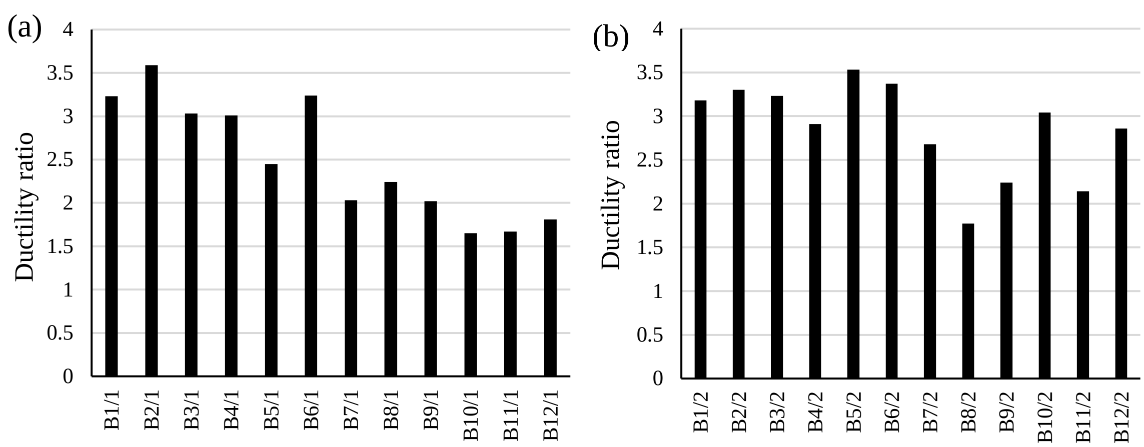


Figure 6.8 Ductility ratios (a) beams optimized from study 1, (b) beams optimized from study 2

6.2.5 Toughness

The flexural toughness was calculated as the area under the load-midspan deflection curve up to failure point, which was taken similar to the case of ductility. The toughness values of the all tested beams are listed in **Tables 6.2** and **6.3** and **Figure 6.9**. By looking at the load-midspan deflection curves in **Figures 6.1 and 6.2**, it can be seen that the inclusion of CR appeared to increase the deformability of the tested beam at given load, which indicates an improvement in the energy absorption of beam at comparable load. However, inclusion of CR negatively affected the load-carrying capacity of the tested beams, which in turn limited the overall beams' ability to absorb high energy prior to failure. As shown in **Tables 6.2** and **6.3**, beam with 15% CR reached a toughness of about 90% (10% reduction) of that reached by the control beam (as shown in B4/1 compared to B1/1 and B3/2 compared to B1/2). Similar to the ductility, the highest toughness value was exhibited by the inclusion of 5% CR. Further increase in the percentage of CR (more than 15%) continued to decrease the toughness of the tested beams as confirmed by B4/2 and B7/2-B8/2. On the other hand, B5/1-B12/1 showed an increase in the toughness of beams when the percentage of CR increased more than 15% (similar to the results of ductility ratios), as shown in B6/1 vs B5/1, B8/1 vs B7/1, and B12/1 vs B11/1. This inconsistency in the results is attributed to the fact that the toughness is a combination of strength and ductility, therefore, the unconfirmed effect for high percentages of CR on the beam's ductility directly led to a contrariety in the results of beams' toughness. Similarly, the toughness of beams was affected by changing the concrete type (i.e. SCRC vs VRC) similar to the ductility, in which by comparing the SCRC to VRC, it can be observed that VRC beam (B7/2) exhibited lower toughness than that of SCRC beam (B4/2) by 7.7%.

Figure 6.9b and **Table 6.3** show that combining SFs with CR improved the toughness of the tested beams. For instance, adding 0.35% SFs (35 mm) in B5/2 and B6/2 (with 5% and 15% CR, respectively) increased the toughness by 15.1% and 17%, respectively, compared to beams with no SFs (B2/2-B3/2). These increases achieved beams with a toughness of about 1.16 and 1.06 times, respectively, as much as the control beam. The increase in toughness due to the addition of SFs was more obvious in beam with high percentage of CR, in which adding 0.35% SFs (35 mm) to beam with 35% CR (B9/2) boosted the toughness by 46.6%. This may be related to that at high percentage of CR, the rubber-mortar composite become very weak and more susceptible to the fibres' mechanism in improving the ability to absorb more energy prior to failure. Combining 1% SFs and 35% CR in B10/2 exhibited a toughness higher than that of beam with no CR (B8/2) by 235.1% (which equal to 97% of the toughness of the control beam). Meanwhile, using 0.35% and 1% from 60 mm SFs (in B11/2 and B12/2, respectively) increased the toughness by 39.3% and 213.2% compared to B8/2 (with no SFs), thus indicating a slightly lower efficient compared to 35 mm SFs. Such results may be related to the fact that at a given fibre volume, using shorter/smaller SFs increases the number of fibres that may be oriented perpendicularly to cracks, and hence efficiently contribute to transferring the stress across the cracks allowing the beams to absorb more energy before failure.

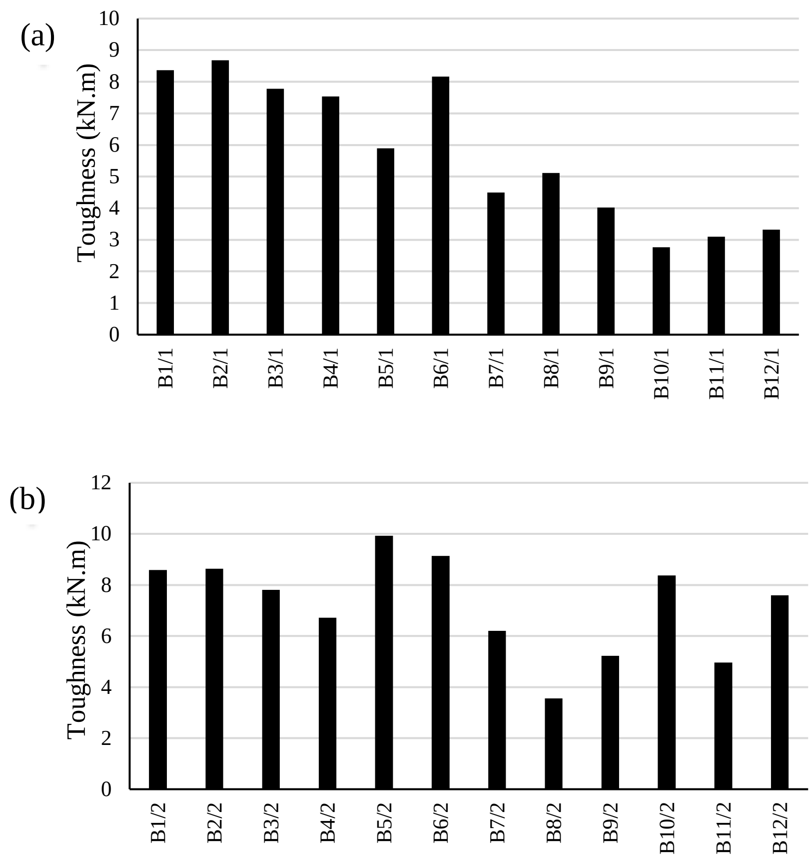


Figure 6.9 Toughness (a) beams optimized from study 1, (b) beams optimized from study 2

6.2.6 Experimental and Theoretical Analyses of Cracking Moment

The first flexural crack was detected with the naked eye and verified by the first step or slope change in the load-deflection response (if possible). **Figure 6.10** presents the cracking moment values (M_{cr}^{exp}) associated with the first flexural crack. The observed cracking moment was also compared to the theoretical values (M_{cr}^{theo}), which were calculated based on equations provided by ACI (2008), CSA (2004), AS 3600 (1988), and EC2 (2005), as follows:

As per ACI (2008):

$$M_{cr}^{theo} = f_r \frac{I_g}{y_t} \tag{6.1}$$

where $f_r = 0.62\lambda\sqrt{f_c'}$ for normal-weight concrete; λ is taken as equal to 1 for normal-density concrete and 0.85 for lightweight sand; y_t is the distance from centroidal axis of the gross section to the extreme tension fibre; and *Ig* is the second moment of area of the gross section (the steel bars are not considered).

As per CSA (2004):

$$M_{cr}^{theo} = f_r \frac{I_g}{y_t} \tag{6.2}$$

where $f_r = 0.6\lambda\sqrt{f_c'}$ for normal-weight concrete; λ is taken as equal to 1 for normal-density concrete and 0.85 for semi-low-density concrete (density ranged from 1850 to 2150 kg/m^3).

As per the AS (1988):

$$M_{cr}^{theo} = Zf_{cf}' \tag{6.3}$$

where f_{cf}' is the characteristic flexural tensile strength of the concrete = 0.6 $\sqrt{f_c'}$; and Z (= I/y) is the section modulus of the uncracked section, referring to the extreme fibre at which cracking occurs.

As per EC2 (2005):

$$M_{cr}^{theo} = f_{ctm} \frac{I_u}{(h - x_u)} \tag{6.4}$$

where f_{ctm} is the mean value of axial tensile strength of concrete = $0.3f_{ck}^{0.67}$; f_{ck} is the characteristic compressive cylinder strength of the concrete at 28 days; I_u is the second moment of area of the uncracked section; x_u is the distance from the neutral axis of the section to the extreme top fibre; and h is the height of the cross section of the beam.

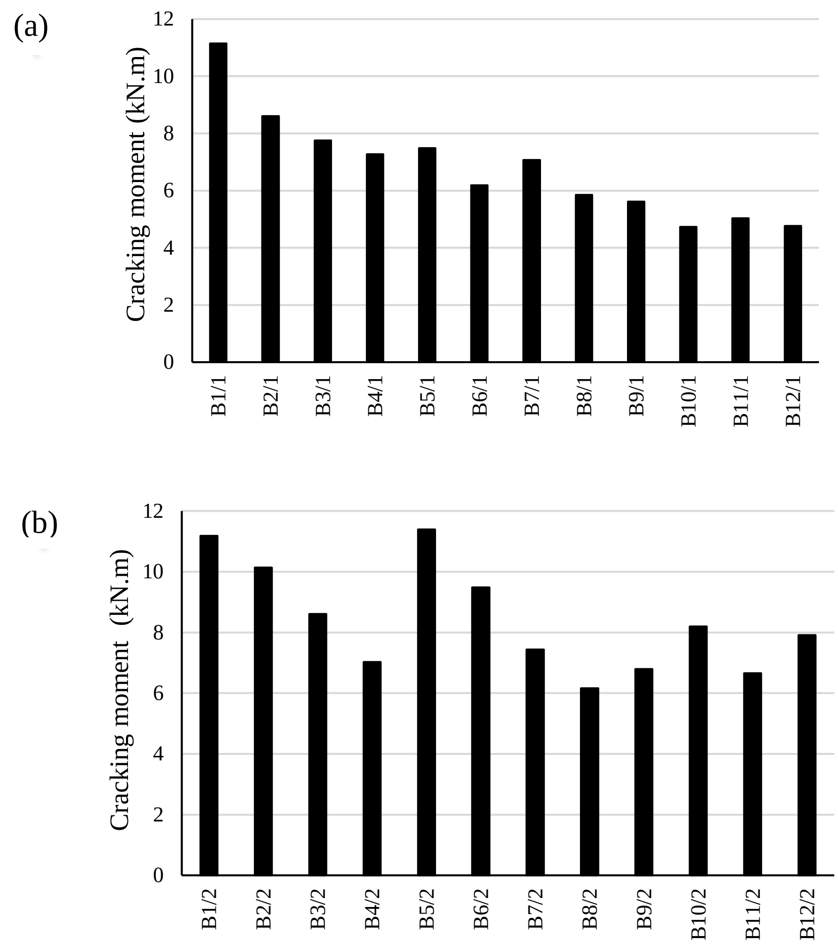


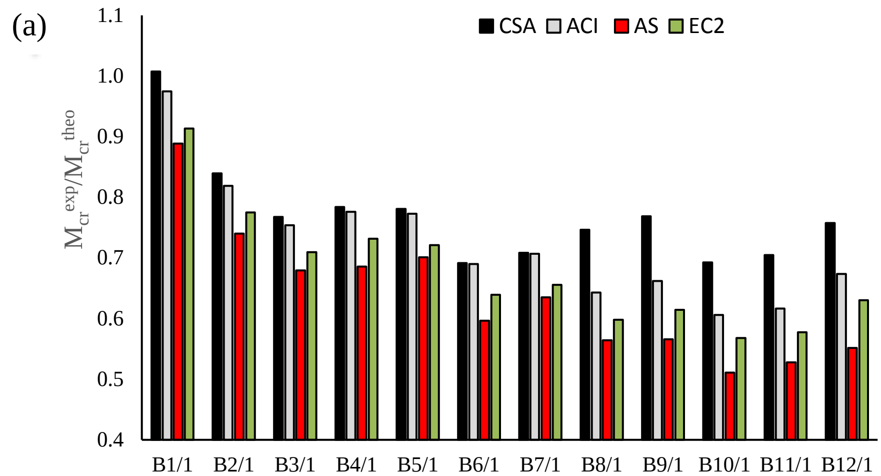
Figure 6.10 Cracking moment: (a) beams optimized from study 1, (b) beams optimized from study 2

6.2.6.1 SCRC and VRC Beams

As shown in **Figures 6.10a** and **6.10b**, the M_{cr}^{exp} decreased as the percentage of CR increased. For example, varying the CR content from 0% to 15% in SCRC beams decreased the M_{cr}^{exp} by 34.8% in B1/1-B4/1 and by 23.1% in B1/2-B3/2. The VRC beams (B12/1 compared B11/1 and B8/2 compared to B7/2) confirmed the negative impact of CR on the first cracking moment of tested beams. This decrease in the cracking moment is directly related to the significant decay in the tensile strength of the concrete with the increase in CR content, which was confirmed by the STS test results (**Table 6.1**). The results also showed that the VRC beam (B7/2) exhibited slightly higher M_{cr}^{exp} than that of SCRC beam (B4/2) by 5.9%.

Figures 6.11 and **6.12** show the experimental-to-theoretical cracking moment (M_{cr}^{exp}/ M_{cr}^{theo}) of the tested SCRC and VRC beam. In this study, the cracking moments were calculated using two approaches. The first approach is based on using a tensile strength derived proportionally from the compressive strength (as proposed by each code design). The second approach is based on using a tensile strength obtained from experiments (STS). **Figures 6.11a** and **6.11b** illustrate the M_{cr}^{exp}/ M_{cr}^{theo} ratios, where the M_{cr}^{theo} was calculated based on compressive strength (i.e. f_r-ACI = $0.62\lambda\sqrt{f_c'}$, f_r-CSA = $0.6\lambda\sqrt{f_c'}$, f_{cf}'-AS = $0.6\sqrt{f_c'}$, and f_{ctm}-EC2 = $0.3f_{ck}^{0.67}$). From the figures, it can be seen that the equations proposed by ACI, EC2, CSA, and AS seemed generally to overestimate the cracking moment of the tested beams, even the beam with no CR (B1/1 and B1/2). These results are in agreement with what other researchers have found (Fathifazl et al., 2009), in which using the ACI equation yielded cracking moment values higher than that obtained from experiments conducted on conventional reinforced concrete beams. However, using ACI and CSA in predicting the cracking moment of beams with no CR exhibited M_{cr}^{theo} values within the range of 1 ± 0.20 of M_{cr}^{exp}, which can be an acceptable accuracy for codes' prediction (Fathifazl et al., 2009). The EC2 and AS gave higher estimations (lower M_{cr}^{exp}/ M_{cr}^{theo} ratios) compared to that of ACI and CSA. This is attributed to the fact that ACI and CSA codes neglect the effect of longitudinal reinforcement in the calculation of the second moment of area of the uncracked section, while AS and EC2 take it into account, thus yielding higher M_{cr}^{theo} compared to M_{cr}^{exp}. **Figures 6.11a** and **6.11b** also show that the inclusion of CR appeared to increase the error of the codes' predictions. This finding indicates that further modifications are needed to take the influence of CR into the calculation of cracking moment.

By using the second approach (based on STS), the codes' equations appeared generally to exhibit better predictions, as shown in **Figure 6.12b** compared to **Figure 6.12a**. Although EC2 and AS showed the lowest M_{cr}^{exp}/ M_{cr}^{theo} ratios compared to ACI and CSA (similar to the first approach), using STS method allowed the investigated codes to yield predictions for SCRC and VRC beams with an accuracy of ± 20%, mostly. These results indicate that using STS (obtained from experiments) can be a reasonable modification for codes design equations to consider the effect of CR in the calculation of M_{cr}^{theo}.



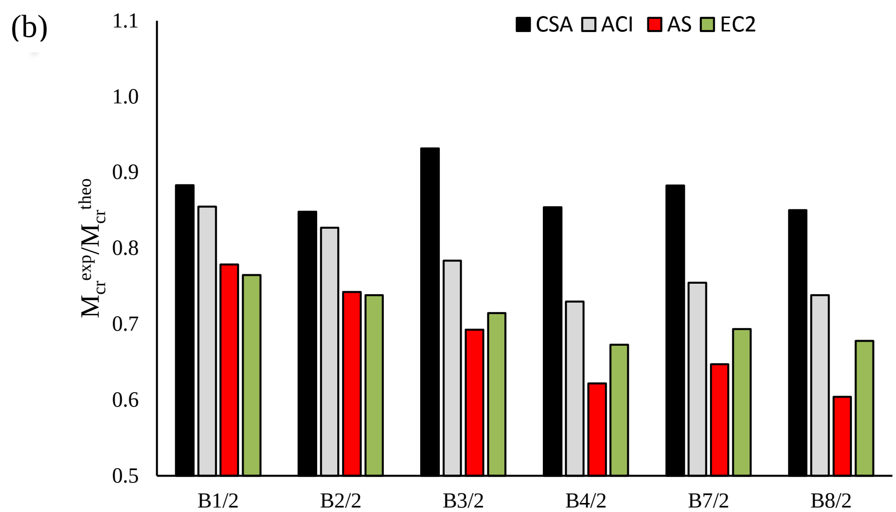


Figure 6.11 The ratio between the experimental first cracking moment to that predicted by code design equations based on compressive strength: (a) SCRC and VRC beams optimized from study 1, (b) SCRC and VRC beams optimized from study 2

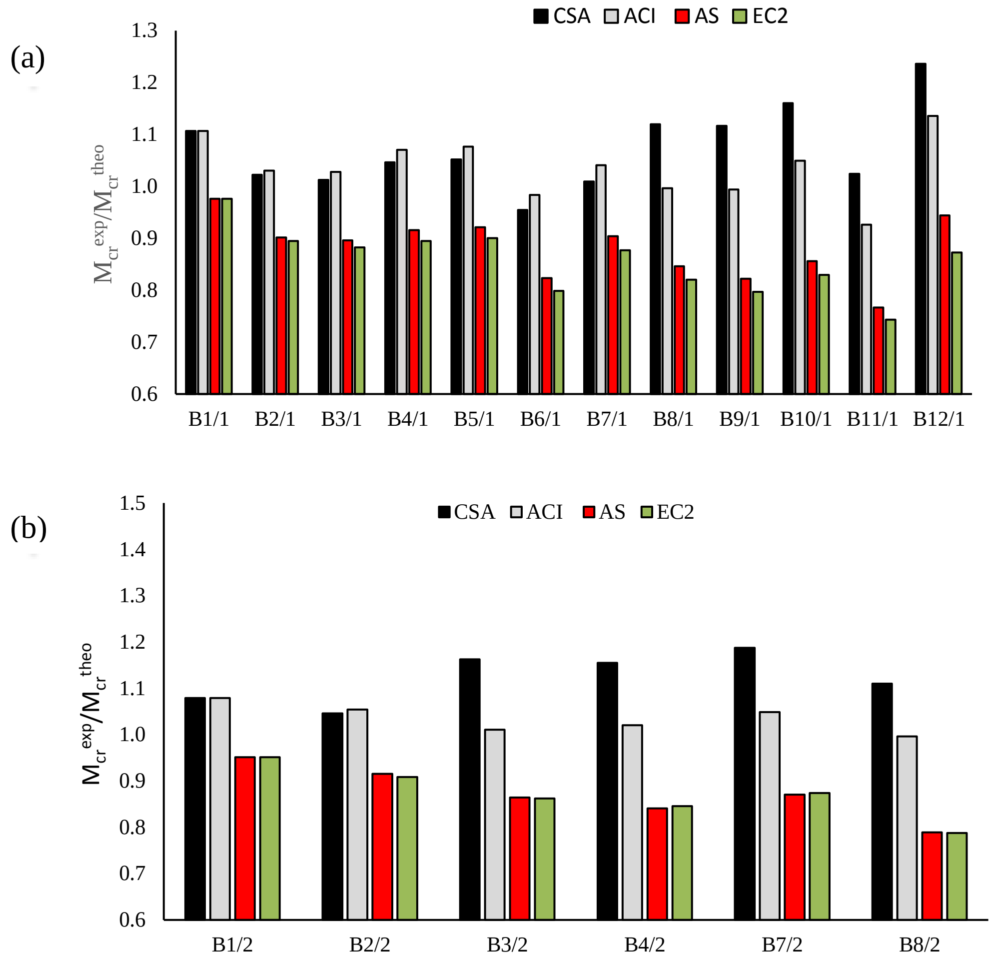


Figure 6.12 The ratio between the experimental first cracking moment to that predicted by code design equations based on STS: (a) SCRC and VRC beams optimized from study 1, (b) SCRC and VRC beams optimized from study 2

6.2.6.2 SFSCRC and SFVRC Beams

Figure 6.10b shows the effect of SFs on the first cracking moment. The results indicated that using SFs exhibited an increase in the first flexural cracking moment values. In SFSCRC beams (B5/2–B6/2), adding 0.35% SFs (35 mm) showed an increase in the M_{cr}^{exp} reached up to an average of 11.3% compared to beams with no SFs (B2/2–B3/2).

Comparing B9/2 to B8/2 (SFVRC compared to VRC) showed a 10.3% improvement in the M_{cr}^{exp} when 0.35% SFs (35 mm) was used. Further increase in the volume of SFs (1%, as shown in B10/2) boosted the M_{cr}^{exp} up to 33.1% higher than the M_{cr}^{exp} of beams with no SFs (B8/2). Using longer SFs (60 mm) in B11/2 and B12/2 increased the M_{cr}^{exp} by 8.1% and 28.43%, respectively, compared to B8/2, thus indicating less improvements than that exhibited by adding 35-mm SFs in B9/2 and B10/2. Such behaviour indicates that higher number of fibres (at a given fibre volume) may help effectively to delay the formation and propagation of macrocracks.

The codes' equations (compressive-strength-based) yielded higher $M_{cr}^{exp}/M_{cr}^{theo}$ ratios when SFs was used, as shown in **Figure 6.13a**. For example, using 0.35% SFs (35 mm) in SFSCRC beams (B5/2–B6/2) showed a $M_{cr}^{exp}/M_{cr}^{theo}$ ratio ranging from 0.76 to 1.02, and these values were higher than those shown by B2/2–B3/2 (SFSCRC's counterpart). Further increases in the amount of SFs led to decreasing the difference between the M_{cr}^{theo} and the M_{cr}^{exp}, in which adding 1% 35-mm SFs (B10/2) exhibited $M_{cr}^{exp}/M_{cr}^{theo}$ ratios ranged from 0.78 to 1.08. This could be attributed to the fact that the used codes' equations did not take into account the effect of fibres in the calculation of M_{cr}^{theo}, but only considered the 28-day compressive strength that was unaffected by the inclusion of SFs, resulting in a misleading prediction. Similar results were observed with the addition of 60-mm SFs.

In the second approach of calculating the M_{cr}^{theo} (based on STS), it was noted that using STS of SFSCRC or SFVRC in the codes' equation greatly overestimated the cracking moment. It should be noted that, although the tensile strength associated with the first cracking load may have improved by the inclusion of SFs (as shown by the improved $M_{cr}^{exp.}$ of B5/2-B6/2 compared to B2/2-B3/2 and/or B9/2-B12/2 compared to B8/2), it might not be reliable to use the ultimate STS test results to predict the cracking moment. This is because, as observed in STS test, after the tested cylinders experienced the first cracking, the fibres' bridging mechanism allowed the samples to sustain more loading until the pullout/rupture of the fibres. Since it is not easy to detect the contribution of fibres on delaying the propagation of macrocracks in concrete composite and hence increasing the tensile strength against the first crack, it may be possible to use the STS of the counterpart SFSCRC and SFVRC mixtures with no SFs in order to predict the cracking moment. For instance, as seen from **Figure 6.13b**, using the STS of B2/2 and B3/2 mixtures to calculate the M_{cr}^{theo} of B5/2 and B6/2 showed acceptable estimations. Similar results were observed when the STS of B8/2 mixture was used to predict the M_{cr}^{theo} of SFVRC beams (B9/2–B12/2). The EC2 and AS yielded cracking moment in a range of 1 ± 0.2 of the experimental values, while the ACI and CSA conservatively predicted the cracking moment.

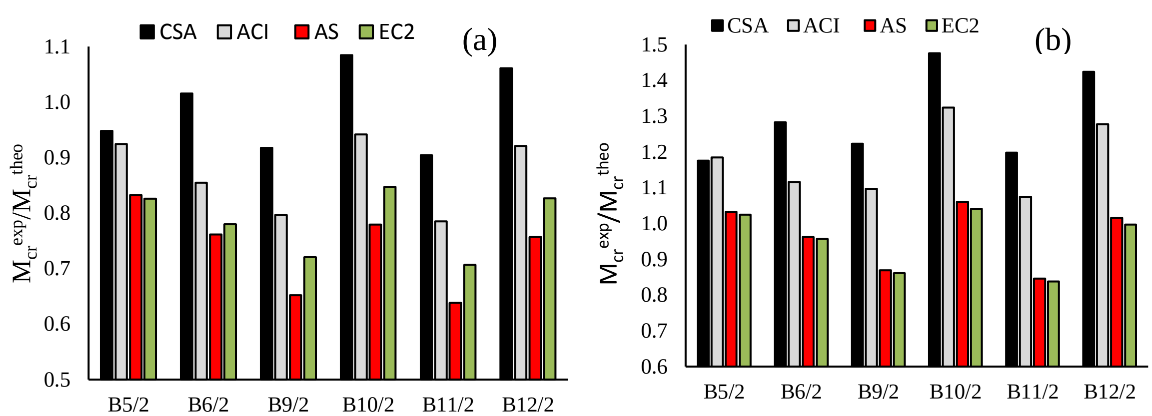


Figure 6.13 The ratio between the experimental first cracking moment to that predicted by code design equations for SFSCRC and SFVRC beams (a) based on compressive strength, (b) based on STS

7. Discussion of Results from Experimental Study 4: Shear Behaviour of Large-Scale Rubberized Concrete Beams with/without SFs

7.1 Introduction

This chapter highlights the effect of CR with/without SFs on the shear behaviour and cracking characteristics of large-scale reinforced concrete beams made with no stirrups. The performance of different proposed models in predicting the shear capacity of tested beams was also evaluated, in this study. The tested beams were developed with varied percentages of CR (0% to 50%), different SFs volume fractions (0%, 0.35%, and 1%), and different SFs lengths (35 mm and 60 mm). The results of the fresh properties, 28-day compressive strength, and STS of the tested beams' mixtures are presented in **Table 7.1**. The results obtained from the shear tests conducted on the 12 large-scale reinforced concrete beams are summarized in **Table 7.2**.

Table 7.1 Fresh and mechanical properties of tested beams' mixtures (study 4)

Beam/Mix #	Mixture designation	T_{50} (sec)	V-funnel (T_0) (sec)	L-box ratio H2/H1	SR %	Air %	HRWR (L/m^3)	f'_c (MPa)	STS (MPa)
SCRC/SFSCRC mixtures									
1	SCC-0CR	1.95	7.01	0.91	2.08	1.5	3.43	65.61	3.98
2	SCC-5CR	2.39	8.5	0.88	2.71	2	3.43	58.44	3.72
3	SCC-15CR	2.96	10.59	0.82	5.83	3.1	3.75	48.35	3.34
4	SCC-25CR	3.35	14.3	0.77	8.33	4.6	3.75	38.35	2.75
5	SCC-5CR-0.35SF	2.62	9.75	0.8	2.92	2.4	4.63	59.15	4.36
6	SCC-15CR-0.35SF	3.31	12.05	0.75	6.04	3.5	4.63	49.45	3.86
VRC/SFVRC mixtures									
Beam/Mix #	Mixture designation	Slump (mm)				Air %	HRWR (L/m^3)	f'_c (MPa)	STS (MPa)
7	VC-25CR	180				3	3.18	40.26	2.83
8	VC-35CR	145				3.3	3.18	29.73	2.51
9	VC-35CR-0.35SF	185				3	3.64	31.10	3.24
10	VC-35CR-1SF	85				3.1	3.64	32.38	4.40
11	VC-35CR-0.35LSF	170				3.2	3.64	30.71	3.38
12	VC-35CR-1LSF	80				3.4	3.64	31.51	4.73

Table 7.2 Results of the shear test

Beam #	1st Diagonal cracking load (kN)	Failure load (kN)	Ultimate shear load, V_u (kN)	Normalized shear strength (v_{nz})	Post-diagonal cracking %	Failure mode	Absorbed energy (kN.mm)	At failure		
								No. of cracks	Max. crack width (mm)	Failure angle (deg.)
SCRC/SFSCRC beams										
B1	132.55	250.70	125.35	0.31	47.13	Shear	301.52	9	8	37
B2	123.87	230.13	115.07	0.30	46.18	Shear	328.65	10	7	28
B3	111.21	195.97	97.99	0.29	43.25	Shear	249.71	11	5.5	33
B4	102.31	174.24	87.12	0.28	41.28	Shear	230.52	11	5	30
B5	136.12	283.59	141.80	0.37	52.00	Shear	458.66	10	3	31
B6	126.77	244.74	122.37	0.35	48.20	Shear	324.81	12	2.8	32
VRC/SFVRC beams										
B7	105.87	181.25	90.63	0.29	41.59	Shear	197.50	8	4.5	27
B8	91.19	145.10	72.55	0.27	37.15	Shear	164.10	9	3.8	21
B9	117.88	233.76	116.88	0.42	49.57	Shear	336.87	9	2.5	28
B10	149.02	366.57	-*	-*	-*	Flexure	1045.25	12	5	-
B11	111.21	209.32	104.66	0.38	46.87	Shear	261.19	11	2	26
B12	142.34	343.65	-*	-*	-*	Flexure-shear	930.56	13	3	22

* The value is not calculated as the beam failed in flexure

7.2 Results and Discussion

7.2.1 Failure Mode and Cracking Behaviour

7.2.1.1 Effect of CR on SCC and VC

Figure 7.1 shows the crack pattern of all tested beams at failure. From the figure, it can be seen that the SCRC, SFSCRC, and some VRC beams (B1-B4, B5-B6, and B7-B8, respectively) failed in shear. During the early stage of loading, the applied load was carried by uncracked concrete section up to the occurrence of first crack. By increasing the load, more fine vertical flexural cracks formed near the mid-span of the beam, in addition to new cracks appeared away from the mid-span on the two sides of the beam. With further increase in the load, more cracks started to form away from the mid-span and spread diagonally towards the loading zone with angles ranging from 28 to 37, until the beam failed suddenly along a single major shear crack.

Figures 7.1 and **7.2,** and **Table 7.2** show the crack pattern and crack widths/numbers of all tested beams. At failure, the tested beams indicated that as the percentage of CR increased the maximum crack width decreased (similar to that observed in the beams under flexure), but with a slight increase in the number of cracks. Varying the percentage of CR from 0% to 25% in SCRC mixtures reduced the maximum crack width from 8 mm to 5 mm, while the number of cracks increased from 9 to 11. Similar behaviour was observed in SFSCRC beams (B5-B6) and VRC beams (B7-B8). These results may be attributed to the reduced tensile strength of concrete at high CR content, which encouraged the development of higher number of cracks with relatively reduced crack width (as observed in flexural testing-study 3). By comparing SCRC to VRC, it can be observed that the failure pattern of SCRC beam exhibited higher cracking in terms of cracks' number and maximum width, as shown in **Table 7.2** and **Figures 7.1** and **7.2**.

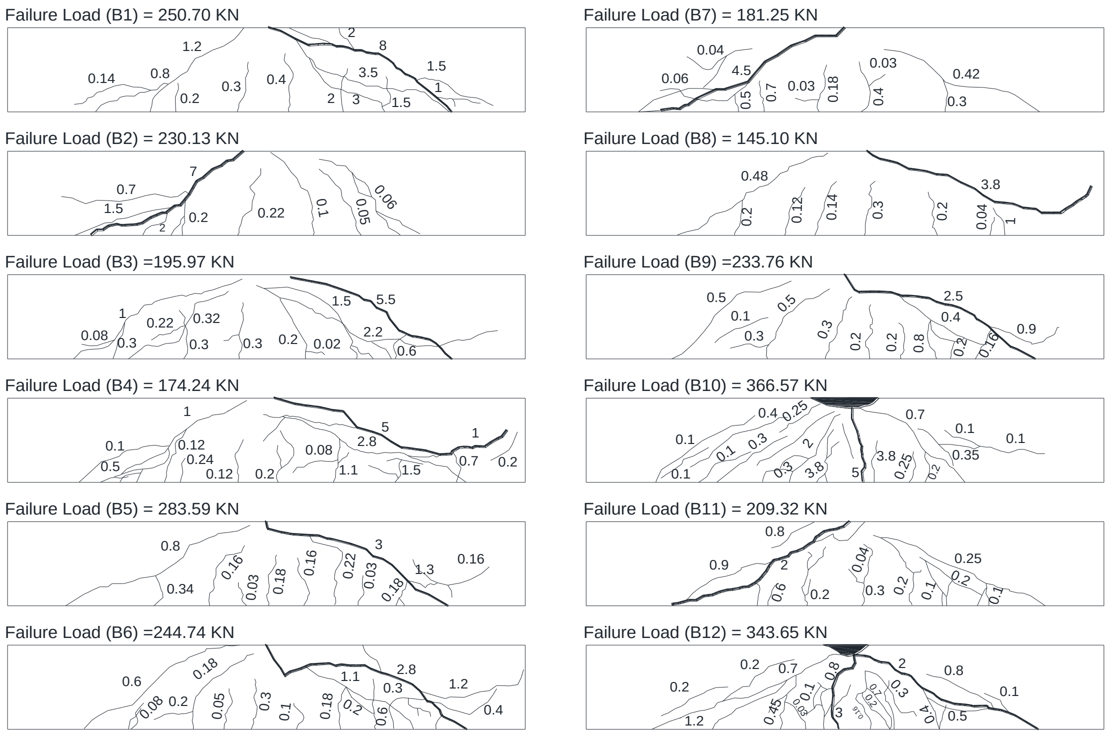


Figure 7.1 Crack patterns of tested beams at failure (crack width in mm)

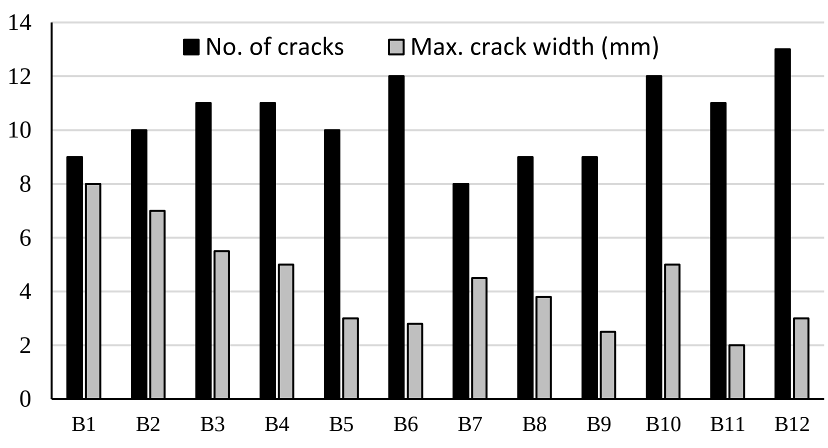


Figure 7.2 Cracks number/max width at failure

7.2.1.2 Effect of Combining SFs with CR on SCRC and VRC

From **Figure 7.1**, it can be seen that the SFSCRC beams with 0.35% SFs (0.35 mm length) (B5-B6) failed due to the formation of a single major diagonal crack, showing a shear failure mode similar to the beams with no SFs (B2-B3) but in a less brittle manner (higher deformations as shown in **Figure 7.3**) and at relatively higher loads. The failure patterns also showed that the developed cracks were spaced more closely when the SFs were added. In addition, using 0.35% SFs effectively helped to reduce the openings of cracks due to the fibres' stitching action, which in turn carried the tensile stress across the crack and consequently delayed a localized crack growth. For example, as the SFs content increased from 0% to 0.35% the maximum crack width at failure load decreased by an average of 53%, as shown in B5-B6 compared to B2-B3, respectively. Similar behaviour was observed in SFVRC beams (B9 compared to B8), in which adding 0.35% SFs (35 mm) showed a reduction in the crack spacing and widths. **Table 7.2**, **Figures 7.1** and **7.2** also indicate that beam with long SFs (60 mm) appeared to have smaller crack widths compared to that of short fibres (35 mm) but with no significant change in the failure mode, as shown in B11 compared to B9. Increasing the 35-mm SFs from 0.35% to 1% made the beam fail in flexure; a major vertical flexural crack was formed followed by a concrete crushing at the compression zone near the mid-span, as shown in B10. Meanwhile, the beam with 1% SFs (60 mm) (B12) failed in flexural-secondary shear mode (i.e. flexural failure followed by a formation of major single diagonal crack). These test results indicate that, through the addition of SFs (especially 1% volume), it may be possible to reduce the amount of shear stirrups required to achieve a flexural failure in conventional beams.

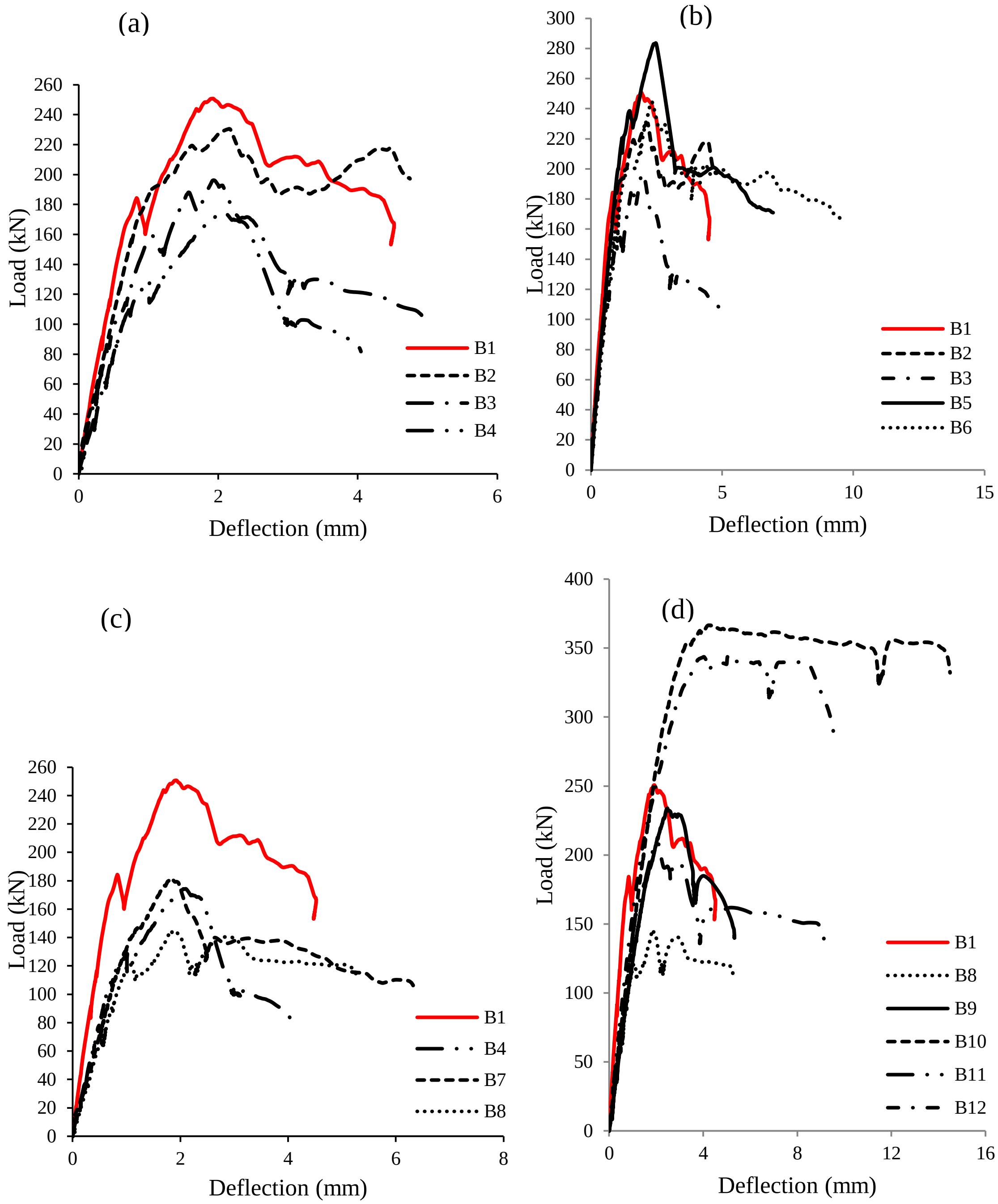


Figure 7.3 Experimental load-midspan deflection responses: (a) SCRC with CR only, (b) SCRC comaperd to SFSCRC, (c) SCRC compared to VRC, (d) VRC compared to SFVRC

7.2.2 Experimental Load-Deflection Curve

Figure 7.3 shows the load mid-span deflection curves of the tested beams. By looking at **Figure 7.3a**, it can be seen that the beams made with CR (B2, B3, B4) appeared to behave similarly to this without CR (B1). In general, up to the first cracking load, all tested beams experienced the elastic behaviour where the deflection is linearly proportional to the applied load. Beyond the first crack, the curves were almost linear but with a slightly lower slope as the beams' stiffness decreased due to the formation of macrocracks. With further increase in the applied load, the curves deviated from linearity and a higher rate of deflection is exhibited until the occurrence of failure. From **Figure 7.3a**, it can also be observed that increasing the percentage of CR from 0% to 25% (B1 to B4) appeared to increase the deformability of SCRC beams at a given load, which indicates a reduction in the beam's stiffness as the CR content increased. Similar behaviour was observed in VRC beams when the percentage of CR increased from 25% to 35% (B7 to B8), as shown in **Figure 7.3b**. Such decrease in the stiffness was due to replacing the conventional sand with flexible rubber particles, which in turn decreased the overall stiffness of the tested SCRC and VRC beams (as explained in study 3). By examining the load-deflection curve of the SCRC beam compared to its counterpart VRC beam (B4 vs. B7) in **Figure 7.3b**, it can be noted that up to almost 70% of failure load both beams showed comparable behaviour, but beyond this level of load the SCRC beam (B4) experienced slightly higher deformation compared to the VRC beam (B7).

By checking the effect of including 0.35% SFs, **Figures 7.3c** and **7.3d** show that SFSCRC (B5-B6) and SFVRC (B9) beams with 0.35% SFs presented slightly increased stiffness and maximum deflection at ultimate load compared to their counterpart beams without SFs, SCRC (B2–B3), and VRC (B8), respectively. However, adding a higher volume of fibres (1%) increased the beams' stiffness and allowed the beams to sustain higher ultimate load accompanied with larger corresponding deflections (B10 and B12 compared to B8). This indicates a less brittle behaviour and an obvious improvement in the energy absorption of tested beams.

7.2.3 Shear Capacity

7.2.3.1 Effect of CR on SCC and VC

Table 7.2 and **Figure 7.4** show the effect of CR on the ultimate load/2 (refers to the failure shear load in beams failed in shear) and normalized shear strength of all tested beams. The results indicated that increasing the percentage of CR decreased the failure shear load of SCRC beams. Varying the percentage of CR from 0% to 25% reduced the failure shear load of SCRC beams by 30.5%. The SFSCRC and VRC beams (B5-B6 and B7-B8, respectively) confirmed the negative impact of CR on shear strength of beams. According to Taylor (1974), the strength of the compression shear zone appeared to represent about 20% to 40% from the total shear capacity of beams in case no shear reinforcement is used. Therefore, decreasing the compressive strength of concrete, due to replacing the fine aggregate by CR as seen in **Table 7.1**, can significantly decline the overall shear capacity of beams. However, the failure shear load (V_u) was normalized to account for the effect of different compressive strengths. As known, the shear strength is proportional to the square root of the compressive strength of the concrete (f'_c), the normalized shear strength (v_{nz}) was calculated as follows, **Equation 7.1**:

$$v_{nz} = V_u/bd\sqrt{f_c'} \tag{7.1}$$

.

The normalized shear strengths (in **Table 7.2** and **Figure 7.4**) were found to be decreased as the percentage of CR increased. For example, Increasing the percentage of CR from 0% to 25% (B1–B4) reduced the normalized shear strength up to 9.1%. Such behavior could be attributed to some reasons as follows:

- The softness of the rubber particles may reduce the friction forces that develop across the diagonal shear cracks due to aggregate interlock mechanism, which contributes in a range of 35% to 50% to the shear strength capacity of beams (Taylor, 1974) by providing resistance against slip.
- The tensile strength of concrete within the region of shear can also be weakened by inclusion of CR, as shown in the STS results, which in turn allows diagonal cracks to be developed in the beam at relatively lower loads, eventually causing failure.

The reduction in the failure shear load (ultimate load/2) and normalized shear strength appeared to be more pronounced at high percentages of CR: increasing the CR content from 25% to 35% (B8 compared to B7) showed a reduction of 20% and 6.95 in the failure shear load and normalized shear strength of beams. This finding may be attributed to the fact that the weakened rubber-mortar interface is significantly increased at high levels of CR replacement, which heightens the presence of poor bonding in concrete composite and allows higher cracking growth, thus limiting the beam's ability to carry higher loads.

Although using CR generally reduced the failure shear load of the beams, it beneficially contributed to developing semi-lightweight concrete with density varied from 2128 to 2014 kg/m^3 (CSA, 2004) as the percentage of CR ranged from 15% to 35%, respectively.

By comparing B7 to B4, it was found that the VRC beam carried failure shear load and normalized shear strength slightly higher than its SCRC counterpart by around 4% and 3.6%, respectively.

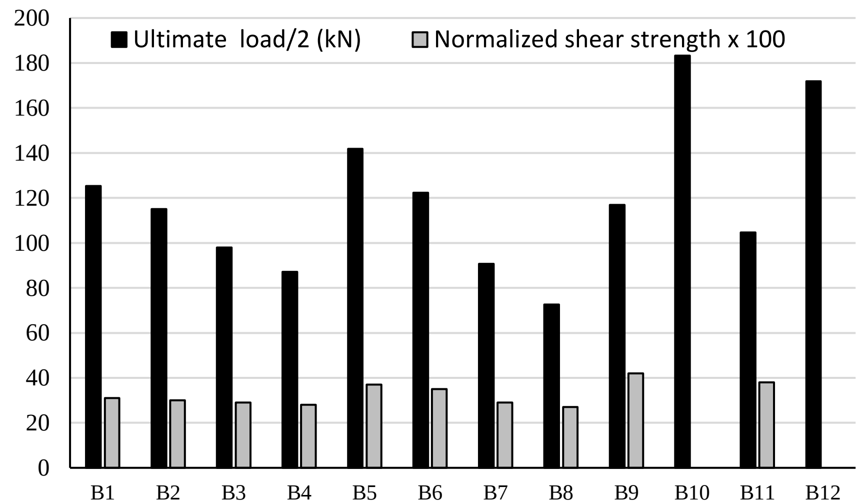


Figure 7.4 Ultimate load/2 (refers to the failure shear load) and normalized shear strength of tested beams

7.2.3.2 Effect of Combining SFs with CR

Table 7.2 and **Figure 7.4** show that including SFs increased the failure shear load and the normalized shear strength. For instance, adding 0.35% SFs to SCRC mixtures improved the failure shear load and the normalized shear strength by an average of 24.1% and 23%, respectively, as observed by comparing B5 and B6 to B2 and B3, respectively. As shown from the results, the addition of SFs caused almost a same increase in both the failure shear load and the normalized shear strength, which is due to the insignificant effect of SFs on the compressive strength of mixtures. Such finding indicates that the increase in the shear capacity of beams could be mainly attributed to the fact that (a) the contribution of fibres to restricting the widening and propagation of diagonal cracks, thus increasing the aggregate interlock and preserving a bigger uncracked compression zone that increases the shear capacity of beams (Ding et al., 2011); and (b) fibres that are perpendicular to the diagonal cracks may act as aggregate particles with a very elongated shape (Tahenni et al., 2016), which can develop a special type of aggregate-mortar interlock, thus improving the shear transfer capacity. The beneficial impact of SFs on enhancing the ultimate shear load and the normalized shear strength of beams was also confirmed in SFVRC beams. The effect of SFs appeared to be more pronounced in beams with high percentages of CR (B9) compared to those with low CR content (B5 and B6). Adding 0.35% SFs to beams with 35% CR raised the failure shear load and the normalized shear strength by 61% and 57.5%, respectively (as in B9 compared to B8), and this is more than twice the improvement observed in B5 and B6 (5% CR and 15% CR, respectively). This may be attributed to the fact that at a higher CR content (35%) the rubber-concrete composite became weaker and more affected by the fibres' mechanism in arresting the crack growth and improving the aggregate interlock, which then greatly increased the shear capacity of beams (as observed in flexural testing-study 3). A similar effect was observed in the results of STS: at low CR content (5% and 15%), adding 0.35% SFs (35 mm) increased the tensile strength by 17.2% and 15.6%, respectively, while with higher CR content (35%) this increase reached up to 29.1% (**Table 7.1**). It should be noted that increasing the volume of SFs (35 mm) to 1%

made the beam to fail in a flexural mode with a capacity of 2.53 times as much as beams with no SFs (B8). The results also indicated that adding 60-mm SFs also increased the capacity of beam, but this increase was less than that observed with 35-mm SFs. Using 0.35% and 1% of 60-mm SFs as in B11 and B12, respectively, exhibited a 44% and 137% increase in the ultimate load compared to 61% and 153% increase in beams with 35-mm SFs (B9 and B10, respectively). Some possible reasons that may result in making longer SFs to provide lower capacity compared to shorter SFs:

- As the diameter and/or length of fibres decreased for a given volume, the number of single fibres increases, which may result in a higher probability of single fibres being oriented perpendicular to the diagonal cracks. Such orientation can develop greater bridging/stitching actions and aggregate-interlock mechanism along cracks, which heighten the fibres' contribution to the beam' strength.
- Typically, in concrete the weak link is the interfacial bond between aggregate and cement mortar, which usually contains numerous microcracks. Therefore, the longer SFs with a relatively higher surface area are more vulnerable for higher number of microcracks (compared to short fibres), which negatively affects the fibre-mortar bonding.

- If a rubber particle is placed beside a steel fibre, the bond between the cement gel and steel fibre gets weaken. In such case, the rubber particle helps in propagating the crack around the steel fibre, which in turn makes fibre-mortar debonding the dominant mechanism, and hence reduce the ability of fibres to hold cracks. This effect may be more significant in case of longer fibres due to their higher surface area and lower numbers compared to short SFs (for a given fraction volume).

It is worth noting that combining 15% CR and 0.35% SFs (35 mm) in B6 exhibited a normalized shear strength 12.4% higher than that of the control beam, while a combination of 35% CR and 1% SFs (VRC beams B10 or B12) helped to produce semi-lightweight concrete beams with a capacity of almost 1.5 times as much as the value obtained in the beam with no CR (B1).

7.2.4 Post-diagonal Cracking Resistance

The post-diagonal cracking resistance of each beam is defined as the resistance the beam can show after the occurrence of the first diagonal crack. **Table 7.2** and **Figure 7.5** show the values of post-diagonal cracking resistance, which were calculated for each beam by dividing the difference between the ultimate failure load and the load recorded at the first diagonal crack by the ultimate failure load.

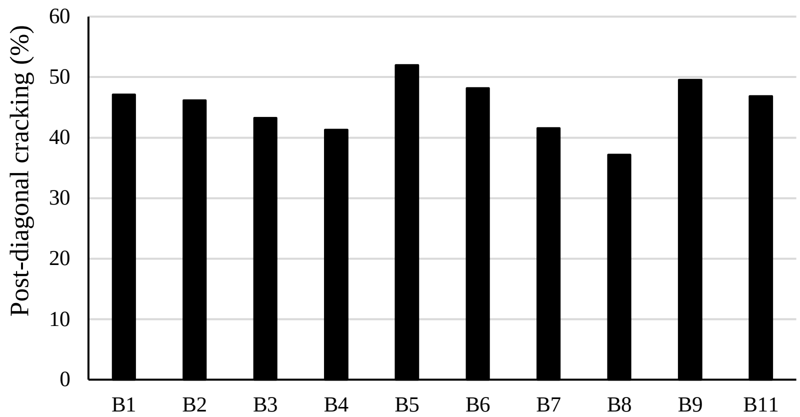


Figure 7.5 Post-diagonal cracking resistance of tested beams

7.2.4.1 Effect of CR on SCC and VC

From **Table 7.2** and **Figure 7.5**, it can be seen that the results of the post-diagonal cracking resistance showed a trend similar to that of the failure shear load and normalized shear strength. Increasing the percentage of CR showed a reduction in the post-diagonal cracking resistance; for example, varying the percentage of CR from 0% to 25% decreased the post-diagonal cracking resistance of SCRC by 12.4%. Similarly, by comparing B8 to B7 (VRC beams), it can be observed that increasing the percentage of CR by increments of 10% showed a reduction in the post-diagonal cracking resistance of up to 10.7%. This behaviour is attributed to the same reasons caused a reduction in the shear capacity of concrete. Comparing VRC to SCRC (B7 compared to B4) showed that both beams had comparable post-diagonal cracking resistance.

7.2.4.2 Effect of Combining SFs with CR on SCRC and VRC

Table 7.2 and **Figure 7.5** show that the post-diagonal cracking resistance of both SCRC and VRC beams improved when SFs were used. This improvement is attributed to the fibres' bridging action (transferring stress between crack faces) and their role in stitching the diagonal cracks, which provided a higher residual strength to concrete beyond the first diagonal crack. Using 0.35% SFs in SCRC beams with 5% and 15% CR (B5 and B6) increased the post-diagonal cracking resistance by 12% (on average) compared to beams with no SFs (B2 and B3). This improvement was more pronounced in beams with a high percentage of CR; for example, combining 35% CR with 0.35% SFs (35 mm) in B9 exhibited an increase in the post-diagonal cracking resistance of up to 33.4% compared to B8 (beam with no CR). This increase was lower when 60-mm SFs were used, as shown in B11, in which the post-diagonal cracking resistance increased by 26.2%. It should be noted that the post-diagonal cracking resistance was not calculated for B10 and B12 because the failure mode was flexural and flexural-secondary shear, respectively. The results also showed that B6, with a combination of 15% CR and 0.35% SFs (35 mm), exhibited a similar post-diagonal cracking resistance to the control beam (B1).

7.2.5 Energy Absorption Capacity

From load-deflection curves in **Figure 7.3**, it can be observed that the use of CR and/or SFs contributed to the deformability and strength of the tested beams, and hence can directly affect the capacity of beams to absorb energy up to failure. To compare the energy absorption capacity of tested beams, the ultimate absorbed energy was determined by measuring the area under the load-deflection curve up to the failure load. **Table 7.2** and **Figure 7.6** shows the calculated absorbed energy for all tested beams.

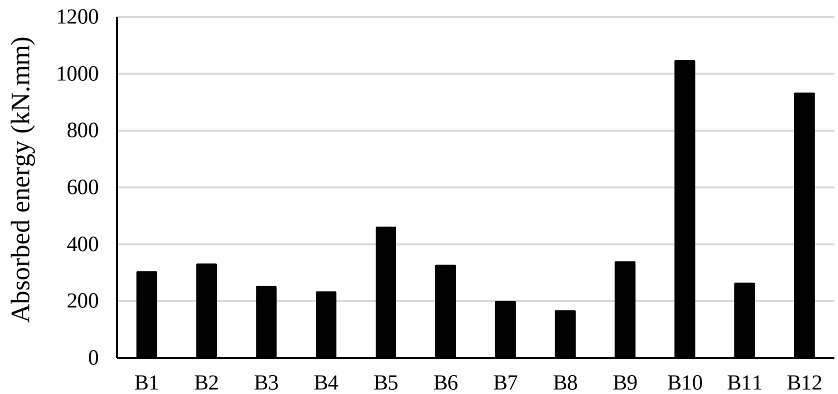


Figure 7.6 The energy absorption capacity of tested beams

7.2.5.1 Effect of CR on SCC and VC

Since no shear reinforcement was used in the tested beams, the energy absorption capacity of beams is directly affected by both the beam's deformability and shear strength of rubber-mortar composite. Replacing the conventional fine aggregate with low-stiffness rubber particles can increase the flexibility of concrete composite, which in turn contributes to heightening the beam's deformability at a given load, as shown in **Figure 7.3a**. However, as explained earlier, the mechanical behaviour of rubber-mortar composite significantly decreased as the content of CR increased, which greatly reduced the ability of beams to sustain higher shear loads and hence limited the amount of absorbed energy under shear loading. As shown in **Figure 7.3a**, increasing the percentage of CR reduced the area enclosed by the load-deflection curve, which indicates a reduction in the energy absorption capacity of tested beams. Varying the percentage of CR from 0% to 25% in SCRC beams reduced the absorbed energy by 23.6% (as shown in **Table 7.2** and **Figure 7.6**). A similar trend of results was observed by examining the load-deflection curves of B8 vs. B7 (VRC beams). The results also showed that the SCRC beam (B4) absorbed a higher amount of energy at failure than the VRC beam (B7), as both beams showed comparable strength but with relatively higher deformability for the SCRC beam.

7.2.5.2 Effect of Combining SFs with CR on SCRC and VRC

As shown in **Table 7.2** and **Figure 7.6**, combining CR and SFs in both SCC and VC beams greatly improved their energy absorption capacity. In SFSCRC beams (B5-B6), it can be observed that using 0.35% SFs (35 mm) exhibited an average increase of 34.8% in the amount of the absorbed energy compared to beams with no SFs (B2-B3). Using the same amount of SFs in beams with a higher percentage of CR (35%), as in VRC beams, showed higher improvement in the energy absorption capacity of the beams. As shown in B9 compared to B8, using 0.35% SFs (35 mm) improved the ability of beams to absorb energy by 2.05 times. The result also indicated that increasing the volume of SFs (35 mm) to 1% (as shown in B10) raised the absorbed energy up to more six times as much as beams with no SFs (B8). These results are attributed to the beneficial impact of SFs on restricting the widening and propagation of cracks, which allows the tested beams to sustain higher loading and experience larger deformations. Increasing the length of SFs to 60 mm exhibited a declined enhancement in the energy absorption capacity of beams compared to that of beams with 35-mm SFs, as shown in B9 and B10 compared to B11 and B12, respectively. This finding is attributed to the same possible reasons that may increase the effectiveness of short fibres (35 mm) compared to long fibres (60 mm) (explained in section 7.2.3.2), which helps the beams experience higher loads and deformations and allows the beams to absorb higher energy before failure. It is worth noting that SCRC beams with maximum CR and SFs (15% CR and 0.35% SFs, B6) absorbed 7.7% more energy compared to the control beam (B1), while VRC beams with maximum combination of CR and SFs (35% CR and 1% SFs) exhibited energy absorption capacities of 3.47 and 3.1 times higher than that of B1 for 35-mm SFs (B10) and 60-mm SFs (B12), respectively.

7.2.6 Theoretical Predictions of the Shear Strength

7.2.6.1 SCRC and VRC Beams

Four design codes that have gained greater approbation worldwide, namely the ACI 318 (2008), EC 2 (2005), AASHTO-LRFD (2007), and CSA (2004), were used to predict the ultimate shear capacity of the tested SCC, SCRC, and VRC beams. It should be noted that since the aforementioned code models do not include the effect of SFs in their calculations, only beams without SFs were compared with the prediction of these codes. The details of the equations used are shown in **Table 7.3**.

Table 7.3 Theoretical models of the shear strength for beams with/without SFs and with no stirrups

Code	**Model**	**Explanation**
ACI	$V_c = \left(0.16\,\lambda\,\sqrt{f_c'} + 17\,\rho\frac{d}{a}\right)\,bd\ \le 0.29\,\sqrt{f_c'}bd$	f_c'= cylinder compressive strength (MPa) λ= lightweight concrete modification factor (1.0 for normal-weight concrete, 0.85 for sand-lightweight concrete, and 0.75 for all lightweight concrete) ρ= tensile reinforcement ratio d = effective depth of beam (mm) a = shear span (mm) b = width of beam (mm)
EC2	$V_c = [0.18\,\eta\,K(100\rho f_c')^{1/3}]b_w\,d$	η= factor to account for lightweight concrete (η = 0.4+0.6$\rho/2200$) K= size effect factor (K=1+$\sqrt{200/\mathrm{d}}$ ≤ 2.0)
AASHTO-LRFD	$V_c = 0.083\beta\,\lambda\sqrt{f_c'}bd_v$	β = factor accounting for shear resistance of cracked concrete. d_v = effective shear depth (the greater of 0.9 of the beam depth or 0.72 of the beam height)
CSA	$V_c = \ \lambda\,\beta\sqrt{f_c'}bd_v$	
Investigator	**Model**	**Explanation**
Sharma	$v_u = \left[\frac{2}{3}f_t'\left(\frac{d}{a}\right)^{0.25}\right]$	f_t' = splitting tensile strength of concrete (MPa)
Narayanan and Darwish	$v_u = \left[2.8\frac{d}{a}\left(0.24\left(\frac{f_c'}{20-\sqrt{F}} + 0.7 + \sqrt{F}\right) + 80\rho\frac{d}{a}\right) + 0.41\,\tau F\right]$	For a/d ≤ 2.8 F = fibre factor = [V_f (l_f/d_f) D_f] V_f= fibre volume lf/df = fibre aspect ratio D_f = the bond factor dependent on the shape of the steel fibres (0.5 for circular section plain fibre, 0.75 for crimped fibre or hooked fibre, and 1 for indented fibre) τ= fibre–matrix interfacial bond strength, taken as 4.15 MPa based on recommendations of Swamy et al. (1974).
Ashour et al.	$v_u = \left[\left(0.7\,\sqrt{f_c'} + 7F\right)\frac{d}{a} + 17.2\,\rho\frac{d}{a}\right]$	ACI Code Modification
Khuntia et al.	$v_u = \left[\left(0.167\left(2.5\frac{d}{a}\right) + 0.25\,F\right)\sqrt{f_c'}\right]$	For a/d ≤ 2.5 (ACI Code Modification) D_f= 2/3 for plain and round, 1.0 for hooked or crimped fibres
Imam et al.	$v_u = \left[0.6\,\Psi\,\sqrt[3]{\omega}\left((f_t')^{0.44} + 275\sqrt{\frac{\omega}{\left(\frac{a}{d}\right)^{0.44}}}\right)\right]$	Where, $\Psi = \frac{1+\sqrt{5.08/d_a}}{\sqrt{1+d/(25\,d_a)}}$ = size effect d_a is maximum aggregate size in mm; ω = reinforcement factor = ρ (1+4F); the bond coefficient (D_f) for F factor is taken = 1.0 for hooked fibre = 0.9 for deformed fibre = 0.5 for smooth fibre
Kwak et al.	$v_u = \left[3.7\left(3.4\left(\frac{d}{a}\right)\left(\frac{f_c'}{20-\sqrt{F}} + 0.7 + \sqrt{F}\right)^{\frac{2}{3}}\left(\rho\frac{d}{a}\right)^{\frac{1}{3}}\right) + 0.8\,(0.41\,\tau F)\right]$	For a/d ≤ 3.4

Figure 7.7a shows the ratio of experimental-to-predicted shear capacity (v_{exp}/v_{pred}) for each tested beam. The results indicate that all the codes' equations highly underestimated the shear strength of SCC, SCRC, and VRC beams. By looking closely at the four models, it can be seen that EC 2 (2005) had the lowest v_{exp}/v_{pred} ratios (the most conservative code) compared to the other codes. These ratios ranged from 1.1 to 1.39. The CSA (2004) exhibited lower v_{exp}/v_{pred} ratios for B1–B2 compared to those obtained by the ACI 318 (2008) and AASHTO-LRFD (2007), while the CSA appeared to be more conservative than the ACI 318 (2008) and AASHTO-LRFD (2007) for B3–B4 and B7–B8. This finding is attributed to the fact that the predictions of the CSA (2004) for B3–B4 and B7–B8 were subjected to a reduction by a factor of λ (= 0.85), in which the density of concrete used in those beams fell within the range of 1850 and 2150 kg/m^3 (which is classified as a semi-lightweight concrete as per CSA (2004)). Unlike the CSA (2004), for the case of replacing the total volume of fine aggregate by lightweight sand, the ACI 318 (2008) and AASHTO-LRFD (2007) recommend that the reduction factor of λ (= 0.85) be applied. And since the rubber partially replaced the fine aggregate, the reduction factor λ was linearly interpolated between 0.85 and 1. The results also indicated that increasing the CR content appeared to decrease the v_{exp}/v_{pred} ratios for all design codes. This is due to the fact that all the equations do not take the impact of CR into account in their calculations, which may indicate a need for further investigations to highlight the rubber-concrete composite's contribution to the shear strength of beams.

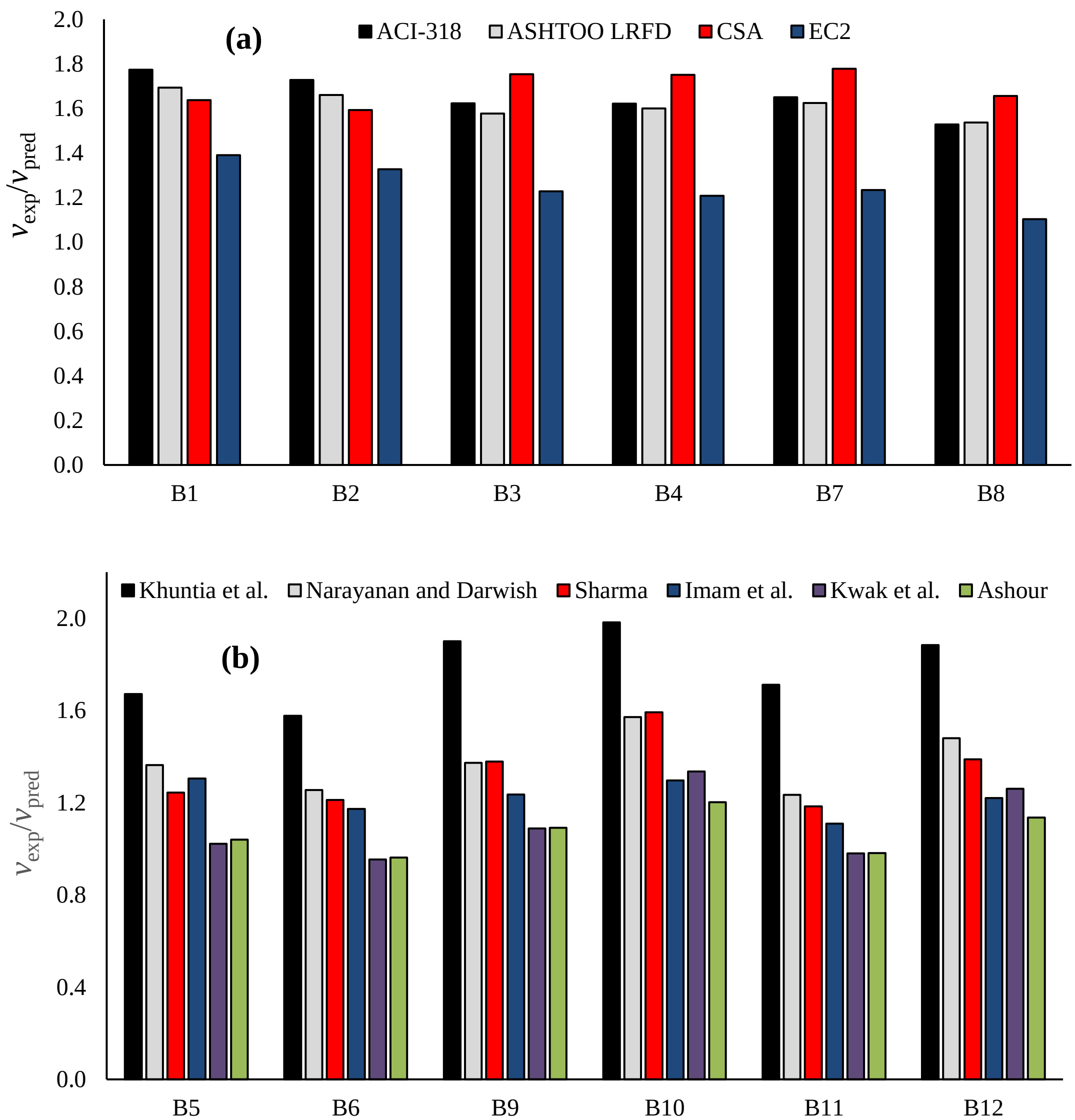


Figure 7.7 The ratio between the experimental shear strength to that predicted by (a) code design equations, (b) researchers' models

7.2.6.2 SFSCRC and SFVRC Beams

The ultimate shear strengths of SFSCRC and SFVRC beams obtained from the conducted experiments were compared with those predicted by six of the existing models available in the literature as these models include the effect of SFs in their calculations. The details of the investigated models are shown in **Table 7.3**.

The v_{exp}/v_{pred} ratio for each beam is shown in **Figure 7.7b**. The model developed by Khuntia et al. (1999) appeared to be the most conservative model of those used in this investigation, showing v_{exp}/v_{pred} ratios ranged from 1.58 to 1.98, respectively. The models developed by Narayanan and Darwish (1987), Imam et al. (1994), and Kwak et al. (2002) provided reasonably better predictions, in which the v_{exp}/v_{pred} ratios have a range of 1.23-1.57, 1.11-1.3, and 0.95-1.33, respectively. Meanwhile, the closest predictions were shown by Ashour et al. (1992) as they have a v_{exp}/v_{pred} ratio ranged in 0.96-1.2. Despite the simplicity of the model proposed by Sharma (1986), which did not consider the fibres' volume, fibres' aspect ratio, and/or reinforcement ratio, the model was able to conservatively predict the shear strength of beams with a v_{exp}/v_{pred} ratio ranged from 1.18 to 1.59. By examining the predicted values of each model, it can be clearly seen that increasing the percentage of CR resulted in a reduction of the v_{exp}/v_{pred} ratios (as shown in B6 compared to B5). Hence, further research is required to include the effect of CR in these equations in order to safely predict the contribution of CR to the shear strength of fibre-concrete composites.

8. Conclusions and Recommendations

8.1 Conclusions

The research program carried out in this thesis included four sequential experimental studies, which investigated the use CR with/without SFs to develop new types of concrete with promising potentials for multiple structural applications. These studies mainly aimed to extend the use of waste rubber in concrete industry, especially when SCC is used. Different binder contents, SCMs, aggregate sizes, entrained air admixture, and SFs types were used to optimize the fresh and mechanical properties of the developed mixtures. The conducted studies in this thesis also presented an evaluation for the shear and flexural behavior of large-scale reinforced concrete beams made with CR with/without SFs. In addition, the performance of some design codes and empirical equations was evaluated in predicting the shear strength, flexural capacity, and cracking moment of the tested beams.

The analysis of the experimental results obtained from the completed studies in this research work led to the following conclusions:

8.1.1 Optimizing the Fresh Properties, Stability, and Strength of SCRC Using Different Mixture Compositions and SCMs (Experimental Study 1)

- Increasing the percentage of CR in SCRC mixtures reduced the flowability, passing ability, stability, unit weight, and mechanical properties, whereas it increased the air content and HRWRA demand.

- It is possible to develop successful SCRC mixtures without SCMs with a maximum CR percentage of 15% (having compressive strength of 37.4 MPa). Such mixtures can have a minimum binder content of 500 kg/m^3 and a w/b ratio of 0.4. Further increases in the percentage of CR resulted in a significant decrease in the fresh properties and stability of mixtures.
- Increasing the binder content of SCRC mixtures from 500 kg/m^3 to 550 kg/m^3 significantly improved the fresh properties and stability. Mixtures with 550 kg/m^3 binder content showed lower HRWRA demand and higher flowability, passing ability, and segregation resistance compared to mixtures with 500 kg/m^3 binder content. Increasing the binder content from 500 kg/m^3 to 550 kg/m^3 also improved the 28-day compressive strength, STS, FS, and ME by an average of 11.9%, 7%, 10%, and 10.4%. Mixtures with 550 kg/m^3 binder content allowed safe use of up to 20% CR in SCRC mixtures with acceptable fresh properties, no sign of segregation, and with a minimum compressive strength of 32.8 MPa.
- Compared to GGBS and FA, MK proved to be the most effective SCM at enhancing the fresh properties and stability of SCRC mixtures. The addition of MK improved the viscosity and particle suspension of SCRC mixtures, which resulted in increased passing ability. Using MK in SCRC mixtures also alleviated the reductions in the mechanical properties with higher percentages of CR, as it improved the 28-day compressive strength, STS, FS, and ME by an average of 49.2%, 17%, 14.6%, and 24.9%, respectively. SCRC mixtures with 550 kg/m^3 binder content and 20% MK showed acceptable fresh properties, stability, and strength with up to 30% CR,

achieving a compressive strength of around 40 MPa and a density of less than 2150 kg/m^3, which is classified as a semi-lightweight concrete according to the CSA (2004).

- Using a larger coarse aggregate size (20 mm compared to 10 mm) in SCRC mixtures increased the flowability but decreased HRWRA demand, passing ability, stability, and mechanical properties.
- Using entrained air in SCRC mixtures greatly improved the flowability and passing ability but significantly decreased the stability, compressive strength, STS, FS, and ME. Despite the reduction of the compressive strength with the inclusion of entrained air, SCRC mixtures with MK and entrained air could be developed with up to 40% CR with acceptable fresh properties, stability, and strength (25.7 MPa). This high percentage of CR contributed to developing semi-lightweight mixtures with a density of less than 2100 kg/m^3.
- SCRC mixtures showed more ductile failure behaviour compared to mixtures with no CR. Samples with higher percentages of CR showed insignificant spalling, very fine cracks, and no splintering or spalling at the ultimate compressive and/or tensile failure compared to samples with no CR.
- Using waste CR as a replacement for fine aggregate in concrete showed promising results in producing a new type of eco-friendly environmentally concrete having higher energy absorption, acoustic insulation, and reduced self-weight compared to conventional concrete.

- Both the drop-weight test and flexural impact loading test showed that the impact resistance of SCRC mixtures improved by replacing the fine aggregate with CR. The drop-weight test presented 30% CR replacement as the optimum percentage to obtain maximum impact energy absorption. Meanwhile, the 20% CR mixture showed the highest impact resistance in the flexural-loading test.
- In the drop-weight test, the difference between number of blows for ultimate failure and first crack increased as the CR increased, which indicates a reduction in the brittleness of SCRC or an increase in the ductility of rubber-cement composite.
- The results showed that using higher binder content and/or adding MK improved the impact resistance in each of the drop-weight and flexural impact loading tests. On the other hand, using entrained air exhibited lower impact resistance while using a larger aggregate size had insignificant effect on the impact resistance.
- The UPV test showed that increasing CR replacement led to lower UPV due to the ability of CR particles to limit the propagation velocity of waves through concrete. High air content resulting from the addition of CR or entrained air can also lower the UPV. On the other hand, mixtures with MK and/or higher binder content, in which a denser structure enhanced the transmission of waves in concrete, exhibited higher UPV values.

- By evaluating the signal strength and signal energy of the tested mixtures measured using AE technique, it is worth noting that the acoustic absorption capacity of SCRC mixtures can be improved by using CR. Increasing the percentage of CR from 0% to 50% can significantly contribute to the wave attenuation. This behaviour offers a promising potential for SCRC to be used in applications that need a high level of acoustic insulation.

8.1.2 Use of SFs to Optimize SCC Mixtures Containing CR (Development of SFSCRC) (Experimental Study 2)

- Using 550 kg/m^3 binder content for mixtures containing 20% MK and 30% FA helped to develop SCRC mixtures with up to 30% CR replacement, satisfying the criteria of self-compactability. However, increasing the percentage of CR in SCRC mixtures showed a reduction in the flowability, passing ability, stability, and unit weight, while the air content and HRWRA demand increased (confirming the findings of study 1).
- Although increasing the percentage of CR in SCC mixtures negatively affected the compressive strength, STS, FS, and ME, the impact resistance in both the drop-weight test and flexural impact loading test showed a great enhancement. The drop-weight test showed a continuous increase in the impact energy absorption of SCRC up to 30% CR replacement. On the other hand, the ultimate impact resistance in the flexural-loading test showed improvement up to 25% CR (close to the value obtained from study 1, which was 20%) (confirming the findings of study 1).

- In the drop-weight test, increasing the CR content increased the difference between number of blows of ultimate failure and first crack, thus indicating an improvement in the ductility of concrete (confirming the findings of study 1).
- Adding SFs to SCRC increased the measured air content and HRWRA demand but reduced the fresh properties, especially the passing ability, which limited the possibility of combining higher percentages of CR and large volumes of SFs. With 550 kg/m^3 binder content (incorporating 20% MK + 30% FA), it was possible to produce SCRC mixtures containing up to 15% CR reinforced with 0.35% SFs (35-mm length) meeting the acceptable properties of SCC. Increasing the binder content to 600 kg/m^3 with the same fibre type/content allowed up to 25% CR to be used successfully in SFSCRC.
- Using 0.35% SFs (35 mm length) in SCRC mixtures increased the 28-day STS and FS of by an average of 20.5% and 19.5% (compared to SCRC with no SFs), but with no significant effect on compressive strength and ME. The results of impact energy absorption of SCRC mixtures were greatly enhanced by the inclusion of 0.35% SFs (35 mm length); for example, the addition of 0.35% SFs increased the ultimate impact resistance of the drop-weight test and flexural impact loading test by an average of 2.68 and 2.33 times, respectively.
- Increasing the volume of SFs from 0.35% to 0.5% could improve the STS, FS, and impact energy absorption of SCRC mixtures; however, the high blockage in the L-box test limited the possible application for these mixtures, especially in structural elements with heavy reinforcement. Similar behavior was observed when the length

of SFs increased from 35 mm to 60 mm. It should be noted that increasing the SFs' volume and/or length did not show a significant impact on the compressive strength and ME of mixtures.

- The results showed that using higher binder content (600 kg/m^3 instead of 550 kg/m^3) improved the 28-day compressive strength, STS, FS, and ME by 4.7%, 6.2%, 7.3%, and 0.27%, respectively. The impact resistance in each of the drop-weight and flexural impact loading tests also showed a slight enhancement reaching up to 16.3% and 10.2%, respectively, as the binder content increased from 550 kg/m^3 to 600 kg/m^3.
- VRC mixtures showed slightly enhanced mechanical properties and impact resistance compared to their SCRC counterparts, and this may be attributed to the fact that the VRC mixtures entrapped less air than the SCRC mixtures.
- Since the problems of the fresh properties were not a factor in developing VRC, as shown in SCRC, higher percentages of CR up to 40% could be used safely in VRC, which achieved further density reduction but with a decrease in the mechanical properties. Using very high CR contents (more than 30%) also showed a declined enhancement in the ultimate impact energy for the drop-weight and flexural impact loading tests (i.e. achieving impact resistance lower than mixtures of 30% CR, but still higher than the mixtures with no CR).
- In the development of SFVRC mixtures, a larger volume of SFs up to 1% could be successfully used. Increasing the SFs volume from 0% to 1% in SFVRC mixtures improved the 28-day compressive strength, STS, FS, and ME by 6.8%, 93.3%,

75.6%, and 5.6%, respectively. The addition of 1% SFs increased the ultimate impact energy in both the drop-weight and flexural impact loading tests by 4 and 7.15 times, respectively, (compared to beam with no SFs). These results indicate the possibility of developing VRC mixtures with higher ductility, energy absorption, and impact resistance, which indicates a promising potential for structural applications subjected to high-impact loads and seismic activities.

- Using 0.35% (35-mm) SFs appeared to compensate for the reduction in the STS and FS of SCC mixtures as a result of adding 10% CR. Meanwhile, the reductions in the STS and FS of VRC as a result of adding 35% CR were found to be recovered by using 1% SFs (35-mm).
- Inclusion of CR and SFs in concrete production can be considered as a potential technique to develop new types of concrete with decreased self-weight and high-impact resistance. In SCRC mixtures, the maximum possible combination of 15% CR and 0.35% SFs that can be used successfully with 550 kg/m^3 binder content showed an impact energy absorption 3.73 times higher in drop-weight test and 4.13 times higher in flexural impact loading test than that obtained by mixtures with no CR and SFs. Meanwhile, the combination of 1% SFs and 35% CR in VRC mixture appeared to increase the energy required to break the tested specimens by 7.54 times in drop-weight test and 15 times in flexural impact loading test higher than that found in mixtures with no CR and SFs.

8.1.3 Flexural Performance of Large-Scale Rubberized Concrete Beams with/without SFs (Experimental Study 3)

- Increasing the CR content appeared to narrow the crack widths, improve the beams' deformability at a given load, and reduce the self-weight. Using high CR percentage also contributed beneficially to developing an environmentally friendly structural member made with semi-lightweight concrete having a density of less than 2150 kg/m^3.
- Using a CR replacement of 5% can improve the beam's deformation capacity, ductility, and toughness without affecting the ultimate flexural load, significantly. SCRC beam with 15% CR was able to reach an ultimate load, ductility, and toughness of about 93.7%, 97.3%, and 90.6% (on average), respectively, of those reached by the control beam, indicating a promising potential for structural applications. Further increase in the CR content led to a higher reduction in the ultimate capacity of SCRC and VRC beams, but the ductility and toughness showed unconfirmed effect for the high percentages of CR.
- Slight differences were observed between VRC and SCRC in terms of first crack load, ultimate flexural load, ductility, toughness, cracking behavior, and/or overall failure mode.
- Combining SFs with CR compensated for the reductions in flexural capacity, ductility, and toughness of the tested beams resulting from the addition of CR. The use of SFs also allowed a high percentage of CR to be used, achieving further increases in the beams' deformability and reduction in self-weight.

- At service load, adding CR with/without SFs restricted the cracks' opening, satisfying the limitations of maximum crack width given by CSA, ACI 318-95, BS 8110, ACI 224R-01, and CEB-FIP MC90 (with respect to specific exposure classes). This indicates the potential applicability of using rubberized concrete safely in some exterior-exposed structures. However, at failure stage, the SFSCRC and SFVRC beams exhibited higher cracking (number and widths) compared to their SCRC and VRC counterpart beams due to the higher deflections experienced by SF beams.
- Increasing the volume of SFs (35 mm length) from 0.35% to 1% in SFVRC beams showed an obvious increase in the first cracking load, flexural capacity, ductility, and toughness. Adding long SFs (60 mm length) into SFVRC beams, at the same volume of SFs, exhibited improvements slightly less than those observed when 35-mm SFs were used.
- Using rectangular stress block analysis recommended by ACI 318 and CSA design codes appeared to underestimate the ultimate flexural capacity of SCRC and VRC beams. However, increasing the CR content negatively affected the codes' conservatism. Similar results were observed in beams with SFs when the method developed by Henager and Doherty (presented in ACI 544.4R) was used to calculate the theoretical flexural capacity of SFSCRC and SFVRC beams.
- Inclusion of CR negatively affected the tensile strength of concrete, which in turn decreased the first cracking moment of the tested beams. The addition of SFs delayed the initiation of the first crack, thus increasing the first cracking moment

by an average of 11% and 33.1% when 0.35% and 1% SFs (35 mm), respectively, were used. Using the ACI 318, CSA, AS 3600, and EC2 equations (based on tensile strength derived from compressive strength) to predict the cracking moment yielded a reasonable value in the case of the beam made with conventional concrete (with no CR). As the CR content increased, the experimental-to-predicted cracking moment ratio decreased, leading to unsatisfactory predictions in all investigated code-based equations. On the other hand, using the investigated code equations based on the experimental STS (instead of the value derived from compressive strength) generally gave better predictions, especially when the CSA and ACI 318 were used. Similarly, estimating the cracking moment of SFSCRC and SFVRC beams using the STS of their counterparts' mixtures with no SFs can provide more reliable and satisfactory prediction.

8.1.4 Shear Behaviour of Large-Scale Rubberized Concrete Beams with/without SFs (Experimental Study 4)

- Using lightweight CR aggregate with low stiffness contributed to increasing the deformability of the tested beams at a given load and reduced their self-weight (as stated in study 3). However, increasing the percentage of CR from 0% to 25% in SCRC beams decreased their failure shear load, normalized shear strength, post-diagonal cracking resistance, and energy absorption capacity by 30.5%, 9.1%, 12.4%, and 23.6%, respectively. These reductions appeared to be more pronounced at high percentages of CR (higher than 25%) compared to lower percentages.

- At 25% CR, the VRC mixture showed slightly higher compressive strength and STS compared to its counterpart SCRC mixture. This increase in the mechanical properties exhibited a slight improvement in the VRC beam's behaviour in terms of failure shear load, normalized shear strength, and post-diagonal cracking resistance compared to that observed for the SCRC beam.
- Beams with 15% CR and 0.35% SFs (35-mm length) showed comparable results to those of the control beam (with no CR) in terms of failure shear load, normalized shear strength, and post-diagonal cracking resistance, but exhibited higher deformability and energy absorption capacity. Using a higher combination of CR and SFs (35% CR and 1% SFs) contributed to developing semi-lightweight beams with much higher ultimate load, deformability, and energy absorption capacity compared to the control beam.
- For the same volume of fibres, using smaller fibres allowed a higher number of single fibres to be distributed in concrete composite (oriented perpendicular to diagonal cracks), which in turn appeared to heighten the fibres' ability to stitch the diagonal cracks, and hence exhibited higher failure shear load, normalized shear strength, post-diagonal cracking resistance, and energy absorption capacity.
- Beams with up to a 35% CR showed failure mode similar to the beam with no CR (shear failure), but was characterized by a narrower crack widths. Inclusion of 0.35% SFs (35 mm or 60 mm) and up to 35% CR in SFSCRC and SFVRC beams continued to reduce the crack widths but with no change in the failure mode. Increasing the SFs volume to 1% further narrowed the crack width and changed the

failure mode from shear to flexure-secondary shear failure (in beams with 60-mm fibres) or to flexure failure (in beams with 35-mm fibres).

- The investigated design codes (ACI, CSA, AASHTO-LRFD, and EC2) were found to be conservative in predicting the ultimate shear strength for beam without SFs (SCC, SCRC, and VRC). EC2 showed the most reasonable predictions for the shear strength compared to the other used design codes. By comparing the CSA, ACI, and AASHTO-LRFD, the results indicated that the CSA gives a better prediction for normal-weight concrete, but in semi-lightweight concrete the predicted values by the AASHTO-LRFD appeared to be closer to values obtained from experiments.
- In the shear strength prediction of beams with SFs (SFSCRC and SFVRC), the equation developed by Khuntia et al. (1999) showed the highest v_{exp}/v_{pred} values compared to all the used equations. The accuracy of the estimation further improved in the results predicted by Sharma (1986), Narayanan and Darwish (1987), and Imam et al. (1994). On the other hand, although the most reasonable prediction was shown by the equations of Ashour et al. (1992), Kwak et al. (2002), they slightly overestimated some strengths with a percentage of less than 5%, which may lead to unsatisfactory design (but within the acceptable range).
- Although most of the code equations and shear design models satisfactorily predicted the shear strength of beams containing CR with/without SFs, increasing the CR content negatively affected their conservatism (as also found in study 3). This finding may indicate that further investigations are required to take the

influence of CR into account in the prediction of shear capacity of beams with/without SFs.

8.2 Research Contribution

The main contributions of the conducted research can be summarized as follows:

- Presenting effective techniques (such as the use of different mixture compositions, SCMs, and SFs) in order to develop a number of successful SCRC mixtures with promising potential uses in structural applications that require high-impact resistance, energy dissipation, and acoustic absorption capacity.
- Utilizing the low-density of waste CR (compared to conventional aggregates) to develop sustainable semi-lightweight concretes that can achieve a more economical design of building.
- Alleviating the lack of sufficient data regarding the applicability of using CR with/without SFs in structural applications.
- Providing information regarding the stiffness, ductility, toughness, and cracking behaviour of SCRC, VRC, SFSCRC, and SFVRC beams under flexural and shear load.
- Evaluating the performance of flexural and shear design models proposed by some of the current design codes and published research against the experimental results obtained from the conducted research.

- The results of flexural and shear testing can also provide a novel database that may help to validate and/or calibrate further analytical and numerical studies (for future studies).

8.3 Recommendations for Future Research

- Further investigations are needed to examine the durability of the SCRC, SFSCRC, VRC, and SFVRC against abrasion, freezing-thawing action, chloride and sulfate attacks.
- Studying the influence of CR with/without SFs on creep and shrinkage of SCC and VC.
- Evaluating the effect of fire on the mechanical properties and structural performance of SCRC, SFSCRC, VRC, and SFVRC.
- Investigating the performance of different full-scale structural members (i.e. columns, beams, walls) made with SCRC, SFSCRC, VRC, and SFVRC under different load conditions (monotonic load, cyclic load, impact loading, fatigue effect).
- Additional research is required to confirm the effect of using high percentages of CR on ductility and toughness of large-scale reinforced concrete beams.
- Further studies are required to modify the current design codes/current proposed models **OR** to establish new models to take into account the effect of CR

with/without SFs into the calculation of cracking moment, flexural, and shear strength of concrete beams.

- Evaluating the effect of changing in the beam' size, longitudinal reinforcement ratio, and shear span-to-effective depth ratio on the shear and flexural performance of large-scale reinforced rubberized concrete beams.
- Studying the influence of different types of fibres such as synthetic fibres on optimizing the mechanical properties and structural performance of both SCRC and VRC.

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