SEPTEMBER, 2017 Ph.D in Civil Engineering OSAMAH MOHAMMED GHAZI AL-KERTTANI

UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF
NATURAL & APPLIED SCIENCE

ASSESSMENT OF SHRINKAGE DEFORMATION AND TRANSVERSE CRACK FORMATION IN SCGC FOR STRUCTURES

Ph.D Thesis
IN
CIVIL ENGINEERING

BY
OSAMAH MOHAMMED GHAZI AL-KERTTANI
SEBTEMBER 2017

Assessment of Shrinkage Deformation and Transverse Crack Formation in SCGC for Structures

Ph.D Thesis
in
Civil Engineering
University of Gaziantep

Supervisor
Assoc. Prof. Dr. ESRA METE GÜNEYİSİ

by
Osamah Mohammed Ghazi AL-KERTTANI
September 2017

REPUBLIC OF TURKEY
UNIVERSITY OF GAZIANTEP
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES
CIVIL ENGINEERING DEPARTMENT

Name of the thesis: Assessment of Shrinkage Deformation and Transverse Crack Formation in SCGC for Structures

Name of the student: Osamah Mohammed Ghazi AL-KERTTANI

Exam Date: 13.09.2017

Approval of the Graduate School of Natural and Applied Sciences

Prof. Dr. Ahmet Necmeddin YAZICI
Director

I certify that this thesis satisfies all the requirements as a thesis for the degree of Doctor of Philosophy.

Prof. Dr. Abdulkadir ÇEVİK
Head of Department

This is to certify that we have read this thesis and that in our consensus opinion it is fully adequate, in scope and quality as a thesis for the degree of Doctor of Philosophy.

Assoc. Prof. Dr. Esra METE GÜNEYİSİ
Supervisor

Examining Committee Members	Signature
Prof. Dr. Mustafa GÜNAL	M Günal
Prof. Dr. Hanifi ÇANAKCI	
Assoc. Prof. Dr. Esra METE GÜNEYİSİ	
Assoc. Prof. Dr. Kasım MERMERDAŞ	K. Mermerda
Assist. Prof. Dr. Dia Eddin NASSANİ	

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Osamah Mohammed Ghazi AL-KERTTANI

ABSTRACT

ASSESSMENT OF SHRINKAGE DEFORMATION AND TRANSVERSE CRACK FORMATION IN SCGC FOR STRUCTURES

AL-KERTTANI, Osamah Mohammed Ghazi
Ph.D Thesis in Civil Engineering
Supervisor: Assoc. Prof. Dr. Esra METE GÜNEYİSİ
September 2017
109 pages

The occurrence of transverse cracking failure resulting from the restrained shrinkage causes a significant structural problem in several type of the structures such as reinforced concrete building, bridge deck, concrete pavement, etc. The size and geometry of the structural members, span length, construction techniques, reinforcement detailing, and concrete properties are important and influencing the cracking in the structure. In this study, in order to increase the possible use of self-compacting glass concrete (SCGC) in the structural applications, firstly, the shrinkage deformation and crack formation in ring type members cast with SCGC were assessed experimentally. The test specimen consists of a 35 mm thick a mould of concreting around a rigid steel ring 25.5 mm in thickness with a diameter of 375 mm and a height of 140 mm. The test was conducted under extensometer and microscope controls to monitor the strain on the prism and crack width on the ring. In addition to such tests, some fresh related performances of the mixtures were evaluated. To this aim, 16 different mixtures were designed considering single and combined use of fine and coarse recycled glass and used for the preparation of test specimens. The analysis of the results showed that the formation of the first transverse crack prolonged and its width propagation reduced in the ring members having structural recycled glass concrete.

Keywords: Crack formation; Performance assessment; Recycled glass; Ring type concrete member; Shrinkage deformation.

ÖZET

YAPILAR İÇİN KENDİLİĞİNDEN YERLEŞEN CAM KATKILI BETONLARDA RÖTRE DEFORMASYONU VE ENİNE ÇATLAK OLUŞUMUNUN DEĞERLENDİRİLMESİ

AL-KERTTANI, Osamah Mohammed Ghazi
Doktora Tezi, İnşaat Mühendisliği Bölümü
Danışman: Doç. Dr. Esra METE GÜNEYİSİ
Eylül 2017
109 sayfa

Kısıtlanmış rötreden kaynaklanan enine çatlak hasarı oluşumu betonarme bina, köprü tabliyesi, beton yol gibi çeşitli yapı tiplerinde önemli yapısal sorunlara neden olur. Yapı elemanlarının boyutu ve geometrisi, açıklık uzunluğu, imalat tekniği, donatı detaylandırması ve beton özelliği bu konuda önemlidir ve bunlar yapılardaki çatlak oluşumunu etkileyen önemli faktörlerdir. Bu çalışmada, yapısal uygulamalarda kendiliğinden yerleşen cam betonun (KYCB) olası kullanımını artırmak amacıyla, öncelikle, bu tür betonlarla yapılan halka tipi elemanlarda rötre deformasyonu ve çatlak oluşumu deneysel olarak değerlendirilmiştir. Test numunesi 35 mm kalınlığında, 375 mm çaplı ve 140 mm yüksekliğinde, 25.5 mm kalınlıkta sert bir çelik halka etrafında dökülü beton kalıptan oluşmaktadır. Ekstansometre ve çatlak mikroskopu kullanılarak test numunelerde oluşan birim deformasyon ve çatlak genişliği izlenmiştir. Ayrıca, karışımların bazı taze özellikleri ile ilgili performansları incenlenmiştir. Bu amaçla, ince ve iri geri dönüştümlü camın tekli ve birlikte kullanımı göz önüne alınarak test numunelerinin hazırlanması için 16 farklı karışım tasarlanmıştır. Sonuçların analizi, ilk enine çatlak oluşumunun uzadığını ve çatlak genişliği ilerlemesininde yapısal cam betonlu halka elemanlarda azaldığını göstermiştir.

Anahtar Kelimeler: Çatlak oluşumu; Performans değerlendirmesi; Geri dönüşümlü cam; Halka tipi beton eleman; Rötre deformasyonu.

To My
Wife (May)
and
Sons (Mohammed & Ali)

ACKNOWLEDGEMENT

I owe special thanks to my supervisor, Assoc. Prof. Dr. Esra METE GÜNEYİSİ, for her generosity and great support to realize this thesis.

Great appreciation goes to the staff of the Graduate School of Natural and Sciences of Gaziantep University and also Iraqi Consulate in Gaziantep for the interest to Iraqi citizens.

I was convicted of thanks and gratitude to Assoc. Prof. Dr. Erhan GÜNEYİSİ for his support to complete this research.

I would like to thank to Süleyman İPEK for his assistance with laboratory work. Thanks are also to my special friends Assist. Prof. Dr. Madhat Al-SOUD and Lec. Ammar MUTAR for their supports.

Finally, I want to express my deep love and my feelings to my mothers and my fathers as well as I must thank my dear brother and sisters for their continuous support and prayers for me to complete my studies.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

LIST OF SYMBOLS/ ABBREVIATIONS

ACI	American Concrete Institute
ACBM	Advanced Cement-Based Materials
A_S	Area of reinforcing steel
ASR	Alkali-Silica Reaction
ASTM	American Society for Testing and Materials
BS	British Standard
EFNARC	European Federation of National Trade Association
EN	European Standard
FA	Fly Ash
GFRC	Glass Fiber Reinforced Concrete
GFRP	Glass Fiber Reinforced Polymer
L	Length of restrained member
LCD	Liquid Crystal Display
NCA	Natural Coarse Aggregate
Ncr	Entire force
NFA	Natural Fine Aggregate
N(t)	Restrained force
NVC	Normally Vibrated Concrete
PCI	Precast Consulting Services
PCP	Precast Concrete Pavements
RCGA	Recycled Coarse Glass Aggregate

RCPT	Rapid Chloride Permeability Test
RFGA	Recycled Fine Glass Aggregate
RGA	Recycled Glass Aggregate
RILEM	Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages
W	Crack width
w/p	Water powder ratio

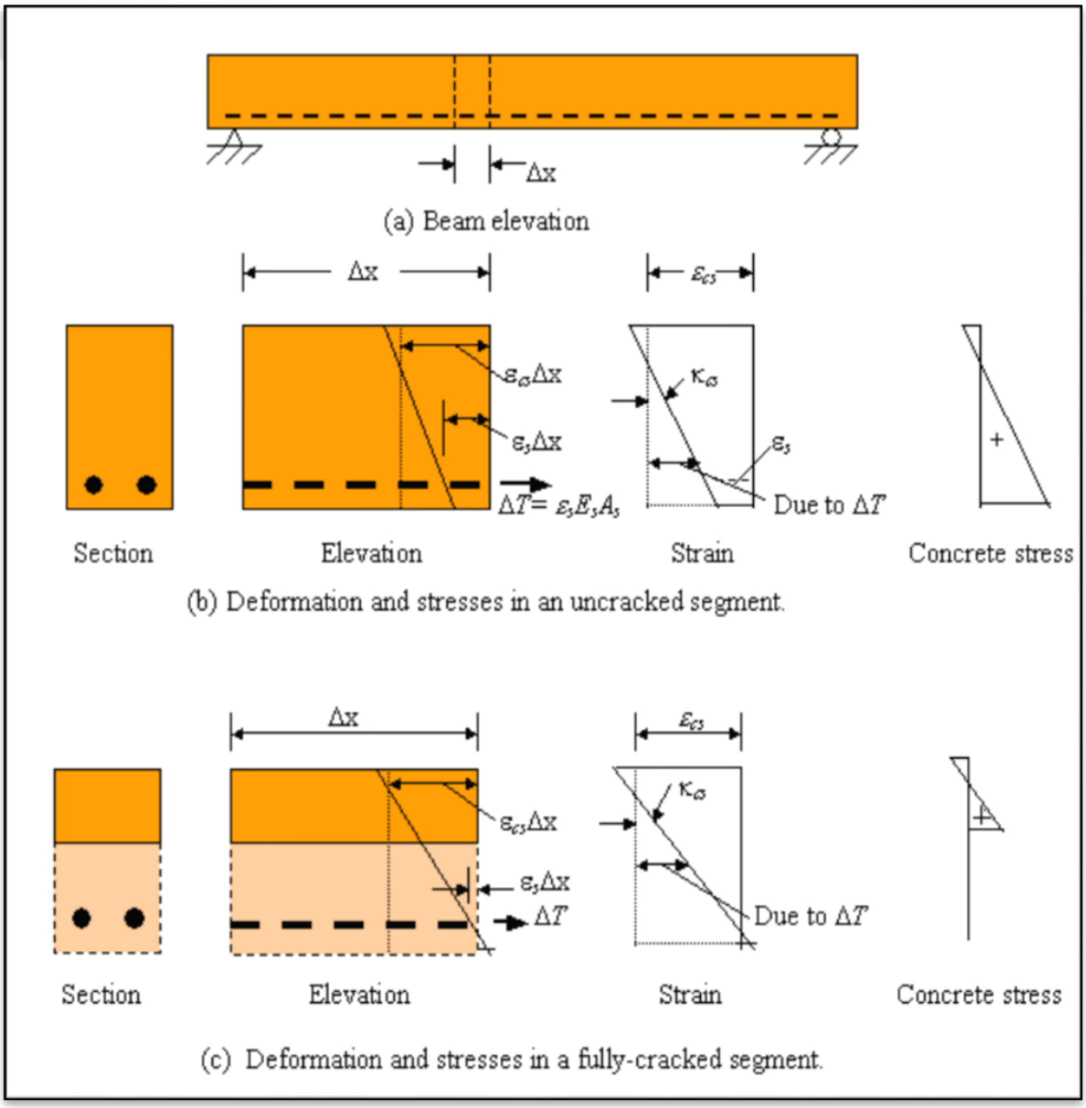
CHAPTER 1

INTRODUCTION

1.1 Causes of cracking and shrinkage mechanisms in structure

Reinforced concrete or concrete structures don't commonly fail due to the inadequate of strength, rather due to the environmental conditions. The most general reason of the damage is related to the development of the cracks in structural system (Mehta, 1993; Hobbs, 1999). Cracks can be observed in concrete structure by various reasons that can be categorized into either mechanical loading or environmental influences. They result in the development of the tensile stress in the structure. This stress creates the cracking that can negatively affect the performance of the concrete structures. For example, continuously reinforced concrete pavements are designed by using longitudinal reinforcing bars so as to hold the shrinkage cracks tight. However, in the transverse direction, the shrinkage cracks may develop over a time period. This may cause the premature deterioration of the structure (Transportation Research Circular, 2006). The shrinkage deformation and cracking depend on many factors such as the rate and magnitude of shrinkage strain, time-dependent material property, creep in structure, strength level, structural geometry (shape and size of the structural members) and structural resistant (Weiss, 1999).

In Figures 1.1 and 1.2, the formation of the shrinkage crack leads to changes in the stress distribution in unrestrained and restrained reinforced concrete members are illustrated, respectively. The first figure shows the behavior of singly reinforced concrete beam due to the shrinkage deformation while the second one indicates that of singly reinforced concrete tension member. In the case of unrestrained condition, the shrinkage can cause stress and strain on an uncracked and a crack beams. At that time, reinforcing steel in the structural members is compressed and leads to the opposite tensile load at the interface between the steel bar and concrete. This causes the crack formation for the restrained condition, the shrinkage deformation brings about the axial tension in the structural elements under the action of the bending due to the external forces. However, for the elements not under significant bending, it is considered that the cracks are happened by direct tension rather than flexural tension (Gilbert, 2001).



(a) Beam elevation

(b) Deformation and stresses in an uncracked segment.

(c) Deformation and stresses in a fully-cracked segment.

Figure 1.1 Shrinkage warping in a singly reinforced beam (Gilbert, 2001)

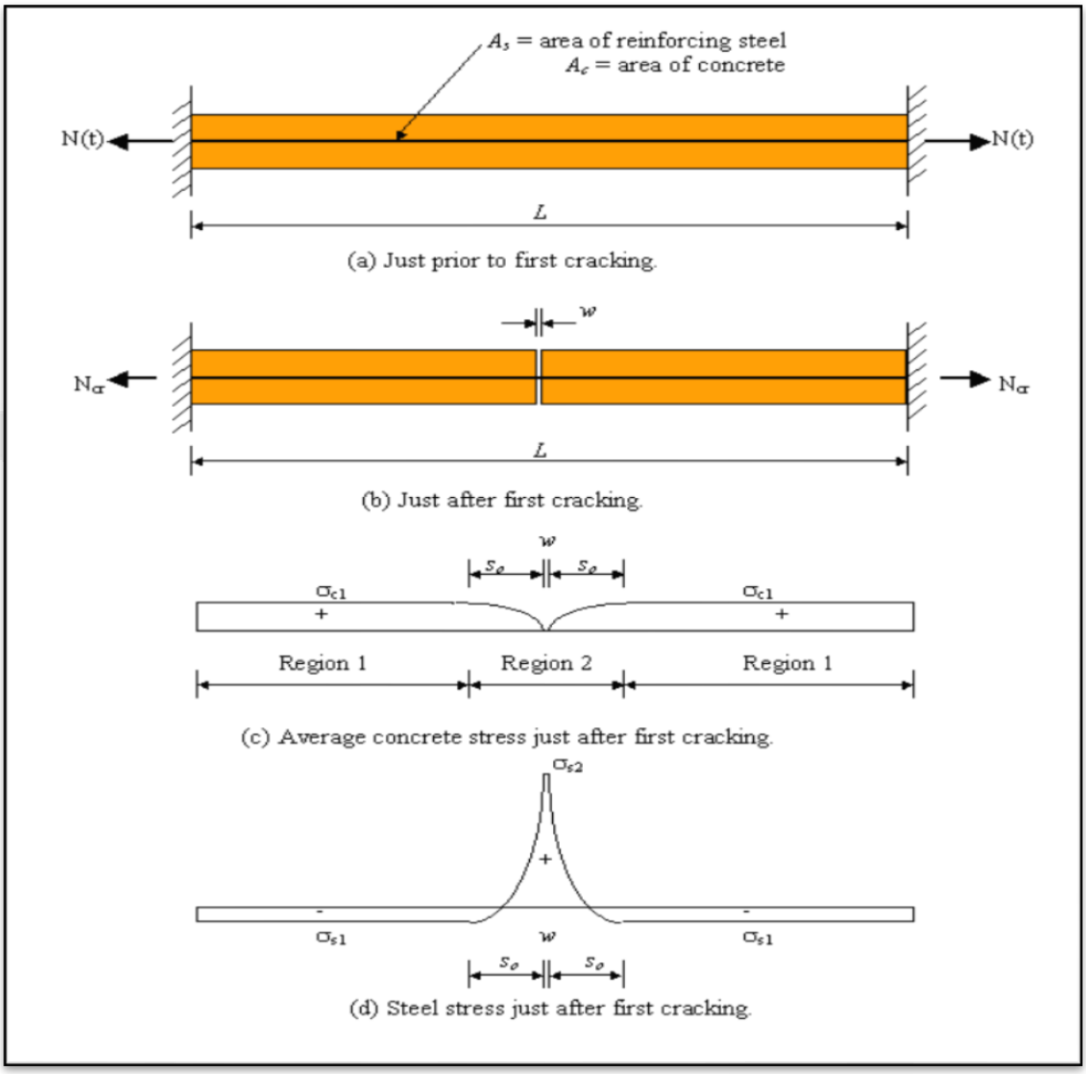


Figure 1.2 First cracking in a restrained direct tension member (Gilbert, 2001)

In Figure 1.3, in site condition, the full-scale prismatic blocks subjected to restrained shrinkage is shown. The tests were instrumented in order to locate and follow cracks formation, space and width. Moreover, in Figure 1.4, in laboratory condition, a reinforced concrete block with one reinforcing bar at crack saturation stage is illustrated. As reportedly, different experimental and numerical studies on the behavior of shrinkage cracking in reinforced concrete or concrete members are needed so as to better understand the mechanisms and establish convenient measures (French national research program, 2014).

Figure 1.3 Block with restrained shrinkage (I shape beam and steel strut) (French national research program, 2014)

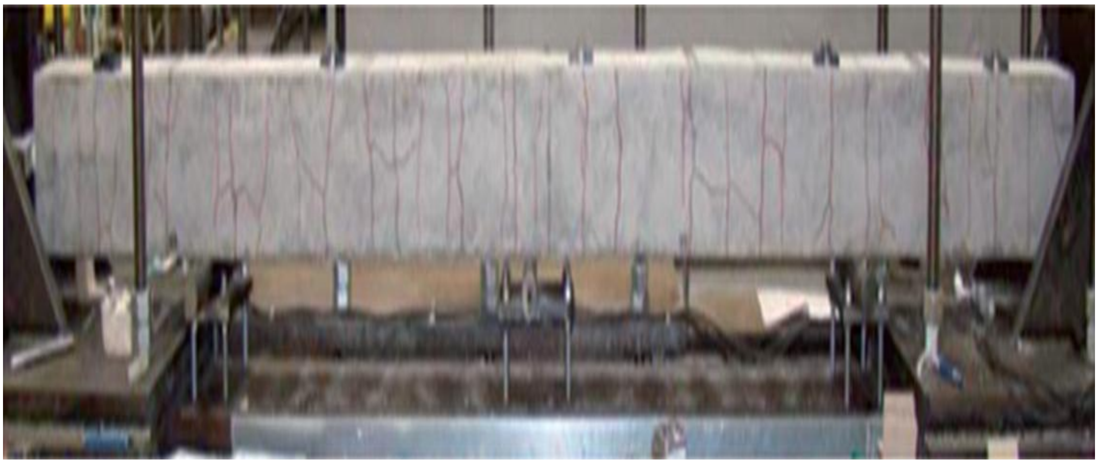


Figure 1.4 Tie with one reinforcement bar at crack saturation stage (French national research program, 2014)

1.2 Description and practical application of SCC

The structural concrete is able to carry the static and dynamic loads and form the integral part of the structures. For this reason, its property and performance are of great importance for the success of the structural system. Normally vibrated concrete is referred to concrete which is consolidated by vibrating apparatus to drive out the restrained air for making the concrete homogeneous and dense. So, the consolidation is the mystery to manufacture a suitable concrete for the best strength and durability properties (The Concrete Society and BRE, 2005). The reduction in proficiency workers and increase reinforcement with small diameter lead to make good concrete was difficult because the fill compaction was difficult to get (Okamura and Ouchi, 1999).

In Japan in early of 1980s, Okamura proposed an idea to design a concrete without vibration. So in 1988, at the Tokyo University the first type of self compacting concrete (SCC) was produced by Ozawa and Maekawa (Ozawa et al., 1989; RILEM TC 174 SCC, 2000).

From that date, many papers deals with SCC properties have been published by many vocational association, such as the American Concrete Institute (ACI), the American Society for Testing and Materials (ASTM), Center for Advanced Cement-Based Materials (ACBM), Precast Consulting Services (PCI) and Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages (RILEM) etc.

As a result of the evolution of SCC at the University of Tokyo, it has been used in many practical structures. The first application of SCC was in a building in June 1990. SCC was then used in the towers of a prestressed concrete cable-stayed bridge in 1991 as shown in Figure 1.5. Lightweight SCC was used in the main girder of a cable-stayed bridge in 1992. Since then, the use of SCC in actual structures has gradually increased. There are many other applications of SCC such as: Bridge (anchorage; arch; beam; girder; tower; pier; joint between beam and girder), Box culvert, Building (as it is shown in Figure 1.6), Concrete filled steel column, Tunnel (lining; immersed tunnel and fill of survey tunnel), Dam (concrete around structure), Concrete products (block; culvert; wall; water tank; slab and segment), Diaphragm wall, Tank (side wall; joint between side wall and slab), Pipe roof (Ruža and Dejan, 2009).

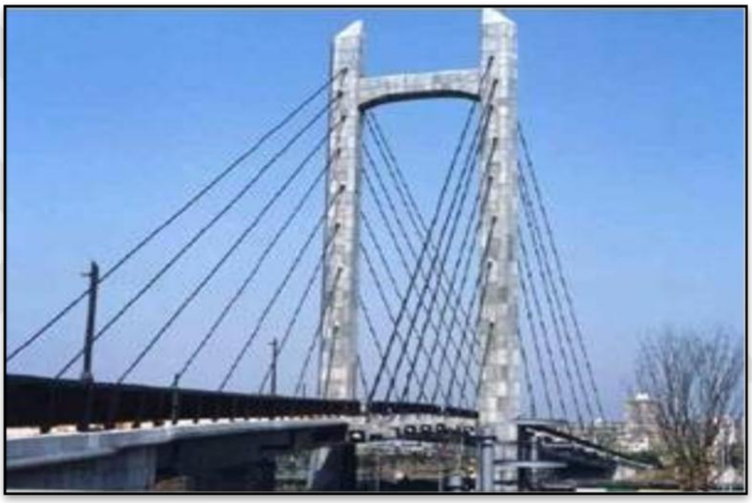


Figure 1.5 Shin-Kiba Ohashi bridge in Japan (Okamura and Ouchi, 2003)

Figure 1.6 Burj Khalifa, UAE (Ruža and Dejan, 2009)

1.3 Potential use of recycled glass for sustainable structures

Soda-lime glass, also called soda-lime-silica glass, is the most widespread type of glass, which is used for windows and glass vessels (flasks and jags) for drinks, feed, and some ware items. Glass paste is often made of tempered soda-lime glass, about 90% of soda-lime glass is of produced from glass (Thomas and Terese, 2005).

The characteristics of soda-lime glass are chemically steady, rationally firm, comparatively cheap, and excessively workable. Because it can be remelted and resoftened for several times, it is perfect for glass recycling (*Wiederhorn, 1969*).

Soda-lime glass is manufactured by fusion the raw materials, such as sodium carbonate (soda), silicon dioxide (silica), aluminum oxide (alumina), lime, dolomite, and small quantities of fining agents (e.g., sodium sulfate, sodium chloride), the temperatures glass furnace is about 1675°C. The degree of furnace depends on the quality of the furnace superstructure material and by the glass installation. Relatively cheap minerals such as trona, sand, and feldspar are usually used as a replacement of pre handling chemicals (De Jong, 1989).

Saving the natural treasures and minimize the request for worthy landfill area leads to thinking about waste recycling. The big problem around the world is discarded beverage glass bottles. In all countries, large proportions of solid waste consist of waste glass, and the major environmental problem is recycling the glass (Topçu, and Canbaz, 2004).

Among numerous kinds of solid rubbish, glass has been popular investigated as a replacement for coarse and fine aggregate and even cement. Because of its chemical composition and physical constituents, recycle waste glass is diagnosed as fine replacement as sand, particularly remarkable for areas lacking in natural wealth and dealing with disposal of wastes (Hongjian and Kiang, 2013).

There are widely a lot of applications of using recycled glass in the construction industry all over the world. The application includes using glass in asphalt concrete (glass–phalt), normal concrete, back-filling, sub-base, tiles, masonry blocks, paving blocks, verification and other ornamental purposes (Parviz, 2012).

For example, Figure 1.7a shows a sidewalk in front of Hubbard Hall doorway in Michigan State also; Figure 1.7b shows a sidewalk amidst Cherry Lane and Breslin Center in Michigan State while, Figure 1.7c shows a curb and outdoor flatwork at the MSU (Michigan State University) Recycling Center; USA(Parviz, 2012).

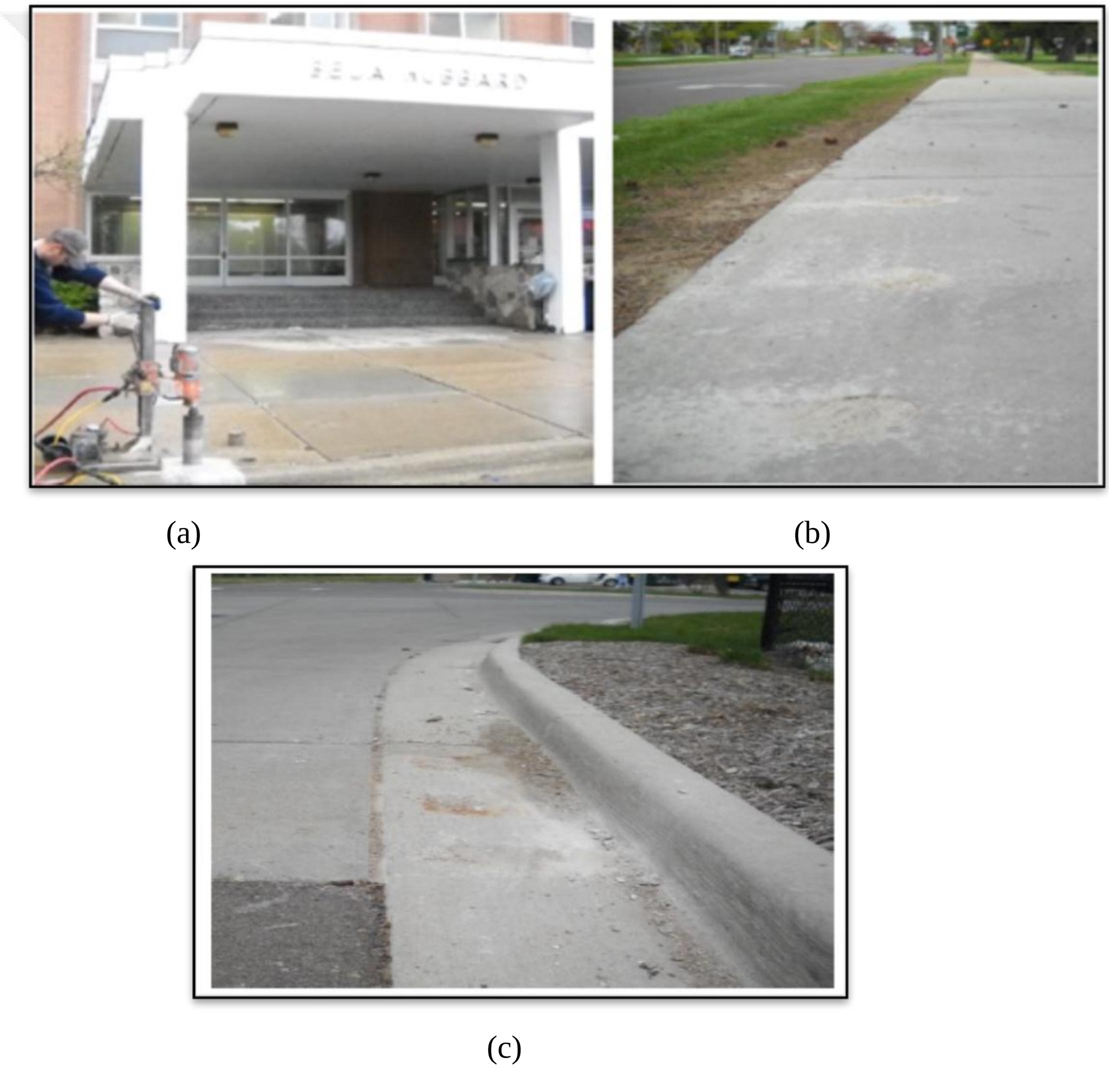


Figure 1.7 Some application of SCCs with 20% replacement of mixed-color waste glass powder in USA (Parviz, 2012)

1.4 **The aim of the project**

The reutilization of waste product in structural applications encourages the development of the sustainable structures. In the current study, to rise the potential use of SCC with recycled glass in the construction practice, firstly the shrinkage deformation and crack formation in the ring member made with such concrete was investigated. For this, shrinkage strain and crack width propagation were measured by means of the extensometer and microscope. Thereafter, some fresh properties were also studied experimentally. Analyses of the results were given comparatively.

1.5 Organization of the thesis

This thesis consists of five chapters:

Chapter 1 provides a glace on causes of cracking and shrinkage in structures, practical application of SCC, potential use of recycled glass for structures and the aim of the project.

Chapter 2 presents a literature review and presents general background information about shrinkage deformation in structures and SCC. Moreover, waste glass, and its use in structural concrete. Also, the use of glass fiber and glass fiber reinforced polymer in structural engineering was discussed. Finally, usage of glass in SCC for structural purpose was also discussed.

Chapter 3 covers the details of the experimental program conducted throughout this study. The preparation of test specimens and testing procedures are included.

Chapter 4 provides the test results and discussion of the program conducted in task 3.

Chapter 5 gives a summary of the findings obtained from this thesis.

CHAPTER 2

LITERATURE REVIEW

2.1 Shrinkage deformation in structures

Concrete shrinkage has become an increasingly important case to be understood because the potential of drying shrinkage as a function of moisture loss may be lead to cracking and contribute to minimize the serviceability. In reinforced concrete or concrete structures, since the concrete have brittle nature and low tensile strength, that's lead to cracking when subjected to load. The results of the cracking are aesthetical defects on the surface of the structures, the permeability of concrete increases, and decrease of mechanical section and reduction of steel reinforcement protection that can reduce the service life of the structures. On the other hand, with age, the concrete mechanical capacity increases due to the time-dependent behavior. At an early age, the concrete can crack under lower stress because it has lower strength. Immediately after casting, the strength and concrete stiffness which can be described by its secant young modulus are negligible also; the mechanical behavior in that time is plastic. During setting, the concrete stiffness increases and failure strain decreases. After setting, the tensile strength increases and failure strain also increases, the strain at that point consider the minimum value for failure strain (Holt and Leivo, 2004). In that moment, cracking risk is at a maximum. A relationship between mechanical properties evolution and degree of hydration has been described through the rate of heat evolution of concrete (Weiss, 1999). As it has been explained, the first mechanical property developed is stiffness, the tensile strength is secondly and compressive strength is the last (Weiss, 1999; Altoubat and Lange, 2001). At early ages, concrete can be subjected to mechanical actions derived from shrinkage. Shrinkage produces a dimensional change leading to stress on the concrete structures when its displacement is restricted and the concrete members cannot deform freely (Caldarone et al., 2005).

There are several types of restraint cases in the structures which fully or partially prevent movements. They can be categorized as external and internal restrains. Figure 2.1 shows the example of such restrains. A structural member which is prevented to move freely due to its support conditions and lateral surroundings is exposed to external restrains. However, the internal restrains are generally resulted from different needs for movement or various parts of the section members (Antona, 2011).

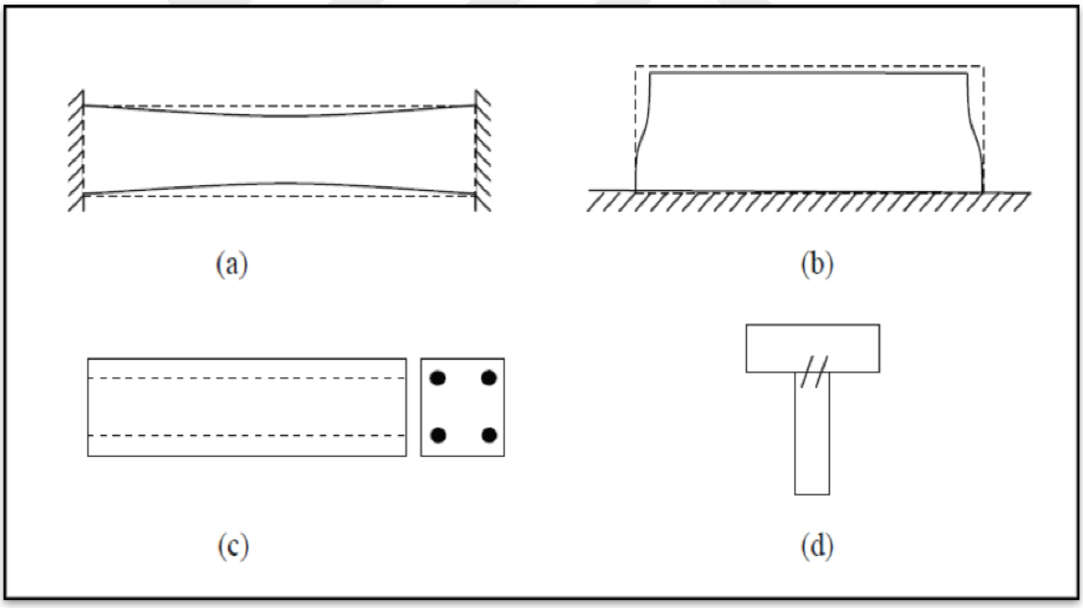


Figure 2.1 Example of external (a) and (b), and internal restraints (c) and (d) (Antona, 2011)

The mechanism of shrinkage cracking in the structures requires some of the same behavior as in the flexural cracking of the structural members. Firstly, the change in the stress state in a restrained member undergoes the drying shrinkage. It is considered that a reinforced member is restrained at the ends. Due to drying out of concrete, the tensile stress increases with time. However, the steel bar remains unstressed since its length is not changed. Under unfavorable conditions, a crack will develop. After observing the first crack, the stress distribution in the structural member will dramatically alter. However, the concrete stress after the first crack is lower than the tensile strength of the concrete as generated in the stress history on the structural member. Cracking makes the member more flexible leading to overall reduction in the induced tensile stress in the uncrack portion of the members. This process is repeated until the concrete pattern in the structural member is established (Cariro and Clifton, 1995).

In Figure 2.2, the cracking in the fixed support reinforced concrete slab caused by the restrained deformation is illustrated. As seen from the figure, shrinkage of concrete results in the occurrence of restrained deformation. Amount of sufficient or insufficient reinforcement in the slab significantly affect the number and wide of cracks (Patric et al., 2000b). The crack width is an important factor for the structures. In Table 2.1, the maximum allowable crack widths suggested by ACI Committee 224 (2001) are illustrated for different service conditions.

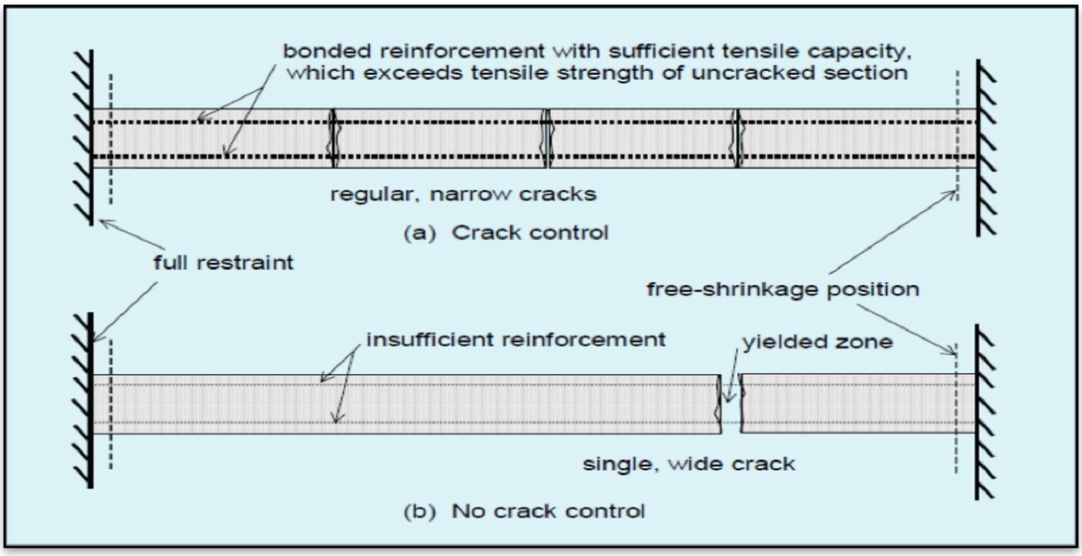


Figure 2.2 Cracking caused by restrained deformation in RC slab (Patric et al., 2000a)

Table 2.1 Maximum allowable crack width (ACI Committee 224, 2001)

Exposure condition	Crack width in	 mm
Dry air or protective membrane	0.016	0.41
Humidity, moist air, soil	0.012	0.3
Deicing chemicals	0.007	0.18
Seawater and seawater spray, wetting and drying	0.006	0.15
Water-retaining structures	0.004	0.10

Several causes can lead to shrinkage in concrete member. At early ages (less than 24 h after casting), the main causes are drying shrinkage, thermal and autogenous. Many factors of concrete characteristics affect on the shrinkage such as (composition, casting, and curing procedures), shape, exposition of the structural members and environmental conditions (temperature, relative humidity and wind velocity) (Almusallam., 2001; Bissonnette et al., 1999; Topçu and Elgün, 2004; Mihashi and Leite, 2004). As the shrinkage which is resulted from the loss of water inside concrete through the members' surface, strain gradients are produced in member sections. Consequently, cracking caused by the shrinkage starts from surface areas in contact with the environment (Mihashi and Leite, 2004). According to that, structural members with large surfaces in contact with an aggressive environment are more liable to cracking due to the shrinkage. Due to the high fines content, structural members made with self-compacting concrete (SCC) may show larger shrinkage and creep than traditional concretes (EFNARC, 2002),while some authors reported a similar behavior (Persson, 2001) and even a lower shrinkage at early ages of SCC incorporated members with regard to traditional concrete (Holt and Shodet, 2002). These differences could be related to the different fines used in each case. In some studies, a delay of the shrinkage beginning of SCC has been reported, due to its lower bleeding rate and, therefore, lower evaporation rate from the exposed surface of the structural members (Holt and Shodet, 2002).

2.2 Description of SCC

Every year about 25 million tons of structural concrete (Europe 10% and China 50%) are used to build up foundations, columns inside buildings, beams and slabs in bridges, roads, drainage system, dams, pavement, even artworks, and port works (European Federation of Precast Concrete, 2010). Typical concrete ingredients are cement, coarse aggregate, fine aggregate and water. So, about 75% to 90% of the volume of concrete composed of raw material removed from ground. Thus, the concrete considers as the largest consumer of natural sources and that lead to thinking about the sustainability of constructions (Naik, 2008).

The Concrete Society and BRE (2005) defined SCC as "the capacity of concrete to flux due to its own weighing and wholly top up the mould, while preserving homogeneity even in the existence of overcrowded reinforcement, and then compacting without the necessity for vibrating compaction". The three basic properties of fresh SCC are: filling ability, passing ability and segregation resistances (De Schutter, 2005; The Concrete Society and BRE, 2005). Filling ability is the properties of SCC to flux due to its own weighing and wholly top up the mould. Passing ability is the properties of SCC to inflow around and through the deterrent such as thin spaces and heavy reinforcement without closing it as shown in Figure 2.3 which makes SCC as a special type of concrete. Segregation resistance is the property that makes SCC homogeneous during transporting and casting (Domone, 2000).

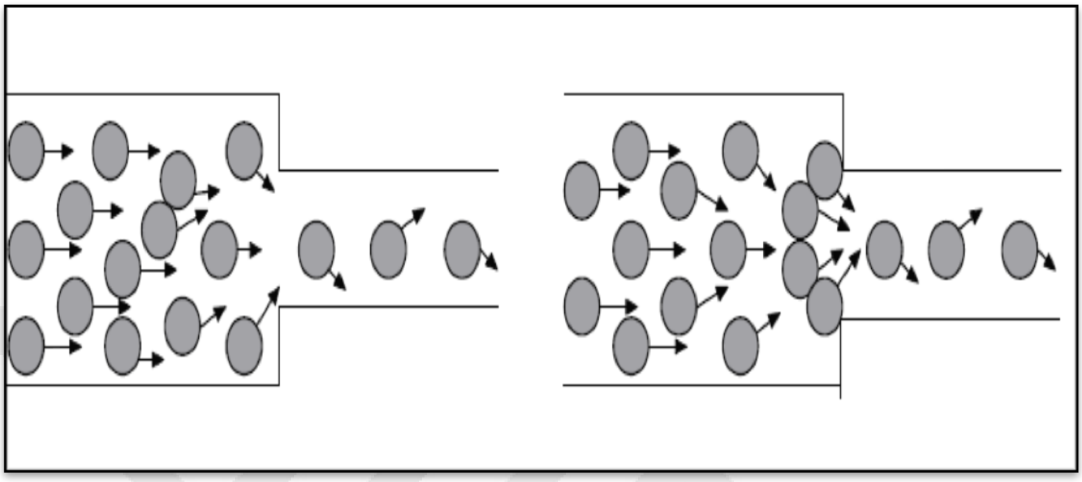


Figure 2.3 Structural of blocking (RILEM TC 174 SCC, 2000)

2.2.1 Advantage and disadvantage of SCC

In the case of comparison between SCC and NVC, SCC has a good recipes, and working conditions and productivity can be enhanced by using SCC (De Schutter et al., 2008; The Concrete Society and BRE, 2005). Less porous transition zone is a result of avoiding interior segregation between solid grains and surrounding liquids which is come from discarded compaction. Also, enhanced in strength, durability, and finishing of SCC can be expected (RILEM TC 174 SCC, 2000).

Use of SCC enhanced structural performance of concrete by raising the rate of reinforcement, reducing the cracks by using smaller bar diameter and using complicated framework. Also, SCC process many properties such as casting homogeneous concrete in narrow sections. Moreover, use of SCC enhanced job cost and reducing the period of construction (Figure 2.4) (Okamura and Ouchi, 2003; RILEM TC 174 SCC, 2000).

Using of SCC eliminates noise pollution and reduces hearing problems which is related to the use of vibrating instruments and that lead to enhanced workplace environment. So, SCC is named as "the quiet revolution in concrete construction"(RILEM TC 174 SCC, 2000; The Concrete Society and BRE, 2005). Due to these reasons, the precast concrete products plants has become of the greatest employer of SCC in Europe (Skarendahl, 2003).

Since SCC needs more powder and admixtures (especially superplasticizers) compared to NVC and that make SCC more expensive than NVC (The Concrete Society and BRE, 2005). Nehdi et al. (2004) and Ozawa (2001) reported that the cost of SCC production increase between 20% and 60% comparing with the same grade of NVC. However, in big construction, savings in labour costs and construction period were much important than the increase in SCC material cost (Billberg, 1999).

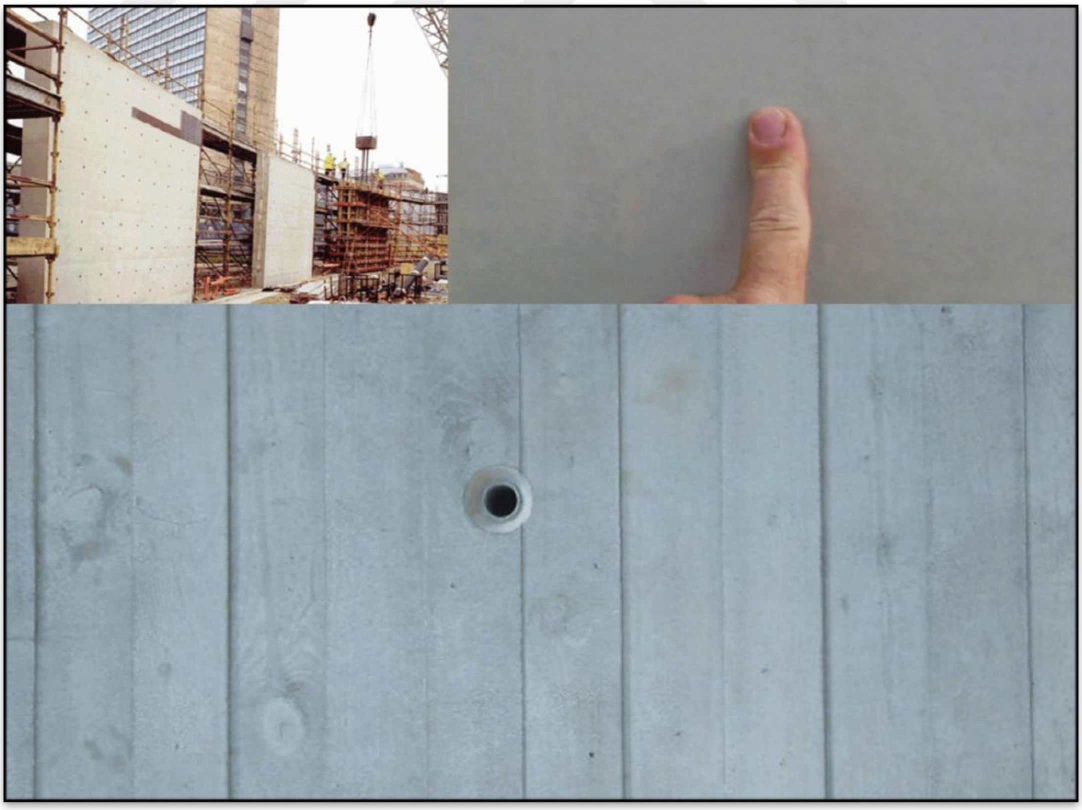


Figure 2.4 Locally superficies terminus at London Piccadilly, Lincoln and Loughborough, UK (Okamura and Ouchi, 2003)

But, the interests of SCC were presents in combined sandwich method, which SCC and NVC casting together in coats with the same construction element (Okamura and Ouchi, 2003; Ouchi, 2001; Ozawa, 2001). Greater care with quality control of SCC is required because the robustness of SCC decreased (i.e. sensitivity increased) with the increased of powder and admixtures (Walraven, 1998).

2.2.2 Classification of SCC

Researchers categorized SCC into three sorts: powder, viscosity-modifying agent (VMA) and combined type, counting on the way to provide viscosity (Dehn et al., 2000; Holschemacher and Klug, 2002; Nawa et al., 1998).

- Powder type SCC is featured by decreasing the ratio of W/P and high content of powder, which are desired to decrease the amount of free water and excess the plastic viscosity.
- VMA type SCC is featured by adding a high viscosity modifying agent VMA amount to increase plastic viscosity.
- Combined type SCC be discovered by adding small dosage of VMA to powder type SCC to enhance the robustness.

2.2.3 Structural application of SCC in practice

Japan has utilized self-compacting concrete (SCC) in bridge, building and tunnel construction since the early 1990s. In the last years, a number of SCC bridges have been constructed in Europe. While, the U.S. precast concrete industry is beginning to apply the technology to architectural concrete. SCC has high potential for wider structural applications in highway bridge construction (Goodier, 2003).

The concrete use in highway bridge construction without vibration is not a new case, e.g. shaft concrete and mass concrete both have been successfully placed without vibrating and settlement of seal concrete is accomplished under waters with the help of a ramie which is also without vibration. Normally, the mass, shaft and seal concretes which are of less power, it is difficult to achieve stable quality and they are less than 34.5 MPa. Optimum use is being focused in the present application of the SCC. That is desired to deliver uniform and compact surface texture, improved and more consistent quality, better and high strength and rapid production and development. Figure 2.5 illustrates progressively increasing applications of the SCC in construction throughout Japan. The quantity of SCC utilized for ready-mixed concrete (cast-in-place) and prefabricated products (precast members) was about 400,000 m^3 in Japan in the year 2000. The pre-stressed, precast concrete production and forecast in place construction have reported numerous benefits by means of the SCC which are: Less labour engaged, greater strength, rapid construction, better quality and stability, reduced problems associated with vibration and low noise-level in the construction sites and plants (Ouchi et al., 2003).

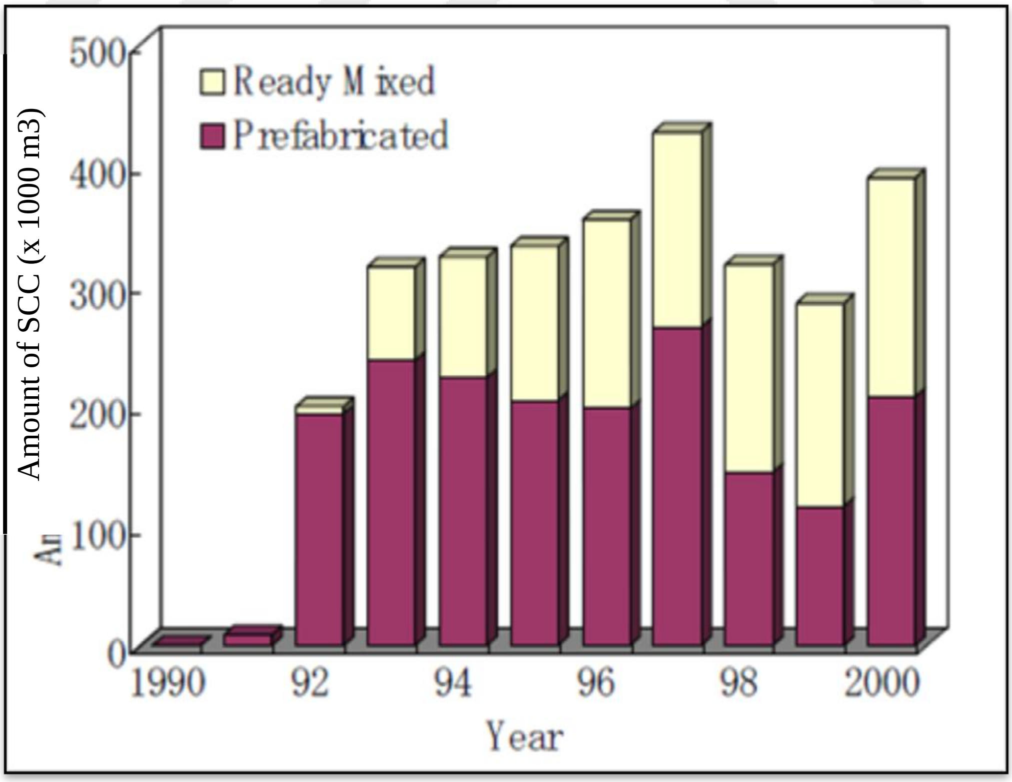


Figure 2.5 Amount of SCC placement in Japan for structural purposes (Ouchi et al., 2003)

Vertical construction elements (structural and nonstructural walls, columns, etc.) including the construction of basement walls which represents about 25% of the concrete market in Canada (Khayat and Aitcin 1998). Schlagbaum (2002) showed that there was an average reduction in labor during the placing process about 30% using SCC. While, Martin (2002) mentioned that in many examples of structural, architectural, and utility products, producers in the United States have reported a decreased patching labor cost from 25-75%.

During the last two decades, SCC has been increasingly used in a different structural application such as bridges, high-rise buildings, caissons, tunnels, and architectural castings. In general, SCC has been used effectively and economically where large quantities of concrete are placed in a tight schedule, or concrete placement is in a confined space, or concrete is placed in thin sections with congested reinforcement, or a special manifestation and finish of the concrete surface is required. Many interesting projects have been described in conference proceedings (Ozawa and Ouchi, 1999; Shah et al., 2002). Four projects with unique features are explained below to illustrate the advantages of using SCC and its versatility.

- Akashi Straits Bridge, Japan – SCC was used in the two massive anchorages of this world's longest suspension bridge (Figure 2.6) (Okamura and Ozawa, 1994; Okamura, 1997).
- Repair of a Parking Garage, Canada – A 6.5 m long beam located under an expansion joint at the entrance to the Webster parking garage was damaged due to advanced corrosion (Figure 2.7) (Zia et al., 2006).
- Precast Modular Jail Cell Unit, USA using SCC exclusively for its precast products (Figure 2.8) (Zia et al., 2006).

- The Sodra Lanken Project (SL), Sweden- SCC has primarily been used in connection with constructions difficult to compact by normal vibration and high demands on aesthetics, as shown in Figure 2.9 (Ouchi et al., 2003).

Figure 2.6 Akashi Straits Bridge, Japan (Ouchi et al., 2003)

Figure 2.7 Webster parking garage, Canada (Zia et al., 2006)

Figure 2.8 Modular Jail, USA (Zia et al., 2006)

Figure 2.9 The Sodra Lanken Project (SL), Sweden (Ouchi et al., 2003)

Also the studies included tests on wall or column elements of significant height. A decrease in situ strength with height would be expected, and the top/bottom strength ratios show largely similar behavior of SCC and NVC mixes, however there was some variations within and between studies. The similarity of strength within the test elements, expressed as coefficients of difference of core strengths, has a tendency to be a little higher for SCC than for NVC, but again there is no proportionate pattern. A similar note applies to the relationship between in situ and cast sample strengths. These tests therefore show that SCC has no greater problems than NVC with regard to in situ characteristics, which was the aim of some of the studies. The entire test elements were prepared with full attention to good practice, e.g. full vibration of the NVC this is one of original driving forces for studies to developed SCC in Japan. Also, the good behavior of SCC depends on the mix being properly designed and produced to have characteristics suitable for the specific application. Clearly, mixes must have adequate filling and passing ability for the specific application, and as noted by Hoffmann and Leeman (2005), any tendency to segregation can have significant detrimental effects (Hoffmann and Leeman 2005).

Khayat et al. (2001) showed that SCC columns exhibited 62% greater ductility than similar NVC columns. The distribution of in-place characteristics along the height of non-reinforced columns was found to be more homogeneous in SCC than NVC.

There is sufficient knowledge of structural behavior for structural performance to prognosticate with reasonable confidence from property data. The relatively limited numbers of test programs on structural elements which have been reported area have generally confirmed this. In spite of some conflicting results, reinforced SCC beams have:

- Similar load capacity compared to NVC.
- Some tendency to greater defections and ultimate strains (consistent with the lower elastic modulus values if compared to NVC.

- Greater shear strength, for SCC beams with no shear reinforcement (Schiessl and Zilch, 2001).

A greater ultimate strain capacity, and hence ductility, of SCC elements has also been examined on columns by Domone (2007), he concluded that it is likely that the apparent ductility of structural elements results from the lower elastic modulus of the SCC in the un-cracked region of the element, and any tendency of the SCC to earlier tensile cracking is lesser importance. Also, Domone (2007) showed that the tests on the behavior of frames under cyclic loading indicate a potential advantage of SCC in seismic design, which is perhaps an area for useful further research.

Precast concrete pavements (PCP) have been used SCC in repair projects as permanent replacements or overlays for long continuous sections of concrete pavements, or in isolated individual or group slabs (Armaghani, 2015). An additional behavior of SCC reported by some authors is an increase in pull-out force, which can lead to best safety margins in some applications, A well-proportioned mix will show good robustness, i.e. can be suitable to specific requirements, e.g. different flows, without losing other performances. Differences in materials can be faced and even some tempering operations at the casting site can be successful. Transportation time and air temperature do not affect SCC more than any other type of concrete, as well as pumping (Walraven, 2003). SCCs have been used worldwide. The concretes with strength grade C60, C70, C80, and C90 are used to apply in high-rise buildings in China. West tower project in Guangzhou is a high rise building, with the height of 425 m; the distances between reinforced bars are short in structure as shown in Figure 2.10 (Feng et al., 2010).

High-performance SCC concrete with a mix designed to provide a low-permeability and high-durability was used in the walls and columns of Burj Dubai tower.

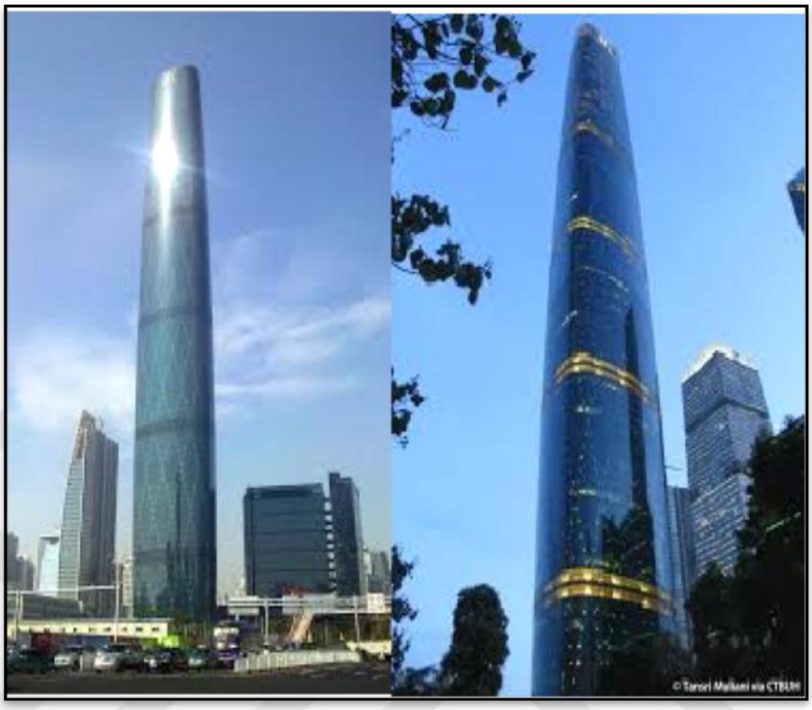


Figure 2.10 West tower project in Guangzhou, China (Feng et al., 2010)

The C80 to C60 cube strength concrete used Portland cement, fly ash, and local aggregates. The C80 concrete had a specified Young's Modulus of 43,800 N/mm^2 at 90 days. Two of the largest concrete pumps in the world were used to deliver concrete to heights over 600 m in a single stage. To reduce the cracks due to the high temperatures of Dubai (about 50^{o}C), the concrete was poured at night, when the air is cooler and the humidity is higher, with ice added to the mix. Special mixes of concrete were made to withstand the extreme pressures of the massive building weight as shown in Figure 2.11 (http://www.burjdubai.com/).

Figure 2.11 Burj Dubai tower, UAE (http://www.burjdubai.com/)

2.3 Waste glass

Glass is a manufactured from calcium carbonate, soda ash and silica which are fused at high temperature and then suddenly cooled, the resulting of this operation is solidification without crystallization. Glass is utilized to manufactured a lot of things, such as glass vessels (containers, bottles), flat glass (windows), cathode ray tube (monitors, TV), and light bulb glass (Byars and Zhu, 2003; Shayan and Xu, 2004). Moreover, the structure of glass can be imagined as a two-dimensional framework of silica tetrahedra (Din, 1979).

One of the main problems which are resulting from the continuity of technology industrial progress and overpopulation is eliminated of waste materials that are generated. These waste materials consist of concrete, ceramics, iron and glass.

Request to decrease the waste has developed to find out other uses for waste materials instead of burial it in landfills. Many of concrete plants considered the concrete as a good container for waste materials, which makes the waste material unhurt and fixing the pollution problems. Utilization of waste materials in concrete and also in concrete structure not only environmental friendly but, it enhanced the engineering properties (Koh, 2014).

According to United Nations 7% of solid waste which is about 200 million tons is glass in all over the world. The current solution is still most of the waste glass goes to landfill (Topçu and Canbaz, 2004). McCoach et al. (2013) pointed that only 59% of 2.5 million tons of waste glass every year in UK is recycled and the other goes to landfill. The big problem around the world is discarded beverage glass bottles. In all countries, large proportions of solid waste consist of waste glass, and the major environmental problem is recycling the glass, since the glass is not biodegradable, landfills do not supply an environment-friendly solution (Topçu and Canbaz, 2004).

In Turkey, glass recycling rate was only 25% in 2009 because, not enough money for recycling programs and low societal sensibility of division recyclables also, the absence of a good-organized system for recoverable waste (Cihat et al., 2013). In Hong Kong about 0.14 million tons of waste glass every year only 3.3% of this amount is reused (EPD, 2010). Ideally, the waste glass should either be reused or remanufactured to get new glass vessels. However, transporting costs and classifies the waste glass according to colors, types, and so on makes that pure fantasy. So to solve this problem there is many ways to reuse the waste glass. One of these ways is reused the waste glass in cement and concrete manufacture for economical cost and for saving the natural sources (Tom and Andrew, 2011; Tuncan et al., 2001).

Many European Union countries imposed taxes on the cement industry and using of natural sand and coarse aggregate to preserve the environment and these taxes consist of powder, fuss, visual intrusion, loss of comfortable and harm to biodiversity. Also, the cost of landfill which needed to deface the waste material increase in Europe from 2£ in 1996 to 80 £ in 2014 for each tonne of waste material (HMRC, 2014).

2.3.1 Waste glass in construction industry

According to the definition by United Nations, sustainable development is development that meets the needs of the present without compromising the capability of future generation to meet their own needs (United Nations, 1987). As the most exceedingly utilized construction substance around the world, concrete plays a leading role in the development of sustainability in construction industry. As recommended by BACSD (2005), sustainable concrete includes the following elements:

- Concrete must be specified, designed, and proportioned for its intended application with mixtures developed for durability (where appropriate), resource conservation, and minimal environmental impact.
- Production of concrete ingredients, production of concrete, and construction practices must be environmentally responsible.
- Concrete, in all applications, must be sustainable and must be viewed as such by owners and the public at large.
- The concrete industry must remain competitive.

One of the methods to enhance the work of construction plants with respect to sustainable evolution would be decrease the amount of Portland cement and using a waste material resulting from industries which included cementitious properties such as fly ash, ground granulated blast furnace slag, condensed silica fume. Another way to enhance the environment by using waste industries such as waste glass and broken concrete as an alternative to fine and coarse aggregate. The mystery to successful consumption of these wastes is knowledge of ingrained properties which can enhance the properties of concrete, in addition with decreasing any harmful effects result from using these wastes material (Dhir et al., 2005). Also due to approximately zero absorption of waste glass that makes recycled waste glass is used in concrete application that needed to decrease the absorption and drying shrinkage (Lam et al., 2007).

Using of recycled glass cullet in cement and concrete fructification has many advantages:

- Decrease the cost of waste disposable, since there is an increase in landfill tax and push to decrease landfilling.
- Saving large amount of natural sources as raw material and that lead to conserves the environment.
- Prolong the landfill space.
- Minimizing the amount of CO_2, NO_X and other air contaminated gases which resulting from the production of cement clinker.
- It gives hope using waste glass in other applications without any increase in cost or quality (Shi and Zheng, 2007).

Glass cullet is segments of cracked glass in different colors which possess barely any recycling possibility. Utilize of waste glass cullet in the construction is one of the extreme efficient way because of the constructions industries required a lot of materials. Furthermore, the load on the storehouses might be reduced when using glass cullet. Glass aggregate is a good recycled material to use as aggregate because of low water absorption. Also the hardness of glass grants concrete high abrasion resistance. Fine glass aggregate has pozzolanic reactivity lead to decrease cement content. So, the price of concretes will be reduces. Also, light weight concrete can be produced by using glass after special process (Topcu et al., 2008).

2.3.2 Possible use of waste glass in structural concrete

The waste glass can be utilized in structural concrete in different forms as powder and aggregate. The relevant explanations from the literatures are given here. Since glass amorphous and consist of large quantities of calcium and silicon, so theoretically, it is pozzolanic or cementitious product if it is grounded finely. For that reason and due to cement is more expensive than glass, thus glass can be used as Portland cement replacement in concretes for economics and environmental advantages (Shi and Zheng, 2007; Jin et al., 2000; Shayan and Xu, 2004). Nishikawa et al. (1995) found that when glass was crushed to same grading of cement, the compressive strength of cement paste increase when the cement replaced by glass up to 25% by weight at age of 90 days.

Dyer and Dhir (2001) reported that the growth of compressive strength depend on the colors of finely grounded glass cullet. They pointed that the compressive strength of paste containing green and clear colors increase slightly at 28 days with cement replacement about 10% comparing to control mix, while cement paste containing the same content of amber glass was barely reached the strength of control mix. They found that, due to pozzolanic reaction the rate of strength gain of paste with glass was higher comparing to control mixes.

Shao et al. (2000) used three groups of glass (150 to 75μm, 75 to 38μm and less than 38μm) in lime-glass mixture as an indicator of pozzolanic activity. For all groups the replacement of cement by cement powder was 30%. Actually all the particles of three groups were coarser than the cement particles. They found that, the strength of the third group (less than 38µm) met the demand of the target strength at 7 days, while the strength of the first group (150 to 75µm) was less than the target strength and this behavior according to research due to coarser particles of glass to participate.

Cassar and Camilleri (2012) utilized implosion mechanism to transfer waste glass since waste glass claimed to have fine particles which were abrasive and also because the pollutants were not smaller in size so it could be easily to remove. They concluded that concrete with cement substitution by 10-20% imploded glass would typical to use in building near to or at the sea because that type of concretes had an altitude resistance to ion penetration.

The strength of concretes containing glass was a proximally equal to the strength of concretes containing fly ash (FA). Fineness more than 300 m^2/kg of glass could extent an activity index equal to BS EN 450 FA (Byars et al., 2004). Shao et al.(2000) explained that the strength of concrete containing 30% ground glass with particle size 38µm more than the strength of concrete consisting 30% Class F FA.

Topcu and Canbaz (2004) found that concrete containing only glass powder showed strength more than strength of concrete containing FA at early and late ages. In spite of this high alkali amount there was no decay observed in concrete strength at later ages. On the contrary, there has been an increase in strength with time, the compressive strength of concrete consisting glass and FA increasing to 120% and 102%, respectively when the curing period increase from 3 to 90 days.

Shayan and Xu (2006) showed that the addition of 10 µm glass powder to concrete as a substitution of cement lead to increase the compressive strength when the glass powder 10% but, when the addition of glass powder ranging from 10 to 30% the compressive strength started to decrease. Taha and Noumu (2008) reported that when using 45 μm glass powder to concrete instead of cement lead to decrease the compressive strength.

Tuncan et al. (2001) measured the suitability of the FA and glass to use in concrete. They concluded that the compressive strength increased with all additions. Freeze-thaw resistance test pointed that the addendum of glass and FA improved the durability properties of concrete. They recommended 15% glass and 30% FA blended mixtures, since that mixture gave the best result according to compressive strength, indirect tensile stress, and permeability.

Shi and Wu (2005) produced self-compacting lightweight concrete by using glass powder and FA to increase resistance to segregation and filing ability. They found that glass powder reduces the setting time and increases the shrinkage, strength and chloride resistance of concrete. They concluded that finer glass powder lead to increase pozzolanic activity.

Bignozzi and Sandrolini (2004) compared the mechanical and physical characteristics of mortar consisting of milled glass cullet as fine filler with mortar containing calcareous filler. They reported that the compressive strength when calcareous replaced by milled glass increases, and that increase became more obvious when curing period increase. For example, when the concrete curing time increase from 30 to 60 days, the strength increases by 34%.

Ozkan and Yuksel (2008) exacted the durability properties of cement mortars with waste glass as pozzolan, at replacement upto 50%. It was observed that the residual strength reduced as the substitution ratio was increased, except for the case of 10% replacement ratio for which the residual strength was found to be more than that of reference mix.

Shayan and Xu (2006) also explained that drying shrinkage of concrete containing 20-30% glass powder with 10µm more than that of control mix, and when the glass powder increased the drying shrinkage increase. These results confirmed with the consistent of Jawed and Skalny (1978) when they explained the effect of alkali on shrinkage.

Dumitru et al. (2010) used 7.5, 15 and 25% of powder glass as substitution of cement in concrete. The compressive strength of concrete with glass powder was less than that of reference mix and drying shrinkage was higher with concrete containing glass powder. However, all mixes were meeting the design requirements.

Nwaubani and Poutos (2013) examined the concrete mortar using grounded green glass with fineness of 300µm. The results indicated that the flow tables were decreased with increases the amount of glass amount. Also, increasing the amount of glass leads to increase the water absorption.

Liu (2011) tested the fresh and hardened characteristics of mortar made of green glass as a fractional substitution level by volume of cement and /or fine natural aggregate. The compressive strength, splitting strength, ultrasonic pulse velocity and dynamic modulus of elasticity were decreased as the amount of glass increased; this minimize is higher at early stages however, this minimize reduces with age.

Matos et al. (2016) replaced 50% of the waste glass powder instead of cement and limestone in SCC. In terms of viscosity and filling ability both types of SCC correspond to VF2 class. It was concluded that the coefficients of chloride diffusion for control samples was decreased for SCC with waste glass powder.

Natural aggregate is unlike glass aggregate in texture and particle shape. Coarse glass aggregate pocess angular and sharp edges, flat shape, ease of fragmentation and smooth surface. While fine glass aggregate have less tendency to fragment, more regular shape and the sizes of particles are less than 1.5 mm which is similar to natural sand (Polley et al., 1998). Furthermore, the specific gravity of natural aggregate (about 2600 kg/m^3) is greater than that of glass aggregate (around 2500 kg/m^3). In addition, glass does not have the property of absorption water (Koh, 2014).

The utilization of recycled glass as aggregate in concrete has become common in last two decays, due to increase the research especially at Columbia University in NewYourk which leading to improve the aesthetic appeal of the concrete. Also, used of recycled waste glass enhanced the long- terms strength and thermal insulation since, the glass aggregate have a good thermal properties (Poutos et al., 2008).

Meyer and Baxter (1997) worked on many studies using the glass aggregate as gravel. They concluded that structural concrete can be produced with 100% glass aggregate using different proportions of clear and amber glasses and Portland cement with 20% metakaolin. They found that the value and rate of expansion has little affected by the size of glass aggregate which was used. Zhu and Byars (2004) pointed that the expansion increased with the increased of glass aggregate size when tested varying glass aggregate size up to 12 mm and its effect on expansion of concrete.

Polley et al. (1998) wrote that the amount of water needed to glass aggregate concrete was more than that required to reference concrete to reach the same workability. Also, they reported that the compressive strength of concrete made of glass aggregate as gravel and a concrete made of glass aggregate as both fine and gravel was less than that for concrete consist of glass aggregate as sand at ambient and elevated temperatures.

Topcu and Canbaz (2004) utilized glass aggregate as a replacement of natural coarse aggregate with grain size between 4-16 mm, the substitution was between 0 - 60%. They found that the slump, air content and fresh unit weight decreased as the glass aggregate increased. While the flowability was increased with the increases of glass aggregate content. Their analysis indicated that the compressive, flexural, and indirect tensile strengths were reduced as the glass aggregate increased.

Zhu (2004) studied the alkali-silica reaction (ASR) between glass and cement in concrete. He used glasses from two different sources and tested the concrete according to ASTM C1260 and BS 812-123. Results showed that there was an expansion in concrete produced from both sources due to ASR. Also, it was found that the glass aggregate could be used as a potentially "fit for purpose" products for the precast concrete technology.

Collins and Bareham (1987) said that used of doubtful aggregate might be reduced the ASR and finally decreases the expansion of concrete. After that Ducman et al. (2002) explained that porous glass does not make the concrete expand if it is used as aggregate. Since expanded glass aggregate is considered as low strength and needs a lot of water to absorb leading to difficulties in concrete placing.

Shi and Wu (2005) studied the effect of 18 different type of expanded glass aggregate with two different type of expanded clay in cement. They concluded that concrete could be produced with 50% by volume replacement of glass aggregate with a good ratio of density to compressive strength of concrete to use it in structural concrete.

The influence of substitution of fine and coarse aggregate by waste glasses on fresh and hardened concrete tested by Terro (2006). He reported that the compressive strength for large amount of glass minimized by 20% comparison with the compressive strength of ordinary concrete when the temperature increased to 700^{o}C. In spite of that when the replacement of fine and coarse aggregate was 10% there is no effect on the characteristics of concrete at normal and high temperature.

Castro and Brito (2013) said that the workability of concrete had affected by the size of glass aggregate. The w/c ratio must be increased to reduce the loss of workability if the glass aggregate is utilized as fine aggregate. When the replacement of natural aggregate by 20% of glass aggregate; there is a growth in compressive strength up to 13.6%. Used of glass aggregate decreased water absorption (capillary was felled by 10.1% and immersion reduced by 3.8%), the shrinkage decreased by about 7.4% and carbonation felled by 21.7%.

Also, Castro and Brito (2013) used recycled structured and car window panels as aggregate in SCC. The mixtures consisting 0, 5, 10, and 20% of recycled glass aggregates as substitution of natural aggregates were used in three series fine and coarse, individually or together. It was concluded that the workability of concrete with glass is highly influenced by the grain size of the recycled glass and that leading to an increase in the w/c ratio from 0.55 to 0.58 for the mixture with the 20% combination of fine recycled glass aggregate. Also, the mixtures with together combination of fine and coarse recycled glass aggregate behave better in expression of water absorption by capillarity. Finally, the shrinkage of concrete with recycled glass aggregate is the same to that of the normal SCC. However, the mixes with the minimum shrinkage are those with bilaterally fine and coarse recycled glass aggregate.

Kou and Poon (2009) tested SCC by utilizing waste glass as a partial substitution of fine aggregate with 10, 20, and 30%, and granite aggregate with maximum size of 10 mm in proportions of 5, 10, and 15%. The mechanical characteristics reduced with increasing of recycled glass. While the drying shrinkage decreased and resistance to ion penetration increased with raising the amount of recycled glass in SCC.

Zammit et al. (2004) tested the compressive strength of concrete consisting of glass aggregate as a fractional substitution of fine aggregate in different proportions. It was reported that the typical proportion of substitution for mechanical properties was 50% because it gave compressive strength 10% higher than that of ordinary concrete; also this mix gave the higher slump.

Otherwise, Topcu and Canbaz (2004) explained that the addition of waste glasses to concrete as aggregate did not influence on the workability of concrete, but reduced the fresh unit weight, slump and air content. Furthermore, they demonstrated that as the waste glass dosage raised the compressive, in direct tensile and flexural strengths in addition to Schmidt hardness decreased. These results were compatible within Park and Lee (2004) who used brown glass. However Tuncan et al. (2004) findings were contradicted with these results. Tuncan et al. (2004) concluded that the addition of glass aggregate increased the indirect tensile strength.

Dhir et al. (2005) tested the influence of grading of fine glass aggregate on long term strength of concrete until one year. The long time curing was selected to let from an alkali silica reaction to fully development. The results were match with ordinary concrete containing natural sand as fine aggregate with the same grading. It was demonstrated that when the material became finer the behavior of concrete consisting of glass was improved.

Corinaldesi et al. (2005) pointed that when natural fine sand was replaced with ground glass particle sizes up to 100μm; there was no harmful effect but on the contrary at microscopic level there was enhancement in mortar mechanical behavior. While the major trouble of utilizing glass as aggregate is that the downy and clear superficies of glass grains which lead to decrease the bond strength between cement paste and glass aggregate (Taha and Nounu, 2008a).

Topcu et al. (2008) examined the utilization of a series of glass colors (three different glass colors white, green and brown), mineral material and chemical additives to replace fine aggregate by glass to concrete in so as to minimize the expansion. It was observed that the greatest expansion with white glass, and the expansion increased with increased the amount of glass.

Saccani and Bignozzi (2010) examined the expansion of mortar bar using w/c ratio of 0.5 and c/s ratio of 1:3; these mixtures consist of various amount of glass as sand and searched the effects of alkalinity and color. It was found that there is no expansion when using soda-lime glass while mortar containing lead-silicate glass showed expansive trends and gave critical expansion results.

Limbachiya (2009) crushed the glass until it matched with British Standard requirements for fine aggregate, but it was irregular in texture and sharper. It was found that there was a reduction in fresh characteristics of concrete with such glass. However, it was concluded that there was no differences in strength results between ordinary concrete and concrete containing 15% glass replacement.

Chen et al. (2011) examined the fresh and hardened characteristics of concrete consisting of recycled liquid crystal display glass as a fractional substitution of fine aggregate. The results explained that the ultrasonic pulse velocity and surface resistance of concrete containing glass were slightly more than that of normal concrete and the peak results were obtained with 30% replacement.

Ali and Al-Tersawy (2012) tested SCC consist of 350, 400 and 450 kg/m^3 cement content with 0.4 w/c proportion and six ratios of glass added as partial substitution of fine aggregate 0, 10, 20, 30, 40, and 50%. It was found that the slump flow rose with increase the glass content while the compressive, splitting tensile, bending strengths and modulus of elasticity decreased as the glass content increased. The results showed that acceptable SCC can be manufactured by utilizing recycled glass as a fractural substitution of fine aggregate.

Lee et al. (2013) alleged that for dry mix concrete blocks the substitution of sand by glass aggregate derive to rise in water absorption and the value of absorption related to the amount of glass which was used in concrete. It was found that there was a lose in compressive strength due to higher water absorption which leads to enhance the void ratio of concrete consisting of glass aggregate compared to concrete containing natural sand.

Yasser et al. (2013) utilized recycled glass as fine aggregate instead of natural fine aggregate in six various weight proportions starting from 0 to 50%. They found that the fresh properties of SCC with recycled glass were improved while the hardening properties were shown to be decreased as the amount of the recycled glass rise.

Ling et al. (2011) tested the feasibility of 100% recycle glass as sand in architectural white cement mortar. The w/b ratio was 0.4 for all the mixtures to manufacture highly workable waste glass self-compacting white cement mortar. The fresh, mechanical and durability properties were tested. It was found that the fluidity of mortars containing glass increased with the increases of recycled glass up to 100% replacement.

Pereira et al. (2008) said that the sorptivity of concrete containing glass as partial replacement of sand decreasing with increased the recycled glass. Hongjian and Kiang (2013) also used four colors of glass (green, brown, clear and mixed) in five different proportions upto 100% as a substitution of fine aggregate. The results pointed that the flowability of concrete consisting of glass was decreased with addition of glass with all replacement regardless of colors because of many reasons such as sharp edge, angular shape and ascent aspect ratio.

Koh (2014) found that the slump and flow table values were reduced when the content of fine glass aggregate increases regardless the color of glass. The bulk density, ultrasonic pulse velocity and compressive strength of hardened concrete consisting glass were lower than that of conventional concrete. Dumitru et al. (2010) also examined the concrete with 30, 45 and 60% of crushed fine glass as a substitution of natural sand. It was showed that the compressive and flexural strength increased up to 45% and decreased after that, while the indirect tensile strength was marginally decreased at that percentage. The shrinkage and diffusion coefficient were reduced.

2.3.3 Addition of waste glass as a fiber in structural engineering

A number of the researches were carried out to examine the fresh and hardened characteristics of SCC when adding waste glass as a fiber. For example, Mastali et al. (2016) investigated the SCC made by usual ingredients such as cement, fine aggregate, coarse aggregate, water, mineral admixture fly ash and broken concrete at different substitution ratios 5, 10, 15, 20%. To improve the property of SCC made with the use of broken concrete and fly ash, waste glass fiber has been added to the mix. The same concept was also apply but with different proportions of the glass fiber in the literature (Zhang et al., 2015; Tobbi, et al., 2012; Moustafa and El Gawady, 2016; Baena et al., 2016; Phani et al., 2015; and Salih and Ghazi, 2001). Waste glass fiber in different ratios of 0.15, 0.20, and 0.30 by weight of cement has been added to the mixture which consists of broken concrete and gave the highest strength (Maranan et al., 2015). Barluenga and Hernández-Olivares (2007) concluded that the amounts of glass fiber around 600 g/m^3 shown the maximum cracking control ability comparing to normal SCCs, but larger amounts did not increase the fiber efficiency. Figure 2.12 shows some structural application of glass fiber reinforced concrete (GFRC).

Since, glass fiber reinforced polymer (GFRP) have many properties like high strength, lightweight, resistant to salt water, chemicals, and the environment, can be molded into complex shapes, low maintenance, good durability and beauty these properties made GFRP has widely range of construction applications such as interior and exterior of domes, fountains, columns, balustrades, planters, panels, sculptures, entryways, moldings, facades, cornices, porticos, cupolas, signs and roofs. Yu et al. (2016) checked the impact resistance and mechanical characteristics of SCC reinforced with waste glass fiber reinforced polymers by 0.25, 0.75, and 1.25% of fiber volume fractions.

Figure 2.12 Some structural application of GFRC (Canton, and Nassau, 2014)

The results pointed that addendum waste glass fiber reinforced polymers enhancing the impact resistance and the mechanical characteristics of the reinforced SCC with glass fiber reinforced polymers, these results conform to the results of other authors (Chandramouli et al., 2010; Chira et al., 2016; Kumar and Rao, 2015; and Rabadiya and Vaniya, 2015). Figure 2.13 shows the use of waste GFRP in the construction.

Figure 2.13 Utilization examples of GFRP in different constructions (Toutanji and Saafi, 2000)

2.3.4 Usage of glass in SCC for structural purpose

According to Concrete Society and BRE (2005), glass has a chance to be used as a partial replacement of cement in SCC. But the fineness of crushed glass should be more than 70% of particles passing 0.063mm. While EFNARC (2002) concluded that crushed glass can be used in SCC when the specific surface area is more than 2500 cm^2/gm and the particle size is less than 0.1mm. For the time being there is a move to embrace a new technique for transferring the municipal waste glass to an effective recycled waste glass. The steps of producing available material such as aggregate and pozzolanic additives in construction materials from waste glass were shown in Figure 2.14. The waste glass bottles are delivered to factories for washing and crushing to the desire sizes of particle and in general the particle size of glass should passes 10 or 5mm sieve. After that, the 5mm particle sizes are grinding to the glass powder with 75-150µm grain diameter to be used as pozzolan for cement replacement in concrete (Ling et al., 2013).

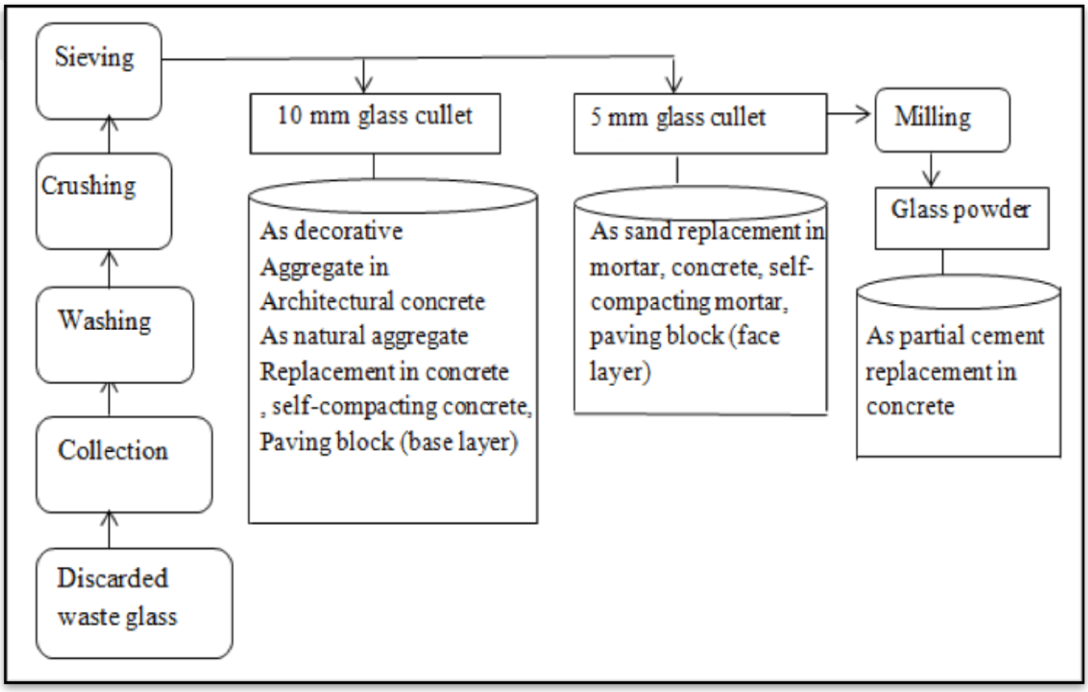


Figure 2.14 Steps of converting waste glass to valuable products and its use in the construction (Ling et al., 2013)

Shi and Wu (2005) reported that the crushed glass successfully used as partial replacement of cement (ratio of replacement was 15%) to produce lightweight SCC. The fineness of glass was not mentioned but it showed an increase in pozzolanic reactivity than Class F fly ash. The fresh properties were: no segregation and visual bleeding was observed, there was a decrease in slump flow by 25mm, L-box blocking ratio reduced by 23% and an increase of 0.8 seconds in V-funnel time. Also some researchers used glass cullet in concrete as fine aggregate to get architectural and decorative applications (Shi et al., 2004; Byars et al., 2004; Meyer, 2003). Moreover, a number of SCGC and architectural mortar using different colors and particle sizes of recycled glass aggregates were produced at the laboratory. Some of these samples are shown in Figure 2.15 with 100% replacement of recycled glass (Ling et al., 2013).

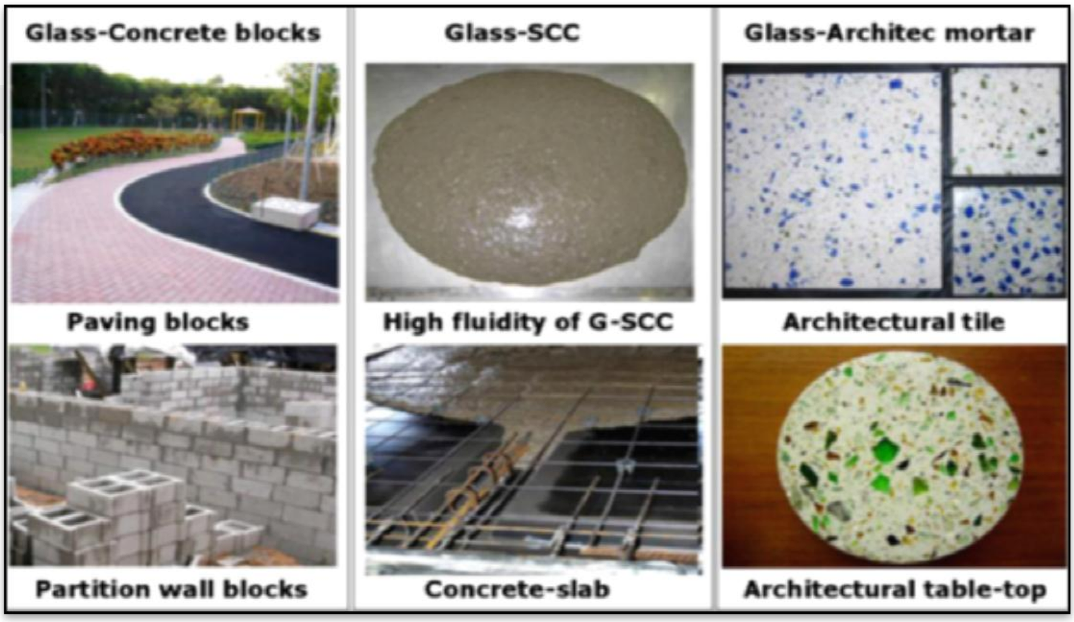


Figure 2.15 Some samples of SCGC applications and architectural mortar with 100% recycled color glass (Ling et al., 2013)

Byars and Zhu (2003) mentioned that in UK there are many structural application have been carried out using glass such as: glass aggregate and pozzolan in pre-cast concrete paving slabs, use of glass pozzolan and aggregate in fielding and plat process slabs, use of glass pozzolan and sand in low grade ready mixed concrete, use of glass pozzolan and aggregate in semi-dry concrete blocks, use of glass pozzolan and aggregate in wet-pressing concrete kerbs and use of glass pozzolan and sand in cast concrete roof tiles, as shown in Figure 2.16; while Figure 2.17 shows some pictures from construction site for recycled waste glass.

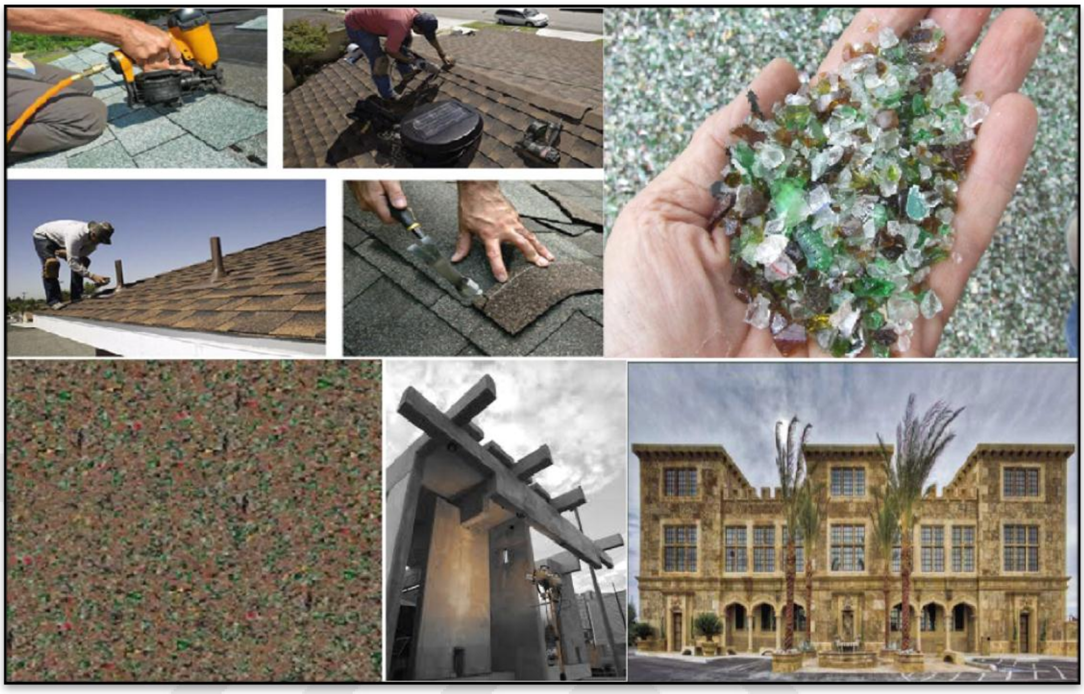


Figure 2.16 Some structural application of recycled glass (Byars and Zhu, 2003)

Figure 2.17 Some pictures from the construction site for recycled glass in structures (Koehler and Fowler, 2007)

CHAPTER 3

METHODOLOGY

3.1 Introduction

In the concrete or reinforced concrete structures, the shrinkage failure plays important roles in the service life of such structures. For this reason, in the current study, the shrinkage deformation and crack width propagation in ring members made with self-compacting glass concrete (SCGC) were mainly investigated. Besides this, the fresh states of SCGC were studied to better understand the properties of such SCGC and increase its possible uses in structural applications.

3.2 Materials

The type of cement which used in this work was normal Portland cement of CEM I 42.5 R (PC) which corresponds to ASTM Type I grade. It has a specific gravity of 3.15 and a surface area (Blaine) of 326 m^2/ kg. Table 3.1 showed the physical and chemical analysis of the cement. It is supplied by Çimko Cement Factory. According to ASTM C 618 (2002) the fly ash (FA) used in this research was a class C type. It has a specific gravity of 2.04 and a surface area (Blaine) of 379 m^2/ kg. Table 3.1 showed the physical and chemical analysis of FA which was used. A polycarboxylic-ether type superplasticizer (SP) with a specific gravity of 1.07 and PH of 5.7 was used in all mixtures.

Two types of aggregate natural and recycled waste glass aggregate were used as fine and coarse aggregate. In this study, recycled green glass aggregate used in different levels from 0 to 100 % as a partial and entirely replacement of sand, gravel, and both according to ASTM C 150 (1974).

Table 3.1 Chemical composition and physical properties of PC and FA

Chemical analysis (%)	**PC**	**FA**
CaO	63.84	2.24
SiO_2	19.79	57.2
Al_2O_3	3.85	24.4
Fe_2O_3	4.15	7.1
MgO	3.22	2.4
SO_3	2.75	0.29
K_2O	-	3.37
Na_2O	-	0.38
Loss on ignition	0.87	1.52
Specific gravity	3.15	2.04
Specific surface area (m^2/kg)	326	379

The particle size gradation obtained through the sieve analysis and physical properties of recycled glass aggregate are presented in Table 3.2. The process of collecting, cleaning and crushing bottles were carried out as shown in Figure 3.1.

The chemical analysis of glass was shown in Table 3.3. Specific gravity for coarse and fine glass aggregate was 2.55 and 2.53 respectively. The water absorption of glass was 0.065%. Maximum size of coarse aggregate was 11.2 mm. Fineness modulus for fine and coarse aggregate was 3.03 and 5.76, respectively.

Natural aggregate is used for fine and coarse aggregate. The particle size gradation through the sieve analysis and physical properties of natural aggregate are shown in Table 3.2. The specific gravity of coarse and fine aggregate is 2.69 and 2.39 respectively. The coarse aggregate used was river gravel with a nominal maximum size of 16 mm. The water absorption of them is 0.77and 1.09% respectively. Also fine aggregate, a natural river was used with a maximum size of 4 mm. Fineness modulus for fine and coarse aggregate is 2.72 and 6.1, respectively.

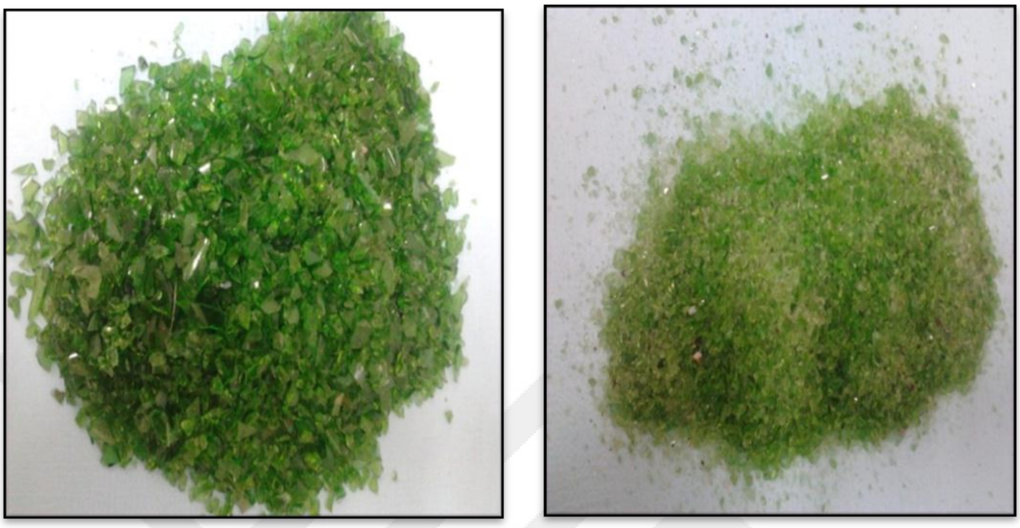


Figure 3.1 Recycled waste glass coarse and fine aggregate

Table 3.2 Sieve analysis of the natural and recycled glass aggregate

Sieve size mm	**% Passing**			
	Natural aggregate		**Recycled glass aggregate**	
	Fine	**Coarse**	**Fine**	**Coarse**
16	100	100	100	100
11.2	100	60	100	100
8	100	30.4	100	24.1
4	100	0.0	100	0.0
2	58.1	0.0	51.6	0.0
1	37.2	0.0	30.9	0.0
0.5	24.2	0.0	10.6	0.0
0.25	8.7	0.0	3.4	0.0

Table 3.3 Chemical compositions of recycled waste glass aggregate

Component	Green glass cullet
SiO_2	71.907
Al_2SO_3	2.242
Na_2O+K_2O	9.577
$CaO +MgO$	15.597
SO_3	0.222
Fe_2O_3	0.011
Cr_2O_3	0.301
P_2O_5	0.056
K_2O	0.533
TiO_2	0.063
SrO	0.010
ZrO_2	0.014

3.3 Design of mixtures

Three different series of structural SCGC mixtures were designed with a constant water/ binder material (w/b) ratio of 0.35 and binder materials content of 570 kg/m^3 .The 1st mixture (M1) was the reference mix therefor, it consists of 100% natural sand and 100% natural coarse aggregate. While, the first series of mixtures which include (M2, M3, M4, M5 and M6) were designed to replace natural fine aggregate (NFA) by recycled fine glass aggregate (RFGA) at different proportions 20, 40, 60, 80, and100 %. The replaced of natural coarse aggregate (NCA) with recycled coarse glass aggregate (RCGA) was done in the 2nd series which containing (M7, M8, M9, M10 and M11) with 20, 40, 60, 80, and100 %.

While, series III contains (M12, M13, M14, M15 and M16) used RFGA and RCGA instead of NFA and NCA at levels of 20, 40, 60, 80, and100%. Therefore, 16 different SCGC mixtures were designed as given in Table 3.4. The mixture M14 (RFGA60RCGA60) for example, contains 60% RFGA, 40% NFA, 60% RCGA and 40% NCA.

3.4 Casting, test specimens and conditioning

In the production of structural SCCs, the mixing sequence and duration are so important that a special procedure proposed by Khyat et al. (2000) was employed to supply the same homogeneity and uniformity in all mixtures. The batching sequence consisted of homogenizing the natural and recycled glass (fine and coarse) aggregates for 30 s in a rotary planetary mixer, then adding about half of the mixing water into the mixer and continuing to mix for one more minute. Thereafter, the natural and recycled aggregates were left to absorb the water in the mixer for 1 min. After that cement and fly ash were added, the mixing was resumed for another 1min. Finally, the superplasticizer with remaining water was introduced, and the concrete was mixed for 3 min and then left for a 2 min rest. Eventually, the concrete was mixed for additional 2 min to complete the mixing sequence. The structural concretes were designed to give a slump flow diameter of 70 ± 3 cm which was achieved by using the superplasticizer at different dosage.

After the mixing procedures had been completed, tests conducted on the fresh and hardened state of structural SCGCs by using prisms and ring specimens. Test specimens were prepared according to each test conditioning before testing.

Table 3.4 Design of mixture proportions

Series No.	Mix. No.	Mix ID.	Binder kg/m^3	Water kg/m^3	Cement kg/m^3	FA kg/m^3	SP kg/m^3	NFA kg/m^3	NCA kg/m^3	RFGA kg/m^3	RCGA kg/m^3
	Mix 1	RFGA0RCGA0	570	199.5	456	114	4.45	762.4	762.4	0.0	0.0
Series I	Mix 2	RFGA20RCGA0	570	199.5	456	114	4.39	609.9	762.4	161.4	0.0
	Mix 3	RFGA40RCGA0	570	199.5	456	114	4.22	457.4	762.4	322.8	0.0
	Mix 4	RFGA60RCGA0	570	199.5	456	114	4.13	305.0	762.4	484.2	0.0
	Mix 5	RFGA80RCGA0	570	199.5	456	114	3.99	152.5	762.4	645.6	0.0
	Mix 6	RFGA100RCGA0	570	199.5	456	114	3.88	0.0	762.4	807.0	0.0
Series II	Mix 7	RFGA0RCGA20	570	199.5	456	114	4.39	762.4	609.9	0.0	144.5
	Mix 8	RFGA0RCGA40	570	199.5	456	114	4.33	762.4	457.4	0.0	289.1
	Mix 9	RFGA0RCGA60	570	199.5	456	114	4.33	762.4	305.0	0.0	433.6
	Mix 10	RFGA0RCGA80	570	199.5	456	114	4.29	762.4	152.5	0.0	578.2
	Mix 11	RFGA0RCGA100	570	199.5	456	114	4.28	762.4	0.0	0.0	722.7
Series III	Mix 12	RFGA20RCGA20	570	199.5	456	114	4.28	609.9	609.9	161.4	144.5
	Mix 13	RFGA40RCGA40	570	199.5	456	114	4.10	457.4	457.4	322.8	289.1
	Mix 14	RFGA60RCGA60	570	199.5	456	114	3.99	305.0	305.0	484.2	433.6
	Mix 15	RFGA80RCGA80	570	199.5	456	114	3.88	152.5	152.5	645.6	578.2
	Mix 16	RFGA100RCGA100	570	199.5	456	114	3.76	0.0	0.0	807.0	722.7

3.5 Tests for shrinkage deformation and crack width

The knowledge of shrinkage is very important to the engineer in the design of structure. For monitoring the drying shrinkage and weight loss of the SCGCs, four 70x70x280 mm prisms were used as per ASTM C157. Immediately after demoulding the specimens, the gage length was formed by gluing pins on the surface as shown in Figures 3.2 and 3.3. The initial gage length and the specimen weight were measured and consecutive readings were carried out every 24 h for the first 3 weeks and then 3 times a week. At the same time, weight loss measurements were also performed on the same specimens. Specimens were maintained in drying cabinet at 23^{o}C and 50% relative humidity for about 50 days. The length change was measured by means of a dial gage extonsometer with 200 mm gage length which had a capability of measuring 0.002 strrain.

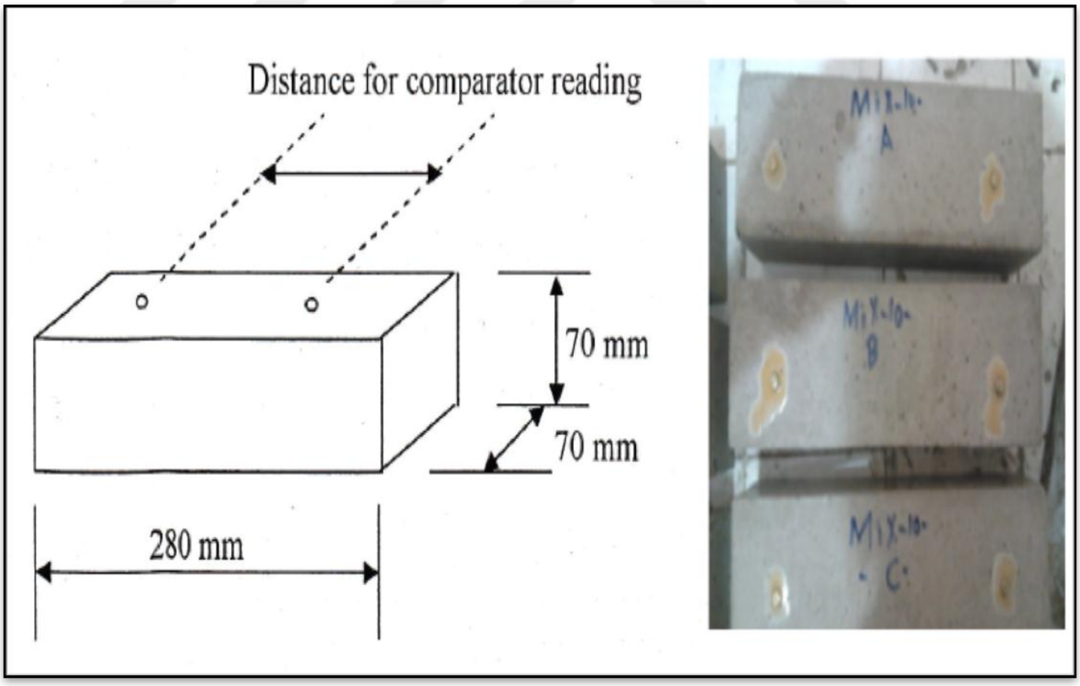


Figure 3.2 Presentation of drying shrinkage test set up of shrinkage test specimens

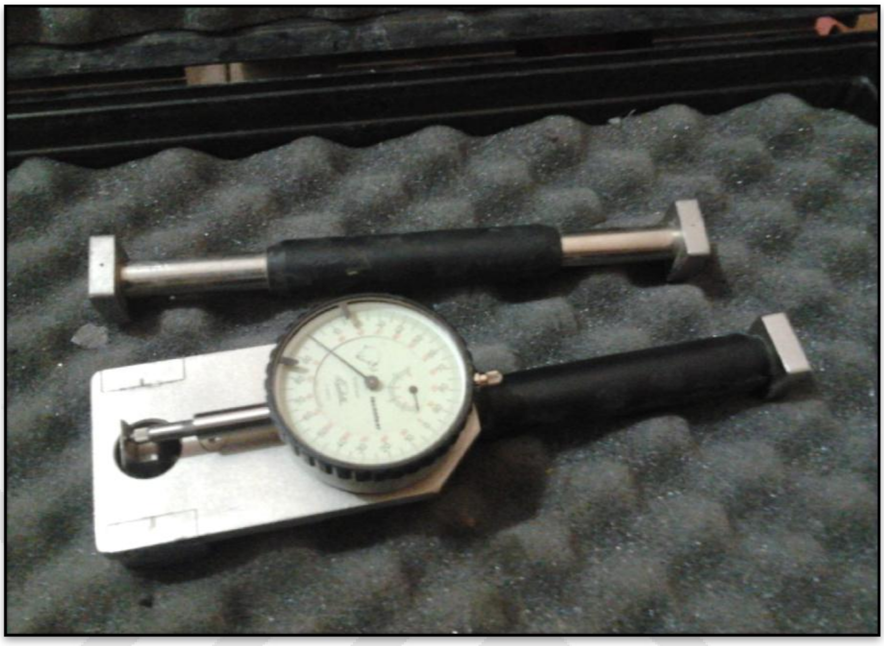


Figure 3.3 Photographic view of dial gage extonsometer apparatus

Ring-type specimens were used in this study to observe the restrained shrinkage induced cracking of structural concrete. For such a ring, as the concrete was subjected to an internal pressure induced by the restraining inner steel tube, the difference between the values of the tensile hoop stress on the outer and the inner surface of the concrete was only 10%. Also, the maximum value of the radial stress was 20% of the maximum hoop stress. Thus, it can be assumed that the concrete annulus was essentially subjected to a uniform, uniaxial tensile stress when it was internally restrained by the steel ring. In addition, the width of the specimen (140 mm) was four times its thickness (35 mm), so that a uniform shrinkage along the width of the specimen can be assumed (Wiegrink et al., 1996; Grzybowski et al., 1990; Sarigaphuti et al., 1993).

To measure the crack widths on ring members, a special microscope setup was used. The presentation of the ring mould, special microscope and restrained samples are shown in Figures 3.4, 3.5 and 3.6. After the outer steel ring had been stripped off, the top surface of the concrete ring was sealed off using silicon rubber, so that the drying would be allowed only from the outer circumferential surface. After that, the specimens were exposed to drying in a drying room at 23^{o}C and 50 % relative humidity, as per ASTM C157 for about 50 days.

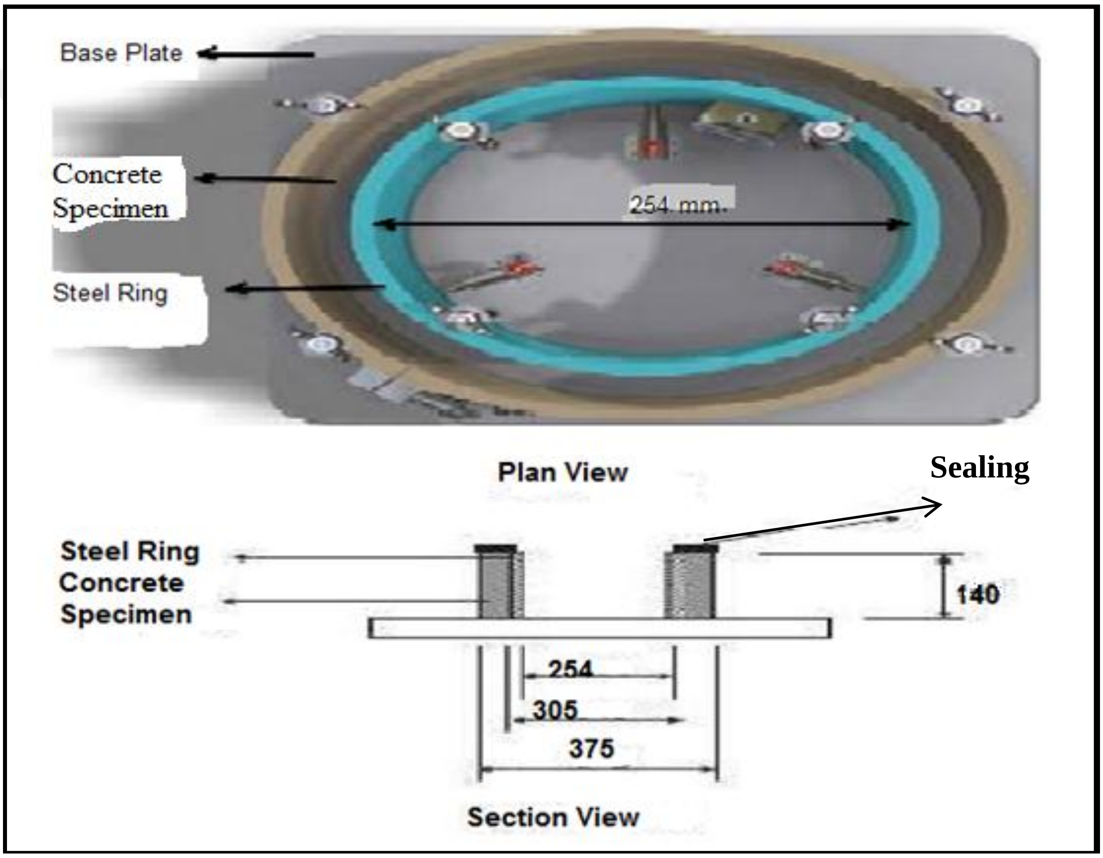


Figure 3.4 Presentation of restrained shrinkage ring member (in mm)

Figure 3.5 Photographic view of crack width measurement apparatus

Figure 3.6 Photographic view of restrained shrinkage samples

3.6 Tests for some fresh aspects

The slump flow test specified by Japan society of civil engineers evaluates the capacity of structural concrete to flow under its own weight without any resistant, except from friction of surface and test based on the slump cone test, used for traditional one. To measure the slump flow, an ordinary slump flow cone is filled with SCGC without any compaction and leveled. The cone is lifted and average diameter of the resulting concrete spread is measured as seen Figure 3.7. In the slump flow test, the time (T_{50}) was also measured which determines the time taken for the concrete to reach the 500 mm spread circle.

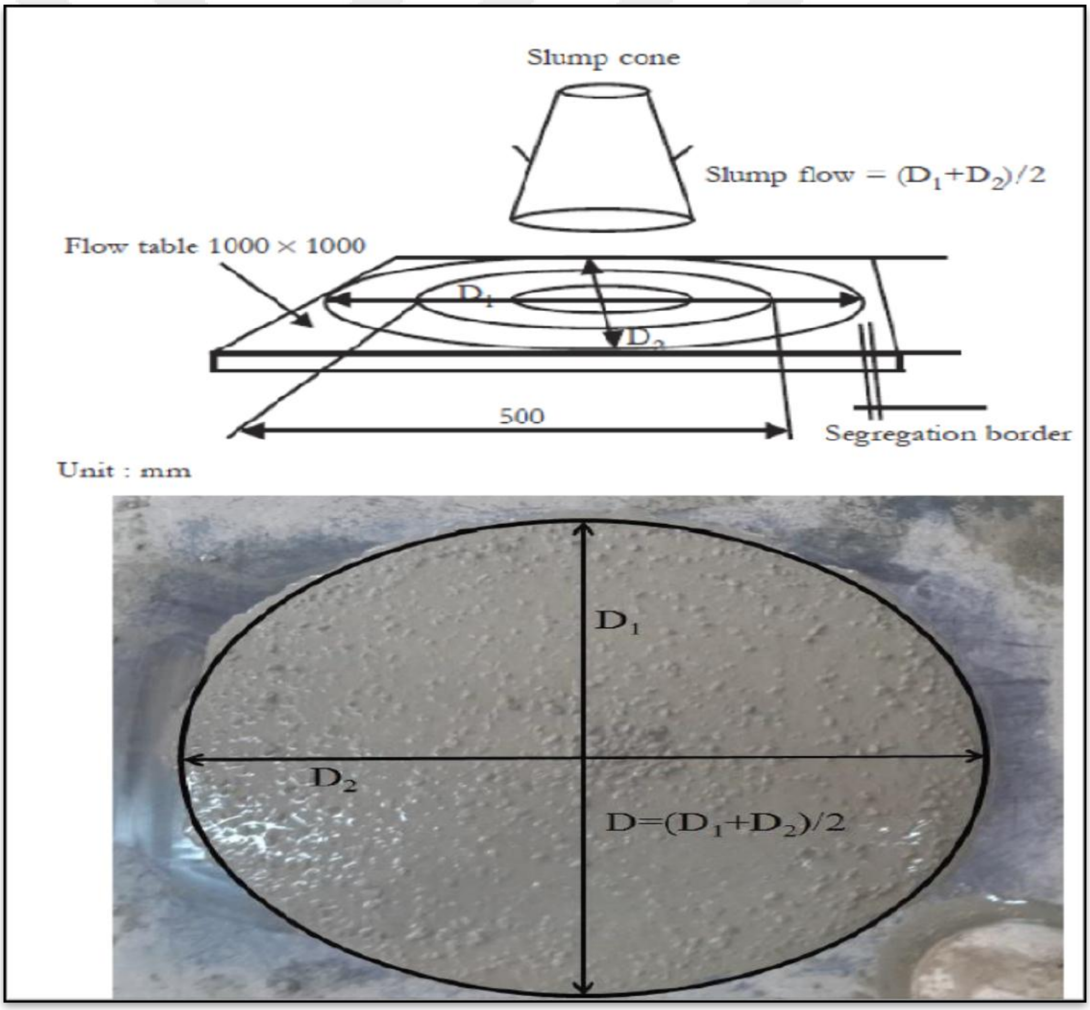


Figure 3.7 Presentation of measurement of slump flow diameter

The flowability and viscosity of the fresh concrete can be tested with the V-funnel test, whereby the flow time is measured. The funnel is filled with about 12 litters of concrete and the time taken from opening the trap door and complete emptying the funnel as shown in Figure 3.8. According to Khayat et al. (1997), a funnel test flow time less than 6 sec is recommended for a structural concrete to qualify for self -compacting. According to EFNARC, a funnel test flow time ranging from 6 to 12 sec is considered adequate for the structural purposes.

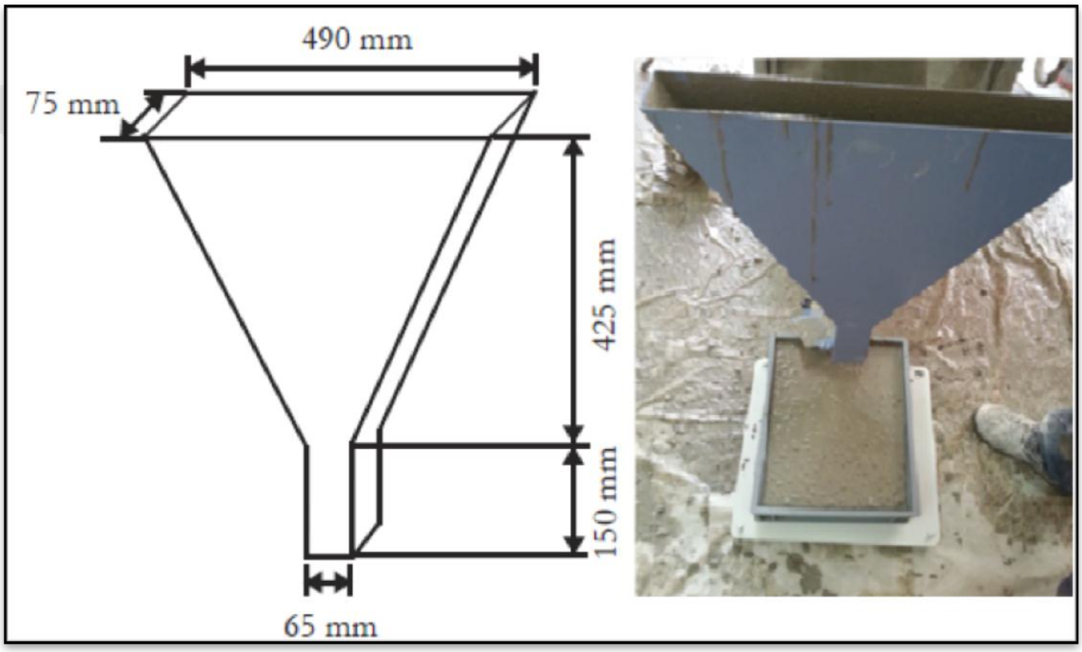


Figure 3.8 Presentation of V-funnel flow time measurement

L-box test is a widely used test, suitable for construction site use and laboratory. It determines filling and passing ability of structural SCC and loss of stability (segregation) can be discovered visually. The L-box apparatus consist of a rectangular section box in the shape of an "L", with a vertical and horizontal section, separated by a movable gate, in front of which vertical lengths of reinforcement bar are fitted as illustrated in Figure 3.9. The ratio H_2/H_1 is represents blocking ratio. While, the T_{20} and T_{40} times are an indication for the filling ability. This test determines the flow of structural concrete in presence of reinforcement impediments.

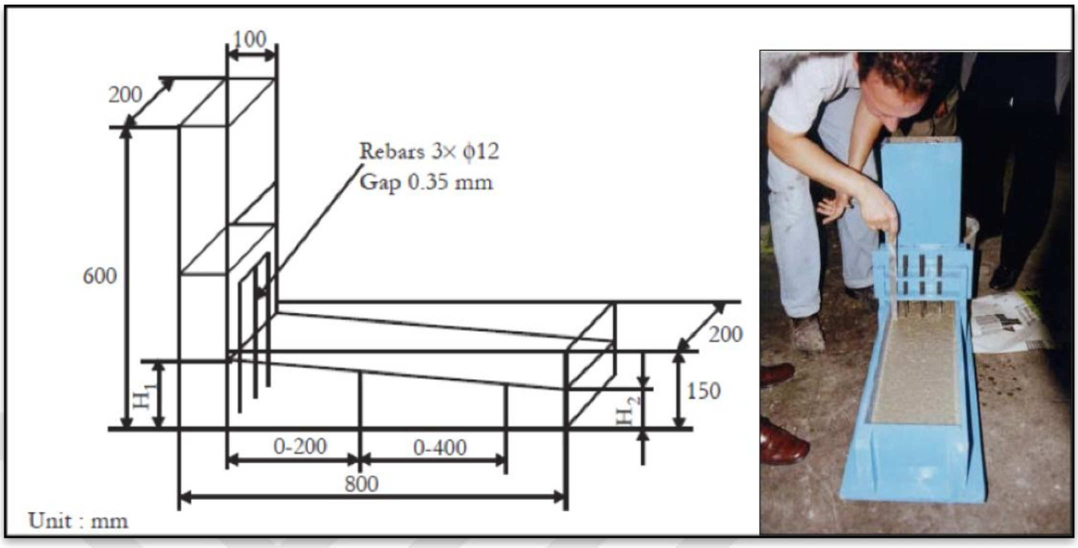


Figure 3.9 Presentation of L-box apparatus

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Shrinkage deformation and crack

4.1.1 Shrinkage development in test prism

For a structure to be serviceable, cracking is required to control and the deflection should not be excessive. In this regard, the shrinkage has a critical role in each of these properties of the service load response of the structure. The crack control in a reinforced concrete or precast concrete structure is obtained by limiting the stress increment. Many codes specify the maximum steel stress increments. However, only some of them explain adequately for the gradual increase in existing crack widths with time because of mainly shrinkage or time dependent formation of new cracks from tensile stress caused by restraint shrinkage (Gillbert, 2001). On this issue, drying shrinkage tests can provide necessary information on how the drying shrinkage stresses develop. The change in volume of the concrete is not equal to the volume of water lost. When the loss of free water occurs, first; this causes little to no shrinkage. As the drying of concrete continuous, the adsorbed water is removed. This adsorbed water is held by hydrostatic tension in the small capillaries. The loss of this water produces tensile stress, which cause the concrete members to shrink. The shrinkage due to this water loss is significantly larger than that associated with the loss of free water (Neville, 1996; Wiegrink et al., 1996).

The shrinkage depends on many factors such as: w/c ratio, degree of hydration, relative humidity, curing temperature, aggregate properties, admixtures, duration of drying, and cement composition (Neville, 1996). Drying shrinkage tests alone cannot offer sufficient information on the conduct of concrete structure because practically all concretes are restrained in some way either by the constructed or by reinforcement. However, measurement of shrinkage depending on drying which can provide important information on how the drying shrinkage stresses increase (Shah et al., 1998; Wiegrink et al., 1996). As a result, the observation of free shrinkage of the concrete elements allows investigators to directly know the mechanical deterioration in the concrete which causing distortions that depending on time.

The strain developments versus time of shrinkage for different SCGCs demoulded 24 hr after casting are presented in Figures 4.1 through 4. 7. Also, the final values of the average of three samples of shrinkage strains are given in Table 4.1. It was seen in Figures 4.1 to 4.3 that all the SCGCs showed a stable shrinkage after 30 days. Also, it can be noted that the shrinkage strain were somewhat analogical and convergent at very early ages of the drying period. But, a clear distinction was observed for different concretes after about ten days. The shrinkage strain differed for various concretes depending on the type and ratios of replacement at later ages.

In general from these figures, It can be noted that the shrinkage at 50 days for all mixtures were less than 750 microstrain according to Australian Standard AS 3600 (2004). However, it can be concluded that the use of recycled glass aggregate as a replacement of natural aggregate improving the dimension stability of the concrete. But, this decreasing ratio depending on the ratio and type of replacement also, it was depending on the drying time.

It is evident from Table 4.1, that the shrinkage at the end of 50 day for control mixes was 634.7 microstrain compared to 616-412.8 microstrain for Series I which contain 20-100% RFGA (Mix 2 to Mix 6). The reduced shrinkage could be due to the negligible water absorption capacity of glass particles (Edward; 1966, Alexander and Mindess; 2005, Wang and Huang; 2010). Many researchers have reached the same results when using recycled glass as aggregate. For example Hongjian and Kiang (2013) reported that the drying shrinkage of mortar decreased from 650x10^{-16} for control mortar to 600x10^{-16} for mortar containing 75% recycled glass sand after 56 days of drying. Also, Kou and Poon (2009) said that the drying shrinkage of concrete decreased with increasing glass sand content up to 45%. Ling et al., (2011) showed that the drying shrinkage of white cement mortar and metakaolin with 100% recycled glass as a fine aggregate was 17% less than that of control mixes after 112 days. While for Series II the drying shrinkage increased from 533.5 to 608.9 microstrain when the recycled glass coarse aggregate increase from 20 to 100% (Mix 7 to Mix 11), and for Series III which the replacement consist of all grading aggregates from 20 to 100% (Mix 12 to Mix 16) the drying shrinkage was between 412.8 to 524.2 microstrain.

From Table 4.1, it can be seen that the lowest percentage of decreasing in drying shrinkage was 4.07% with 100% RCGA concrete (mix 11) nevertheless; the highest percentage of decreasing was 93.5% when using 100% RFGA in concrete.

From Figure 4.4, it can be concluded that this increasing in drying shrinkage in Series II and III when the replacement was more than 40% probably because shrinkage is related to the elastic modulus of concrete, this result consistent with the findings of Pereira et al. (2008).

Figures 4.5, 4.6 and 4.7 showed the comparison between drying shrinkage of three series at different ages when the recycled glass aggregate was 20, 60 and 100 % respectively. Through these figures, it can be concluded that the behavior of SCCs which contains more than 40% replacement of recycled glass aggregate change;

because when the replacement of recycled glass aggregate 20% and 40% the maximum value of drying shrinkage of SCCs was when replaced NFA by RFGA (Series I) while when recycled glass aggregate increase more than 40% the maximum value of shrinkage of SCCs was when replaced NCA by RCGA (Series II), after the 29th day of drying period and always when replaced all natural grading aggregate by all recycled glass grading aggregate (Series III) gives the minimum value of shrinkage.

The weight loss of the SCGCs was measured on the same specimens as the free shrinkage test and the values of the weight loss are given in Table 4.1. Moreover, Figures 4.8 to 4.14 present the rate of the water loss during the drying period for varies concrete mixtures. As in free shrinkage, the weight loss for the different concretes was comparable within the first three to seven days, but distinctive weight loss could be measured particularly on seven days onwards. As seen in Table 4.1 and Figures 4.8 through 4.10, increasing the amount of recycled glass aggregate decreased the weight loss of SCCs gradually. However, this reduction depending on factors such as type and ratio of recycled glass aggregate replacement also, it depending on drying period. Although, the weight of specimens was higher than the reference specimen when replacing natural fine aggregate by recycled fine glass aggregate and this deference in weight was increased with the increase of recycled fine glass aggregate in Series I, this behavior because the specific gravity of recycled fine glass aggregate was higher than that of natural fine aggregate which they were 2.53 and 2.39 for recycled and natural fine aggregate respectively. While, the specimens which contain recycled coarse glass aggregate (Series II) and the specimens consist of recycled fine and coarse aggregate (Series III) the weight was decreased with increased the amount of the recycled glass aggregate, because of the specific gravity of recycled coarse aggregate which it was 2.55 less than that of natural coarse aggregate which it was 2.69.

From Figures 4.8 to 4.10, it can be concluded that the weight loss for reference mixture after 50 days of drying was 90.2 g compared to 87- 69.6 g for Series I which the replacement of recycled fine aggregate was 20 to 100%. While the weight loss in Series II when the natural coarse aggregate replaced by recycled coarse glass aggregate was between 87.1 and 79.4 g and the weight loss when replaced all grading natural aggregate by grading recycled glass aggregate from 20 to 100% (Series III) was ranged between 87.9 and 64.3 g at the end of 50 days of drying. Since the absorption capability of the recycled glass aggregate was negligible compared with natural fine and coarse aggregate and that leading to increase amount of capillary pores which filled by water within the internal structure of concrete with the increment of recycled glass that lead to decrease the microstructure of SCGCs and the weight loss will be due to diffusion to the outside environment rather than self-desiccation.

Table 4.1 Microstrain and weight loss measured in test specimens

	Control		Series I					
	Mix-1		**Mix-2**		**Mix-3**		**Mix-4**	
Day	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain
1	0	0	0	0	0	0	0	0
2	40.4	77	40.2	67.7	41.8	35.8	30.3	27.5
3	53.9	209	51.3	121	49.1	117.2	37.3	85.3
4	59.9	214.5	54.4	209.6	52.5	170.5	42	154
5	63.9	269.5	59.5	253	54.9	234.3	46.8	165
6	66.8	280.5	60.9	275	56.7	247.5	50.6	246.4
7	68.1	297	62.7	291.5	58.2	287.7	51.2	280.5
8	70.1	335.5	64.2	291.5	59.1	291.5	52.5	287.7
9	71.6	374	65.2	304.2	60	297	53.6	291.5
10	72.6	401.5	66.2	348.2	61.3	319	55.4	308
11	73.8	412.5	67.4	370.2	62.1	346.5	59.9	327.3
12	75	423.5	68.4	392.2	62.8	379.5	60.8	360.3
13	76.1	429	68.8	430.7	63.6	390.5	60.9	386.1
14	76.6	452.7	69.3	434.5	64.6	420.8	62.1	401.5
15	77.3	507.7	69.8	456.5	65.7	435.6	64	407
16	77.6	521.4	69.9	467.5	65.8	447.2	64.3	412.5
17	78	535.2	69.9	478.5	66.2	459.3	64.7	418
18	78.5	537.9	69.6	484	67.2	467.5	66	429
19	79	540.7	70.7	489.5	67.9	470.3	67.3	440
20	79.3	541.2	70.8	492.3	68.4	473	68	440
21	79.8	546.2	71	506	68.6	475.8	68.7	440
23	81.8	557.2	71.7	511.5	70	475.8	68.8	447.7
25	82.1	559.4	74.4	517	71	475.8	69.6	450.2
27	82.9	561	74.8	522.5	71.7	484	70.4	451.3
29	84.1	572	75.2	533.5	72.9	490	71.5	453.8
31	85	580.8	76.7	539	76	495	73.8	456
33	86.6	592.9	77.6	539	76.9	511.5	75.4	456.5
35	87.3	596.8	79.5	544.5	78.8	539	76.1	459
37	88	602.8	80.2	550	79.1	539	77.3	459.3
39	88.6	607.2	80.7	550	79.8	555.5	78.8	460.1
41	88.9	612.2	81.5	577.5	80.9	555.5	80	463.4
43	89.2	623.2	84	583	81.8	555.5	80.9	464
45	89.7	629.2	84.5	588.5	82.9	555.5	82	465.1
47	90	633.6	85.1	605	84.5	566.5	83	467
49	90	634.7	86.3	616	85.1	591.3	84.7	467.5
50	90.2	634.7	87	616	85.4	591.3	84.8	469.2

Table 4.1 Continued

Day	Series I				Series II			
	Mix-5		Mix-6		Mix-7		Mix-8	
	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain
1	0	0	0	0	0	0	0	0
2	28.8	22	26.3	13.8	40	38.5	35.3	42.4
3	34.6	78.7	33.5	65.5	53.8	84.2	42.6	99
4	38.1	120.5	38.1	108.4	59.3	111.7	48.8	110
5	41	161.4	40.5	155.1	61.8	200.8	53.6	177.1
6	44.8	210.1	43.2	184.8	63.9	231	53.7	198
7	48.6	267.3	46	237.6	66.5	275	55.1	233.8
8	49.8	273.9	48.5	244.8	68.2	238.2	56.1	236.5
9	50.4	277.2	49.3	269	69.8	261.3	57.5	258.5
10	51	305.3	50.1	280.5	71.2	302.5	58.1	273.4
11	52	313.5	51.6	286	72.2	313.4	62.6	277.8
12	55.9	346.5	55.7	307.5	73.1	333.7	63.1	283.3
13	56.1	368.5	56.4	308.6	74.6	342.7	64.5	298.7
14	57.3	396	57.1	315.2	75.1	357.5	66.2	315.2
15	58.9	401.5	58.3	324	75.9	363	66.8	368.5
16	60.5	407	58.6	332.8	76.7	377.9	68	382.3
17	62.1	412.5	59	341.6	77.6	386.7	70.1	393.3
18	62.4	420.8	59.7	343.2	78.8	388.9	70.2	404.3
19	62.8	429	60.5	345.4	78.8	394.4	70.3	404.3
20	62.9	434.5	60.9	346	79.1	404.3	70.7	407
21	63	437.3	61.4	346.5	79.6	404.3	71.2	407
23	63.5	438.9	62.3	349.3	79.9	416.4	71.8	418
25	62.6	440.3	61.3	355.3	80.6	427.4	72.3	458.2
27	64.1	442.5	61.5	382.3	81.3	440	72.7	467.5
29	65	445.8	61.9	383.9	81.9	459.3	73.3	467.5
31	65.8	447.7	62.1	385.3	82	484	75.1	484
33	67.2	448.3	63.4	388.2	82.2	489.5	76.4	495
35	68.6	453.5	64.9	398.8	82.5	495	78.3	500.5
37	69.3	453.8	65.3	400.2	83	500.5	79.3	504.4
39	70.2	453.8	66.1	402.5	83.3	503.3	79.9	513.2
41	70.4	453.8	66.7	404.3	83.4	519.8	81.2	520.9
43	70.8	454.3	67.3	409.9	83.7	519.8	81.8	520.9
45	71.2	454.6	68.5	412	86.6	519.8	82.5	520.9
47	71.8	460.1	68.7	412.4	86.8	526.4	83.3	526.4
49	71.8	463.4	69.3	412.5	87.1	533.5	85	533.5
50	71.8	464.8	69.6	412.8	87.1	533.5	85.3	539

Table 4.1 Continued

Day	Series II						Series III	
	Mix-9		**Mix-10**		**Mix-11**		**Mix-12**	
	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain
1	0	0	0	0	0	0	0	0
2	34.6	53.4	25.1	60.5	22.9	62.2	33.2	72.3
3	44.4	100.7	33.9	113.3	33.6	137.5	46.8	117.2
4	47.2	115.5	38.6	167.8	35.6	214.5	50.8	132
5	49.1	192.5	41.8	198.8	40.7	214.5	53.3	190.9
6	51.7	201.9	43.6	212.9	41.3	258.5	55.5	203.5
7	53	248.3	45.2	250.5	43.5	264	57.2	227.2
8	54.6	253	46.8	258.5	45.4	286	57.9	227.2
9	55.6	275	48.4	308	47.1	308	58.7	251.4
10	56.5	280.5	50.4	284.4	49.1	321.8	59.9	276.7
11	57.3	326.2	51.7	339.4	50.1	379.5	61.2	280.2
12	58.3	335.5	52.5	339.4	50.8	379.5	62.3	286.375
13	59.2	346.5	53.3	349.3	51.5	390.5	63.4	295
14	59.9	359.2	54.6	374	52.1	407	64	300
15	60.5	372.4	55.8	390.5	52.9	412.5	64.6	303.3
16	61.6	392.2	56.4	415.3	53.5	416.4	65.6	305.3
17	62.4	399.9	57.4	418	54	421.9	66.2	310.8
18	62.5	418	58.3	425.2	54.2	429	66.8	317.9
19	62.9	432.9	59.6	440	54.3	449.4	67.5	324
20	63.7	436.2	59.8	454.9	54.4	467.5	68.5	332.5
21	64.4	440	59.9	458.2	54.9	478.5	69.4	350.4
23	65	443.9	61.7	458.15	55.7	508.8	69.5	357.8
25	69.9	469.2	64.6	486.8	62.9	511.5	70.8	382
27	70.7	485.7	69.5	504.4	63.5	530.8	71.5	383.9
29	72.5	498.9	70.7	517	64	533.5	72.8	384. 5
31	73.5	520.9	71.6	533.5	66.6	546.2	73.6	386.7
33	76.4	528	73.7	544.5	73.5	548.4	74.3	392.7
35	78	533.5	74.2	544.5	74.1	557.2	75.3	393.8
37	78.3	533.5	76	550	74.5	559.4	76.6	396
39	79.4	542.9	78.8	550	74.7	563.8	77	397.4
41	80.3	546.2	79.9	561	74.9	581.4	77.8	401.2
43	81	550	80.9	572	75.1	594	78	404.5
45	82.4	550	81.3	572	75.4	594	78.3	408.4
47	82.8	550	81.8	577.5	75.7	599.5	78.4	409.8
49	84	550	83	577.5	79	605	78.9	412.5
50	84	550	83.3	577.5	79.4	608.9	78.9	412.8

Table 4.1 Continued

Day	Series III							
	Mix-13		Mix-14		Mix-15		Mix-16	
	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain	Av. wt. loss(g)	Av.length microstrain
1	0	0	0	0	0	0	0	0
2	33.2	66	23.7	40.2	28.1	38.5	25.7	33
3	42.1	100.7	32.8	92.1	32.2	75.35	30.4	70.4
4	46.2	128.2	37.9	121	35.5	119.1	34.6	104.8
5	49.9	155.7	40.5	151.8	37.8	133.7	36.5	125.1
6	52.6	188.7	43.2	172.2	39.7	166.7	38	162.8
7	54.5	195.8	45.5	194.2	40.6	187	39.8	181.5
8	56.3	217.8	46.9	203.5	41.5	199.7	41.2	191.1
9	58.2	234.3	48.5	231	42.7	228.8	41.7	215.3
10	59.6	267.3	50	262.4	43.9	243.7	42.5	234
11	60.6	277.2	51.5	264	45.4	256.3	43.4	246.4
12	61.4	286	52.3	278	46.4	268.4	44.4	255
13	62.8	297.3	53	296.7	47.2	288	45.7	267.9
14	63	303.9	54.3	302.2	48	293	46.7	272.5
15	63.8	308	55	333.9	49	344.3	47.6	347.9
16	63.9	308	55.1	333.9	49.8	353.7	48.2	361.4
17	64	319.3	55.3	341	50.5	353.7	49.3	366.9
18	64.7	329.5	55.6	341	51.2	359.2	50	368.5
19	65.5	336.9	56	353.7	52.3	364.7	50.8	374
20	66.2	346.5	56.6	372.4	53.1	375.7	51.6	377.9
21	66.9	366.3	57.3	372.4	53.3	388.9	52.4	390.5
23	67.4	366.3	58.5	397.7	54	416.4	53.2	445.5
25	68.3	392.2	59.2	405.4	55.1	451	54.2	454.9
27	69.3	414.2	60	414.2	56.1	454.3	55.4	471.4
29	69.6	418	60.3	418	57	454.3	56.5	478.5
31	70.1	418	60.5	430.7	58	473	57.4	480.2
33	70.7	418	61.2	430.7	58.8	473	58.4	500.5
35	71.4	418	61.8	438.4	60.4	491.2	59.2	500.5
37	71.9	418	62.3	438.4	61.1	502.2	60.8	504.4
39	72.2	418	62.5	438.4	61.9	502.2	61.5	517
41	72.7	418	62.8	449.4	62.3	506	62.3	517
43	73	425.2	63.3	454.9	62.8	506	62.8	518.7
45	73.5	425.2	63.9	460.4	63.1	506	63.1	518.7
47	73.9	429	64.1	462	63.6	506	63.5	518.7
49	75.2	429	64.5	469.2	63.9	511.5	64	524.2
50	75.2	429	64.5	469.2	63.9	520.3	64.3	524.2

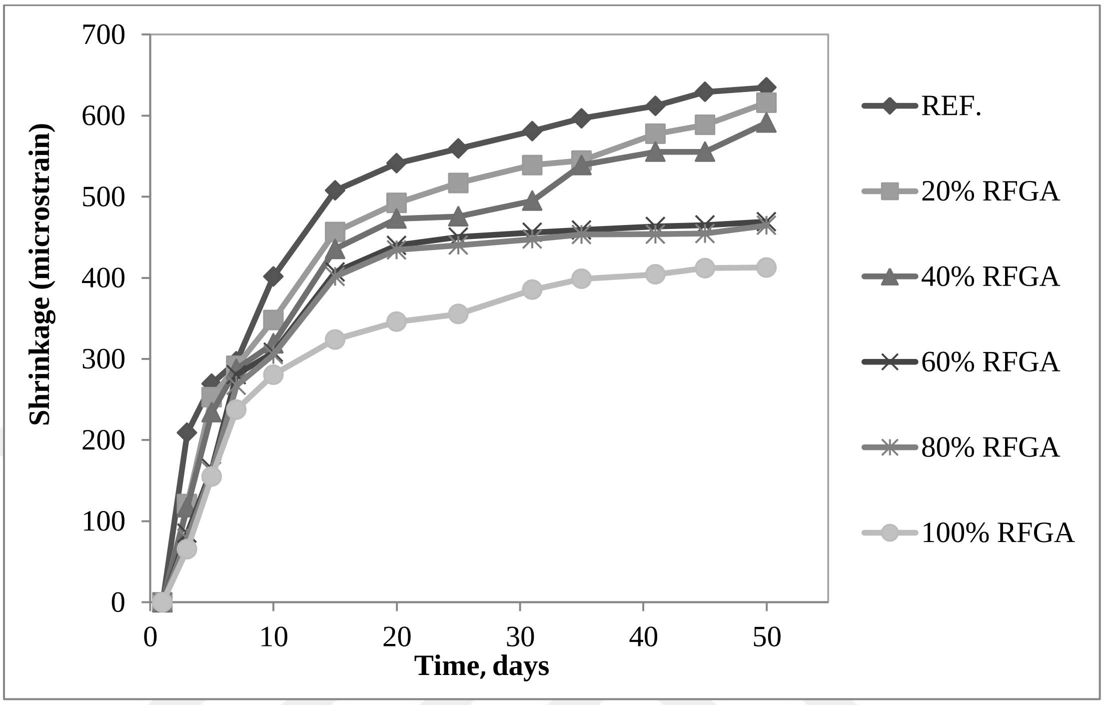


Figure 4.1 Shrinkage strain vs. time (Series I)

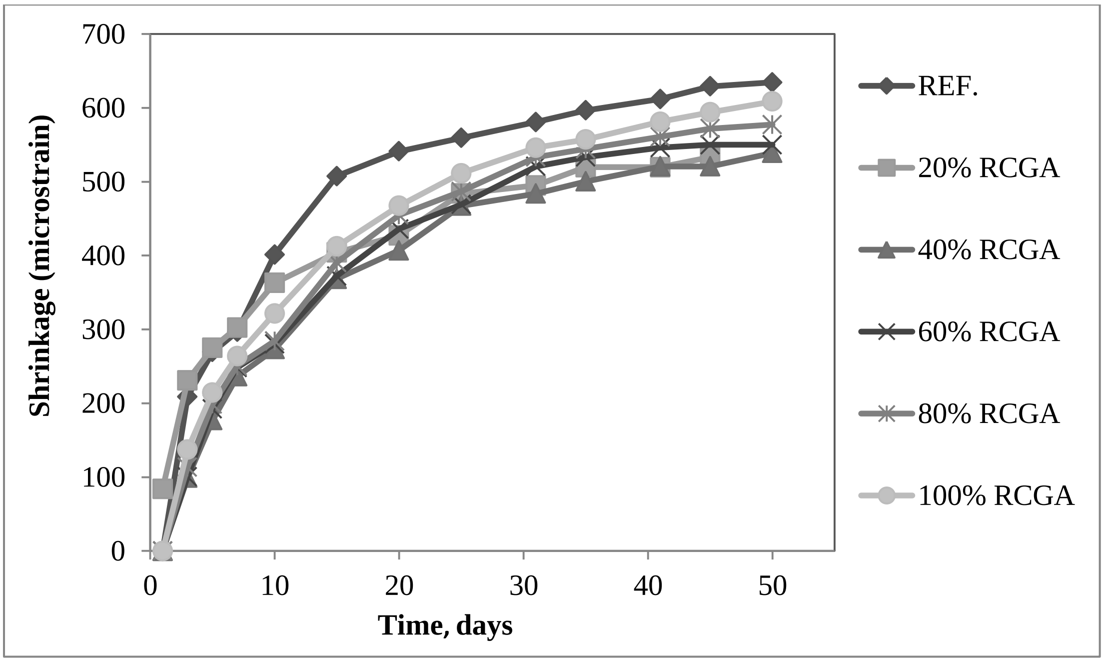


Figure 4.2 Shrinkage strain vs. time (Series II)

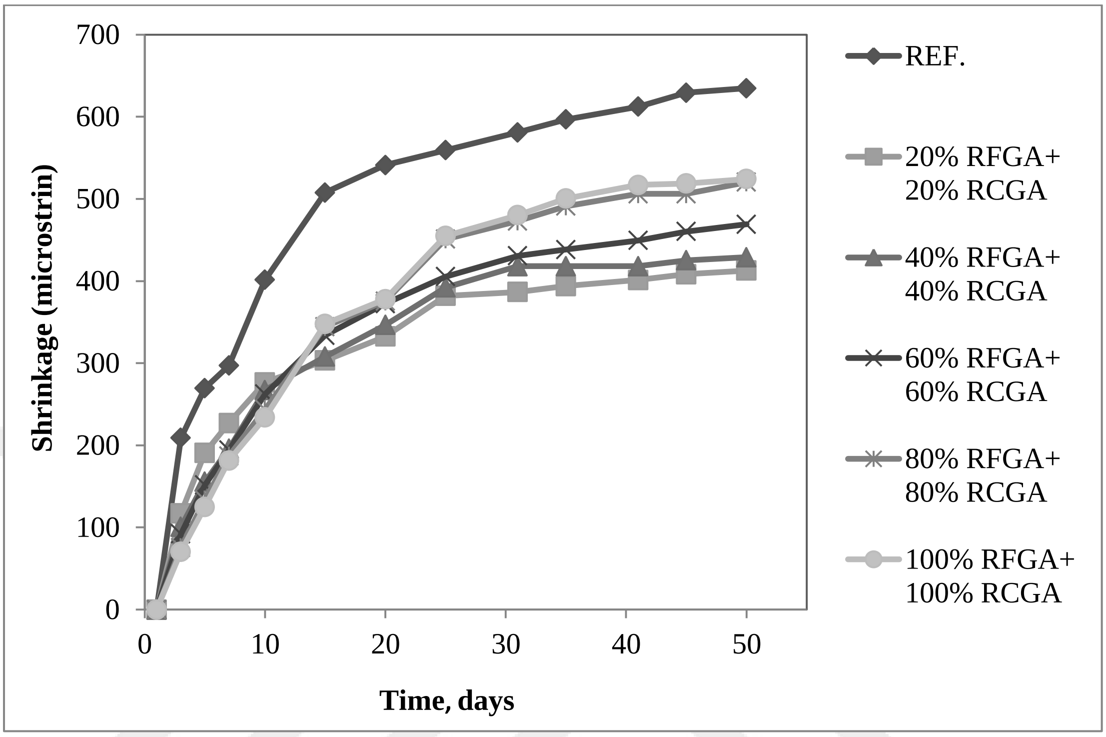


Figure 4.3 Shrinkage strain vs. time (Series III)

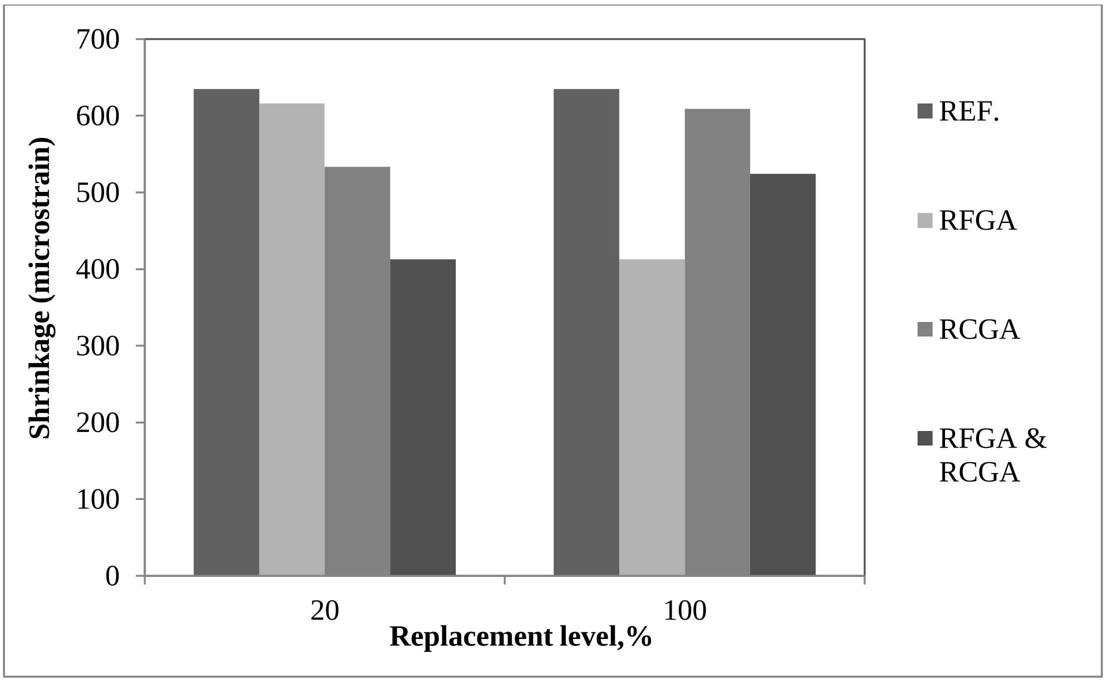


Figure 4.4 Shrinkage strain at 50 days for 20 and 100% replacement

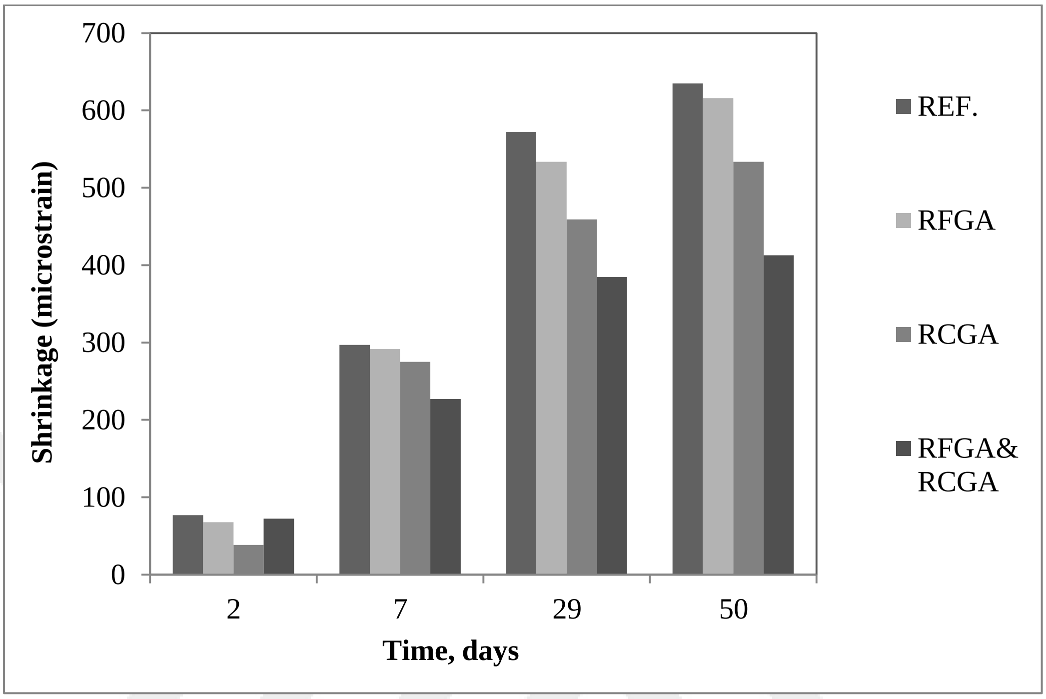


Figure 4.5 Shrinkage strain at 20% replacement

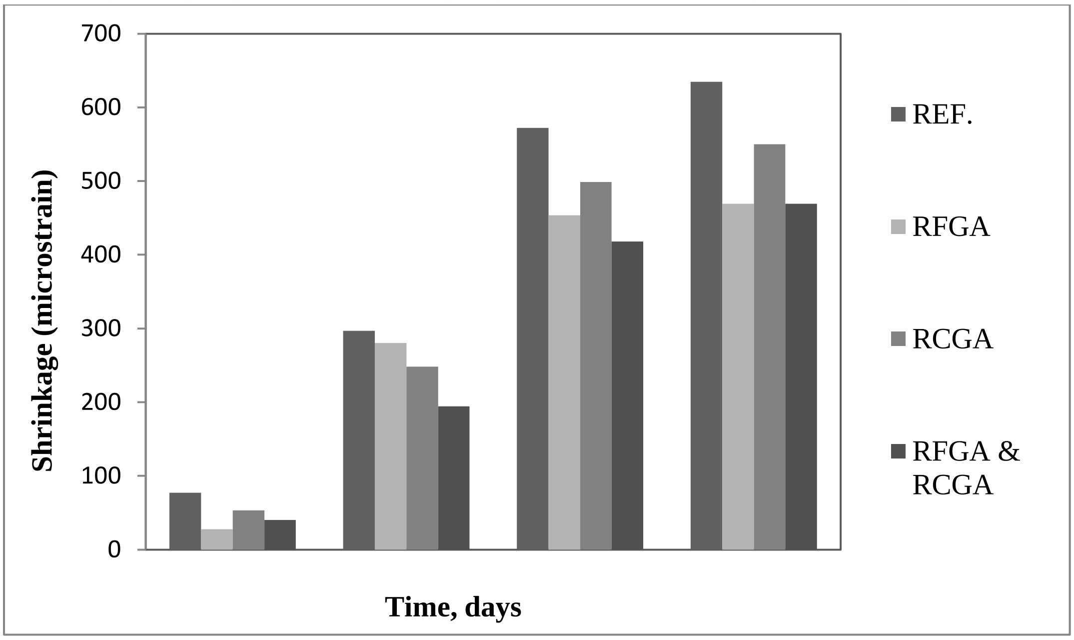


Figure 4.6 Shrinkage strain at 60% replacement

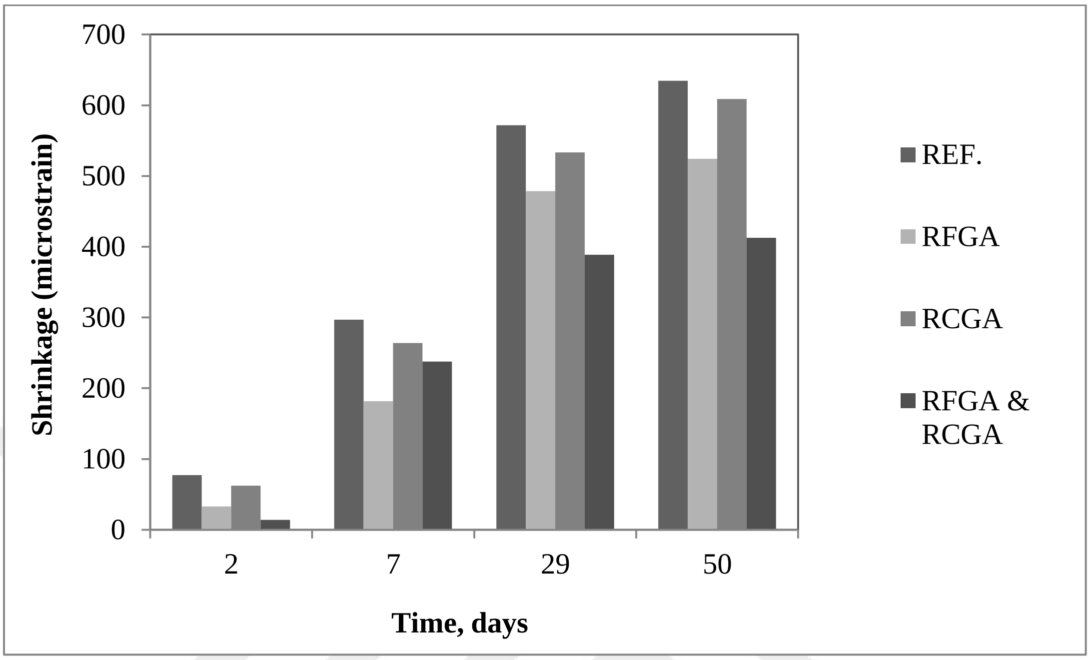


Figure 4.7 Shrinkage strain at 100% replacement

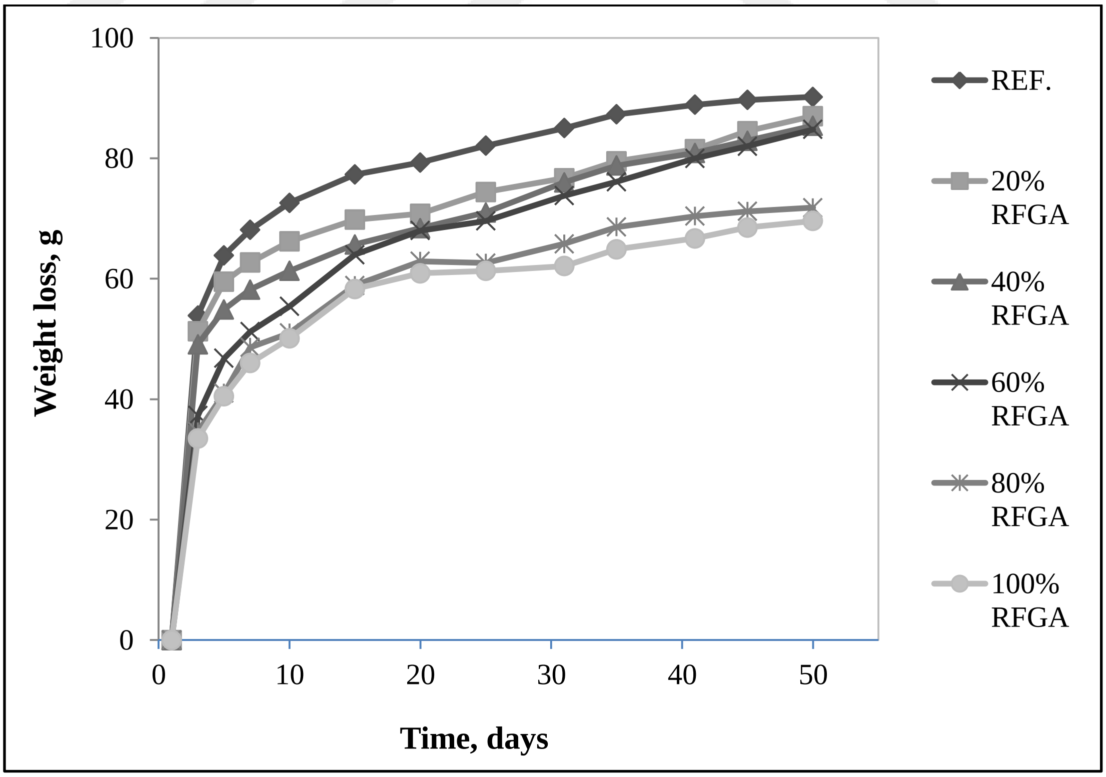


Figure 4.8 Weight loss vs. time (Series I)

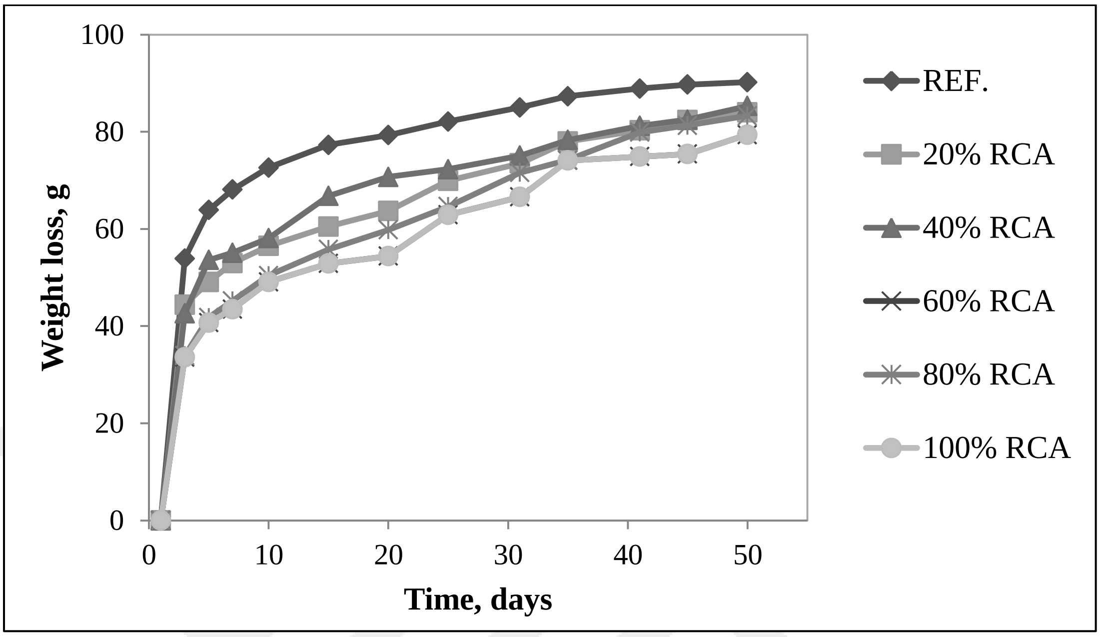


Figure 4.9 Weight loss vs. time (Series II)

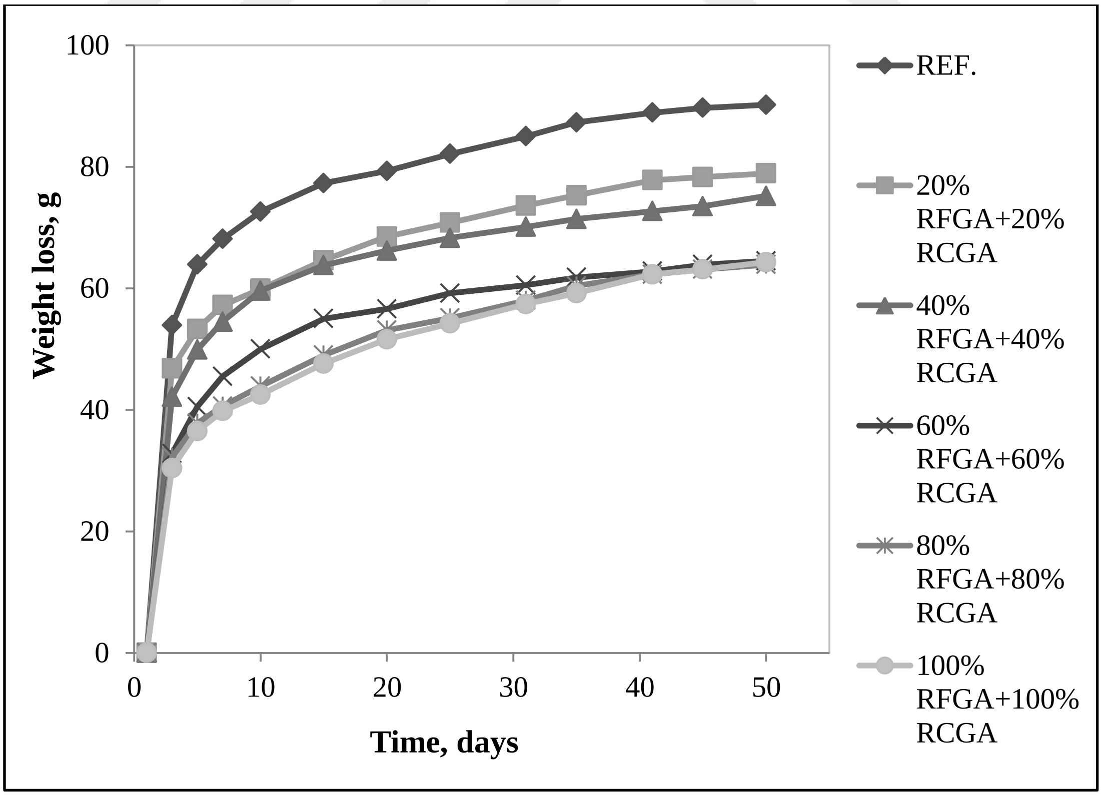


Figure 4.10 Weight loss vs. time (Series III)

4.1.2 Restrained shrinkage failure in ring type concrete members

Tensile stresses are generated in structures when volume changes which caused by moisture loss, temperature increases, and chemical reactions are restrained. Also, due to concrete brittle behavior and low tensile strength, concrete elements can crack when loaded. When these tensile stresses are high enough, they may result in cracking. These cracks will lead to increase of permeability, reduction of mechanical section and reduction of steel reinforcement protection in reinforced concrete structures. These cracks can accelerate the deterioration of concrete elements and reduce the service life of structures (Barluenga and Hernández-Olivares, 2007).

Since drying shrinkage tests alone cannot offer sufficient information on the behavior of concrete structures since virtually all concrete structures are restrained in some way, either by reinforcement or by the structure. Therefore, the observation of restrained shrinkage cracking behavior of concrete gains a prominent importance.

Weiss (1999), Altoubat and Lange (2001), Mihashi and Leite (2004) reported that the creep of concrete has been observed to be beneficial to reduce cracking risk due to the relaxation of tensile stress produced by drying shrinkage at early age. As creep effects depend on load application time and drying shrinkage can happen at short time after concrete casting, relaxation has to be taken into account to evaluate cracking of concrete at early age.

It can be said that three phenomena are necessary for concrete cracking at early age: a dimensional change (shrinkage), that this deformation produces tensional stress (stiffness) and that this stress is greater than the tensile strength of concrete (Barluenga and Hernández-Olivares, 2007)

Concrete is expected to crack whenever the tensile stress induced by the constraint for the free shrinkage surpasses its tensile strength. The crack developments and the shrinkage cracking age of the restrained shrinkage specimens are shown in Table 4.2 and Figures 4.11 to 4.14 while Figures 4.15 through 4.17 photos shows the crack width for each series compared with the reference mixture.

From Figures 4.11 to 4.13, it can be noted that all the concrete mixtures showed a stable shrinkage after 30 days. Also, these figures explain that the addition of recycled glass as aggregate to SCCs reduced the crack width of SCCs. But this reduction depended on the type of replacement and the ratio of replacement. Figure 4.11 illustrated that when using recycled fine glass aggregate (RFGA) instead of natural fine aggregate (NFA) the crack width decreases when the RFGA increases. This reduction in crack width may be caused by the presence of natural coarse aggregate (NCA) which lead to restrained the concrete and at the same time, the amount of water inside the capillary pores within the concrete structure increased with the increase of RFGA and that reduce the self-desiccation. For example, the crack width at the end of 50 days of drying period for normal SCCs was 0.76 mm compared to 0.494, 0.226 and 0.066 mm for 20, 60 and 100% replacement of RFGA respectively at the same time. This is evident through the pictures in Figure 4.15 which showed the crack width in Series I. While, in the 2nd and 3rd Series i.e. when natural coarse (NCA) and all grading aggregate (NFA and NCA) were replaced by recycled coarse (RCGA) and grading recycled glass aggregate (RFGA and RCGA), the same behavior was observed in Series II and III until the level of replacement of natural aggregate was 40% but, after that an increase of recycled glass content seemed to be a negative effect on the crack width of SCCs as shown in Figures 4.12 and 4.13. This action of SCCs may be due to the reduction in bonding strength between the glass as aggregate and cement paste that lead to increase the crack width because of increase the tensile strain also, the absence of natural coarse aggregate which eliminate the volume changes lead to increase the crack width of SCGCs. For instance the crack width of control mixture was 0.76 mm at the end of 50 days of drying compared to 0.371, 0.32, 0.71, 0.738 and 0.75 mm for 20, 40, 60, 80 and 100% replacement of natural coarse aggregate by recycled coarse glass aggregate respectively (Series II), while when replacement of grading natural aggregate by 20, 40, 80 and 100% of all recycled grading glass aggregate (Series III) the crack width was 0.314, 0.278, 0.577 and 0.657 mm respectively, as obviously seen by photos in Figures 4.16 and 4.17.

Figure 4.14 showed a comparison between the crack widths for three series at different ratios of replacement after 50 days of drying. From that figure, it is obvious that addition of recycled glass aggregate as fine aggregate will decrease the crack width while, up to 40% replacement of recycled glass as coarse or all grading aggregate will reduce the crack width and after that the increase of recycled glass will lead to an increase in crack width.

A similar trend as in crack width was observed when the crack was beginning as shown in Table 4.2. In Series I the initial crack was seen between 21th and 41th day of casting depending on the rate of replacement of RFGA, as the rate of RFGA increase the day to initiate the crack was delay, while the crack in control mixture was observed at the 10th day. However, the crack was started at 13th, 19th, 16th and 11th day of casting for 20, 40, 60 and 100% replacement of RCGA (Series II) respectively. Nevertheless, the crack was initiated after 23th, 37th, 21th and 16th day of casting for 20, 40, 60 and 100% replacement of RFGA and RCGA (Series III) respectively.

Table 4.2 Crack width in ring members

Day to initiate the crack	Crack width (mm)							
		Series I					Series II	
	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5	Mix 6	Mix 7	Mix 8
10	0.22							
11								
12	0.246							
13							0.153	
14	0.28							
15							0.16	
16	0.326							
17							0.193	
18	0.334							
19							0.2	0.16
20	0.406							
21		0.166	0.1334				0.227	0.16
22	0.434							
23		0.216	0.145				0.247	0.18
24	0.474							
25		0.266	0.17	0.153			0.3	0.193
26	0.5							
27		0.286	0.2	0.16			0.3	0.193
28	0.6							
29		0.3	0.214	0.18			0.34	0.2
30	0.654							
31		0.334	0.22	0.186			0.367	0.2
32	0.66				0.134			
33		0.386	0.246	0.186			0.368	0.233
34	0.674				0.174			
35		0.426	0.266	0.186			0.368	0.26
36	0.7				0.186			
37		0.434	0.286	0.2			0.369	0.273
38	0.714				0.2			
39		0.454	0.294	0.2			0.369	0.273
40	0.72				0.206			
41		0.466	0.314	0.2		0.06	0.369	0.293
42	0.746				0.206			
43		0.48	0.326	0.214		0.06	0.371	0.293
44	0.754				0.214			
45		0.486	0.354	0.214		0.06	0.371	0.293
46	0.76				0.22			
47		0.494	0.36	0.22		0.066	0.371	0.293

Table 4.2 Continued

48	0.76				0.22			
49		0.494	0.366	0.226		0.066	0.371	0.313
50	0.76	0.494	0.38	0.226	0.22	0.066	0.371	0.32

Table 4.2 Continued

Day to initiate the crack	**Crack width (mm)**							
	Series II			**Series III**				
	Mix 9	**Mix 10**	**Mix 11**	**Mix 12**	**Mix 13**	**Mix 14**	**Mix 15**	**Mix 16**
11			0.17					
12								
13			0.228					
14		0.2						
15			0.269					
16	0.18	0.28						0.257
17			0.31					
18	0.25	0.32						0.328
19			0.348					
20	0.259	0.35					0.335	0.355
21			0.38			0.23		
22	0.35	0.38				0.26	0.365	0.375
23			0.418	0.152				
24	0.378	0.415				0.28	0.385	0.382
25			0.467	0.172				
26	0.411	0.44				0.310	0.395	0.463
27			0.51	0.172				
28	0.432	0.499				0.385	0.49	0.39
29			0.588	0.267				
30	0.51	0.54				0.395	0.503	0.51
31			0.637	0.281				
32	0.517	0.59				0.395	0.523	0.537
33			0.651	0.281				
34	0.53	0.62				0.405	0.537	0.557
35			0.661	0.294				
36	0.541	0.638				0.405	0.543	0.577
37			0.68	0.294	0.199			
38	0.578	0.68				0.405	0.557	0.597
39			0.709	0.301	0.212			
40	0.611	0.69				0.415	0.557	0.617
41			0.715	0.301	0.212			
42	0.629	0.715				0.425	0.563	0.623
43			0.73	0.301	0.225			

Table 4.2 Continued

44	0.685	0.73				0.425	0.57	0.623
45			0.74	0.301	0.252			
46	0.7	0.738				0.425	0.57	0.637
47			0.748	0.314	0.272			
48	0.709	0.738				0.435	0.57	0.657
49			0.75	0.314	0.278			
50	0.71	0.738	0.75	0.314	0.278	0.435	0.5766	0.657

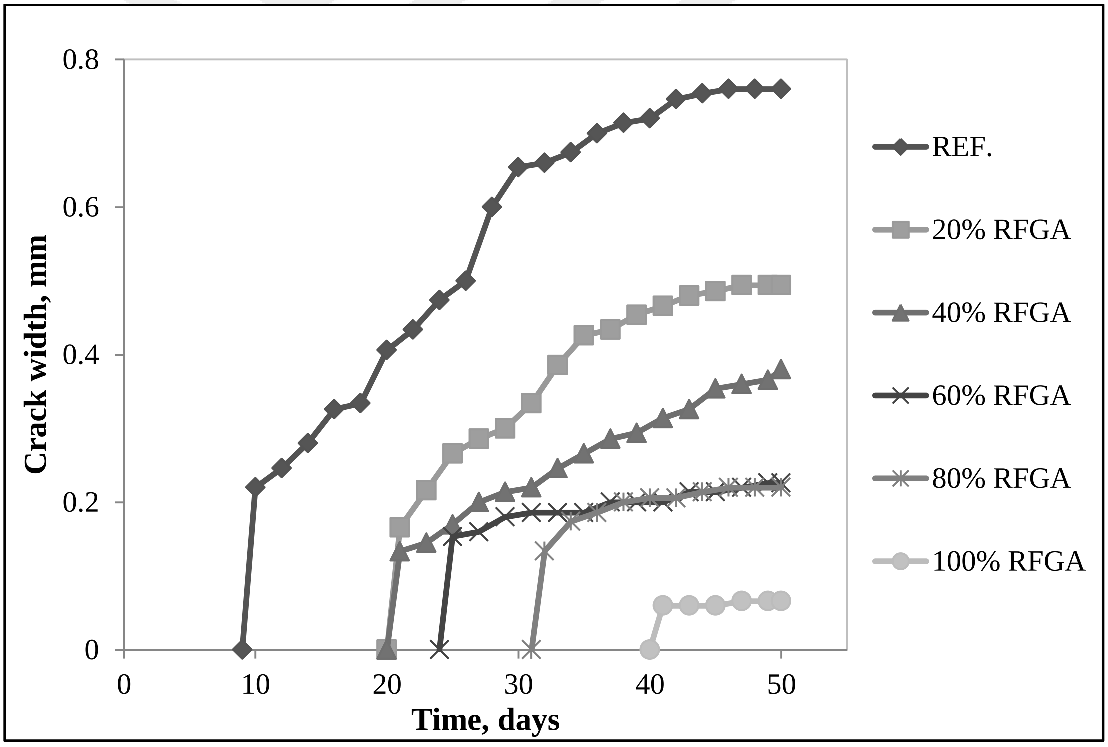


Figure 4.11 Crack width propagation vs. time (Series I)

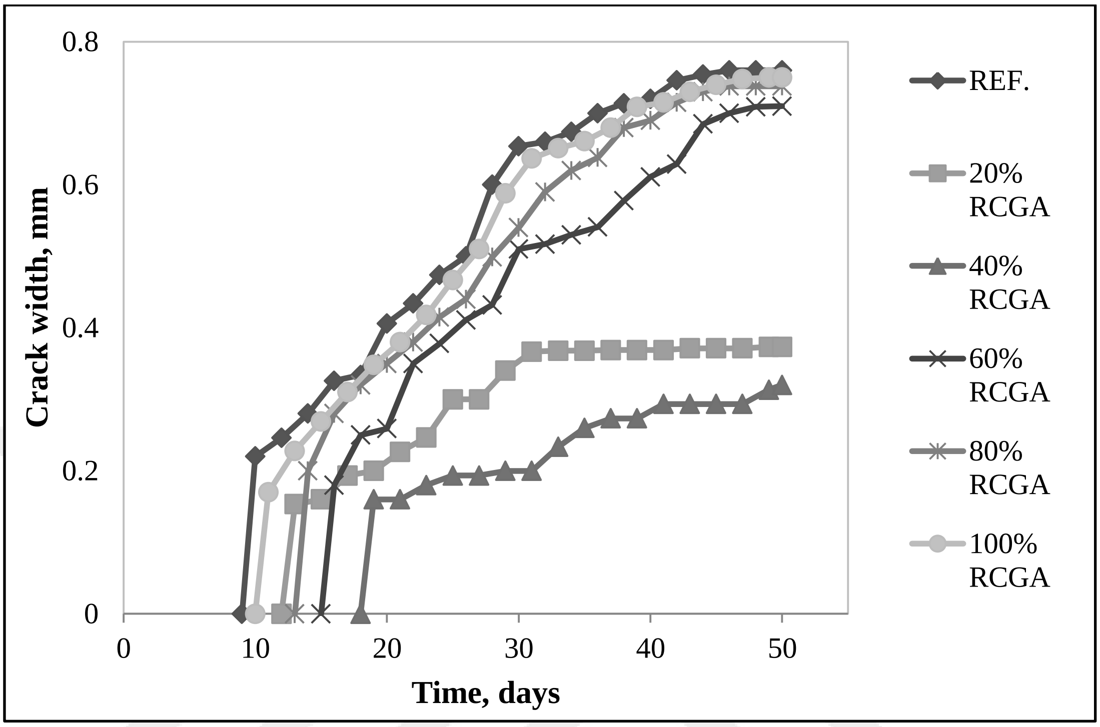


Figure 4.12 Crack width propagation vs. time (Series II)

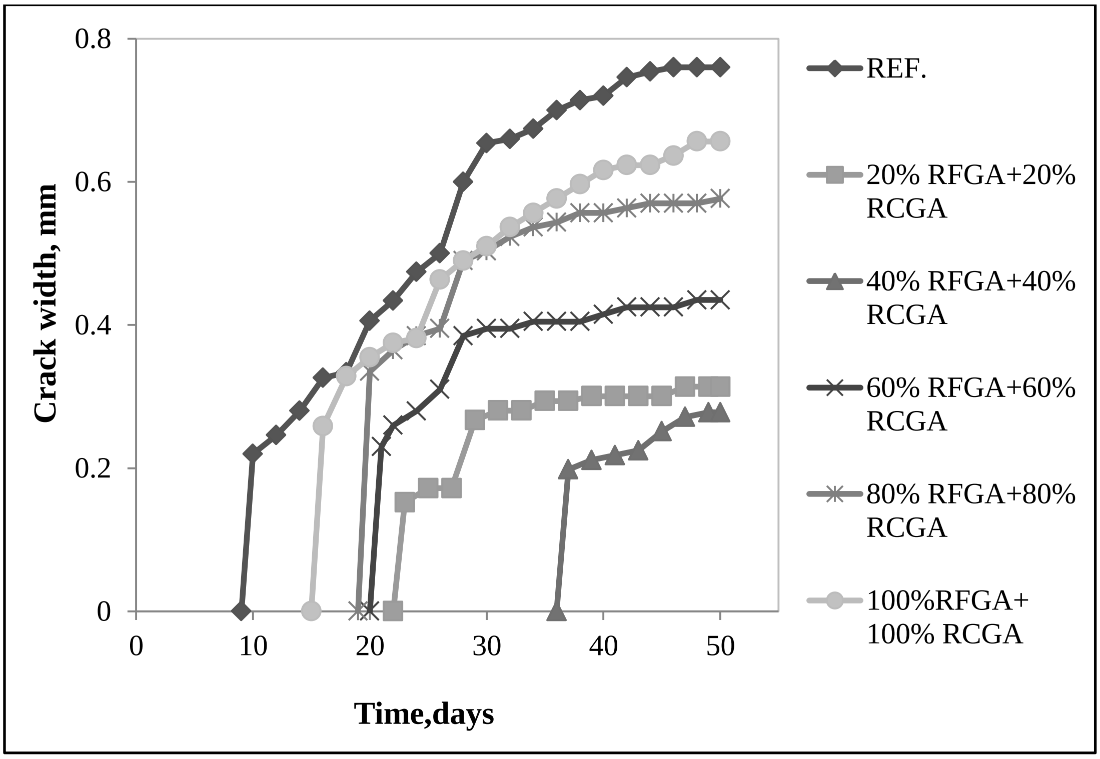


Figure 4.13 Crack width propagation vs. time (Series III)

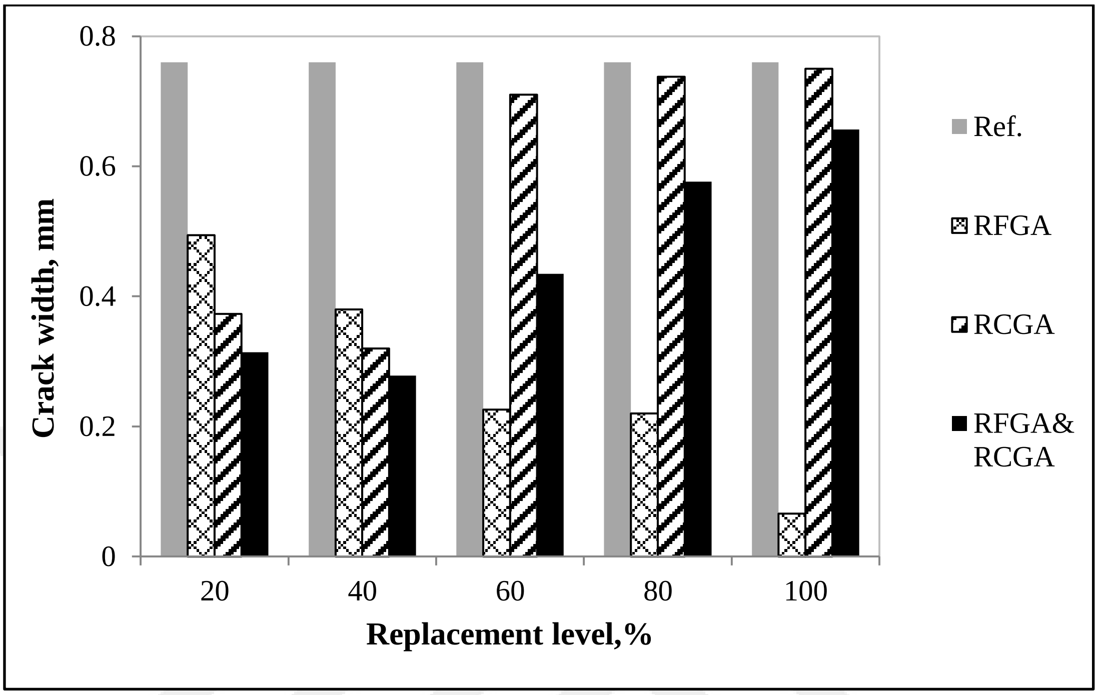


Figure 4.14 Comparison of crack width after 50 days of restrained shrinkage

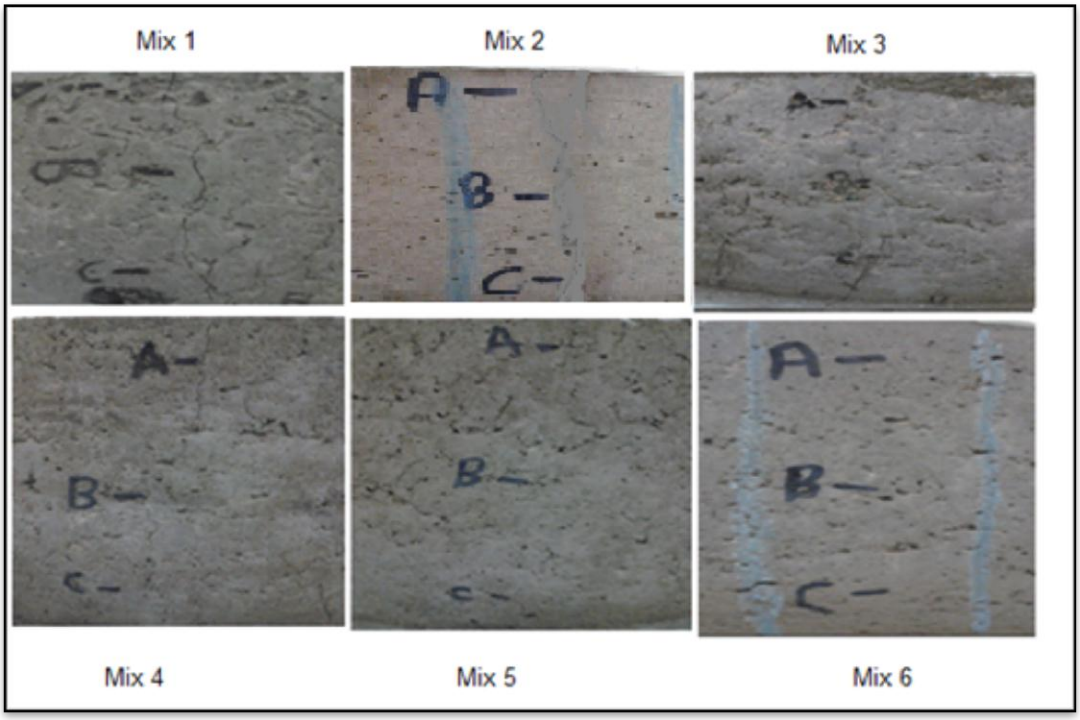


Figure 4.15 Comparison of the crack width of reference and Series I

Figure 4.16 Comparison of the crack width of reference and Series II

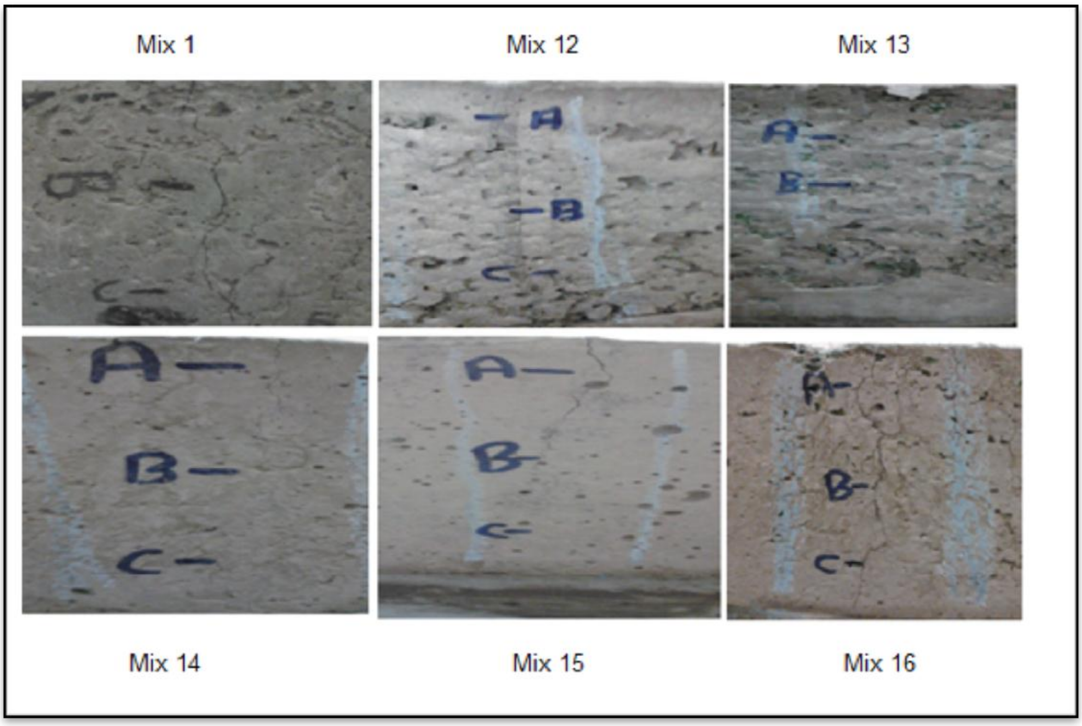


Figure 4.17 Comparison of the crack width of reference and Series III

4.2 Some fresh related performance

It is important to ensure both high flowability and good segregation resistance for assuring that the concrete can flow readily around various obstacles and achieve good filling capacity during the casting in reinforced concrete structures.

In this study, the slump flow diameter of the concretes ranged from 65.0 to 73.5 cm, as shown in Figure 4.18. It can be classified as SF2 category of EFNARC (2002) recommendations which is suitable for many normal applications such as columns and walls because the lower and upper acceptance limit of slump flow diameter according to EFNARC (2002) was 65 and 75 cm, respectively. While, SF1 category contain Mix 15 and Mix 16 which contain 80% and 100% (recycled fine and coarse glass aggregate) respectively because the diameters were 61.5 and 56.0 cm respectively, which can be appropriate for: Unreinforced or slightly reinforced concrete structures that are cast from the top with free displacement from the delivery point like housing slabs; casting by a pump injection system for example tunnel linings. And sections that are small enough to prevent long horizontal flow (e.g. piles and some deep foundations). However, Figure 4.19 showed that Walraven (2003) classified for the structural application of SCC according to its properties.

It was observed that almost all mixes showed no bleeding and segregation except for Mix 15 and M16 which have tendency to segregate. The results indicated that when recycled glass aggregate incorporating to SCCs the slump flow diameter decreased compared to reference mix (Mix1). For example, the diameter of reference mix was 73.5 cm compared to 72.5 to 67.0 cm for Series I and 71.0-65.0 cm for Series II. While for the 3rd Series the diameter ranged between 70.0 and 56.0 cm. This behavior may be due to the granular shape and sharp edge of recycled glass aggregate. While the natural aggregate rounded and without sharp edges. Also, it can be the results of the increase amount of air bubbles with the increment of recycled glass aggregate.

Figure 4.20 shows the effect of addition the recycled glass aggregate on slump flow time T_{50} of SCCs. Figure 4.20 illustrated that the replacement of natural aggregate by recycled glass aggregate increased the time of slump flow for SCCs. For instance, the T_{50} for control mix was 1.9 s. But, it ranged between 2.0-5.55, 2.4-6.25, and 2.25-6.44 s for Series I, II, and III respectively. This was attributed to the sharp edges of recycled glass aggregate make it needs longer time than rounded aggregate. Nevertheless, the results still met the flowability standard time for T_{50} slump flow except when the replacement was 100% (Mix 6) for Series I. While, for Series II and III the T_{50} slump flow was more than the maximum acceptance criteria when the replacement was 80% and 100% respectively (Mix 10, 11, 15 and 16). Similar findings have been reported in the literature mentioned that the flowability of concrete decreased when glass aggregate added to SCCs (Park et al., 2004a; Hongjian and Kiang, 2013a; Topcu and Canbaz; 2004).

In this study, the amount of water kept constant but the amount of superplasticizer (SP) changed to satisfy the requirement of SCCs (Figure 4.21). The amount of SP decreased with increased recycled waste glass aggregate since the lacking absorption ability of recycled glass aggregate, which approached to zero, attributed to this behavior. Also, this decreasing of SP may be another reason to reduce the fresh properties of SCGC.

According to EFNARC (2002), the SCCs having a V-funnel flow time within 6 to 12 s may be highly resistant to possible segregation. The variation of V-funnel flow time of the produced SCGCs is given in Figure 4.22. The time measured via the V-funnel flow was in the range of 8.0-21.0 s depending mainly on the percentage and type of replacement of recycled glass aggregate. It was observed in Figure 4.22; that T_{50} slump and V-funnel flow times were the same trend. As the recycled glass aggregate replacement increase the V-funnel flow time increased, for instance the V-funnel flow time, for reference mix was 5.25 s However, for the series it was ranged between 8.0-11.9, 9.29-19.14, and 11.0-21.0 s for Series I, II and III, respectively. This was attributed to the sharp edges of glass aggregate that make it needs longer time than rounded aggregate. These results are in agreement with some result reported in the literature (Wang and Huang, 2010).

According to EFNARC (2002), it was observed that the all SCC mixtures except for mixes contain 60, 80, 100% RCGA (Series II) and 40, 60, 80, 100% RFGA and RCGA (Series III)) satisfied the EFNARC limitation for structural application.

According to EFNARC (2002) recommendation, viscosity should be specified only in special cases such as best surface finish and in limiting the formwork pressure or improving the segregation resistance. Figure 4.23 showed the relation between T_{50} slump and V-funnel flow times. From that Figure, it can be indicated that all mixtures classified as VS2/VF2. While, the control mixture (Mix1) lies within the requirement of VS1/VF1.

Passing ability of the SCCs measured by means of the L-box test. The test provided H_2/H_1 ratio as a measure of the flowability among reinforcing bars. The variation in the L-box height ratio (H_2/H_1) is presented in Figure 4.24. All mixtures of SCGCs satisfied the EFNARC limitation given for the L-box height ratio. H_2/H_1 ratio value ranged from 0.80 to 0.94.

It was noticed from Figure 4.7 that the addition of recycled waste glass aggregate to SCC decreases the passing ability of SCC. When H_2/H_1 for control mixture was 0.96, it became between 0.94-0.86, 0.92-0.84, and 0.90-0.80 for Series I, II, and III respectively. Actually, the physical characteristics of recycled glass aggregate particle such as harsh, sharp and angular shape may lead to increase the friction between particles itself and/or with binder particles which in turn significantly effects on the flowability of concrete. Also, the increases in recycled glass aggregate lead to decrease in SP dosage and that another reason to reduce L-box height ratio. However, the reduction in L-box height ratio is not so much and all produced concretes located in PA2 base on EFNARC limitations.

Figures 4.25 and 4.26 showed the results of T_{20} and T_{40} flow times for three series. The replacement of natural aggregate by recycled glass aggregate showed increasing in time for T_{20} and T_{40} and effect became more obvious in Series III due to utilizing both grade of recycled glass aggregate. It can be seen that the T_{20} for reference mixture was 1.5 s while, it ranges between 1.8-7.1, 2.48-8.16 and 2.7-9.84 s for Series I, II, and III respectively which means there was an increase of T_{20} in ratios of (16.7-78.9), (39.5-81.2) and (44.4-84.8)% for Series I, II and III respectively . Also, T_{40} have the same trend of T_{20} as shown in Figure 4.9 for example the T_{40} of the reference mixture was 3.81 s, it became between 5.21-15.98, 6.62-18.55 and 6.9-19.25 s for Series I, II, and III respectively and that means there was a progressive increase in T_{40} and this percentage increase was (27.8-76.2), (42.5-79.4) and (44.8-80.2) %.

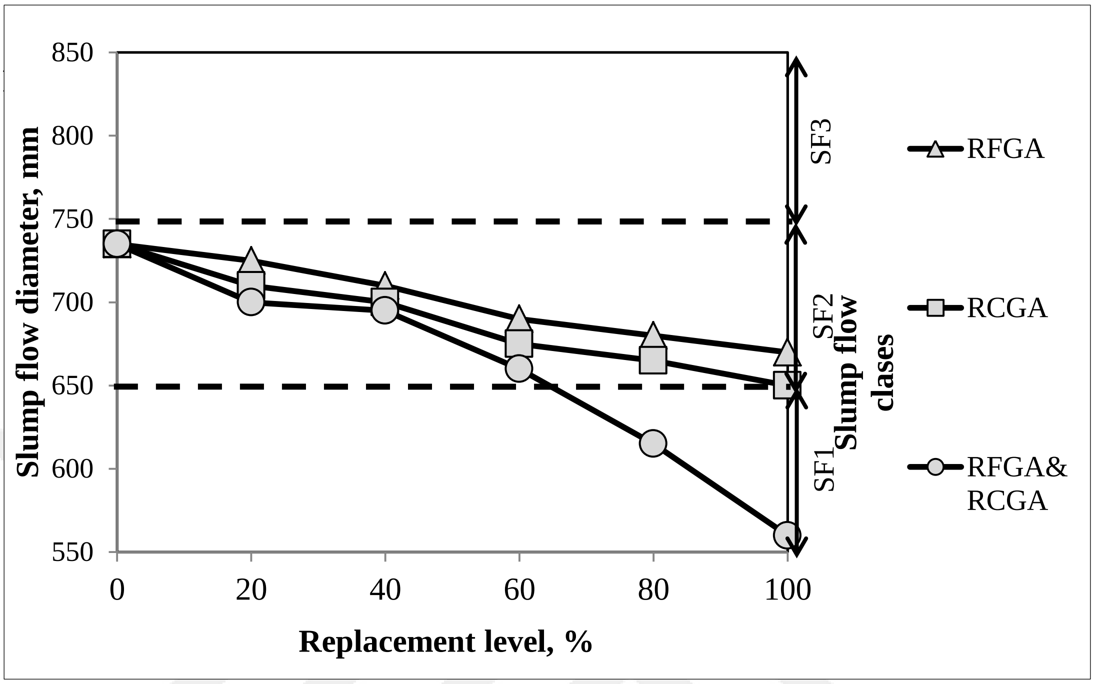


Figure 4.18 Slump flow diameter and classes of SCCs

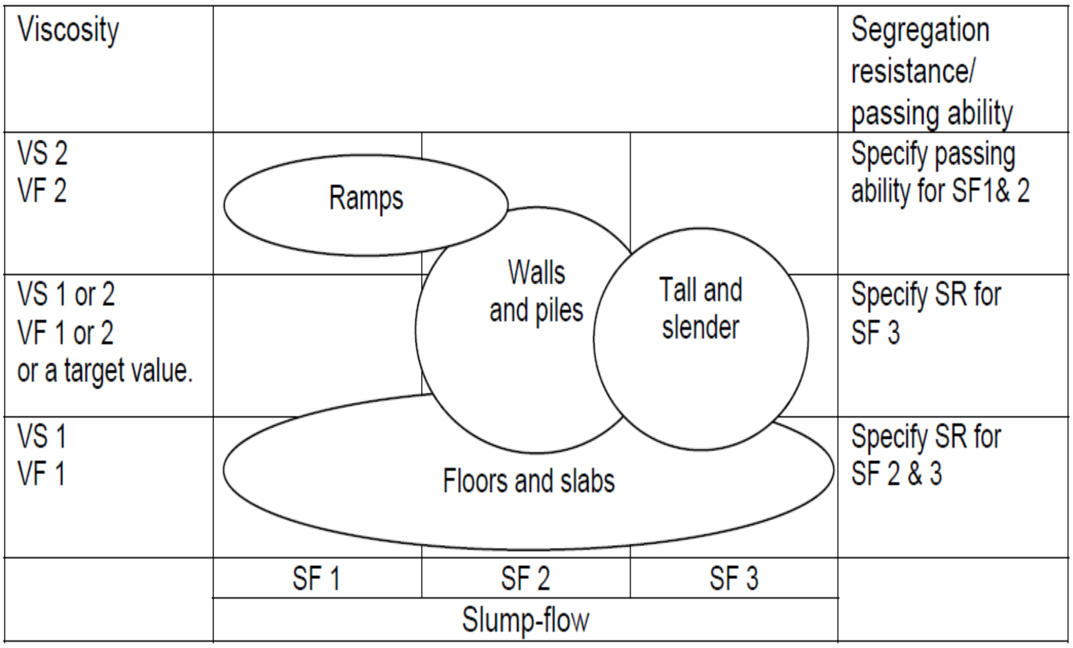


Figure 4.19 Properties of structural SCC for various types of application in structure based on Walraven (2003)

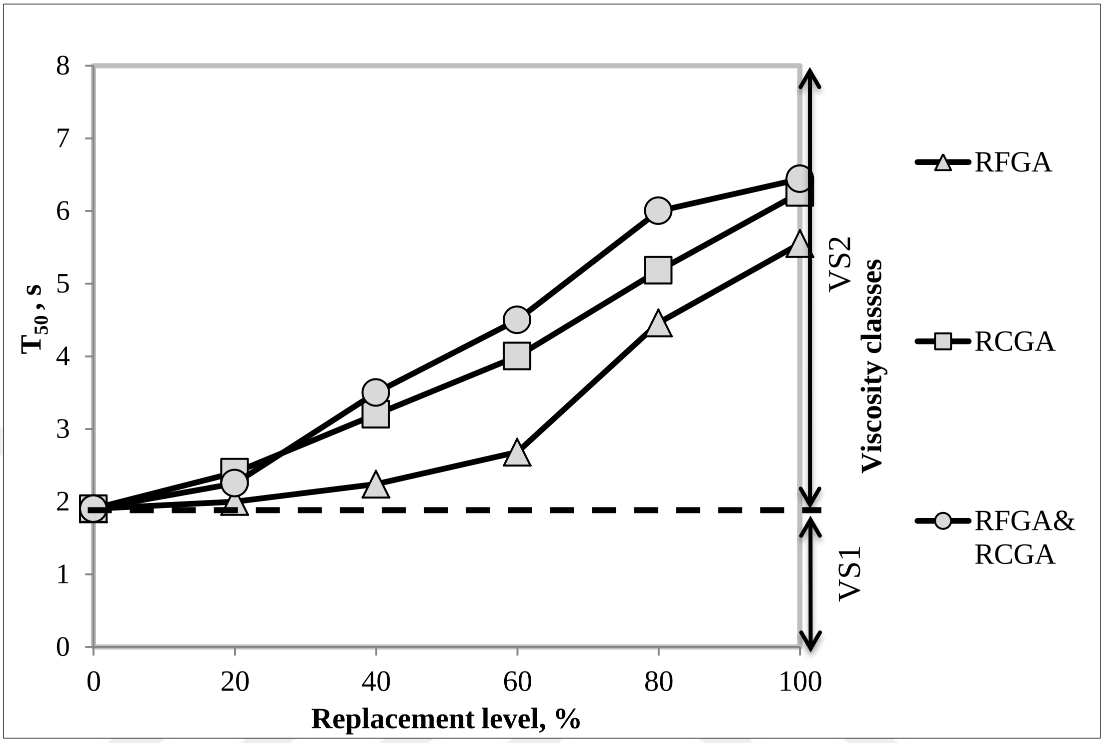


Figure 4.20 T_{50} and viscosity classes

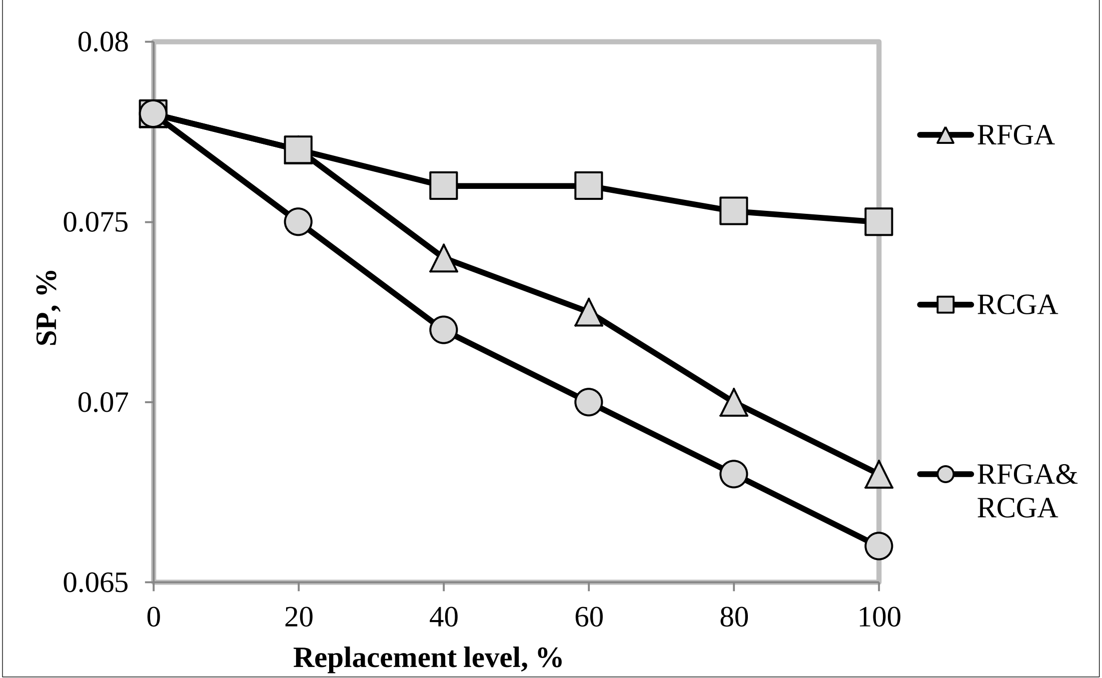


Figure 4.21 Amount of SP for SCGCs

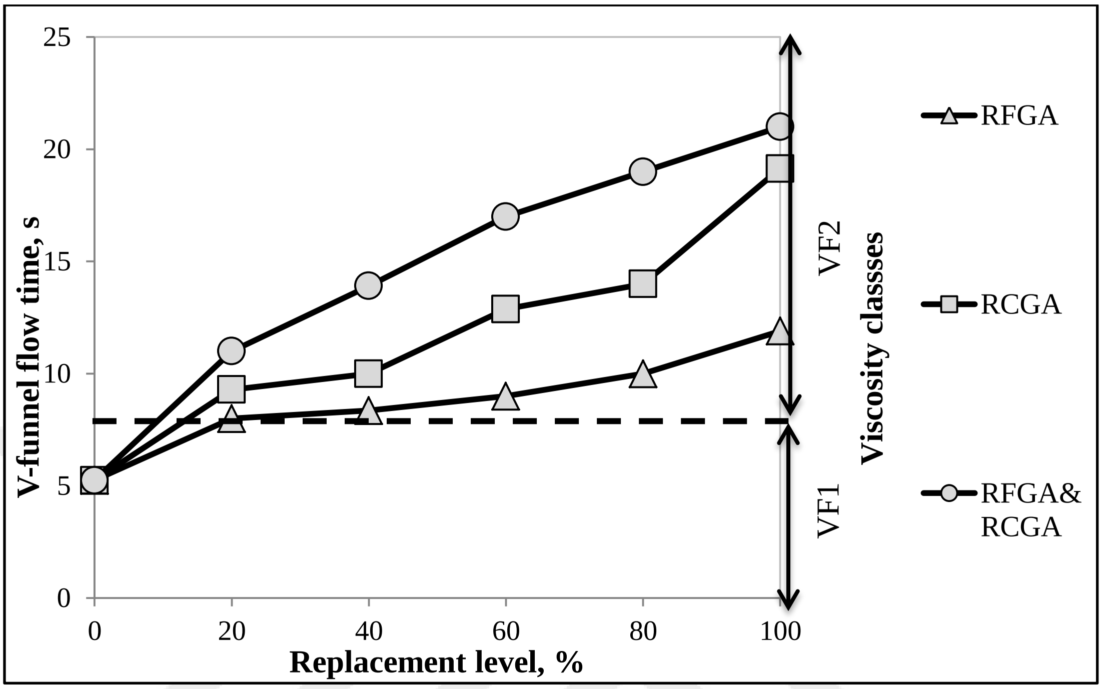


Figure 4.22 V-funnel flow time and viscosity classes

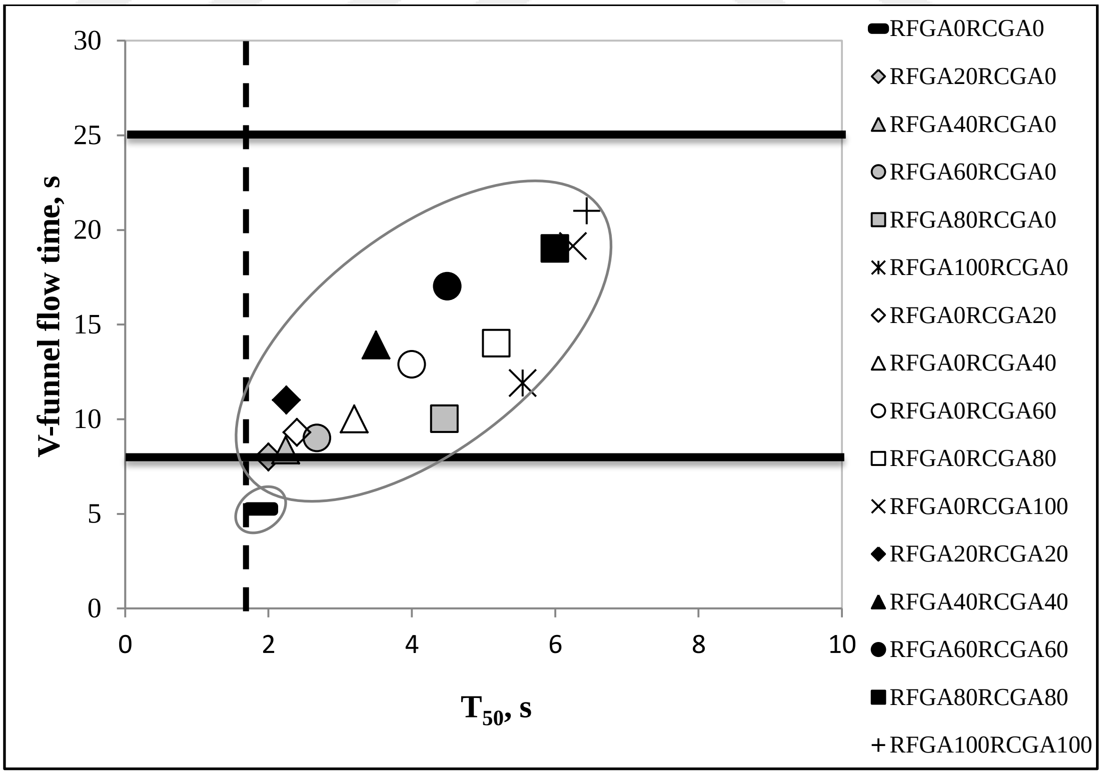


Figure 4.23 T_{50} vs. V-funnel flow time for SCGCs

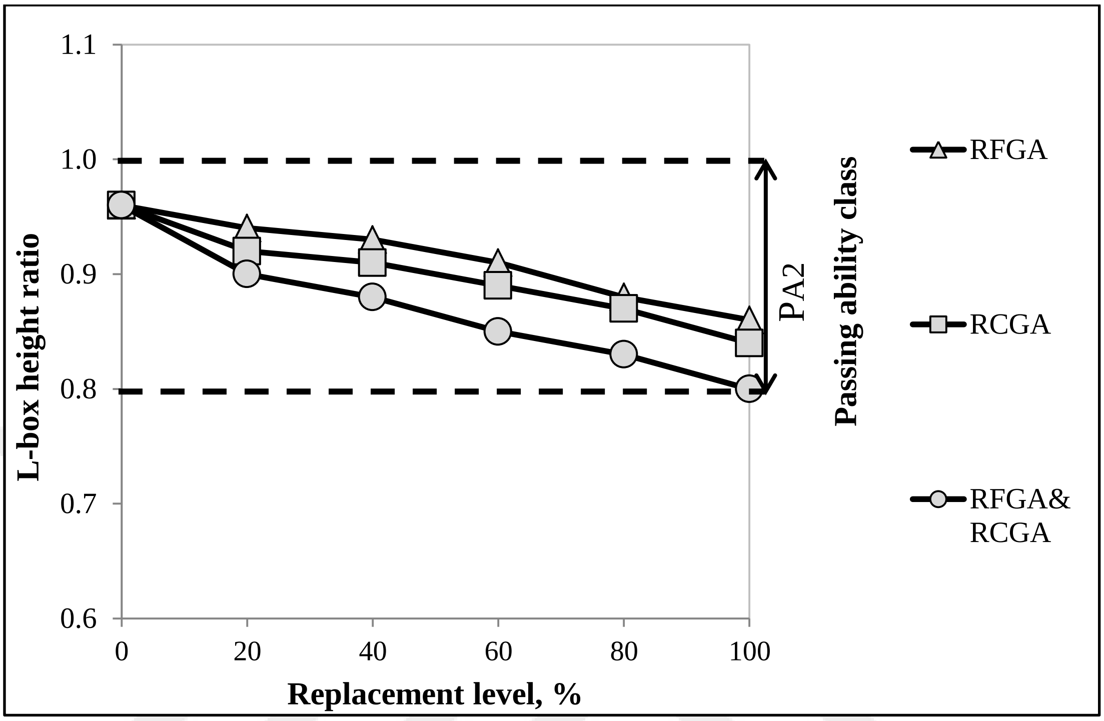


Figure 4.24 L-box height ratio and passing ability classes

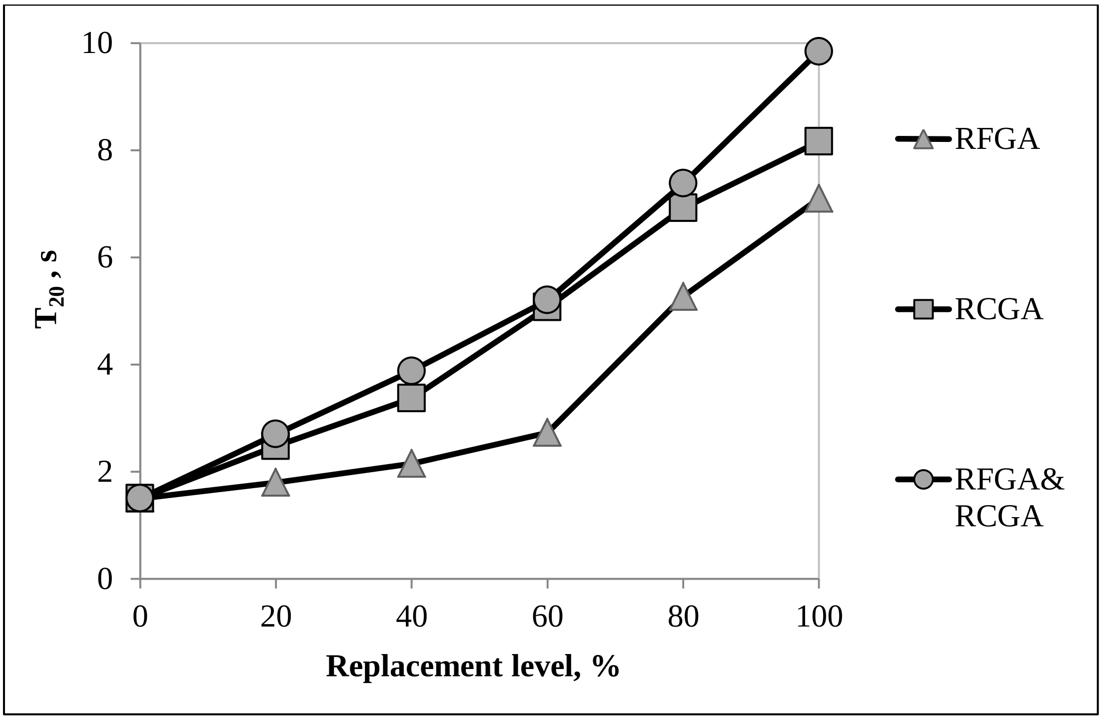


Figure 4.25 T_{20} L-box flow time

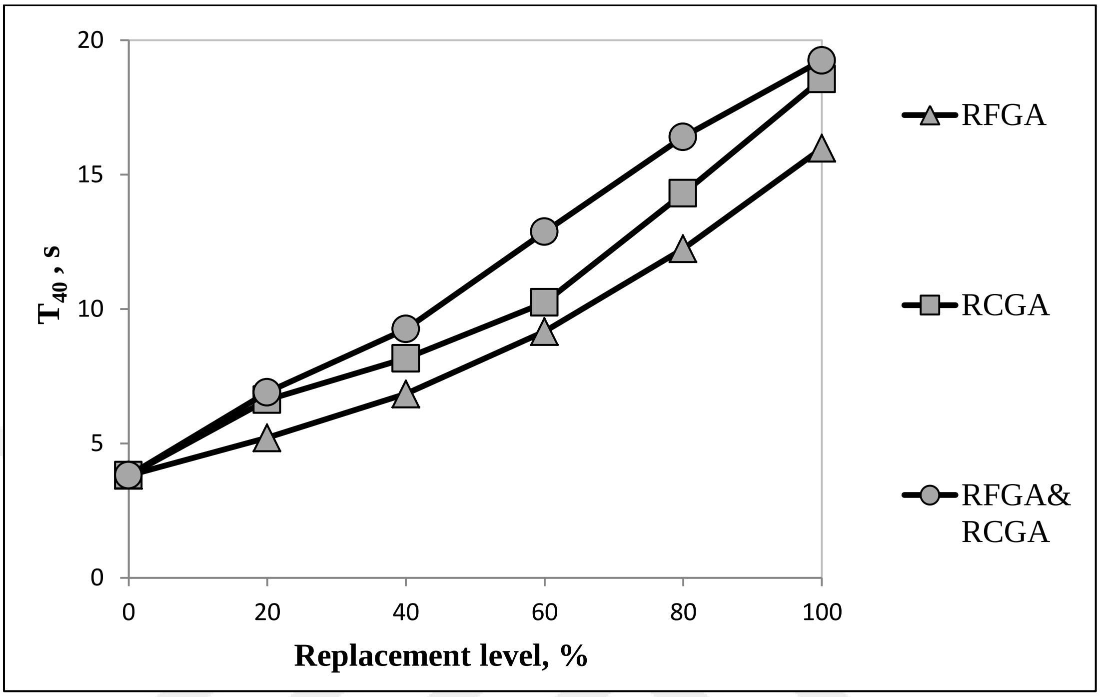


Figure 4.26 T_{40} L-box flow time

CHAPTER 5

CONCLUSIONS

An experimental program was conducted to investigate the deformation and crack propagation due to the shrinkage on the test specimens made with structural SCC having recycled glass. Fresh related properties were also studied so as to increase the possible use of such concrete in structural applications. Based on the findings of this study, the following conclusions were drawn:

1. The characteristics of structural SCC in fresh state are very important. The slump flow values varied from 56 to 74 cm for SCGCs. They are commonly in SF2 class according to EFNARC limitation, which indicates that they are suitable for many normal applications in structure for constructing the reinforced concrete walls or columns, etc. Only two mixtures of SCGCs (containing high amount of glass) were categorized as SF1, but they could be also applied and used for unreinforced or slightly reinforced concrete structure.
2. It was also observed that SCGCs had the acceptable slump flow and V-funnel flow times with regard to EFNARC limitation. Moreover, all SCGCs had the L-box height ratio values between 0.8 and 1.0, which implies a perfect fluid behavior.
3. In general, the shrinkage deformations of all SCGCs after 50 days of drying were less than 750 microstrain according to Australian Standard AS 3600. However, the use of recycled glass reduced the shrinkage strain.

4. The effect of using RFGA (Series I) were very remarkable to reduce the shrinkage deformation and as the RFGA increases the deformation decreases. While, when using RCGA (Series II and III), the deformation decreased up to 40% replacement. But after that, the deformation started to increase gradually.
5. The analysis of the results showed that the crack width in concrete ring members decreased by using RFGA only (Series I). In the case of RCGA (Series II) and both RFGA and RCGA (Series III), the crack width propagations decreased up to 40% replacement and after that this reduction began to decrease.
6. The time to initial cracking can also affected by recycled glass. In Series I, the first crack delayed as the amount of RFGA increased. However, in Series II and III, this delaying was observed up to 40% of replacement and later this delaying began to reduce.
7. It is important to understand the degree and level of cracks due to the volumetric changes in reinforced concrete or concrete structures. The shrinkage induced tensile stress surpasses the tensile capacity of the structural members. In the case of insufficient reinforcement, the cracking would be occurred. The impact of such cracking on durability especially corrosion, is also detrimental to many structures.

REFERENCES

Ali, E. E., Al-Tersawy, S. H. (2012). Recycled glass as a partial replacement for fine aggregate in self- compacting concrete, *Construction and Building Materials*, **35**, 785-791.

Almusallam, A.A. (2001). Effect of environmental conditions on the properties of fresh and hardened concrete. *Cement and Concrete Composites*, **23 (4–5)**, 353–361.

Altoubat, S., Lange, D. (2001). Early age stresses and creep-shrinkage interaction of restrained concrete, *COE Report* **14** for FAA.

American Concrete Institute ACI 224R-01, (2001). Control of Cracking in Concrete Structures. Reported by ACI Committee 224, 1-46

American Society for Testing and Materials (2002). ASTM C 618, Slandered Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for use as a Mineral Admixture in Concrete. West Conshohocken, PA.,USA.

American Society for Testing and Materials (2007). ASTM C157, Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete, West Conshohocken, PA., USA.

American Society for Testing and Materials (2009). ASTM C 1202, Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. West Conshohocken, PA.,USA.

American Society for Testing and Materials (2014). ASTM C1260, Standard Test Method for Potential Alkali Reactivity of Aggregates (Mortar-Bar Method), West Conshohocken, PA., USA.

American Society of Testing and Materials (1974). ASTM C 150-72, Waste glass as coarse aggregate for concrete. West Conshohocken, PA.,USA.

Antona, Bruno Johansson Richard (2011). Crack Control of Concrete Structures Subjected to Restraint Forces. MSc. Thesis, Chalmers University of Technology, Göteborg, Sweden.

Armaghani, J., Kamal, T., Steven, S., Michael, B. (2015). Accelerated Slab Replacement Using Self-Consolidating Concrete. *Transportation Research Record: Journal of the Transportation Research Board*, **2508 (11)**: 93-101

Australia Standard (October 2004). AS 3600, Concrete structures-incorporating AMD 1: May 2002 and AMD 2.

Baena, M., Torres, L., Turon, A., Llorens, M., Barris, C. (2016). Bond behaviour between recycled aggregate concrete and glass fibre reinforced polymer bars. *Construction and Building Materials*, **106**, 449-460.

Barluenga, G., Hernández-Olivares, F. (2007). Cracking control of concretes modified with short AR-glass fibers at early age. Experimental results on standard concrete and SCC. *Cement and Concrete Research*, **37**, 1624–1638.

Based Association Concrete Sustainable Development (BACSD), (2005). White Paper on Sustainable Development. *Concrete International*, **27(2)**, 19-21.

Bignozzi, M. C., Sandrolini, F. (2004). International Conference on Sustainable Waste Management and Recycling: Glass Waste. *Wastes by glass separated collection: A feasible use in cement mortar and concrete*. Universita di Bologna, 117-124.

Billberg, P. (1999). Self-compacting concrete for civil engineering structures – the Swedish experience. *Swedish Cement and Concrete Research Institute*, Stockholm, Sweden.

Bissonnette, B., Pierre, P., Pigeon, M. (1999). Influence of key parameters on drying shrinkage of cementitious materials. *Cement and Concrete Research*, **29 (10)**, 1655–1662.

British Standards Institution (1999). BS 812-123:1999 Testing aggregates – Part 123: Method of determination of alkali-silica reactivity - concrete prism method (incorporating corrigendum No.1). London; BSI.

Byars, EA., Zhu, H. (2003). ConGlassCrete I project Interim progress report. The Waste & Resources Action Programme (WRAP). The University of Sheffield, Valpak Ltd, Warwickshire.

Byars, EA., Zhu, HY., Morales, B. (2004). ConGlassCrete II, Final report. The Waste & Resources Action Programme (WRAP), The University of Sheffield, Valpak Ltd , Warwickshire.

Caldarone, M. A., Peter, C. T., Rachel, J. D., Shrinivas, B. B., (2005). Guide Specification for High-Performance Concrete for Bridges, 1st edition. *Portland Cement Association*.

Canton, D.L., Nassau, J.J. (2014). Architectural fiberglass. *www.4stromberg.com*. Accessed by 25.02.2017.

Carino, N. J., Clifton, J. R. (1995). Prediction of Cracking in Reinforced Concrete Structures. National Institute of Standards and Technology Gaithersburg, USA. MD 20899.

Cassar, J., Camilleri, J. (2012). Utilization of imploded glass in structural concrete. *Construction and Building Materials*, **29**, 299-307.

Castro, S. d., Brito, J. d. (2013). Evaluation of the durability of concrete made with crushed glass aggregates. *Journal of cleaner production***,** **41**, 7-14.

Chandramouli, K., Seshadri, Sekhar T., Sravana, P., Pannirselvam, N., Srinivasa, Rao P. (2010). Strength properties of glass fiber concrete. *Journal of Engineering and Applied sciences*, *5*(4), 1-6.

Chen, S. H., Chang, C. S., Wang, H. Y., Huang, W. L. (2011). Mixture design of high performance recycled liquid crystal glasses concrete (HPGC). *Construction and Building Materials*, **25(10)**, 3886-3892.

Chira, A., Anuj, K. , Tomáš, V., Lenka, L., Andrijana. S., Petr, H.,(2016). Property improvements of alkali resistant glass fibres/epoxy composite with nanosilica for textile reinforced concrete applications. *Materials and Design Journal*, **89**, 146-155.

Cihat, Y., Reza, S. A., Babak, A. A., Kambiz, R. (2013). Evaluation of three test methods for determining the alkali–silica reactivity of glass aggregate. *Cement and Concrete Composites*, **38**, 57–64.

Collins, R.J., Bareham (1987). Alkali silica reaction: suppression of expansion using porous aggregate. *Cement and Concrete Research*, **17(1)**, 89–96.

Corinaldesi, V, Gnappi, G., Moriconi, G., Montenero, A. (2005). Reuse of ground waste glass as aggregate for mortars. *Waste Management*, **25(2)**, 197-201.

De Jong, B. H. W. S. (1989). Glass in Ullmann's Encyclopedia of Industrial Chemistry. Vol. A12: 5th edition. VCH Publishers, Weinheim, Germany.

De Schutter, G. (2005). Measurement of properties of fresh self-compacting concrete. Final report.

De Schutter, G., Bartos, PJM., Domone, PLJ., Gibbs, JC. (2008). Self-compacting concrete. Whittles Publishing.

Dehn, F., Holschemacher, K., Weibe, D. (2000). Self-compacting concrete (SCC) time development of the material properties and the bond behaviour. *LACER* , **5**, 115-124.

Dhir, R. K., Dyer, T. D, Tang, A., Cu Y. J., Wang, L. (2005). Towards maximizing the use of glass cullet in concrete. *Concrete technology unit, Concrete London, University of Dundee*, **39(8)**, 32-34.

Din, Z. (1979). The physical chemistry of silicates (in Chinese). Chinese construction industry press, Beijing, China.

Domone, P.L. (2007). A review of the hardened mechanical properties of self-compacting concrete. *Cement and Concrete Composites*, **29**, 1–12.

Domone, PLJ. (2000). Developments in self-compacting concrete. *State of the art report of RELLIM Technical Report Committee 174-SCC*, 49-65.

Ducman, V., Mladenovic, A., Suput J. S. (2002). Lightweight aggregate based on waste glass and its alkali-silica reactivity. *Cement and Concrete Research*, **32(2)**, 223-226.

Dumitru, I., Song, T., Caprar, V., Brooks, P., Moss, J. (2010). 2ndInternational Conference on Sustainable Construction Materials and Technologies. *Incorporation of recycled glass for durable concrete.* Universita Polytechnica delle Marche, Ancona, Italy, 9 pages.

Dyer, T. D., Dhir, R. K. (2001). Chemical reactions of glass cullet used as a cement component. *Journal of Materials in Civil Engineering*, **13(6)**, 412-417.

Environmental Protection Department (EPD). Waste statistics for 2010. Hong Kong: Environmental Protection Department; 2010. Viewed at: https://www.wastereduction.gov.hk/en/materials/info/msw2010.pdf. Accessed by 25.04.2016.

European Federation of Precast Concrete (2010) The Concrete Case - Workshop on the Management of C&D waste in the EU.

European Federation of Producers and Applicators of Specialist Products for Structures, EFNARC (2002). Specification and guidelines for self-compacting concrete. http://www.efnarc.org. Accessed by 20.11.2014.

Feng, N.Q., Ye, H.W., Gu, G.R., Zhang, J.H., Xu, L.B., Yu, B., Lu, J.B. Wijaya, S. (2010). 35th Conference on our world in concrete & structures. *Study on ultra high performance-self compacting concrete (UHP-SCC) and its ultrahigh-rise pumping technology*. In Singapore.

French national research program, (2014). JRC Ispra – Italy. *Behaviour and assessment of massive structures: cracking and shrinkage*. Available at CEOS.fr. Accessed by 23.03.2017.

Gilbert, I.R. (2001). Shrinkage, Cracking and Deflection-the Serviceability of Concrete Structures. *Electronic Journal of Structural Engineering*, **1(1)**, 2-14.

Goodier, C.I. (2003). Development of self-compacting concrete. *Proceedings of the ICE- Structures and Buildings*, **156 (4)**, 405-414.

Grzybowski, M., Shah, S.P. (1990). Shrinkage cracking of fiber reinforced concrete. *ACI Materials journal.*, **87(2)**, 138–148.

HM Revenue and Customs (HMRC) (2014). A general guide to landfill tax. Available at: < http://customs.hmrc.gov.uk/channelsPortalWebApp/channelsPortalWebApp.portal?_nfpb=true&_pageLabel=pageLibrary_ShowContent&id=HMCE_CL_000509&propertyType=document#downloadopt>. Accessed by 15.03.2015.

Hobbs, D. W. (1999). Aggregate Influence on Chloride Ion Diffusion into Concrete. *Cement and Concrete Research*, **29(12)**, 1995–1998.

Hoffmann, A., Leeman A. (2005). Properties of self-compacting concrete – differences and similarities. *Magazine of Concrete Research* **57(6**), 315–9.

Holschemacher, K., Klug, Y. (2002). A database for the evaluation of hardened properties of SCC. *LACER*, **7**, 124-134.

Holt, E. Leivo, M. (2004). Cracking risks associated with early age shrinkage. *Cement and Concrete Composites*, **26 (5)**, 521–530.

Holt, E., Shodet, O. (2002). Self-compacting concrete: early age shrinkage. *Internal report* **RTE40-IR-21-2002**, VTT.

Hongjian, Du, Kiang, Hwee Tan (2013). Use of waste glass as sand in mortar: Part I – Fresh, mechanical and durability properties. *Cement and Concrete Composites*, **35**, 109–117.

Hongjian, Du, Kiang, Hwee Tan (2013a). Use of waste glass as sand in mortar: Part II – Alkali–silica reaction and mitigation methods. *Cement and Concrete Composites*, **35**, 118–126.

http://en.wikipedia.org/wiki/Burj_Dubai, http://www.burjdubai.com/ Accessed by 05.03.2017.

Jawed, I., Skalny, J. (1978). Alkalies in cement: A review II. Effects of alkalies on hydration and performance of Portland cement. *Cement and Concrete Research*, 8(1), 37-51.

Jin, W., Meyer, C. Baxter, S. (2000). Glasscrete - Concrete with glass aggregate. *ACI Materials journal*, **97(2)**, 208-213.

Khayat, K.H., Aitcin, P.C. (1998). Use of self-consolidating concrete in Canada-present situation and perspectives. Proceedings, Workshop on Self-Compacting Concrete, Kochi, Japan.

Khayat, K.H., Bickley, J., Lessard, M. (2000). Performance of self-consolidating concrete for casting basement and foundation walls. *ACI Materials journal*, **97**, 374–380.

Khayat, K.H., Guizani, Z. (1997). Use of viscosity-modifying admixture to enhance stability of fluid concrete. *ACI Materials journal*, **94(4)**, 332-341.

Khayat, K.H., Patrick, Paultre, Stephan, Tremblay (2001). Structural Performance and In-Place Properties of Self-Consolidating Concrete Used for Casting Highly Reinforced Columns. *ACI Materials journal*. **98(5)**, 371-378.

Koehler, Eric P., Fowler, David W. (2007). Self-Consolidating Concrete for Precast Structural Applications: Mixture Proportions, Workability, and Early-Age Hardened Properties. Technical report by Texas Department of Transportation Center for Transportation Research at The University of Texas at Austin

Koh, Chon Jin (2014). Characteristication of Shape of Fine Recycled Crushed Coloured Glass and the Effect on the Properties of Structural Concrete when used as a Fine Aggregate Replacement. PhD thesis, University of Wolverhampton.

Kou, S.C., Poon, C. S. (2009). Properties of self-compacting concrete prepared with recycled glass aggregate. *Cement and Concrete Composites*, **31(2)**, 107-113.

Kumar, B.A.V.Ram, Rao, J.Venkateswara, (2015). Effect of Inclusion of Glass Fibers and GGBS in Concrete Paver Blocks. *Journal of Mechanical and Civil Engineering*, **12(5),** 81-88.

Lam, C. S., Poon, C. S., Chan, D. (2007). Enhancing the performance of pre-cast concrete blocks by incorporating waste glass - ASR consideration. *Cement and Concrete Composites*, **29(8)**, 616-625.

Lee, G., Poon, C. S., Wong, Y. L., Ling T. C. (2013). Effects of recycled fine glass aggregates on the properties of dry-mixed concrete blocks. *Construction and Building Materials*, **38**, 638-643.

Limbachiya, M. C. (2009). Bulk engineering and durability properties of washed glass sand concrete. *Construction and Building Materials*, **23(2)**, 1078-1083.

Ling, T. C., Poon C. S., Kou S. C. (2011). Feasibility of using recycled glass in architectural cement mortars. *Cement and Concrete Composites*, **33(8)**, 848-854.

Ling, T. C., Poon, C.S., Wong, H.W. (2013). Management and recycling of waste glass in concrete products: Current situations in Hong Kong. *Resources, Conservation and Recycling*, **70 (2013)**, 25– 31.

Liu, M. (2011). Incorporating ground glass in self-compacting concrete. *Construction and Building Materials*, **25(2)**, 919-925.

Maranan, Manalo, Benokrane, Karunasena,Mendis (2015). Evaluation of the flexural strength and serviceability of geopolymer concrete beams reinforced with glass-fibre-reinforced polymer (GFRP) bars. *Engineering Structures*, **101**, 529-541.

Martin, D. J. (2002). First North American Conference on the Design and Use of Self-Consolidating Concrete, Center for Advanced Cement-Based Materials, Northwestern University, Nov, Evanston, IL, USA. *Economic Impact of SCC in precast applications*. 147-153.

Mastali, M., Dalvand, A., Sattarifard, A. (2016). The impact resistance and mechanical properties of reinforced self-compacting concrete with recycled glass fibre reinforced polymers. *Journal of Cleaner Production*. DOI:10.1016/j.jclepro.2016.02.148

Matos, Ana Mafalda, Telma, Ramos, Sandra, Nunes, Joana, Sousa-Coutinho (2016). Durability Enhancement Of SCC With Waste Glass Powder. *Materials Research*. **19(1)**, 67-74.

McCoach, Hugh, Gordon, Francey, Sarah Mann. Wrap (2013). Glass Flow 2012 Final report - Environmental compliance, recycling and sustainability solutions. Valpak Ltd, Warwickshire

Mehta, P. K. (1993). Durability of Concrete—Fifty Years of Progress? *Concrete Durability*, *ACI SP-126*, 1–31.

Meyer, C. (2003). Glass concrete. *Concrete International*, **25(6)**, 55–58.

Meyer, C., Baxter, S. (1997). Use of recycled glass for concrete masonry blocks. *Columbia University final report to New York state energy research and development authority*, **Report no. 97-15**, Albany, New York, USA.

Mihashi, H., Leite, J.P. (2004). State of the art report on control of cracking in early age concrete. *Journal of Advanced Concrete Technology*, **2(2)**, 141–154.

Moustafa, A., El Gawady, M. A. (2016). Strain Rate Effect on Properties of Rubberized Concrete Confined with Glass Fiber–Reinforced Polymers. *Journal of Composites for Construction*, **20(5)**, 249-253.

Naik, Tarun R. (2008). Sustainability of Concrete Construction. *Practice periodical on structural design and construction*, **13(2)**, 98-103.

Nawa, T., Izumi, T. Edamatsu, Y. (1998). In: International Workshop on Self-Compacting Concrete. *State-of-the-art report on materials and design of self-compacting concrete*. 160-190.

Nehdi, ML., Pardhan, M., Koshowski, S.(2004). Durability of self-consolidating concrete incorporating high-volume replacement composite cements. *Cement and Concrete Research*, **34(11)**, 2103-2112.

Neville, AM. (1996). Properties of concrete. Final edition, Pearson Education Limited.

Nishikawa, T., Takatsu, M., Daimon M. (1995). Fracture behavior of hardened cement paste incorporating mineral additions. *Cement and Concrete Research*, **25(6)**, 1218-1224.

Nwaubani, Sunny O., Poutos, Konstantinos I. (2013). The Influence of Waste Glass Powder Fineness on the Properties of Cement Mortars. *International Journal of Application or Innovation in Engineering and Management (IJAIEM)*, **2(2)**, 110-116.

Okamura, H. (1997). Ferguson Lecture for 1996: Self-Compacting High Performance Concrete. *Concrete International*, **19(7)**. 50-54.

Okamura, H., Ouchi, M. (1999). In: The 1st International RILEM Symposium on Self-Compacting Concrete. Skarendahl, A., Petersson, O., editors, RILEM Publications S.A.R.L. *Self-compacting concrete development, present use and future.* France. 3-14.

Okamura, H., Ouchi, M. (2003). In: The 3rd International RILEM Symposium on Self-Compacting Concrete. Wallevik, OH., Nielsson, I., editors, RILEM Publications S.A.R.L., Bagneux. *Applications of self-compacting concrete in Japan*. France. 3-5.

Okamura, H., Ouchi, M. (2003). Self-compacting concrete. *Journal of Advanced Concrete Technology*, **1(1)**, 5-15.

Okamura, H., Ozawa, K. (1994). Self-Compactable High-Performance Concrete in Japan. International Workshop on High Performance Concrete, SP-159, American Concrete Institute, Farmington Hills, MI, 31-44.

Ouchi, M. (2001). In: The 2nd International RILEM Symposium on Self-Compacting Concrete. Ozawa, K, Ouchi, M, editors. *Current conditions of self-compacting concrete in Japan*. 63-68.

Ouchi, Masahiro, Sada-aki, Nakamura, Thomas, Osterberg, Sven-Erik, Hallberg, Myint Lwin (2003). International Sorption Heat Pump Conformance (ISHPC). *Applications of self-compacting concrete in Japan, Europe and the United States*. Japan.

Ozawa, K. (2001). In: The 2nd International RILEM Symposium on Self-Compacting Concrete. Ozawa, K, Ouchi, M, editors. *Utilization of new concrete technology in construction project -Future prospects of self-compacting concrete.* 57-62.

Ozawa, K., Maekawa, K., Kunishima, M., Okamura, H. (1989). Proceedings of the 2nd East-Asia and Pacific Conference on Structural Engineering and Construction (EASEC-2). *Development of high performance concrete based on the durability design of concrete structures*. **1**, 445-450.

Ozawa, K., Ouchi, M. (Editors). (1999). Proceedings of the International Workshops on Self-Compacting Concrete, Concrete Engineering Series 30, ISBN 4-8106-0310-5, Japan Society of Civil Engineers, Tokyo, 399 pp.

Ozkan, O., Yuksel, I. (2008). Studies on Mortars Containing Waste Bottle Glass and Industrial By-Products. *Construction and Building Materials*, **22(6)**, 1288-1298.

Park, S. B., Lee, B. C. (2004). Studies on expansion properties in mortar containing waste glass and fibers. *Cement and Concrete Research*, **34(7)**, 1145-1152.

Park, S. B., Lee, B. C., Kim J. H. (2004a). Studies on mechanical properties of concrete containing waste glass aggregate. *Cement and Concrete Research*, **34(12)**, 2181-2189.

Parviz, Soroushian (2012). Recycled glass in Portland cement concrete. Clean Washington Center, Michigan State University, USA.

Patric, Mark, Andrew, Wheeler, Russell Bridge (2000b). Crack Control of Slabs. Part 1. *OneSteel Reinforcing*.

Patric, Mark, Andrew, Wheeler, Russell, Bridge, Ian, Gillbert (2000a). Crack Control of Beams. *OneSteel Reinforcing*.

Pereira, L. A. de Oliveira, Castro-Gomes, J.P., Santos, P. (2008). DBMC International Conference on Durability of Building Materials and Components. *Mechanical and Durability Properties of Concrete with Ground Waste Glass Sand*. ISTANBUL, Turkey 11-14 May.

Persson, B. (2001). A comparison between mechanical properties of selfcompacting concrete and the corresponding properties of normal concrete. *Cement and Concrete Research*, **31 (9)**, 193–198.

Phani, S.S., Sekhar, T.S., Rao P.S. (2015). High Strength Self Compacting Concrete Beams Under Flexure. *i-Manager's Journal on Structural Engineering,* **4(2)**, 10-18.

Polley, C., Cramer, SM., V.de La Cruz R. (1998). Potential for using waste glass in Portland cement concrete. *Journal of Materials in Civil Engineering* **10(4)**, 210-219.

Poutos, K.H., Alani, A.M., Walden, P.J., Sangha, C.M. (2008). Relative temperature changes within concrete made with recycled glass aggregate. *Construction and Building Materials*, **22(4)**, 557–565.

Rabadiya, S., Vaniya, S. (2015). Effect of Recycled Aggregate with Glass Fiber on Concrete Properties. *International Journal for Innovative Research in Science and Technology,* **2(1)**, 257-265.

Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages, RILEM TC 174 SCC (2000). Self- compacting concrete State-of-the-art report of RILEM technical committee 174-SCC. Skarendahl, A., Petersson, O., editors, RILEM Publications S.A.R.L., France.

Ruža, Okrajnov-Bajić, Dejan, Vasović (2009). Self-compacting concrete and its application in contemporary architectural practice. *Spatium International Review Journal,* **20**, 28-34.

Saccani, A., Bignozzi, M. C. (2010). ASR expansion behavior of recycled glass fine aggregates in concrete. *Cement and Concrete Research*, **40(4)**, 531-536.

Salih, Shakir A., Ghazi, Osamah M. (2001). Engineering Properties of Concrete Member Reinforced with Glass Fiber. MSc thesis, University of Technology, Baghdad, Iraq.

Sarigaphuti, M., Shah, S.P., Vinson, K.D. (1993). Shrinkage cracking and durability characteristics of cellulose fiber reinforced concrete. *ACI Materials journal*, **90 (4)**, 309– 318.

Schiessl, A, Zilch, K. (2001). Proceedings of the second RILEM international symposium on self-compacting concrete Kochi University of Technology. Japan: COMS Engineering Corporation; In: Ozawa, K, Ouchi, M, editors. *The effects of the modified composition of SCC on shear and bond behaviour*. 501–6.

Schlagbaum, T. (2002). Proceedings of the 1st North American Conference On the Design and Use of Self-Consolidating Concrete, Eds. Shah, S. P., Daczko, J. A., Lingscheit, J. N. *Economic Impact of Self-Consolidating Concrete (SCC) in Ready Mixed Concrete*. Chicago, 135-140.

Shah, S. P., Daczko, J. A., Lingscheit, J. N. (Editors). (2003). First North American Conference on the Design and Use of Self-Consolidating Concrete, Conference Notes, ISBN 0-924659-96-3, The Center for Advanced Cement-Based Materials, Northwestern University, Evanston, IL, 426.

Shah, S. P., Weiss, W. J., Yang, W. (1998). Shrinkage Cracking: Can It be Prevented. *Concrete International*, 51–55.

Shao, Y., Lefort, T., Moras, S., Rodriguez, D. (2000). Studies on concrete containing ground waste glass. *Cement and Concrete Research*, **30(1)**, 91-100.

Shayan, A., Xu, A. (2004). Value-added utilization of waste glass in concrete. *Cement and Concrete Research*, **34(1)**, 81-89.

Shayan, A., Xu, A. M. (2006). Performance of glass powder as a pozzolanic material in concrete: A field trial on concrete slabs. *Cement and Concrete Research*, **36(3)**, 457-468.

Shi, C. J., Zheng, K. (2007). A review on the use of waste glasses in the production of cement and concrete. *Conservation and Recycling*, **52(2)**, 234-247.

Shi, C., Wu, Y. (2005). Mixture proportioning and properties of self-consolidating lightweight concrete containing glass powder. *ACI Materials journal*, **102(5)**, 355-363.

Shi, C., Wu, Y., Shao, Y., Riefler, C. (2004). In: Proceedings of the 12th International Conference on Alkali-Aggregate Reaction in Concrete. *Alkali-aggregate reaction expansion of mortar bars containing ground glass powder. Alkali aggregate reaction in concrete*. China, 789–795.

Skarendahl, A. (2003). In: The 3rd International RILEM Symposium on Self-Compacting Concrete. Wallevik, OH, Nielsson, I, editors, RILEM Publications S.A.R.L. *The present - The future*. Bagneux, France. 6-14.

Taha, B., Nounu, G. (2008). Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. *Construction and Building Materials*, **22(5)**, 713-720.

Taha, B., Nounu, G. (2008a). Using lithium nitrate and pozzolanic glass powder in concrete as ASR suppressors. *Cement and Concrete Composites*, **30(6)**, 497-505.

Terro, M. J. (2006). Properties of concrete made with recycled crushed glass at elevated temperatures. *Building and Environment*, **41(5)**, 633-639.

The Concrete Society and Building Research Establishment (BRE) (2005). Technical report No.62 self-compacting concrete: a review. Day RTU, Holton IX, editors, Camberley, UK.

The European Guidelines for Self Compacting Concrete (2005). Specification, Production and Use. A valuable at www.efnarc.org. Accessed by 07.02.2015.

Thomas, P. Seward, Terese, Vascott (2005). High temperature glass melt property database for process modeling. The American Ceramic Society, Westerville, Ohio, USA.

Tobbi, H., Farghaly, A. S., Benmokrane, B. (2012). Concrete columns reinforced longitudinally and transversally with glass fiber-reinforced polymer bars. *ACI Structural journal*, **109(4)**, 551-557.

Tom, Quested, Andrew, Parry. (2011). Sustainable aggregates. Warp, Available at: < http://aggregain.wrap.org.uk/sustainable_2.html>. Accessed by 31.03.2017.

Topçu, I.B., Elgün, V.B. (2004). Influence of concrete properties on bleeding and evaporation. *Cement and Concrete Research*, **34 (2)**, 275–281.

Topcu, IB., Boga, A. R., Bilir, T. (2008). Alkali-silica reactions of mortars produced by using waste glass as fine aggregate and admixtures such as fly ash and Li_2CO_3. *Waste Management*, **28(5)**, 878-884.

Topcu, IB., Canbaz, M. (2004). Properties of concrete containing waste glass. *Cement and Concrete Research*, **34(2)**, 267-274.

Toutanji, Houssam A., Saafi, Mohamed (2000). Flexural behavior of concrete beams reinforced with glass fiber-reinforced polymer (GFRP) bars. *ACI Structural journal*, **97(5)**, 712-719.

Transportation Research Circular E-C107, (2006). Control of Cracking in Concrete, State of the Art. Transportation Research Board

Tuncan, M., Karasu, B., Yalcin, M. (2001). Proceedings of the international offshore and polar engineering conference. *The suitability for using glass and fly ash in portland cement concrete*. Anadolu University, **4**, 146-152.

Tuncan, M., Karasu, B., Yalcin, M. Tuncan, A. (2004). The effects of filler glasses on mechanical properties of concrete. *Key engineering materials*, **3**, 264-268.

United Nations, (1987). *Report of the World Commission on Environment and Development*, Brundtland Commission, Brundtland.

Walraven, J. (2003). Proceedings of 3rd RILEM International Symposium on Self Compacting Concrete, Reykjavik, Iceland, editors Wallevik, O. Nielsson, I., RILEM Publications PRO 33. *Structural applications of self compacting concrete*. Bagneux, France. 15-22.

Walraven, JC. (1998). The development of self-compacting concrete in the Netherlands. In: International Workshop on Self-compacting Concrete. Kochi University of Technology, Kochi, Japan. 87-96.

Wang, H. Y., Huang, W. L. (2010). Durability of self-consolidating concrete using waste LCD glass. *Construction and Building Materials*, **24(6)**, 1008-1013.

Weiss, W.J. (1999). Early-Age Shrinkage Cracking in Concrete. Ph. D thesis, Northwestern University.

Wiederhorn, S.M. (1969). Fracture stress energy of glass. *Journal of the American Ceramic Society* ***52*** *(2), 99–105.*

Wiegrink, K., Marikunte, S.M., Shah, S.P. (1996). Shrinkage cracking of high strength concrete. *ACI Materials Journal*, **93 (5)**, 409–415.

Yasser, Sharifi, Houshiar, Mahmoud, Aghebati, Behnam (2013). Recycled glass replacement as fine aggregate in self-compacting concrete. *Journal of Frontiers of Structural and Civil Engineering*, **7(4)**, 419–428.

Yu, R., DV, van Onna, P., Spiesz, Q.L., Yu, HJH. Brouwers (2016). Development of Ultra-Lightweight Fibre Reinforced Concrete applying expanded waste glass. *Journal of Cleaner Production,* **112**, 690-701.

Zammit, L., Montesin, F. E., Torpiano, A. (2004). Proceedings of the international conference on sustainable waste management and recycling: glass waste. *The use of crushed glass waste as fines in concrete construction*. University of Malta, 125-131.

Zhang, Y., Yang, W., Liu, H., Peiran, Chen, Feng, Liu (2015). Effect of interfacial strength on the flexural behavior of glass fiber reinforced polymer (GFRP) reinforced concrete beam. *Journal of Wuhan University of Technology-Material Science Education,* **30(5)**, 1001-1007.

Zhu, H. Y. (2004). Proceedings of the national seminars on high value use of waste glass in concrete products. *Alkali-silica reaction of glass aggregates in concrete*. Doncaster and London.

Zhu, H. Y., Byars, EA. (2004). Proceedings of the international conference on sustainable waste management and recycling. *Post-consumer glass in concrete: Alkali-silica reaction and case studies*. University of Sheffield, 99-108.

Zia, Paul, Roberto A. Nunez, Luis, A. Mata (2006). Implementation of self-consolidating concrete for prestressed girders .Research Project **2004-25 FHWA/NC/2006-30** Final Report.

CIRRICULAM VITAE

PERSONAL INFORMATION

Name and Surname: Osamah Mohammed Ghazi AL-KERTTANI

Nationality: Iraqi

Date and Place of Birth: 28 May 1975, Baghdad

Marital Status: Married; and I have 2 boys

Phone: +90 535 685 24 03

E-mail: osama_moh75@yahoo.com

EDUCATION

Degree	Institution	Year of Graduation
MS	Branch of Building Materials; Department of Building and Construction Engineering; University of Technology	2001
BS	Department of Building and Construction Engineering; University of Technology	1998

WORKING EXPERIENCE

Year	Place	Enrollment
2006-	Department of Civil Engineering; College of Engineering; AL-Mustansiriyah University	Assistant lecture
2003-2006	Department of Design; General Company for Industrial Design and Construction; Ministry of Industry and Minerals	Senior Engineer
2001-2003	Department of Design; General Company for Industrial Design and Construction; Ministry of Industry and Minerals	Engineer

FOREIGN LANGUAGES

Arabic (Native Language), English

PUBLICATIONS

1. Rahman Khaleel AL-Bawi, Ihsan Taha Kadhim, and **Osamah AL-Kerttani**. (2017). Strengths and Failure Characteristics of Self-Compacting Concrete Containing Recycled Waste Glass Aggregate**.** Advances in Materials Science and Engineering, Article ID 6829510, 12 pages.
2. **Osamah Mohammed Al-Kerttani** and Rahman Al-Bawi. (2017). Shrinkage and permeability properties of self - compacting concretes containing recycled coarse and/or fine glass aggregates. *Int. J. Adv. Res.* **5(5)**, 1650-1666.
3. **Osamah Mohammed G.** (2016). Comparison Study between Hardwood and Softwood. *Journal of Babylon University/Engineering Science*, **23(2)**, 13-19.
4. Prof. Dr. Mohammed Mosleh Salman, Ammar A.Muttar and **Osamah M.Ghazi** (2011). Mechanical Properties of Acrylic Mortar. *Journal of Engineering and Development*, **15(3)**, 6-20.

HOBBIES

Travelling around the world