PROPERTIES OF CONCRETE CONTAINING RECYCLED AGGREGATE AND WASTE GLASS POWDER

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M.Sc. ENGINEERING THESIS

DEPARTMENT OF CIVIL ENGINEERING
MILITARY INSTITUTE OF SCIENCE AND TECHNOLOGY
DHAKA, BANGLADESH

SEPTEMBER 2023

PROPERTIES OF CONCRETE CONTAINING RECYCLED AGGREGATE AND WASTE GLASS POWDER

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PROPERTIES OF CONCRETE CONTAINING RECYCLED AGGREGATE AND WASTE GLASS POWDER

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I hereby declare that the study reported in this thesis entitled as above is my/our own original work and has not been submitted before anywhere for any degree or other purposes. Further, I certify that the intellectual content of this thesis is the product of my own work and that all the assistance received in preparing this thesis and sources have been acknowledged and or cited in the reference section.

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ABSTRACT

Properties of Concrete Containing Recycled Aggregate and Waste Glass Powder

The coarse aggregate and fine aggregate are replaced by the RBA and WG, respectively. A mix design of a total of fifteen different mixtures is planned with a comprehensive test matrix. Fundamental tests of concrete such as density, gradations, air content, slump, as well as the mechanical properties i.e. compressive strength, splitting tensile strength, and flexural strength of RBA-based WG concrete at different ages are investigated following ASTM standards. Subsequently, a non-destructive test method ultrasonic pulse velocity is also examined to understand the pulse conductivity through produced concrete. For further investigation, a microstructural analysis is also performed using scanning electron microscopy. It is observed that the compressive strength diminishes with a higher amount of reclaimed brick aggregate. In contrast, a 12.5% higher strength can be achieved with the addition of 20% glass content though the strength falls if further glass is added as fine content. Similar trends are observed for the split tensile and flexural strength properties of this RCG. In the SEM, it is observed that up to 20% glass content RCG becomes denser formation with lesser voids; however, the larger voids and fissures are observed as glass content increases.

The research has been extended to investigate the flexural behaviour of the RCG in the reinforced concrete beam. Load-deformation of the beam and stress-strain response of the used rebar's were recorded by a standard data acquisition system including LVDT, strain gauges with a 20-channel data logger. The flexural capacity of RCG-made beams is very much comparable with control beams as the deviation is only in a range of 1%-8% for adding glass content up to 20% replacement. The experimental results are compared with the established codes such as ACI-318-14. The experimental value is near to the theoretical value calculated through the ACI-318-14 code.The outcome of this study may contribute to the application of RBA and WG as ingredients of normal and reinforced concrete.

NOTATION

RCG	Recycled Concrete with Glass
RBA	Recycled Brick Aggregate
RBCA	Recycled Brick Coarse Aggregate
WG	Waste Glass
RGFA	Recycled Glass Fine Aggregate
RG	Recycled Glass
EPD	Environmental Prottection Department
MSW	Municipal Solid Waste
RGBC	Recycled Glass Brick Concrete
WGP	Waste Glass Particle
RC	Reinforced Concrete
SEM	Scanning Electron Microscopy
ACI	American Concrete Institute
ASTM	American Society for Testing Materials
LVDT	Linear Variable Differential Transformer
ASR	Alkali Silica Reaction
NCA	Natural Coarse Aggregate
UPV	Ultrasonic Pulse Velocity
Pcr	Cracking Load (kN)
Py	Yeilding Load (kN)
Pu	Ultimate Load (kN)
Mcr	Cracking Moment (kN-m)
My	Yeilding Moment (kN-m)
Mu	Ultimate Moment (kN-m)

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CHAPTER 1
INTRODUCTION

1.1 Introduction

Various artificial derivations have been created by the construction sector that are effective at enhancing sustainability. Reusing the materials, equipment, and wastes that would otherwise burden the terrain and enclose small pockets of available land reduces the loss of land and the landscape due to relatively less digging. Nowadays, recycling is a common practice because it protects the planet's resources (Terro, 2006). It is estimated that only 85.9 million metric tons of cement are manufactured in the United States alone, as opposed to the staggering 200 million metric tons produced globally (US Geological Survey, 2017). Twenty billion tonnes of concrete are thought to be consumed worldwide per year. We require 14 billion tonnes of natural aggregate to produce this much concrete.

According to a recent estimation, the globe must deal with the issue of disposing of 12 billion tonnes of demolished concrete trash every time buildings and other reinforced concrete designs are destroyed . Around 17.2 billion complexions of burnt bricks are produced every time through around,5000 slip-up kilns across the country. According to reports, the USA produced 11.4 million tons of trash glass in 2017, accounting for 4.2 percent of total external solid waste at that time. In the UK, the Department of Environment, Food, and Rural Affairs (DEFRA) reported that the UK generated 2.4 million tons of waste glass in the time 2017. Only 33 percent of waste glass in the USA is recovered; the remainder is dumped in dumpsters. Another report claimed that 67.6 percent of the glass garbage produced in the UK was collected in 2017.

The statistics on the recycling and disposal of waste glass in Hong Kong from 1997 to 2015 were gathered from the Environmental Protection Department (EPD) report (Environmental Protection Department (1997-2015) and are shown in Fig. 1.1 Glass bottles make up the majority of the daily waste glass generation, which amounts to over 300 ton. Between 2012 and 2015, the government attempted to collect between 5-16% of this waste glass(Lu and Poon, 2019) . Recycling waste glass in concrete can serve as an alternative to natural aggregates and reduce potential risks to the hazardous environment. Although the use of recycled glass up to a definite percentage can be a better replacement for cement and aggregates.

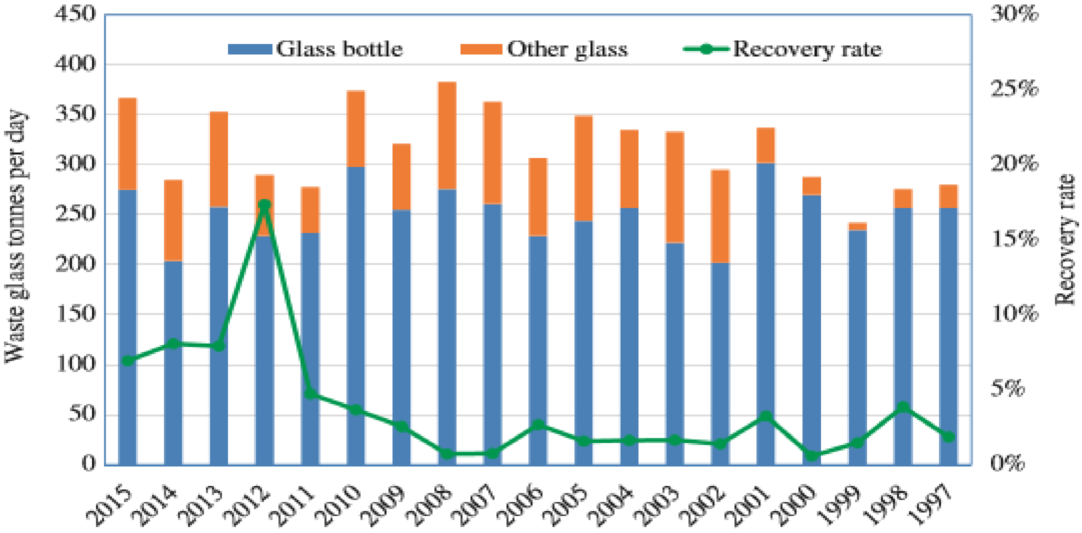


Fig.1.1 Recovery percentage of waste glass in Hongkong (Lu and Poon, 2019)

EPA measures the generation, recycling, composting, combustion with energy recovery, and landfilling of glass materials. EPA used statistics from the Glass Packaging Institute's numbers on glass container shipment to estimate glass container generation. In 2018, glass generation in all products was 12.3 million tons in the United States, which was 4.2 percent of all MSW generation. The amount of recycled glass containers was 3.1 million tons in 2018, for a recycling rate of 31.3 percent. The total amount of combusted glass in 2018 was 1.6 million tons. This was 4.8 percent of all MSW combustion with energy recovery that year. In 2018, landfills received approximately 7.6 million tons of MSW glass.

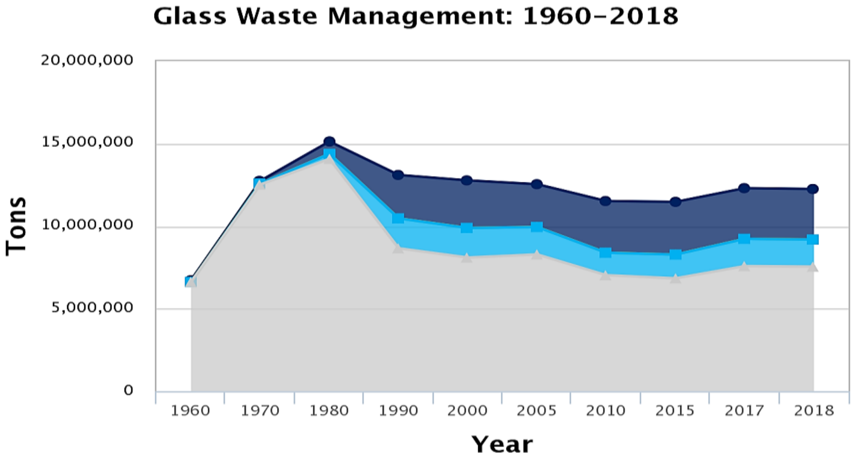


Fig. 1.2: Glass Waste Management of U.S.A. (EPA-1960-2018)

In developing nations like Bangladesh, new high rise structures are built by razing old buildings, which were often made with masonry or reinforcing concrete structures. Bricks make up the majority of a historic building's construction. Because of this, a lot of recycled brick aggregate is being produced, which can be used in construction. An ancient government administrative building that was demolished to make room for a high-rise project is seen in Fig. 1.3. A lot of waste will be produced when a building like this is destroyed. This kind of waste cannot be broken down. Additionally, the production of new aggregates harms the ecosystem. Recycling is a potential solution for green concrete and sustainable building.

Fig. 1.3: Demolished of an old administrative building in Bangladesh

Reusing or recycling resources is a priority for developed nations. Although there are significant obstacles regarding strength, research into utilizing glass in concrete is still ongoing. Recycled concrete is also a well-established concept. Recycled concrete and glass are combined and thoroughly examined in this study. Along with the mechanical characteristics of concrete, the flexural characteristics of recycled glass brick concrete (RGBC) are also examined.

1.2 Background and Motivation

Reusing and recycling demolished concrete and construction materials has attracted immense interest to researchers and engineering communities because of their significant role in combating carbon emission, climate change and protecting natural resources. The global demand for concrete is rising to the point where natural resources are limited. The majority of existing buildings and structures in the subcontinent regions are made of masonry or brick. Many brick-oriented constructions in these regions will cease to function within the next 10 to 20 years, leaving no other choice than to demolish them. Additionally, the amount of waste glass is growing daily, and the majority of it is not biodegradable. In certain studies, discarded glass has been utilized in place of cement, fine aggregate, or even coarse aggregate. However, there is no research on the combined impact or behavior of recycled concrete glass (RCG) that may contribute to the commercial development of RBA-based glass concrete.

1.3 Research Objectives

The main objectives of the present research are

i. To examine the physical properties of fresh and hardened concrete containing recycled brick as coarse aggregate (RBCA) and waste glass powder (WGP).

ii. To investigate the mechanical properties of concrete containing RBCA and WGP as the replacement of coarse aggregate and fine content, respectively.

iii. To investigate the flexural behavior of concrete beams comprising RBCA and WGP mixed concrete through four-point bending tests.

1.4 Scope of the Thesis

In this research work, recycled brick aggregate (RBA) and waste glass are core materials. Recycled Brick (RB) is collected from a 30 years old demolished building and then proceed a standard form to use as coarse aggregate in concrete. Another core materials of this research is Waste glass (WG) which is collected from Puran Dhaka waste tube light processing factory.As Waste Glass (WG) is used as the replacement of fine aggregate. So,the particle distribution curve is within the limit of ASTM C33 limits after several sieving. Besides a number of basic test will be occurred for deterimining the properties of aggregate.A proper mix design is prepared before casting procedure. For cyclindrical specimen there are fifteen batches and for prism beam and reinforced concrete (RC) beam contains twelve types of specimen .For determining workaibility of concrete slump and air content test is occurred according to ASTM C143 and ASTM C231 respectively. Besides compressive strength,splitting tensile strength and flexural test through center point loading is occurred according to ASTM C39,ASTMC496 and ASTM C293. ASTM C78 standard is followed for four point flexural test of Reinforced Concrete (RC) beam. Linear Variable Differential Transducer (LVDT) is installed in the mid part and left mid part of the beam. Ultrasonic Pulse Velocity (UPV) of cylindrical specimen is occurred according ASTM C597. In addition Scanning Electron Microscopy (SEM) is occurred to get microstructure images of concrete.

1.5 Organization of the Thesis

Apart from this chapter, the whole report is divided into five more chapters. The content of these five chapters is as follows:

Chapter 2 presents a review of nearly a hundred articles related to Recycled glass concrete.

Chapter 3 presents the methodology of targeted tests according to ASTM guidelines to meet the objectives of the research. It also presents the working procedure in time of casting and flexural test setup of beam. In addition, UPV and SEM test procedures are explored.

Chapter 4 presents the result of physical properties of aggregates, fresh and mechanical properties of recycled concrete containing glass (RCG). Targeted first two objectives are met in this chapter. Several code comparisons with the experimental value are also described. In addition, several comparison and result of UPV and SEM test procedure is explored.

Chapter 5 presents the result of the flexural test of the reinforced concrete (RC) beam. Several data from LVDT, Strain gauge, and UTM are presented. In addition, the ACI 318-14 code comparison with the experimental result is also explored.

Chapter 6 is the last chapter of this report which provides the concluding remarks. In the end, some recommendations are provided for future research purposes.

. CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Consumption of natural resources like sand, brick, and stone should be kept to a limit for sustainability. Reusing or recycling can help ease the strain on natural resources due to this. Recycled aggregate is a usual or established research topic. Numerous investigators have attempted to replace coarse gravel, sand, and even cement with wasted glass. According to numerous research studies, employing glass increases strength up to a limit. However, another team of researchers demonstrated a contrary result on the use of glass on concrete. Fig.2.1 shows the statistics and percentage of research content used for review in this chapter. Near to a hundred articles have been reviewed in this chapter and most of the articles are from the last ten years. This chapter contains a review of types of waste glass, the chemical composition of glass, fresh properties of recycled glass concrete like workability, hardened properties of concrete, conductivity, ASR expansion, density, and properties of RBCA and at the end summary of this chapter.

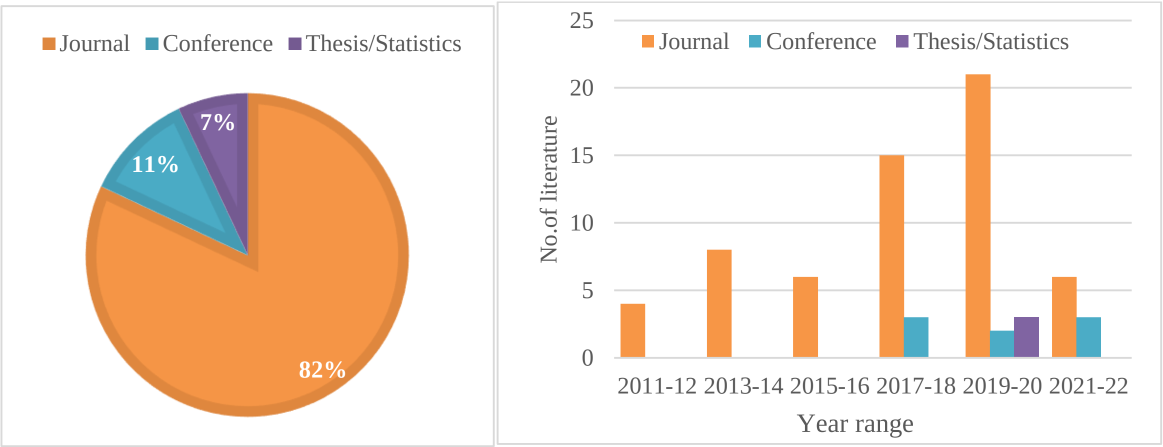


Fig. 2.1 (a) Research statistics of literature on Recycled Glass Concrete (RGC), (b) researches reviewed in this article (2011- 2022)

2.2 Waste Glass

The crushed glass exhibits an angular form, sharp edges, a smooth surface texture, and a greater aspect ratio than natural sand, as is seen in Fig.2.2 due to its brittle nature (Tan and Du, 2013). Here, in the Fig.2.2, different types and color glasses are shown. In addition, the micro structures of glass under the scanning electron microscopy (SEM) can be seen as shown in Fig.2.3 (Idir et al., 2020).

Fig. 2.2 Crumb Glass (a) appearance of natural and glass sand (b) flat glass

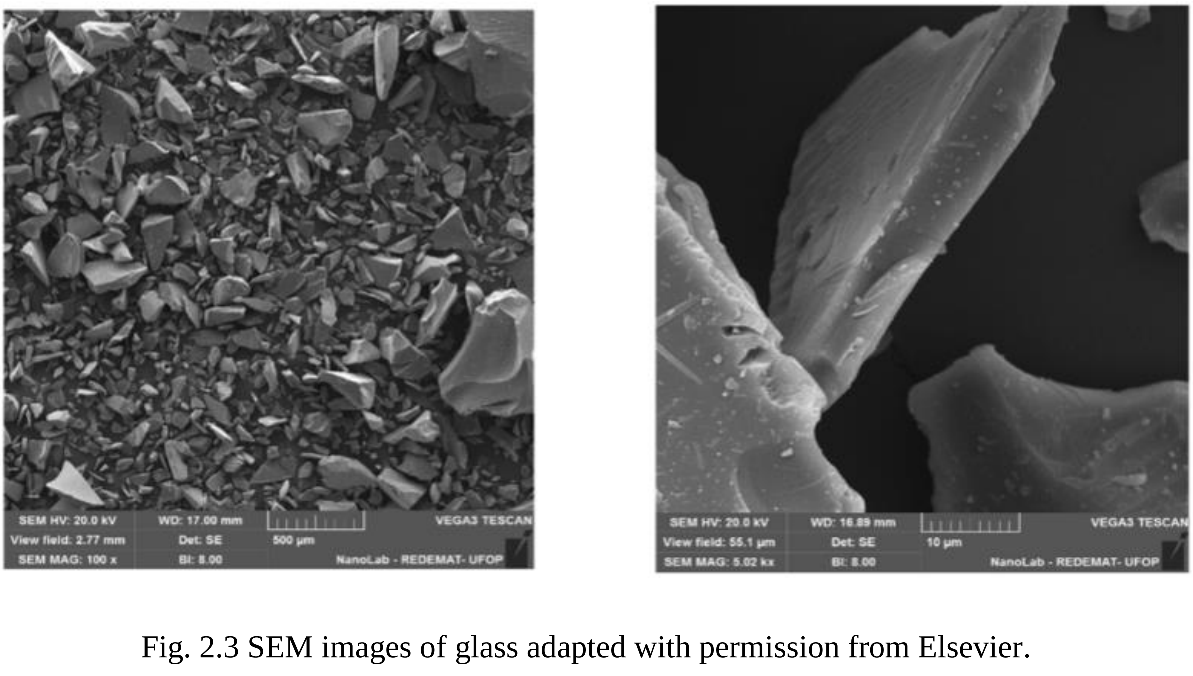


Fig. 2.3 SEM images of glass adapted with permission from Elsevier.

2.3 Chemical Composition of Glass

Chemical compounds of different types of glass, cement, and sand were represented in Table 2-1. It is evident that the main ingredient of all glass is SiO_2. Interestingly, the presence of

SiO_2 in types of all glasses is nearly consistent which is about 70% which is quite near to sand but much higher than that in cement. Besides, the major compound of cement is CaO (65-67) % whereas glass contains only 7-12 %. The significant presence of Na_2O increases the density, refractive index, thermal expansion coefficient, bulk modulus, and Poisson's ratio of glasses, and decreases Young's modulus of the glass. On the other hand, K_2O prevents the crystallization of glasses and promotes the final formation of glass.

Table 2-1: Chemical composition of cement, sand & different glasses (Du and Tan, 2014) (Idir et al., 2020)

Composition (%)	Cement	Sand	Brown Glass	Green Glass	Clear Glass	Flat Glass	Hollow Glass	Windshield Glass
SiO_2	20.80	88.54	72.08	71.22	72.14	72.16	69.89	70.11
Al_2O_3	4.60	1.21	2.19	1.63	1.56	0.68	1.92	1.86
Fe_2O_3	2.80	0.76	0.22	0.32	0.06	0.12	1.05	1.04
CaO	65.4	5.33	10.45	10.79	10.93	7.80	12.31	11.67
MgO	1.30	0.42	0.72	1.57	1.48	4.38	1.34	1.37
SO_3	2.20	-	-	-	-	0.21	0.14	0.11
Na_2O	0.31	0.33	13.71	13.12	13.04	0.21	0.16	0.07
K_2O	0.44	0.31	0.16	0.64	0.62	14.46	13.18	13.76
TiO_2		0.05	0.10	0.07	0.05			
Cr_2O_3			0.01	0.22				

It is evident from the ternary diagram of $CaO-Al_2O_3-SiO_2$ presented in Fig 2.4 that glass might be used in cement-based products. The pozzolonic reaction's primary reactive ingredient is SiO_2 and with the addition of glass, the composition possesses its highest amount (Harrison et al., 2020) . However, the amount of CaO in cement is much greater than in glass powder which contributes major strength of mortar. Nowadays, mixes of Portland cement made from fly ash (FA) or granulated blast-furnace slag (GBFS) are extremely popular; and using waste glass in concrete may also be an option.

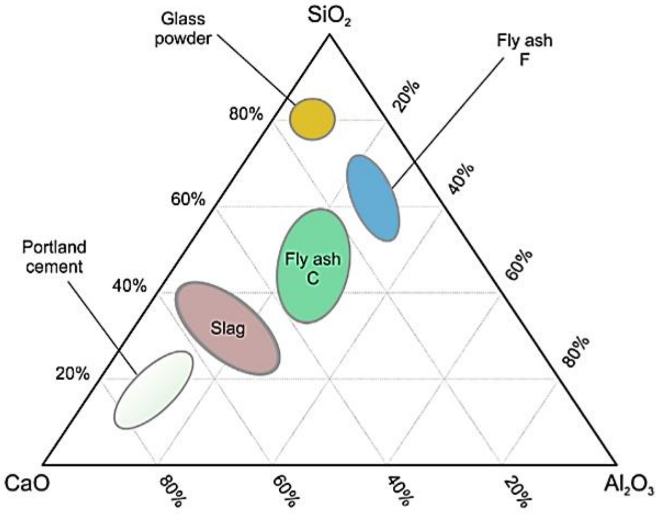


Fig.2.4 CaO-AL_2O_3-SiO_2 ternary diagram of glass powder, FA and GBFS, and Portland cement (adapted with permission from Elsevier) (Harrison et al., 2020)

2.4 Fresh Properties of Glass Concrete

Fresh properties like workability, air content, and aggregate sizes are very important for the recycled glass concrete (RGC) to make it a feasible constituent of the concrete. Those properties decide the mixing procedure, internal bonding, water absorption, casting ability, etc.

2.4.1 Workability

The ability of a concrete mixture to be worked is a well-known metric for assessing concrete. It has three characteristics, namely cohesion, water retention, and flow. Concrete's mobility is largely used to gauge how easily it can be worked. A typical slump test of concrete is presented in Fig. 2.5. Concrete workability can be separated into four categories based on the slump value: S1, tough concrete mixture i.e. very low workability (slump 10-40 mm), S2 medium workability (slump of 50 mm to 90 mm), S3 fluidity concrete (slump of 160 mm or less), and plastic concrete (slump greater than 160mm) (Jia et al., 2015) .

Fig. 2.5 Typical slump test of concrete (Jia et al., 2015)

The slump value of waste glass concrete is presented in Table 2-2. The first column of the table indicates the amount of natural coarse aggregate (NCA) and the second column presents the coarse aggregate percentage replaced by recycled glass. Similarly, Fine Aggregate (sand) replaced by Recycled Glass is presented as (RGFA). A group of experimental results shows that incorporating glass as a replacement for fine aggregate provides better workability than normal one (Bostanci, 2019, Arivalagan and Sethuraman, 2021, Elavarasan, 2016, Haramkar et al., 2018, Jia et al., 2015, Ammash et al., 2009). In contrast, some researchers claimed a relatively lower slump value than that results in the control condition i.e., using sand (Arivalagan and Sethuraman, 2021, Pratheba.S, 2018, J.Premalatha 2019, Ibrahim, 2020). This can be described by the fact that the fine glass powder absorbs a larger amount of water compared to that in the normal concrete and hence reduce the slump value. However, the variation of workability for both types of cases is negligible. Overall, it can be concluded that the application of Recycled Glass Coarse Aggregate (RGCA) yields a comparatively lower slump value (Gerges et al., 2018).

The addition of glass sand did not modify or trend the slump readings significantly. Although the slump of concrete would be lessened by the sharper edge and more angular form of crushed glass sand (Limbachiya, 2009, Du and Tan, 2014, Park et al., 2004, Taha and Nounu, 2009). The cement paste's workability was slightly affected by the RWG composition since the glass particles wouldn't absorb water from it. Researchers followed the European standard EN 12350-2 is followed in conducting the consistency test. Fig. 2.6 (a) shows the slump values of concrete containing different percentage (%) of recycled glass for different concrete grades. The result indicated that with the increase of glass content in C30 concrete, the slump value initially decreased (up to 50%) and increased for further addition of glass. The behavior is opposite for C45 and C60 concrete. In Fig. 2.6 (b) first three mixtures are showing values that are in the acceptable boundaries (8-12cm). The exception is the result from mixture 4 which may happen due to the presence of the super-plasticizers (Grujoska et al., 2020). The results are showing that the slump is decreasing with the increase of the glass in the mixture. This phenomenon can be described by the fact that the glass particles are absorbing comparatively lesser amounts of water than natural aggregate particles(Grujoska et al., 2020).

Table 2-2. Slump values of concrete containing glass concrete

Coarse Aggregate		Fine Aggregate		Slump	Ref.
NCA (%)	RGCA (%)	NFA (%)	RGFA (%)	(mm)	(Gerges et al., 2018)
100,67,50,33,0, 100	0,33,50,67,100,0	100,100,100, 100, 100,0	0,0,0,0,0, 100	100,100,70,70, 30,90	(Bostanci, 2019)
100	0	100,90	0,10	68,75	(Ibrahim, 2020)
100	0	100,95,90,85, 80,75, 70,65,60,55, 50	0,5,10,15,20, 25,30, 35,40,45,50	100,98,96, 95,94,92, 89,87,86,85, 85	(Elavarasan, 2016)
100	0	100,90,80,70	0,10,20,30	65,68,73,60	(J.Premalatha 2019)
100	0	100,90,80,70	0,10,20,30	52,48,60,59	(Arivalagan and Sethuraman, 2021)
100	0	100,90,80,70	0,10,20,30	35,53,65,72	(Pratheba.S, 2018)

100	0	100,90,80,70	0,10,20,30	52,38,43,48	(Haramkar et al., 2018)
100	0	100,90,80,70	0,10,20,30	35,53,65,72	(Ammash et al., 2009)
100	0	100,90,80,70	0,10,20,30	25,29,34,40	(Arivalagan and Sethuraman, 2021)
100	0	100,90,80,70	0,10,20,30	97,95,72,65	(Haramkar et al., 2018)
100	0	100,90,80,70	0,10,20,30	35,53,65,72	(Jia et al., 2015)
100	0	100,50,0	0,50,100	47.8,48.2,54.6	(Haramkar et al., 2018)

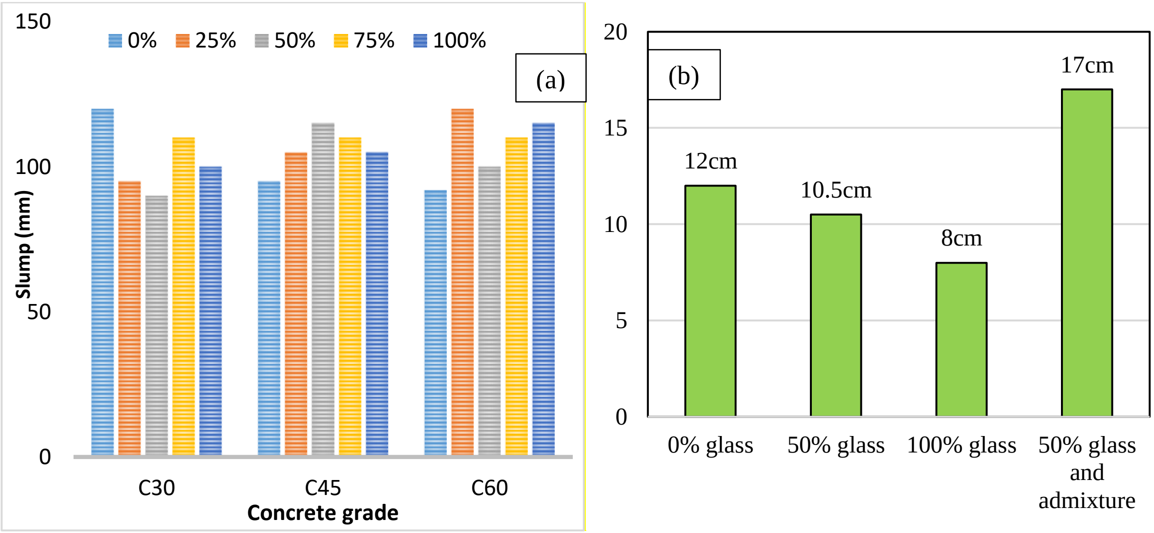


Fig. 2.6. Slump values of fresh recycled glass concrete (a) concrete grade and (b) with different mixing proportions (Du and Tan, 2014, Grujoska et al., 2020).

The concrete flow test is another measure of workability that usually determines the possibility of a rise in the mortar base perimeter following 15 drops on a flow table. As can be seen from Fig. 2.7, the flow ability of glass beach mortar decreased as the glass content increased. Flow rates for full-bodied brown, green, transparent, and mixed-color glass beach mortar, were independently 75%, 90%, 60%, and 82%, respectively of those for typical beach mortar (Tan and Du, 2013). This phenomenon of RGC can be correlated to the slump value where it is observed that the presence of glass powder reduces the slum value and hence flow of concrete also decreases.

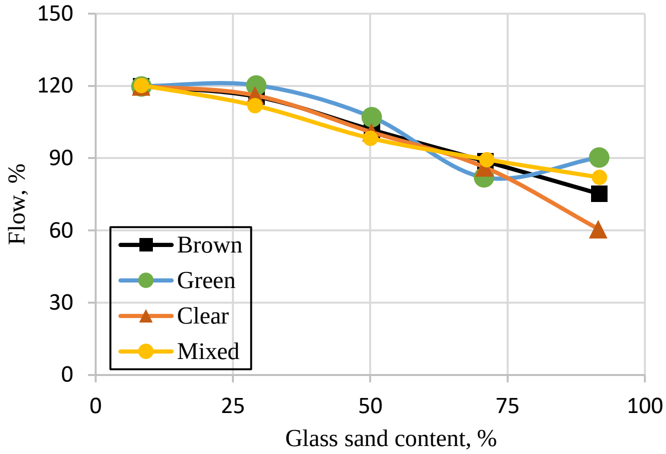


Fig.2.7 Flow of cement mortar containing different proportions and types of glasses (Tan and Du, 2013).

2.4.2 Air Content

The percentage of glass sand in concrete influences the air content. It is observed from Fig. 2.8(a) that the air contents vary in a range of 0.75% - 1.5% for all concrete grades. With a glass content of 25%, the air content is observed to be reduced, though the value increases linearly with higher glass contents (Du and Tan, 2014). The behavior is very much closed to that observed by Park et al. (Park et al., 2004) where they claimed that the air content of glass sand concrete rises as high as 41% for the glass content of 70%. In contrast, the air content of the glass sand mortar is nearly constant (air content of 3%) up to a glass content of 75% for different glasses as presented in Fig. 2.8(b) though the value rises sharply for the glass content of 100% (complete replacement of fine content), particularly of the green and clear glass. The higher air content was observed for very high glass content because the irregular and sharper edges of glass particle cause voids inside the mix which allows more air retention at the glass particles' surface (Tan and Du, 2013).

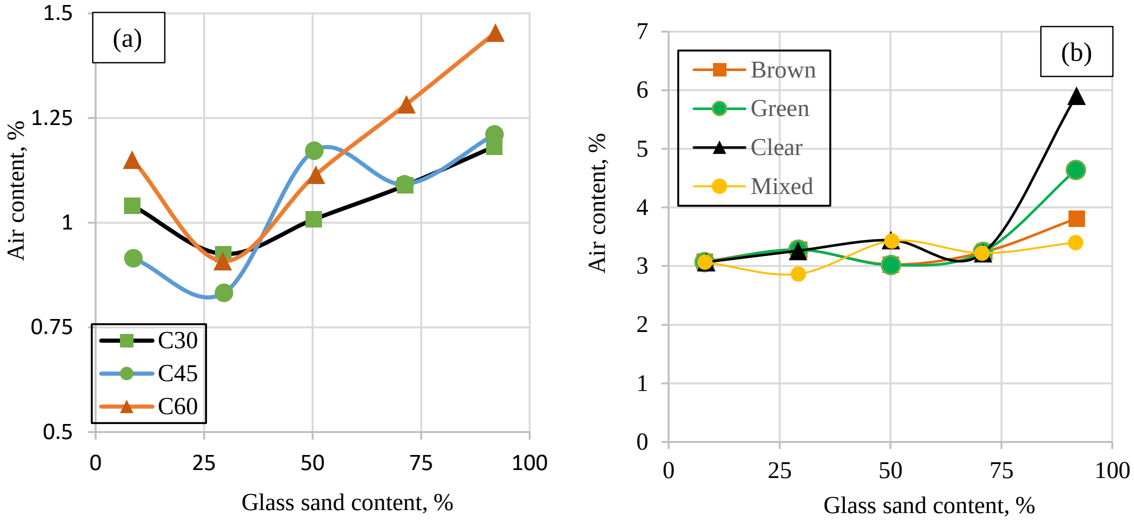


Fig. 2.8 Air content with glass sand content for different (a) concrete grades and (b) colors of glasses.

2.5 Hardened Properties of Concrete

2.5.1. Compressive Strength

Compressive strength is the major concern of concrete since its structural applications directly depend on the compressive strength properties of concrete. Numerous 28 days compressive strength test data were collected from various peer-reviewed publications as shown in Table 2-3. Here, recycled waste (RG) is used as a replacement for Cement, Fine aggregate, and Coarse aggregate. Using RG as a replacement of natural coarse aggregate (NCA) is termed as recycled glass concrete aggregate (RGCA) results in a lower strength compared to that obtained from normal fresh concrete. Usually, RGCA replacement up to 30% yields a significant change of strength which is about 8-12% (Nwofor and Ukpaka, 2017, Gerges et al., 2018, Sopov et al., 2020). Srivastava et al (2014) revealed that RGCA compressive strength was increased with the increasing addition of coarse aggregate up to replacement of 20%. However, their claim was found only for a lower percentage of NCA replacement by glass.

Many researchers used recycled glass's finest version as a replacement for cement. Up to 10% cement replacement yields a reasonable improvement in concrete inters of strength parameters in a range of 6 to 25% (Abbas et al., 2021, Ling and Poon, 2011) . The increase of strength happens because the relatively higher fineness of glass powder fills the gaps among other constituents of concrete at nanoscale that ultimately improves the compressive strength of concrete. On the opposite hand, different types of w/c ratios and various % of glass powder showed a rapid change in compressive strength (Salih and Alrubaie, 2018).

Many researchers showed much interests in employing RG as a replacement for the fine aggregate (RGFA) of concrete. Most of them revealed that using 20-30% RG as a replacement for fine aggregate (mainly sand) in concrete yields a significant improvement in compressive strength (Jeba Samuel, 2018, Arivalagan and Sethuraman, 2021, Elavarasan, 2016, Pratheba.S, 2018, Rjoub and Tamimi, 2019, Alducin-Ochoa et al., 2021, J.Premalatha 2019, Ibrahim, 2020, Gautam et al., 2012). In addition, they also claimed that there is no significant reduction in compressive strength due to the presence of RGA as a fine content of concrete. However, if the replacement level exceeds 30%, the strength properties may decline as observed in many research works. This phenomenon may be described by the fact that at a relatively lower percentage fine glass may fill the gap among the aggregate and increase the overall compressive strength. On the other hand, higher glass content in concrete yields smaller bonding between the fine content because of the smoother surface of the fine glass, and hence lower compressive strength can be obtained.

Table 2-3: Influence of recycled glass on Compressive Strength of glass concrete

W/C ratio	RGCA (%)	RGFA (%)	Compressive Strength (MPa)	Ref.
0.55	0,33,50,67,100,0	0,0,0,0,0,100	25.2,22.7,18.9,18.3,10.8,20.9	(Gerges et al., 2018)
-		0,10,25	32,36.8,37.9	(Alducin-Ochoa et al., 2021)
0.53,0.52,0.50, 0.48,0.50,0.54,0.56	-	0,5,10,15,20, 25, 30 (Wt. of Cement)	37.80,31.30,32.55,33.35,32.10,29.70,28.40	(Salih and Alrubaie, 2018)
0.45,0.45,0.64,0.64	-	0,10,0,10	48,42,36,35	(Bostanci, 2019)
0.50		0,5,10,15,20, 30,40	27,29,31,27.5,20,16,14	(Aper ZAVA, 2020)
0.50		0,10,20,30, 40,50	30.33,31.33,31,29.66, 29.33,24.33	(Gautam et al., 2012)

0.50	-	0,5,10,15,20,25,30,35,40,45,50	34.2,36.5,37.2,37.7,38.12,38.87,34.06,32.72,32.53,31.12,28.09	(Ibrahim, 2020)
0.50	-	0,100	51.2,34.7	(Czapik et al., 2021)
0.41	-	0,25	40,46	(Rjoub and Tamimi, 2019)
0.50	-	0,10,20,30	30.33,31.33,31,29.66	(Elavarasan, 2016)
		0,10,20,30	26,27.10,27.50,28.80	(J.Premalatha 2019)
		0,10,20,30	25,36.80,25.80,24	(Pratheba.S, 2018)
0.50	0,0,30,30	0,30,30,0	30,27,30,43	(Sopov et al., 2020)
0.50	0,10,20,30,40,50		29.67,31,29.67,25.33,27.33	(Srivastava et al., 2014)
0.45	-	0,10,20,30	27.3,29.2,30.2,29.8	(Jeba Samuel, 2018)
0.40	-	0,5,10,15	22.5,23.2,22.3,21.38	(Lokesh et al., 2017)
0.45	-	0,10,20,30	23.57,26.88,27.11,22.76	(Arivalagan, 2021)
0.30	0,25,50,75,100		36.91,40.64,43.49,44.35,43.10	(Jabal et al., 2021)
0.45-0.5	-	0,10,15 (Wt. of Cement)	43,54,52	(Ubeid et al., 2020)
0.55-0.6	-	0,10,20,30	29.68,33.03,27.14,25.11	(Haramkar et al., 2018)
0.45	-	0,10,15	21.45,19.22,19.1	(Mishra et al., 2020)
0.50	-	0,20,40,60	33.45,32.49,30.9,30.71	(Nwofor and Ukpaka, 2017)
0.50	0,20,40,60		33.45,34.46,31.93,26.74	(Nwofor and Ukpaka, 2017)
	-	0,2.5,5,7.5, 10 (Wt. of Cement)	36.8,39.5,41.5,40.8,39.2	(Abbas et al., 2021)

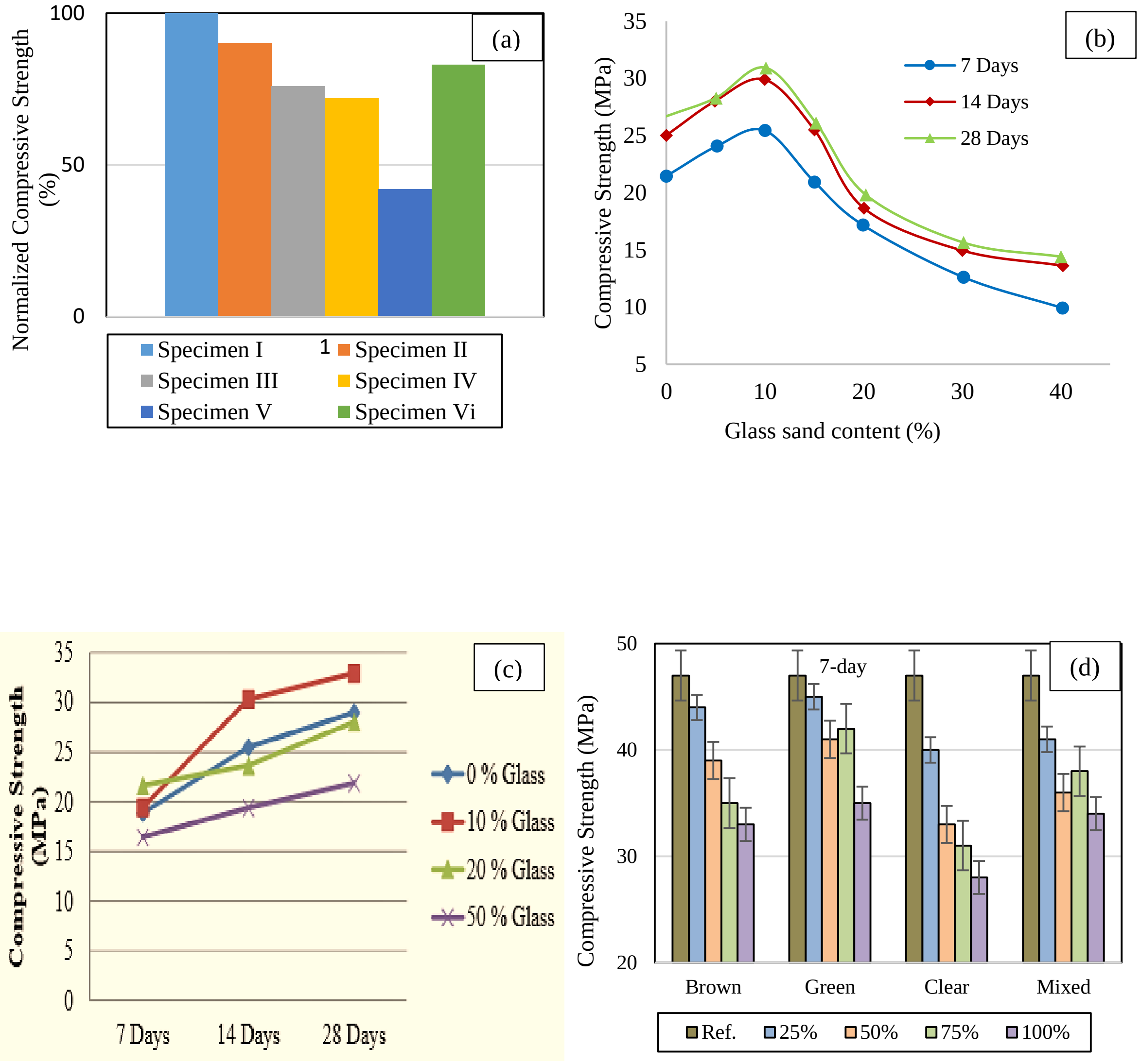
	0,10,30,50,100	46.19,39.95,31.17,14.16,4.23	(Drzymała et al., 2020)
	0,50,100	47.8,48.2,54.6	(Wang et al., 2014)

Based on previous research, the compressive strength of RGC specimens is presented in Fig. 2.9 and 2.10 where the waste glass was employed as a replacement for fine aggregate and cement, respectively. In Fig .2.9 (a) Samples ID I-V were prepared based on the RG replacement of coarse aggregate with different proportions of 0%,33%,50%,67%, and 100%, respectively, and specimen VI was fine glass sand. It is observed that there is a clear decline of compressive strength (10%-58%) with the increase of RGCA percentage (33%-100%). Replacing 100% glass as a fine aggregate in specimen VI reduced the compressive strength by 17% .

Previously, it was evident that 10% RGFA provides improved strength than the normal concrete which was 19- 25% approximately as shown in Fig.2.9 (b) and (c). Besides, after using 30% of RGFA compressive strength began to decline which is similarly evident in the references However, there are pieces of evidence where it is also found that with the rise in the proportion of glass particles, there is a decline in compressive strength regardless of the color of the glass at 7 days ages of hardened concrete as presented in Fig. 2.10 (d). In addition, WG levels of 15, 30, and 60% reduced concrete's 28 days compressive strength by 2%, 8%, and 13%, respectively, compared to the control concrete as shown in Fig. 2.9 (e).

It can be observed from the Fig. 2.9 (f) that as the WG particle size is decreasing, the strength properties are increasing. This may happen due to the fact the finer glass particles can travel finest pores of the aggregates and hence make the concrete more compact. The time dependent strength increment is quite significant for fine glass powder. The outcome of this research was further proved by where they claimed that with the addition of glass powder, an excellent pozzolanic effect is always seen, with a 180-day compressive strength that is at least 80% higher than the associated 28-day compressive strength. This may happen because the increased amount of CaO in this combination (high glass content) continues the reactions for a longer period which ultimately increases the strength at 180 days.

Quite a few researchers have used waste glass as a replacement for cement in concrete. Glass contains almost 72% SiO2 and is near about 12% CaO. For CaO and SiO2 content, glass has adhered binding properties compared to that present in the sand only. The compressive strength at different mixing ratios is presented in Figure 2.10 (a-f) (Limbachiya, 2009, Bentchikou et al., 2017, Hasani et al., 2022, Du and Tan, 2014, Ling et al., 2011, Aper ZAVA, 2020, Herki et al., 2017, Ling and Poon, 2011, J.Premalatha 2019, Gerges et al., 2018, Corinaldesi et al., 2016, Tan and Du, 2013, Rahim et al., 2014) . The results acknowledged that the compressive strength increased proportionally with the curing process because the hydration process was still continuous until getting the full strength of concrete. However, in the case of employing a mixture of waste glass as a partial replacement of cement, seemed to be a reduction in compressive strength as shown in Fig. 2.10 (a-c,d).



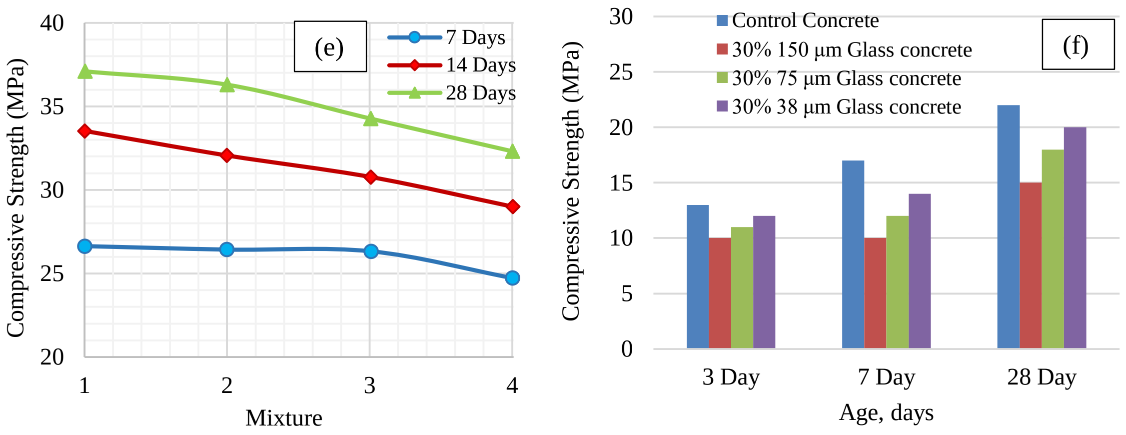


Fig. 2.9 Influence of Glass as a replacement of sand on the Compressive Strength of RGC for different (a,e) mixtures (b, c) ages (d) colors (f) glass powder sizes

Fig. 2.10 (a) shows a 50-60% reduction of mortar strength for 11-15% glass mixed mortar. Fig. 2.10 (b) and (c) revealed that the reduction of mortar strength is nearly 20-30% for the replacement of 20% glass regardless of the glass colors. In comparison to other concrete, 30% RG concrete demonstrated a lesser strength gain. It is also evident that the strength can be improved with the addition of fly ash. This rationale can be explained as the reduction in lime after the reaction that played a serious role in the production of calcium silicate hydration which is liable for the strengthening of concrete. Also, the presence of impurities in each of the crashed waste glasses affected the strength properties of the concrete. However, there is evidence that the incorporation of WG as a replacement for cement can improve the mortar strength, particularly at the 20% replacement as shown in Fig. 2.10 (d). Another research outcome presented in Fig. 2.10 (e) and (f) claimed that the 20% replacement with a ratio 0.26% W/C ratio shows the maximum compressive strength for both 56 and 112 days including a variation with it different types of w/c ratios at 56 days and 112 days in Fig. 2.10 (e, f). Here, compressive strength is rising as compared to normal concrete for up to 20% glass powder before beginning to decline.

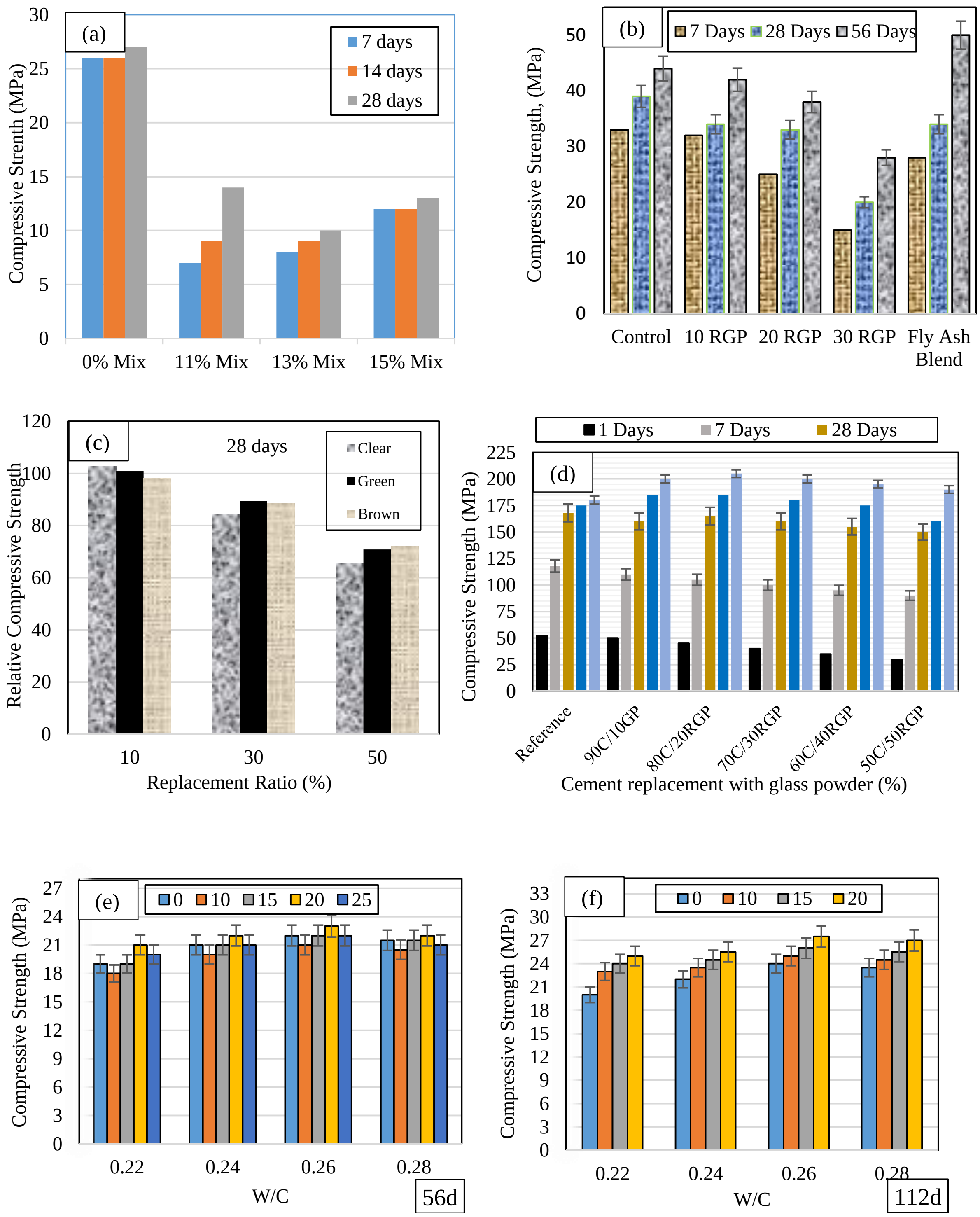


Fig. 2.10. Influence of varying waste glass proportions on the Compressive Strength of cement mortar for different (a, b, d) ages (c) glass color (e, f) W/C ratio (khalil et al., 2018, Schwarz et al., 2008, Wilson et al., 2019, Özkan and Yüksel, 2008, Al-Zubaidi et al., 2017, Li et al., 2021, Tamanna and Tuladhar, 2020)

2.5.2 Splitting Tensile Strength

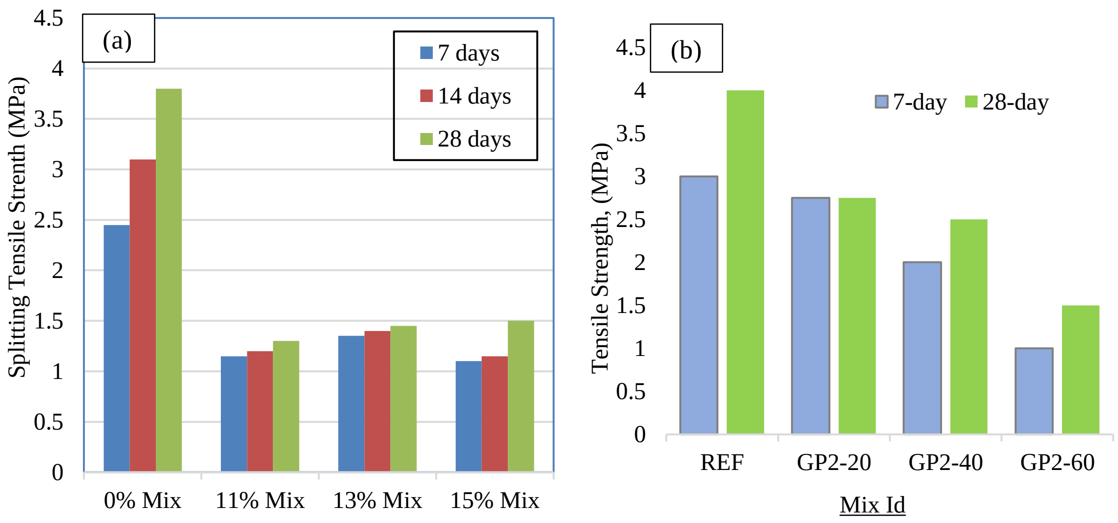
Quite a few studies have been conducted on the split tensile tests to determine the tensile properties of concrete made from recycled glass concrete (RGC) as presented in Table 2-5. The table presents the split tensile strength of RGC where RG was used either as the replacement of fine content of the coarse aggregate. Here, concrete with RG as fine aggregate (RGFA) shows that the tensile strength is comparatively smaller than that of normal concrete (Arivalagan and Sethuraman, 2021, Rjoub and Tamimi, 2019, Ammash et al., 2009). In contrast, some research showed that increasing the value of tensile strength with the addition of RGFA (Elavarasan, 2016, Pratheba.S, 2018, Lokesh et al., 2017). Besides, it is also evident that the tensile strength increases with the addition of RGCA up to a certain percentage like 20-30%, for cement and the outcome revealed that the compressive strength can be increased by as and decreases with the higher RGCA (Jabal et al., 2021, Ibrahim, 2020). Recycled glass is additionally used as a replacement high as 15% of replacements than that of the control specimen. Practically, the concrete strength is very much sensitive to the size, shape, glass type, and surface roughness of the recycled glass.

Table 2-5: Split Tensile Strength of Concrete containing RG as Coarse or Fine Aggregate

W/C	RGCA%	RGFA%	Tensile Strength (MPa)	Ref.
0.5	0,5,10,15,20,25,30,35, 40,45,50		2.98,3.27,3.29,3.32,3.36,3.43,2.95,2.86,2.66,2.38,2.35	(Ibrahim, 2020)
0.41		0,25	4.1,3.9	(Rjoub and Tamimi, 2019)
0.5		0,10,20,30	2.3,2.52,3.21,3.1	(Elavarasan, 2016)
		0,10,20,30	3.45,3.40,3.46,3.04	(Arivalagan and Sethuraman, 2021)
		0,10,20,30	2.9,3.83,3.8,3.24	(Pratheba.S, 2018)
0.4		0,5,10,15	2.9,3.1,2.74,1.9	(Lokesh et al., 2017)
0.45		0,10,20,30	3.45,3.40,3.46,3.04	(Arivalagan and Sethuraman, 2021)
0.3	0,25,50,75,100		3.12,3.40,4.62,4.87,4.90	(Jabal et al., 2021)

0.45-0.5		0,10,15 (Cement)	3.9,4.8,5	(Ubeid et al., 2020)
	0,10,30,50,100		8.3,6.9,7.43,4.55,3.84	(Drzymała et al., 2020)
0.5		0,10,20,30,40	3.75,3.6,3.55,3.48,1.9	(Ammash et al., 2009)

The tensile strength of RGC composed from different publications suggested that primarily, the split tensile strength decreases with the increase of RGFA as presented in Fig. 2.11(a) and (b). This may happen because the smoother surface of glass creates relatively weaker bonding between waste glass and other constituents of concrete that directly effects adversely on the tensile strength of the RGC. However, some researchers claimed that RGFA up to a certain percentage, improves the overall tensile strength of RGC regardless of water cement ratio (W/C) and age of the concrete. The maximum value of split tensile strength is observed at 20% fine replacement by WG at W/C ratio of 0.26. Fig. 2.13 (e) shows that the tensile strength decreased after 50% WG replacement whereas it was observed that the 100% replacement yields the maximum tensile strength for all concrete grades.



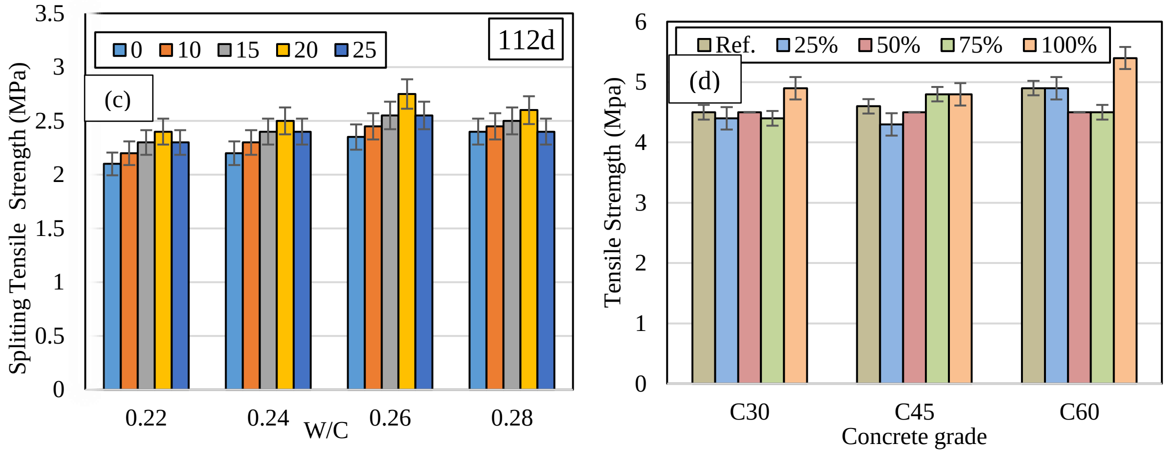


Fig. 2.11. Split tensile strength of RGC for different mixing ratios (a, b) with age (c) W/C ratio and days and (d) concrete grade (Du and Tan, 2014, J.Premalatha 2019, Kalakada and Doh, 2020, Al-Zubaidi et al., 2017, Li et al., 2021, Tan and Du, 2013, Grujoska et al., 2020)

2.5.3 Flexural Strength

Bending strength tests are necessary to understand the flexural properties of concrete. Limited but very useful flexure test data were collected from the literature as presented in Table 2-6. Very few evidences are found in the literature where RG has been used as a replacement for coarse aggregate. They claimed that the flexural strength increases as the RGCA increases in the concrete. On the other hand, RGFA up to 20% yields an improvement in flexural strength (Arivalagan and Sethuraman, 2021, Sunarsih et al., 2021). However, one more research showed that flexural strength increased up to 5% RGFA only (Lokesh et al., 2017). Some researchers used recycled glass particles as a replacement for cement and showed that up to 10% of replacement gives better strength than a normal one (Ubeid et al., 2020, Abbas et al., 2021). Another researcher substituted recycled glass for coarse aggregate, and the results revealed that flexural strength increased as the amount of recycled glass increased. (Jabal et al., 2021). This phenomenon can be described by the mechanism that for a smaller percentage of glass the weaker bonding is not dominant as the glass powder fills the fine pores of other aggregates and hence the flexural strength increases with the addition of RG.

Table 2-6: Flexural properties of glass concrete

W/C	RGCA%	RGFA%	Flexural Strength (MPa)	Ref.
0.5		0,100	8.3,5.1	(Czapik et al., 2021)
0.4		0,5,10,15	5.5,6,4.7,4.21	(Lokesh et al., 2017)
0.45		0,10,20,30	4,4.01,4.6,3.9	(Arivalagan and Sethuraman, 2021)
0.3	0,25,50,75,100		4.06,5.63,6.92,8.78, 9.21	(Jabal et al., 2021)
0.45-0.5		0,10,15 (cement)	4.41,5.18,4.83	(Ubeid et al., 2020)
		0,2.5,5,7.5,10 (cement)	4.96,5.11,5.21,5.34, 5.13	(Abbas et al., 2021)
		0,10,20,30,40	2.06,2.41,2.94,2.74, 2.45	(Sunarsih et al., 2021)

A good number of flexural strengths test data are collected and a part of them are presented in the Fig. 2.12 (a-d). Figure 14a shows that the flexural strength of concrete reduces with the increase of glass percentage though the strength can be improved with the addition of admixtures for the case of 50% glass. Another research by (Du and Tan, 2014) claimed that with the addition of RG, flexural strength improves even up to 100% regardless of concrete grade as shown in Fig. 2.12 (b). Fig. 2.12 (c) and (d) show the influence of RG% on the flexural strength for different W/C ratios and ages. As presented in the figures, the experimental investigation claimed that the maximum flexural strength of RGC is found for 25% RG as a replacement of fine content for all W/C ratios and also at both 56 days and 112 days. The result can be correlated to the compressive strength and tensile strength test data where it is also observed that at a low percentage of RG the strength improves but at a higher percentage, it usually decreases as the glass percentage increases. The reason behind the improvement at a low percentage is that the fineness of the glass powder makes more integrated concrete.

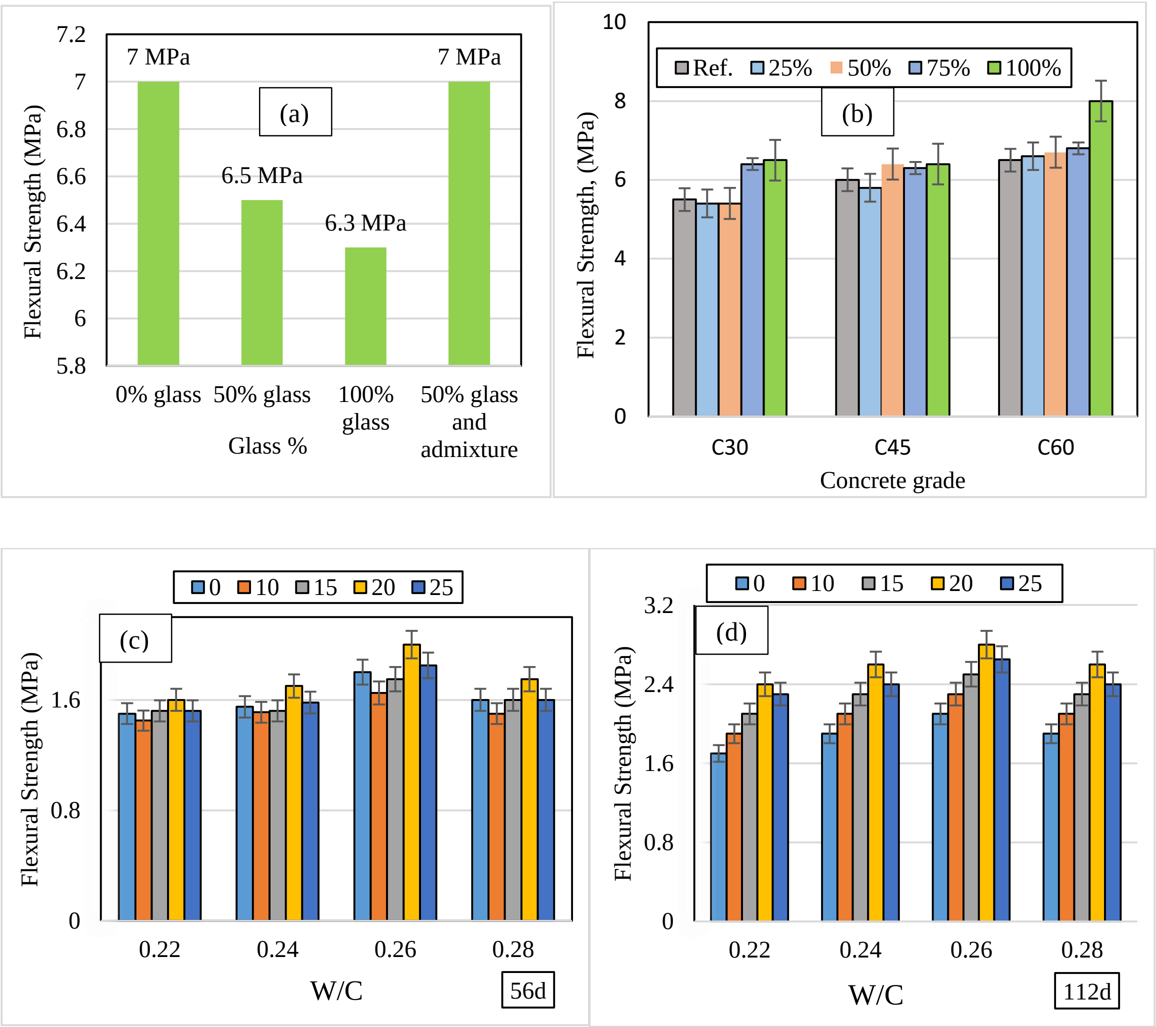


Fig. 2.12. Flexural strength of RGC with (a) varying sand replacement by RG, (b) with different concrete grades (c, d) with age and W/C ratios (Bentchikou et al., 2017, Du and Tan, 2014, Ling et al., 2011, Ling and Poon, 2011, J.Premalatha 2019, Grujoska et al., 2020)

2.6 Conductivity

The conductivity of glass concrete has been studied quite a few times by several researchers as presented in Fig. 2.13 (a-b). Previously conducted rapid chloride penetration tests (RCPT) have been highlighted in Fig. 2.13 (a, c), and here Dnnsm was a non-steady state migration coefficient. Except for the low glass content in C30 and C45 concrete as shown in Figure 16(a), the entire charge passed at 28 days for an equivalent w/c. The value was found significantly reduced by increasing the glass sand content. For C30 and C45 concrete mixtures, plain or 25% glass concrete exhibited a charge above 2000 coulombs, indicative of moderate permeability consistent with ASTM C1202. The quantity of transferred charge is decreasing as the number of days and % of glass content increase, which implies permeability decreases, as presented in Fig. 2.13 (b, d). Fig. 2.13 (c) displays further RCPT data. All of the mortar specimens had high total charge passing values, with the typical sand mortar displaying the greatest value of 6764 (± 966) Coulombs. This is due to the porous nature of cement paste and the absence of coarse particles. The charges % that were migrated through the 50% brown, green, clear, and mixed glass sand mortar compared to the conventional sand mortar was found 93%, 69%, 71%, and 64%, respectively. According to a prior research by Kou and Poon (2009), conductivity values were found comparatively lesser value, where they reported a 60% reduced charges can be migrated when 45% of the natural sand is substituted with glass sand (Kou and Poon, 2009).

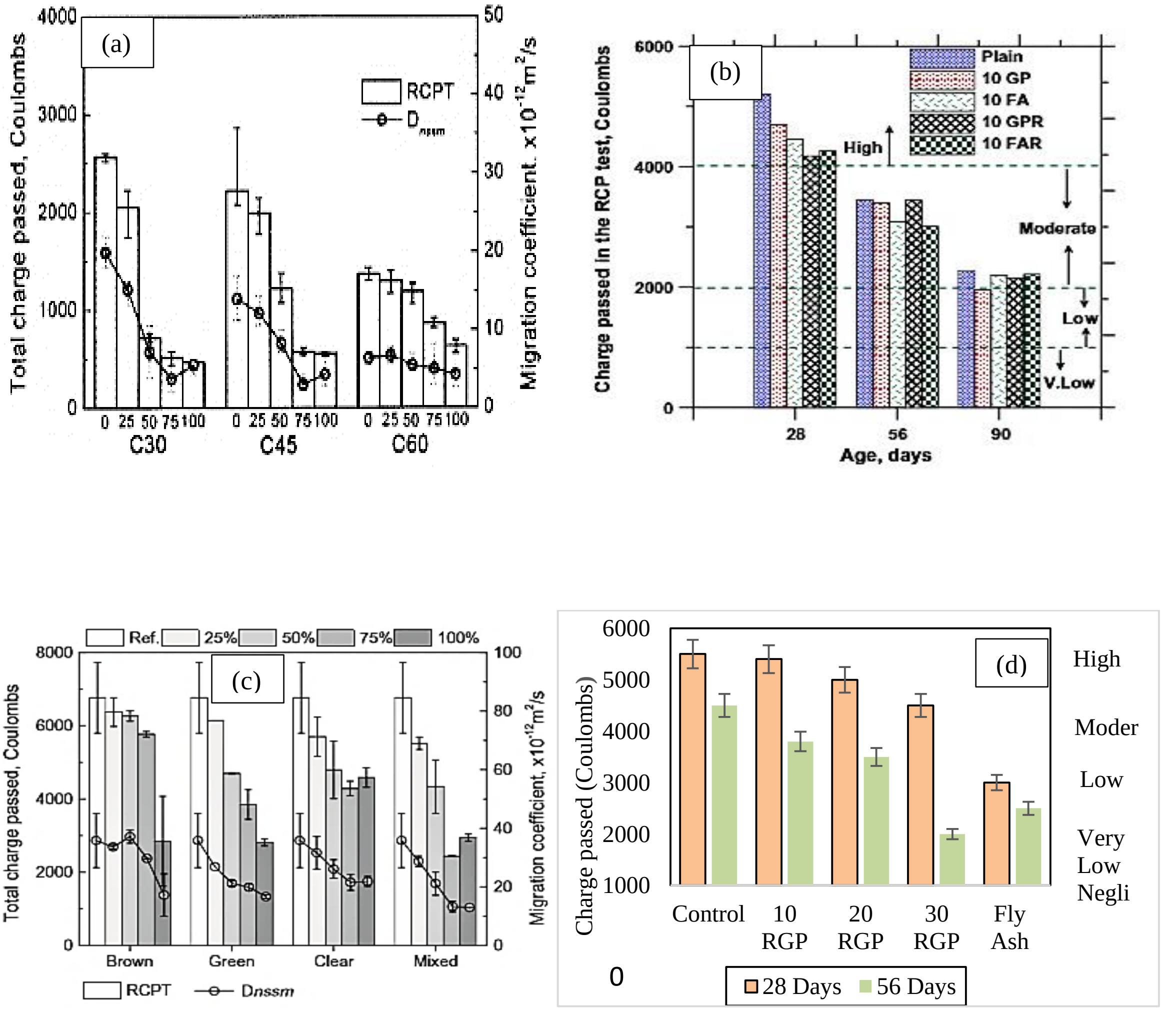
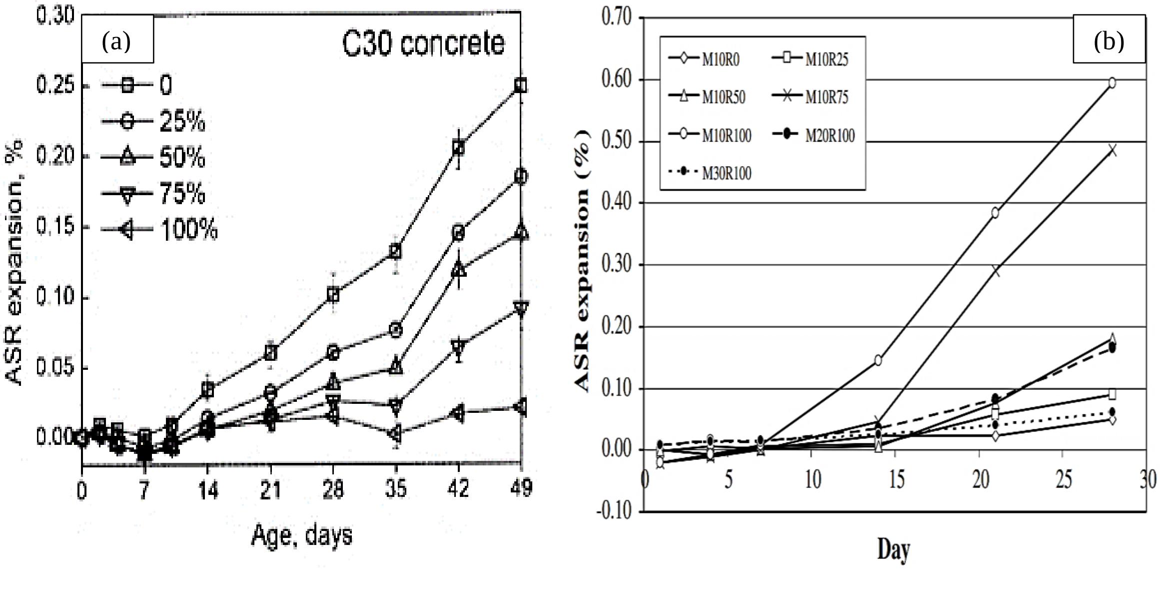


Fig. 2.13 Conductivity of glass concrete for (a) concrete grade (b) RG (c) different colors (d) different ages

2.7 ASR expansion

Alkali-Silica Reaction (ASR) expansion behavior is shown in Fig. 2.14. In fig. 2.14 (a), all concrete mixtures showed expansion but 0.1%, and 0.2% at 14 and 28 days, respectively. Here at 49 days, only the reference specimen crossed 0.2% expansion. An identical trend was also observed in Fig. 2.14 (c) (Schwarz et al., 2008). It is claimed by quite a few researchers that the presence of glass in concrete is innocuous in alkali reactivity (Limbachiya, 2009, Zhu et al., 2008, Du and Tan, 2013). Fig. 2.14 (b) also shows similar evidence as Fig. 2.14 (a) where it is evident that the ASR expansion is very much dominant after the age of 15 days. . Here, the ASR expansion grew significantly as the RG content rose from 0% to 100%. Even though 10% MK had previously been used to replace cement at the age of 14 days, all of the mortar bar mixtures had ASR expansion within the permitted limits (0.10%), except for the M10R100 mix. It is also observed that ASR expansion value of M10R100 was around 0.60%, was measured at 28 days. Here, the ASR expansion grew significantly as the RG content rose from 0% to 100% (Ling et al., 2011).

Research outcomes on the expansion of the mortar bar specimen, containing 100% WG, nearly 0.2% before 3 days have been displayed in Fig. 2.15. Expansions were just 0.2% after 4 days when the WG content was 0%. As a result, no significant alkali-silica reactions were observed when WG content decreases for this reason (Baykal, 2003).



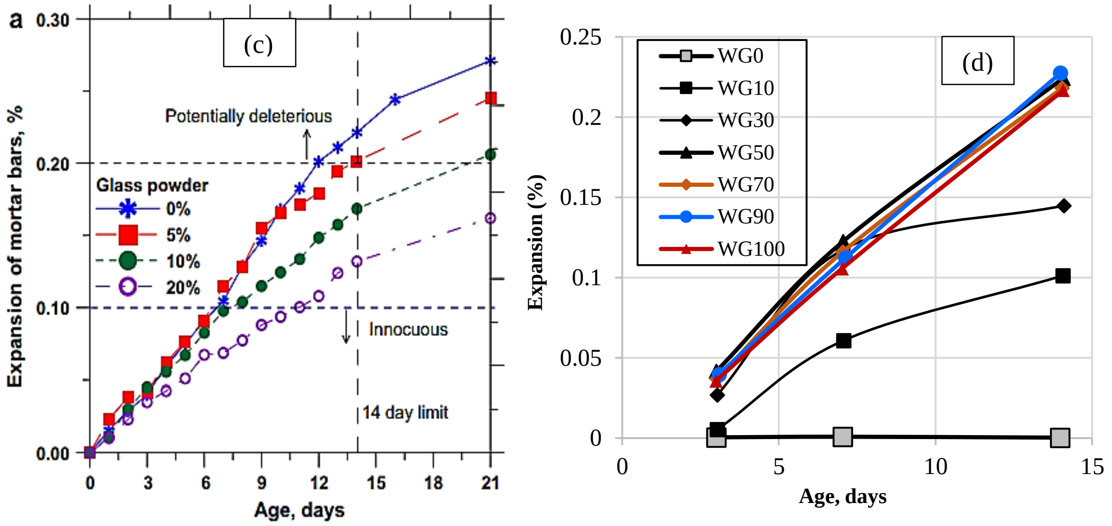


Fig.2.14 (a-d) Expansion behavior of different RGFA containing concrete with time Figure 20 (a-c) are adapted with permission from Elsevier (Du and Tan, 2014, Ling et al., 2011, Schwarz et al., 2008, Liu et al., 2015)

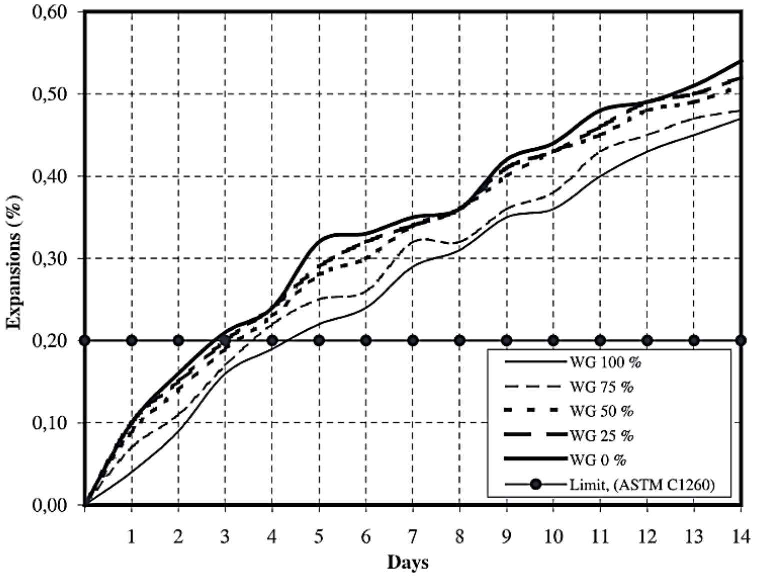


Fig. 2.15. Expansion behavior of different % of RG as a replacement of Coarse Aggregate

2.8 Density of RG concrete

Density of concrete is a very important parameter for its practical application. Fig. 2.16 (a-d) and 2.17, present the density of glass concrete mixed as a replacement of fine and coarse aggregate, respectively. Different types of grades or different types of RGFA showed a lower density compared The to that of the normal concrete as presented in Fig. 2.16 (a, b, d). The figures also show that the density of RGC decreases as the percentage of WG increases in the concrete. Moreover, the dry density of RGC is smaller than that of the fresh condition.

However, a lower particle size showed better density compared to a bigger one as suggested by (Kalakada and Doh, 2020). Since glass sand has a lower density than fresh sand due to its lower specific gravity the hardened density of RGC is also lower than that of normal concrete (Du and Tan, 2014).

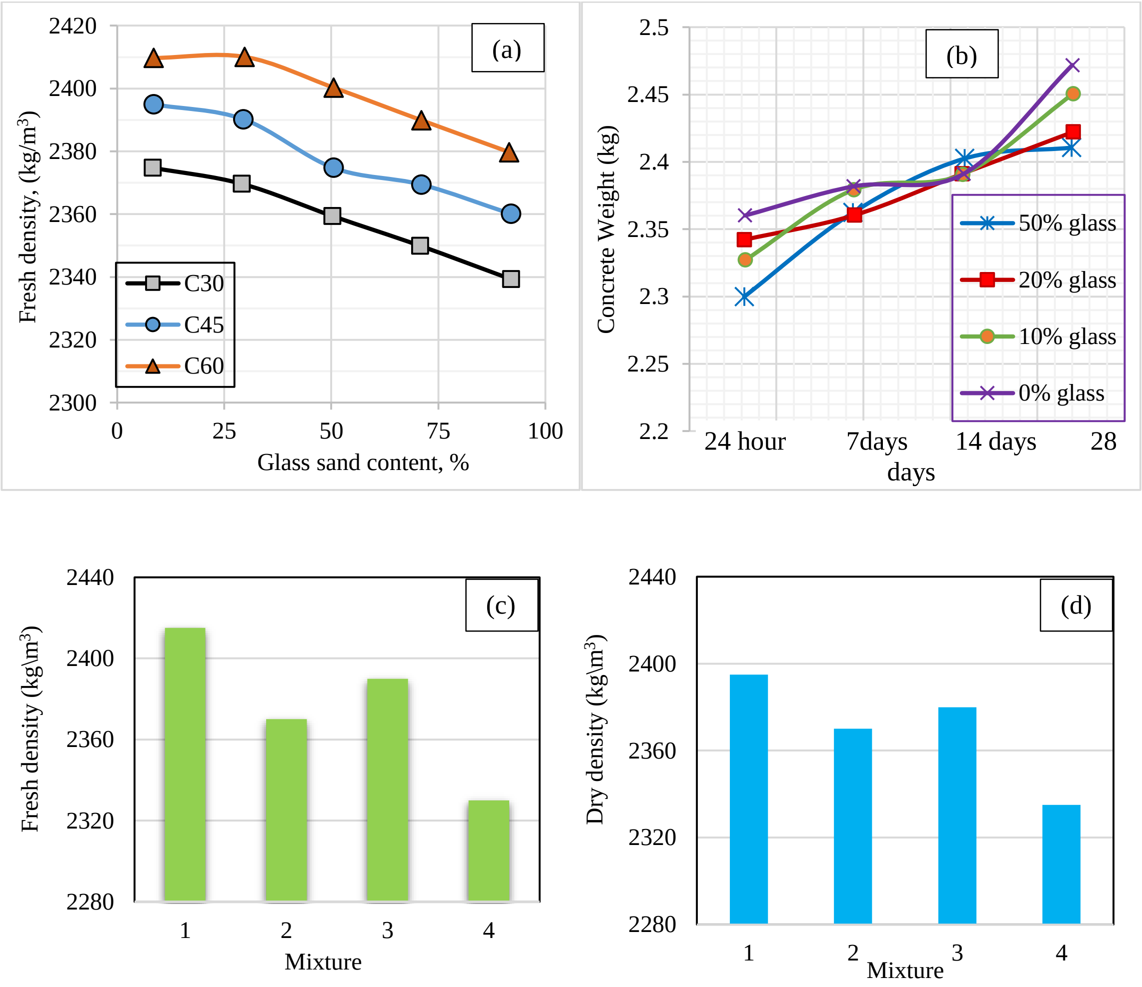


Fig. 2.16 (a-d) Fresh and hardened density of concrete with WG for (a) concrete grade (b) time and proportions (c, d) mixtures (Du and Tan, 2014, Herki et al., 2017, Kalakada and Doh, 2020, Tan and Du, 2013, Rahim et al., 2014)

Fig. 2.17 demonstrated the densities of concrete made from gravel and RGCA. The cubic samples of glass concrete exhibited approaching gravel concrete after 28 days due to their sparkling look and smoothness. Except for 20% glass replacement, all of the samples of concrete displayed denser specimens, which may be attributed to the proper placement of glass as an aggregate in the cement-sand combination (Fahad and Ali, 2020).

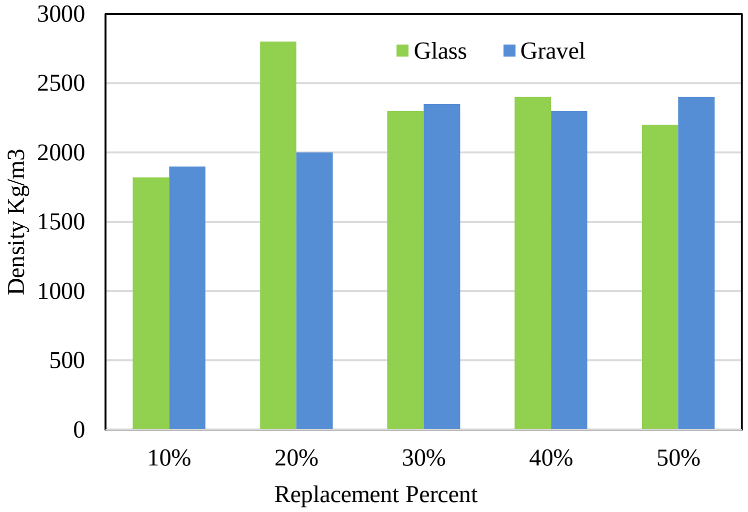


Fig. 2.17: Density of Concrete containing RG as replacement of CA

2.9 Properties of Recycled Brick Aggregate (RBA)

Several studies are available where normal brick aggregate (as coarse and fine) properties were examined and even compared with stone chips/aggregates. However, research on recycled brick aggregates is still limited. One of the major issues with recycled brick aggregates is the high water absorption capacity. Adhered old mortar paste in recycled aggregates tend to absorb water from the concrete mix and leaves less water for binder reaction (Gerges et al., 2018). This high water absorption together with the irregular shape of recycled aggregates may cause lower slump/workability of fresh concrete (Tittarelli et al., 2018). It is also worth mentioning that most old mortar paste structure are porous, i.e., the presence of lots of micro voids, which is also a reason for the high water absorption of this type of aggregates (Tan and Du, 2013).

However, a contradiction in the mechanical properties of concrete with brick aggregate is reported by several authors. Bangwar et al. found about 10% lower compressive strength of concrete at 28 days of testing when 50% of the coarse aggregates was replaced by brick aggregate. Similarly, Debieb & Kenai reported about a 5 to 10% lower strength for 25% fine brick aggregate replacement. Authors have found a maximum 30% strength reduction for full fine aggregate replacement. Conversely, Another research showed that the utilization of fine crushed brick aggregate in concrete up to 25% with natural sand showed the same 90-day strength as the control mix without any brick aggregate (Agwa et al., 2020). It was further proved by Mohammed et al. that brick aggregates do improve the mechanical properties of concrete. The compressive strength and Young's modulus of concrete made with brick aggregate were found to be higher than the concrete made with stone aggregate. The authors also concluded that recycled brick aggregates show better performance than the normal brick aggregates though the abrasion and absorption capacity of recycled brick is higher. Although the durability of brick aggregate concrete is not covered in this study, however, some previous studies mentioned that the durability of concrete may be susceptible to brick aggregates.

2.10 Summary

A good number of researches have already been conducted on the waste glass as an aggregate of concrete. However, there are some key issues that are need to be addressed before its practical application.The fresh and hardened properties of concrete with the combination effect of recycled brick aggregate and RG were not analyzed before. Non-destructive test like Ultrasonic Pulse velocity in such concrete was not evaluated previously.The application of RBA-GC in structural elements such as beams was not analyzed previously.Based on the comprehensive exploration of the existing literature, the key points can be summarized as follows

a. Using RG in concrete as a cement or coarse aggregate provides comparatively better workability than the normal one. Though the workability of concrete containing RG as fine replacement decreases with the increasing percentage of RG, it improves workability up to a certain percentage. Overall, the performance depends on the shape, size, and type of RG used in concrete.
b. Incorporating RG up to 20-30% in concrete as a fine aggregate gives a positive value of compressive strength compared to a normal one. However, it shows decreasing trends when it is used as a replacement for cement or coarse aggregate. The strength properties of RG mixed concrete vary with the different types of glass, particle sizes, and shapes.
c. Due to lower specific gravity, RGFA showed lower density compared to sand in concrete though the finer particle size of RGFA contributes to a better density and hence relatively lighter concrete. The case of RGCA showed a relatively denser specimen which is close to the normal one.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter includes the overall methods and techniques used for conducting the experimental investigations. Firstly, the physical properties of the waste glass, recycled brick aggregate and other natural aggregates are determined through the ASTM standards. The methods involved in the specimen preparations for physical properties are also highlighted. Test plans and procedures for the mechanical properties of aggregate, mixture proportions, including test matrix, fresh properties of concrete, casting, curing and notation process are presented in this chapter. Specimen preparation and test methods for compressive strength, split tensile strength and flexural properties of recycled brick aggregate concrete with recycled waste glass are also discussed. In addition, test procedure and protocol for scanning electron microscopy (SEM) has also been conducted. Finally, test setup, data acquisition technique and specimen preparation for the four-point bending test of reinforced concrete beam specimens are also demonstrated in this chapter.

3.2 Collection Procedure and Physical Properties test of Core Materials

An experimental program has been designed following the research objectives and scope of work. Before going to determine the mechanical properties, physical aspects of aggregate are required to be identified, especially for conducting a proper mix design. In this part, a series of basic tests for aggregated such as Specific Gravity (S.G.), Fineness Modulus (F.M.), unit weight, etc. test are demonstrated to understand the physical properties of aggregates. In this research work brick aggregate and waste glass are core materials which are shown in Fig.3.1 Coarse aggregate (CA) is partially replaced by the recycled brick aggregate generated from the demolished concrete of a 30-year-old first-generation building as shown in Fig. 3.1 (a). After eliminating the debris, recycled CA was obtained through the process of screening, sifting, and washing of the demolished concrete. Normal brick coarse aggregate (NBCA) is obtained from the locally available fresh 1st class brick crushed through the manual process. Both recycled CA aggregates and normal brick aggregate (NBA) were sieved to make them 4.75 to 19mm downgrade following ASTM C136-14. The table shows the physical properties of aggregate like sand, brick, recycled brick, and glass.

In this investigation, waste glass is used as a partial replacement for fine aggregate. The locally available well-graded natural sand with a maximum grain size of 4.75 mm satisfies the need for natural fine aggregate. Sand is graded and its sieve analysis is carried out in accordance with ASTM C136-14. Waste glass powder (WGP) was collected from the old town where wastes are processed on demand. Basically, here waste glass is extracted from tube glass and then processed into powder form to make sure it fit to be used as the fine aggregate as shown in Fig. 3.1. In this study, waste glass is used in powder form as a partial replacement of sand. Fig.3.2 represents the particle distribution curve of sand and waste glass powder (WGP) which is within the recommended standard of ASTM C33.

Fig. 3.1: Core materials of this research (Recycled Brick and Waste Glass)

Table 3-1: Physical properties of aggregate

Variables	NBCA	RBCA	Sand	RG
Specific Gravity	2.1	2.1	2.59	2.46
Absorption Capacity (%)	19.21	18.23	4	3.8
Fineness Modulus (F.M.)	6.6	6.6	2.6	2.56
Unit Weight (kg/m^3)	1305.02	1310.54	1646.44	1521

Several trials were made to get the particle distribution according to ASTM standard. In this research recycled glass is used as a replacement for sand. there, the particle distribution curve of glass should be within the limit and quite similar to sand. Fig. 3.2 shows the particle distribution curve of recycled glass and sand which is within the limit of ASTM standards.

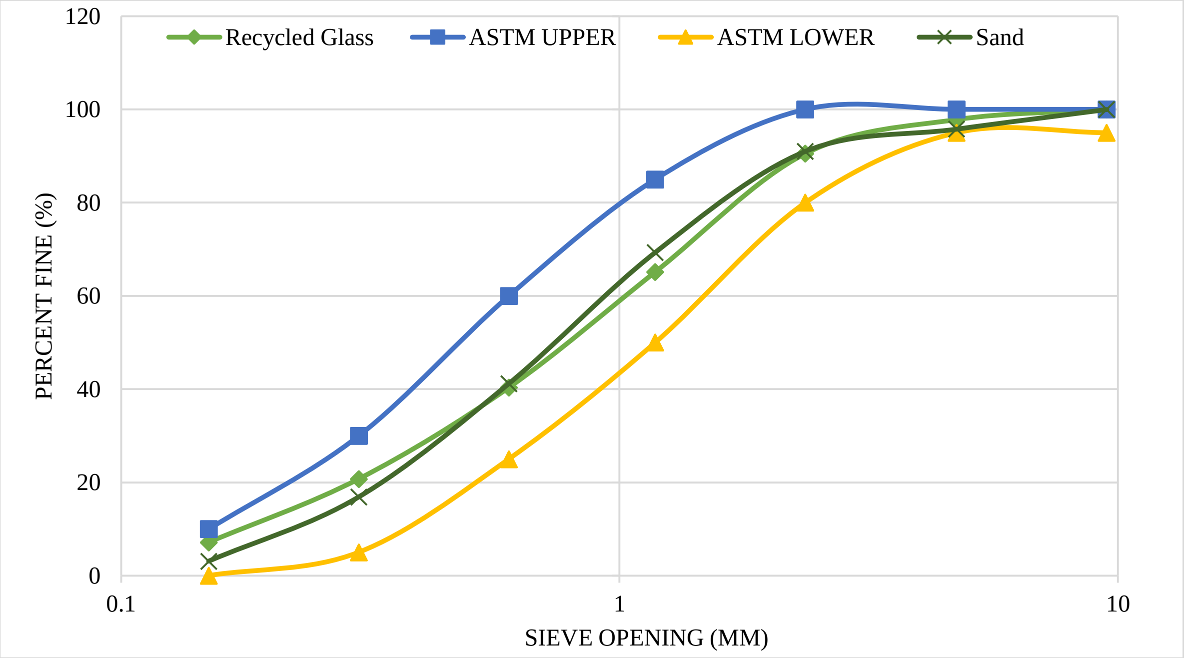


Fig 3.2: Particle Size Distribution Curve of WG and Natural Sand

3.3 Mixture proportions

Two types of specimen are planned for determining the compressive strength properties of recycled brick aggregate based concrete with glass. At first, fifteen different concrete mixes are prepared for cylindrical specimen to support comparative analysis. Then based on this result another twelve batches of prism beam (100mm×100mm×500mm) has been cast. A total of twelve batches mixture were prepared for determining the flexural strength of the prism beam. A target compressive strength of 25–30 MPa (i.e., 28 days concrete strength) is commonly used in designing reinforced brick concrete structures in Bangladesh depending on the category of construction. For this reason, the designed compressive strength was proposed to be 25 MPa to provide more realistic and comparable evidence to the concrete industry. The total Portland cement content and the effective water-cement ratio were kept constant at 340 kg/m^3 and 0.48, respectively. As a result, the variations are in the percentage of natural coarse aggregate, RCA, sand, WG, and cement. The coarse and fine aggregates used in the concrete are in saturated surface dry (SSD) condition.

The percentage of RCA replacement is 10% and 30% which are replaced on a weight basis. In the previous study, it was shown that RCA replacement up to 30% had no large effect on concrete strength, but thereafter there was a gradual reduction in strength as the RCA content increased [4,8,9,36]. Some researchers have mentioned not to exceed 30% replacement level to maintain standard requirements for 5% absorption capacity of aggregates [49]. This is why the RCA replacement level is considered as 10% and 30%. Fine aggregate is replaced from 10 to 100% by waste glass (WG). Fourteen batch details are shown in Table 3-3. For example, RC30G20 means here recycled brick aggregate has replaced about 20% of total coarse aggregate and fine aggregate has replaced about 20% by waste glass. From batch no.4 to 15 amount of recycled concrete (RC) has been kept constant and the amount of glass has been changed to see the proper effect of waste glass powder on concrete.

Table 3-2: Description of specimen identification

Batch identification name: RC_xG_y	Description
RC	Recycled Concrete
x	Amount of Recycled concrete (Coarse %)
G	Glass
y	Amount of waste glass (Fine %)

Table 3-3: The proportions of aggregates for concrete mixture per cubic meter (Cylindrical)

Batch no.	Batch code	NCA (kg)	RCA(kg)	Sand(kg)	WG(kg)
1	RC_0G_0	860	0	690	0
2	$RC_{10}G_0$	774	86	690	0
3	$RC_{20}G_0$	688	172	690	0
4	$RC_{30}G_0$	602	258	690	0
5	$RC_{30}G_{10}$	602	258	621	69
6	$RC_{30}G_{20}$	602	258	552	138
7	$RC_{30}G_{25}$	602	258	517.5	172.5
8	$RC_{30}G_{30}$	602	258	483	207
9	$RC_{30}G_{40}$	602	258	414	276
10	$RC_{30}G_{50}$	602	258	345	345
11	$RC_{30}G_{60}$	602	258	276	414
12	$RC_{30}G_{70}$	602	258	207	483
13	$RC_{30}G_{80}$	602	258	138	552
14	$RC_{30}G_{90}$	602	258	69	621
15	$RC_{30}G_{100}$	602	258	0	690

Table 3-4: The proportions of aggregates for concrete mixture per cubic meter (beam)

Batch no.	Batch code	NCA (kg)	RCA(kg)	Sand(kg)	WG(kg)
1	$RC_{30}G_0$	602	258	690	0
2	$RC_{30}G_{10}$	602	258	621	69
3	$RC_{30}G_{20}$	602	258	552	138
4	$RC_{30}G_{25}$	602	258	517.5	172.5
5	$RC_{30}G_{30}$	602	258	483	207
6	$RC_{30}G_{40}$	602	258	414	276
7	$RC_{30}G_{50}$	602	258	345	345
8	$RC_{30}G_{60}$	602	258	276	414
9	$RC_{30}G_{70}$	602	258	207	483
10	$RC_{30}G_{80}$	602	258	138	552
11	$RC_{30}G_{90}$	602	258	69	621
12	$RC_{30}G_{100}$	602	258	0	690

Table 3-5: Test matrix

Specimen	Size (mm)	No.of batch	For Com. Strength (7,28,56 days)	For tensile and UPV (28 days)	For Flexure (28,56 days) 3 point	For Flexure 28 days 4 point	Total no. of sample
Cylinder	100×200	15	135	45	-	-	180
Prism beam	100×100×500	12	-	-	48	-	48
Beam	100×150×1100	12	-	-	-	24	24

3.4 Workability test of concrete

The slump test is used to understand the workability of fresh concrete. Generally, higher slump indicates higher workability of concrete. Test procedure followed according to ASTM C143 standard. It is necessary to know the behavior of RBA based glass concrete in terms of workability. Besides, air content test indicates the amount of air in the concrete mix at the time of casting. Amount of air content which indicates the amount of void due to air. ASTM C231 is followed for this test. Fig. 3.3 shows the experimental test of the slump test of concrete mix and air content test.

Fig.3.3 (a) Slump test of Concrete mix (b) Air Content test of Concrete mix

3.5 Casting and Notation

Casting is an important step of experimental research. Without proper casting and curing result of the research will not be satisfactory. So, in this research, every step of casting, notation, and curing has been done sincerely and by proper standards. Fig.3.4 shows the aggregates before mixing, doing proper vibration for reducing void, and finally doing casting and giving name of every specimen with date. According to this research plan, 180 cylinders and 48 prism beam has been cast.

Fig.3.4 (a-d) Mixing, Hammering, Casting and Notation

Fig.3.5 Strain gauge installation process of reinforced concrete (RC) beam

Fig.3.6 Notation of beams and cylinder

Another part of this thesis is to determine the flexural strength of the reinforced beam. As per plan 24 beam has been cast according to proper design. Fig.3.5 shows the installation process of strain gauge in steel. After installation, it must be bound with waterproof tape. The outside portion of the wire should be in polythene to protect it from curing water and air. Fig.3.7 shows the curing process of the specimen. For cylindrical and prism beam specimens ponding curing has been chosen and for beam specimens jute shading is preferred.

Fig.3.7 Curing process of cylindrical, prism beam and reinforced beam specimen

3.6 Mechanical properties test of RCG

Generally, concrete is strong in compression and weak in tension. Compressive strength, Tensile strength, and hardened density are the major components of mechanical properties of concrete. The compressive strength test has followed the ASTM C39 standard. Besides splitting tensile strength has been done according to ASTM C496. Compression test of cylindrical specimen has been done for 7,28 and 56 days. The tension test of the cylindrical specimen has been done only for 28 days. Minimum three sample cast for each batch. In total 180 cylindrical has been prepared for testing. To know the behavior of recycled glass concrete it is necessary to do the proper test of mechanical properties.

Fig. 3.8: Compression test setup of Cylindrical specimen

3.7 Ultrasonic Pulse Velocity Test

The ultrasonic pulse velocity (UPV) method, as described in ASTM C597, is a non-destructive method used to determine the quality and integrity of concrete structures. It is performed by monitoring the transmission of elastic waves through concrete. An emitter transducer generates elastic waves in the concrete, which vibrate at their resonant frequency when short pulses of high-voltage electricity are sent. A receiver transducer detects these pulses placed nearby, and the time of transmission is determined by a device containing a timer connected to both transducers. From this, the pulse velocity, C, can be determined by the equation C = L/t, where L is the distance travelled and t is time. Three different configurations of transducers can be used to perform a UPV test. This includes direct, semi direct, and indirect (surface) transmission. Fig.3.9 shows the UPV test of the cylindrical specimen.

Fig 3.9: UPV test of cylindrical specimen

3.8 SEM test

The SEM (Scanning Electron Microscopy) images obtained using BSE imaging are used to quantify the microstructure features of the concrete. The microstructure properties will help determine the physical properties such as compressive, tensile, and flexural strength of the concrete. Generally concrete needs a coating to activate zero conductivity. Gold is perhaps the most widely used coating material for non-conductive SEM samples, but it is not recommended as a sputter coating for research purposes where high-magnification images are required. Gold has a high secondary electron yield and sputters relatively rapidly, but the coating structure is composed of large islands (grains) that can be observed at high magnification in most modern research levels. Several collected sample from the concrete cylinder has been set in the coating machine which is shown in Fig.3.10. After proper coating samples are set to SEM machine to get different scale and magnifications images to ensure the microstructure of Recycled Concrete containing Glass (RCG).

Fig.3.10 Coating on sample

3.9 Flexural test setup for prism beams

For flexural test huge number of prism beam has been ted. ASTM C78 standard has been followed which actually procedure of the third point is loading. Here total length of the beam reinforcement is not provided. The loading rate is 0.5mm per minute according to standard test protocol. The load has been inputted by the Universal Testing Machine (UTM) which loading capacity is 1000KN. Total 12 no. of batches has been cast. Test has been planned to do 28 days and 58 days. In total 48 prism beam has been casted for view flexural response of prism beam without reinforcement. Fig.3.11 shows the three-point bending test setup of prism beam.

Another part of flexural strength test was four-point loading test for reinforced beam (RC). In this part ASTM standard has been followed. Total length of the beam is 1100 mm where one end to support length is 100mm and span length is 900mm. Distance between two point loads is 200mm.A strain gauge is set in steel which is described before in casting part. Weld able strain gauges are installed on steel. It monitors the changes in load on structural elements during and after construction. Loading rate is about 1mm per minute according to standard protocol. Load has been inputted by the Universal Testing Machine (UTM) which loading capacity is 1000 KN. A LVDT has been set at the mid-point of the beam. LVDT is an acronym for Linear Variable Differential Transformer. It is a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal. Fig.3.12 shows the loading setup of four-point bending test.

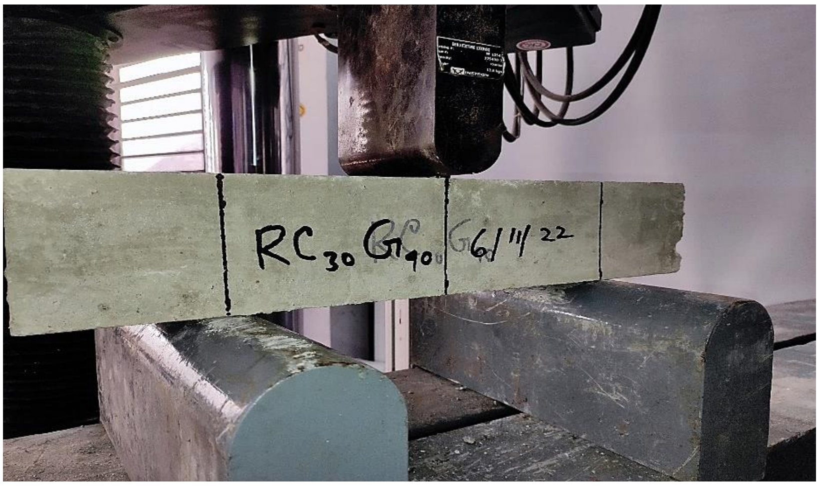
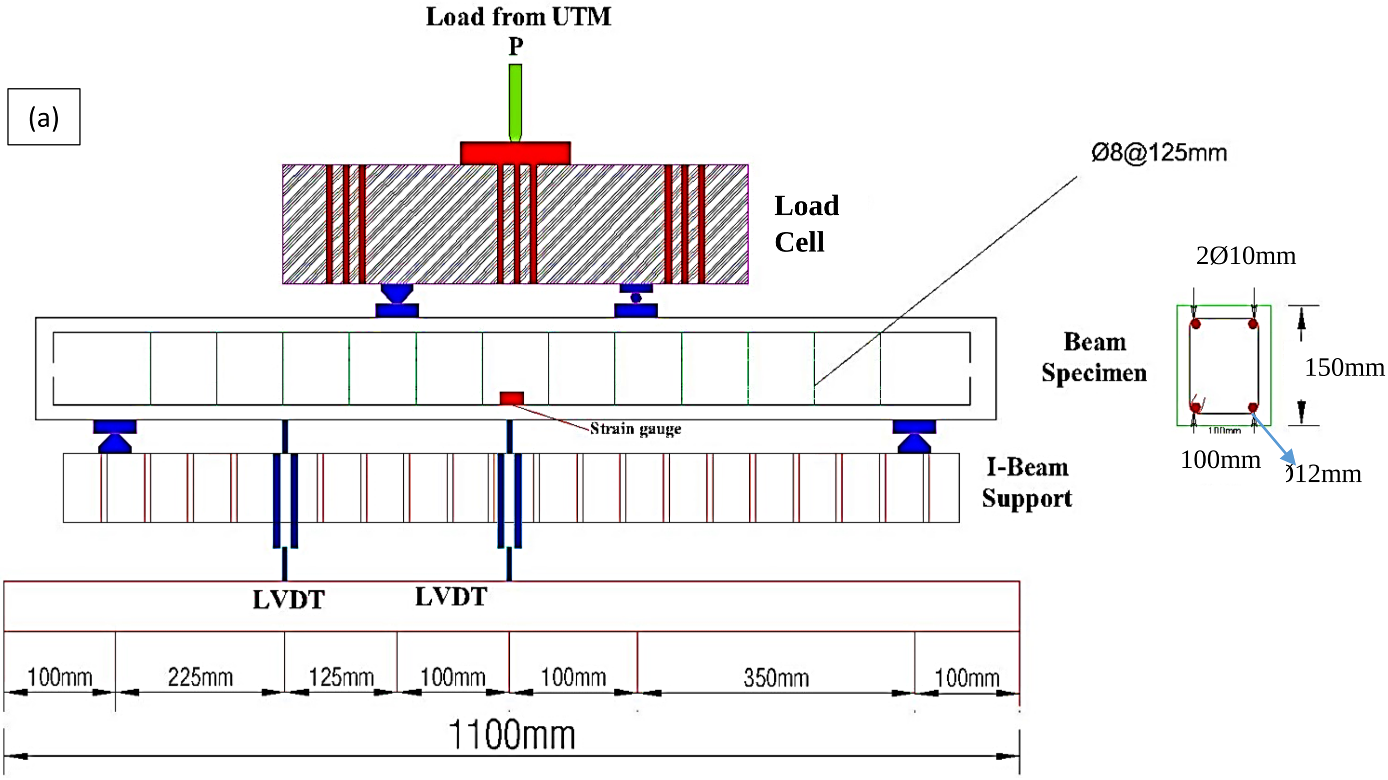


Fig.3.11 Three-point bending test setup of prism beam



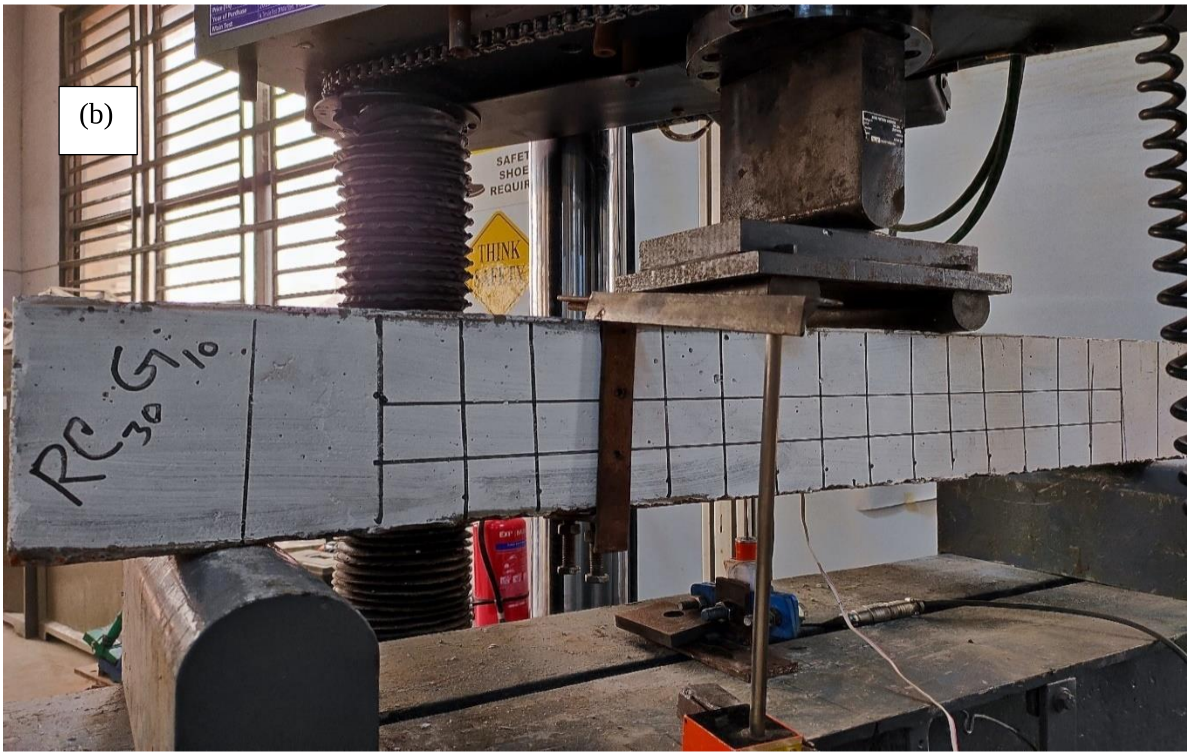


Fig.3.12 (a,b) Four-point bending test setup of reinforced concrete (RC) beam

3.10 Summary

In this chapter,procedure of materials collection ,casting and test methodos are described extensively.To achive the objectives of this research all test procedure has been occurred according to ASTM stanards. The key points of this chapter can be summarized as follows

a) Recycled Brick (RB) is collected from a 30 years old demolished building and then proceed a standard form to use as coarse aggregate in concrete. Another core materials of this research is Waste glass (WG) which is collected from Puran Dhaka waste tube light processing factory.

b) As Waste Glass (WG) is used as the replacement of fine aggregate. So,the particle distribution curve is within the limit of ASTM C33 limits after several sieving. Besides a number of basic test is occurred for deterimining the properties of aggregate.

c) A proper mix design is prepared before casting procedure. For cyclindrical specimen there are fifteen batches and for prism beam and reinforced concrete (RC) beam contains twelve types of specimen .

d) For determining workaibility of concrete slump and air content test is occurred according to ASTM C143 and ASTM C231 respectively. Besides compressive strength,splitting tensile strength and flexural test through center point loading is occurred according to ASTM C39,ASTMC496 and ASTM C293.

e) Ultrasonic Pulse Velocity (UPV) of cylindrical specimen is occurred according ASTM C597. In addition Scanning Electron Microscopy (SEM) is occurred to get microstructure images of concrete.

f) ASTM C78 standard is followed for four point flexural test of Reinforced Concrete (RC) beam. Linear Variable Differential Transducer (LVDT) is installed in the mid part and left mid part of the beam. Besides strain gauge is installed in steel before casting to get proper result.

CHAPTER 4

FRESH AND HARDENED PROPERTIES OF RCG

4.1 Introduction

The fresh and hardened properties of RCG, including the air content test, slump test, compression, tensile, density, and flexural strengths of the prism beam, are discussed in this chapter. The findings of an ultrasonic pulse velocity (UPV) test and a scan from a scanning electron microscope (SEM) will also be briefly explained. Understanding the behavior of a new material type, such as waste tube glass, requires a comparison of this result to the normal specimen. There are other comparisons between compressive strength and density, UPV and compressive strength, compressive strength and tensile strength, and the fluctuation in compressive strength from day to day, which is between 7, 28, and 56 days. A variety of code comparisons, including those for CSA A23.3-14, ACI-318-14, and ACI-209-82, were also provided. A number of code comparisons like ACI-318-14, ACI-209-82, fib-2010, and CSA A23.3-14 were also included for splitting tensile strength.

4.2 Workability of RCG

Concrete workability describes how quickly and uniformly freshly mixed concrete can be laid, cemented, and completed. In general, how fluid the mix is affects how workable concrete is. A slump is a popular name for this. Basically, the more fluid the concrete, the higher the slump, and while the slump is thought of as a measure of water content, it is frequently also used as a measure of concrete consistency. Materials like water content, cement concrete, sand, and aggregate qualities like size, shape, grading, mix design ratio, and usage of admixtures are all factors that determine how workable concrete is. According to a series of experimental findings, replacing fine aggregate with glass improves workability compared to using regular aggregate [13, 14, 16-18, 51]. On the other hand, several researchers asserted that the slump value was considerably lower than what was obtained using sand as the control condition [14, 19-21, 51]. The difference in workability between the two categories of instances, nevertheless, is minimal.

The fifteen Recycled Concrete containing Glass (RCG) specimen slumps are depicted in Fig.4.1. Batch numbers 1 through 4 (RC_0G_0 to $RC_{30}G_0$) are only for samples of recycled concrete (RC) that include no waste glass at all. The slump has grown from batch no.2 to batch no.4 by around 2.82%, 4.2%, and 6.8% when compared to batch no.1. That indicates that using recycled brick material in concrete helps to increase its slump. With more recycled brick used as coarse aggregate, the material is more workable overall. However, the slump has started to lessen for the addition of glass following batch no. 4 ($RC_{30}G_0$). Slump decreased by roughly 6.8% and 11% for batches no. 5 and 6, respectively, in comparison to batch no. 4 ($RC_{30}G_0$). Beginning with batch number seven ($RC_{30}G_{25}$), the slump began to rise by around 3% in comparison to batch number four ($RC_{30}G_0$), and the rise persisted through the last batch ($RC_{30}G_{100}$). Compared to batch no. 6 ($RC_{30}G_{20}$), the slump for ($RC_{30}G_{50}$) has grown by almost 12%. Compared to batch no. 6 ($RC_{30}G_{20}$), the slump for batch no. 15 ($RC_{30}G_{100}$) has increased by roughly 21%. Up to 20% of glass replacement resulted in a decrease in fine aggregate workability, and from 20% to 100% of glass content, workability increased.

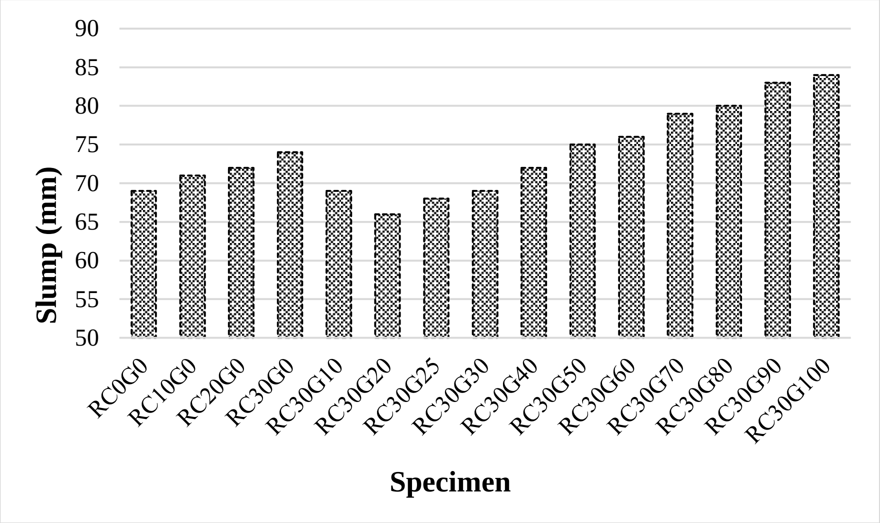


Fig. 4.1 Slump of RCG

The amount of air in concrete is also influenced by the glass sand content. Previous studies have shown that different concrete grades differ somewhat from one another. The air content is seen to decrease at a glass percentage of 25%, while the value increases with higher glass levels (Taha and Nounu, 2009). The air content of concrete with glass sand concentrations at 30%, 50%, and 70%, however, consistently increased by 12-41%, according to Park et al. (Park et al., 2004). The variation in air content is depicted in Fig. 4.2 as a percentage. The presence of air indicates emptiness and promotes improved workability. In comparison to batch no.1 (RC_0G_0), the air content has risen by roughly 0.31, 1.20, and 1.5 percent for batches no.2 ($RC_{10}G_0$), no.3, and no.4, respectively. However, the air content has started to diminish with the addition of glass as fine aggregate. Air content has been reduced by roughly 4.6% and 5.50% for the replacement of glass contents of 10% and 20%, respectively, when compared to batch no. 4 ($RC_{30}G_0$). In contrast to batch no. 6 ($RC_{30}G_{20}$), batch no. 7 ($RC_{30}G_{25}$) had a steady air content, while batch no. 8 ($RC_{30}G_{30}$) saw a start to an increase in air content. Air content has been increased by 3.74% and 10% for batch no.10 ($RC_{30}G_{50}$) and 15 ($RC_{30}G_{100}$) respectively.

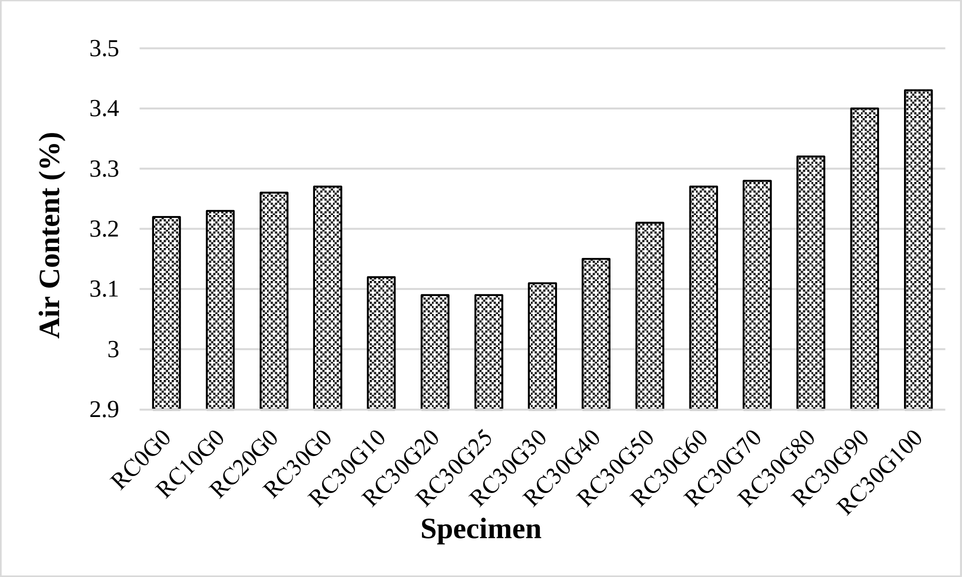


Fig. 4.2 Air Content of RCG

Table 4-1: Air content and Slump test result of RCG

Batch no.	Notation	Air Content (%)	Slump (mm)
1.	RC_0G_0	3.22	69
2.	$RC_{10}G_0$	3.23	71
3.	$RC_{20}G_0$	3.26	72
4.	$RC_{30}G_0$	3.27	74
5.	$RC_{30}G_{10}$	3.12	69
6.	$RC_{30}G_{20}$	3.09	66
7.	$RC_{30}G_{25}$	3.09	68
8.	$RC_{30}G_{30}$	3.11	69
9.	$RC_{30}G_{40}$	3.15	72
10.	$RC_{30}G_{50}$	3.21	75
11.	$RC_{30}G_{60}$	3.27	76

12.	$RC_{30}G_{70}$	3.28	79
13.	$RC_{30}G_{80}$	3.32	80
14.	$RC_{30}G_{90}$	3.4	83
15.	$RC_{30}G_{100}$	3.43	84

4.3 Compressive Strength

One of the crucial mechanical characteristics to consider while evaluating concrete is its compressive strength. Results from tests on compressive strength are generally used to determine whether the concrete mixture delivered to the construction site satisfies the specifications for the specified strength, fc', in the job specification. The fabrication and curing of cylinders subjected to acceptance and quality control testing follow the same processes outlined in ASTM C-31 for standard-cured specimens. For field-cured specimens, ASTM C-31 offers methodologies for calculating the in-place concrete strength. As per ASTM C-39, cylindrical specimens are tested. In order to understand the real behavior of RCG, fifteen batches of recycled concrete glass (RCG) were examined for 7, 28, and 56 days.

The use of RG as a concrete replacement for the fine aggregate (RGFA) piqued the interest of numerous researchers. The majority of them demonstrated that the compressive strength of concrete can be significantly increased by substituting 20–30% RG for fine aggregate (mostly sand) (Jeba Samuel, 2018, Arivalagan and Sethuraman, 2021, Elavarasan, 2016, Pratheba.S, 2018, Rjoub and Tamimi, 2019, Alducin-Ochoa et al., 2021, J.Premalatha 2019, Ibrahim, 2020, Gautam et al., 2012). Furthermore, they asserted that the presence of RGA as a fine component of concrete does not significantly reduce compressive strength. However, as seen in numerous research works, the strength qualities may degrade if the replacement amount exceeds 30%. Additionally, compressive strength started to decrease after employing 30% of RGFA, which is also seen in the references (Ling et al., 2011, Herki et al., 2017, Ling and Poon, 2011, J.Premalatha 2019, Gerges et al., 2018, Corinaldesi et al., 2016, Tan and Du, 2013, Rahim et al., 2014). This phenomenon can be explained by the fact that fine glass can fill in gaps in the aggregate at a relatively lower percentage, increasing the overall compressive strength. On the other hand, due of the fine glass' smoother surface, more glass content in concrete results in smaller bonding between the fine content, which results in lower compressive strength.

The compressive strength of RCG samples varied throughout 7 days, as seen in Fig.4.3. As usual, the strength of the aggregate decreased as the percentage of recycled brick aggregate increased. In comparison to batch 1 (RC_0G_0), the strength of batch 2 ($RC_{10}G_0$) through 4 ($RC_{30}G_0$) fell by roughly 0.94 percent, 2.3%, and 7.5%, respectively. The strength trend began to shift after using glass content rather than sand. In comparison to batch no. 4 ($RC_{30}G_0$), the strength of batch no. 5 ($RC_{30}G_{10}$) and 6 ($RC_{30}G_{20}$) has grown by roughly 7.4% and 12.5%, respectively. But strength started to decline once more starting with batch number 7 ($RC_{30}G_{25}$). This indicates that the strength of the replaced glass has grown by up to 20% before beginning to decline. Strength has decreased by between 27.4% and 72.4% for sand replacement rates of 50% ($RC_{30}G_{50}$) and 100% ($RC_{30}G_{100}$) compared to batch no. 6 ($RC_{30}G_{20}$).

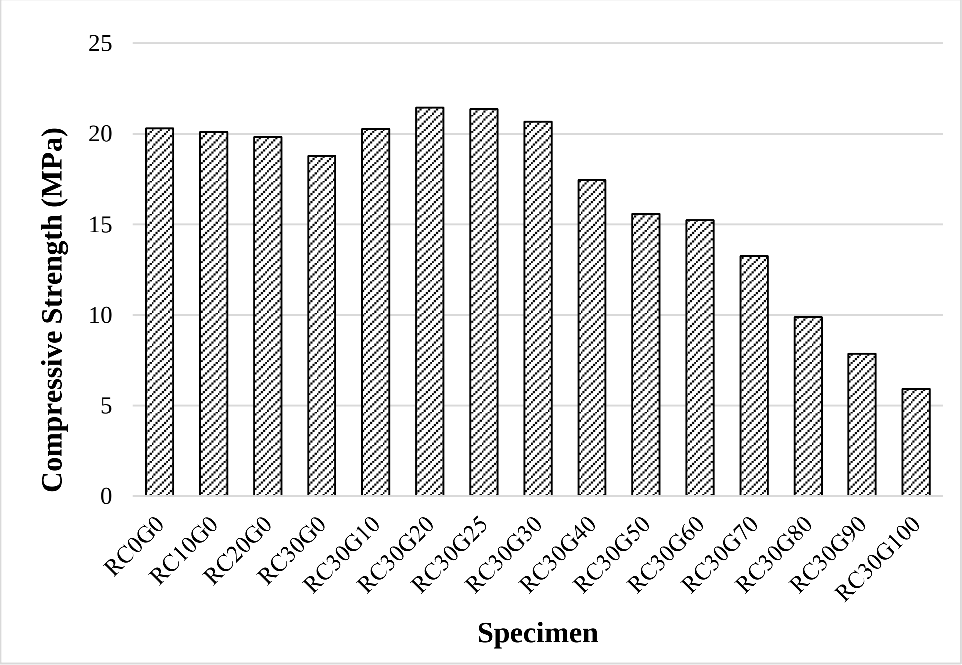


Fig. 4.3 Compressive Strength of RCG (7 days)

The compressive strength changes over fifteen batches throughout 28 days is shown in Fig. 4.4. As usual, every batch's concept strength improved in comparison to the 7-day strength result. Even the pattern of shifting strength is very comparable to that of seven days' strength. Strength has decreased by about 12% when recycled brick aggregate ($RC_{30}G_0$) is added compared to unrecycled brick aggregate (RC_0G_0). The strength of batch no. 4 ($RC_{30}G_0$) has been enhanced by roughly 15.5% to add glass content of about 20% ($RC_{30}G_{20}$). Strength of the substituted glass began to decline at 25% ($RC_{30}G_{25}$), which is approximately 1.2% less than batch no. 6 ($RC_{30}G_{20}$). About 25 to 30 MPa was the design strength we aimed for after 28 days. Seven batches in total have satisfied this design requirement, two of which comprise just recycled aggregate with replacement percentages of around 10% and 20%, and the other four of which contain recycled aggregate with a replacement percentage of about 30% and glass content ranging from 10% to 30%.

The exact value of compressive strength for fifteen batches over 7, 28, and 56 days is displayed in Table 4-2. Strength has increased as usual with the lengthening days. Nearly identical data are presented graphically in Fig.4.5. Compared to the strength result after 7 days, strength improved by 20% to 30% in 28 days. After that, strength grew by roughly 10% in 56 days compared to the test result after 28 days. Another two batches are included in accordance with the targeted strength we have set here. That indicates that out of 15 batches, a total of 9 batches have passed the 56-day strength test. Batch numbers 4 ($RC_{30}G_0$) and 9 ($RC_{30}G_{40}$) have been included as new batches within the scope of this research.

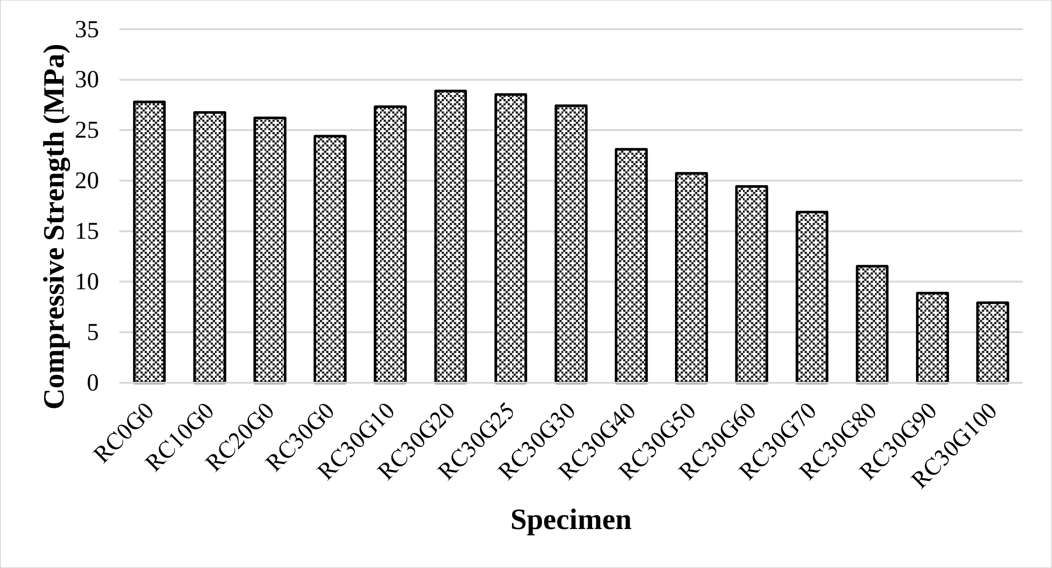


Fig. 4.4 Compressive Strength of RCG (28 days)

Table 4-2: Compressive Strength of RCG (7,28,56 days)

Batch no.	Notation	7 days strength (MPa)	28 days strength (MPa)	56 days strength (MPa)
1.	RC_0G_0	20.293	27.801	30.858
2.	$RC_{10}G_0$	20.103	26.743	29.682
3.	$RC_{20}G_0$	19.821	26.222	29.211

4.	$RC_{30}G_{0}$	18.782	24.412	27.045
5.	$RC_{30}G_{10}$	20.274	27.332	30.327
6.	$RC_{30}G_{20}$	21.453	28.881	31.769
7.	$RC_{30}G_{25}$	21.366	28.543	31.683
8.	$RC_{30}G_{30}$	20.678	27.433	30.379
9.	$RC_{30}G_{40}$	17.456	23.113	25.586
10.	$RC_{30}G_{50}$	15.592	20.732	22.834
11.	$RC_{30}G_{60}$	15.237	19.431	21.376
12.	$RC_{30}G_{70}$	13.252	16.895	18.586
13.	$RC_{30}G_{80}$	9.883	11.526	12.677
14.	$RC_{30}G_{90}$	7.868	8.883	9.772
15.	$RC_{30}G_{100}$	5.924	7.912	8.702

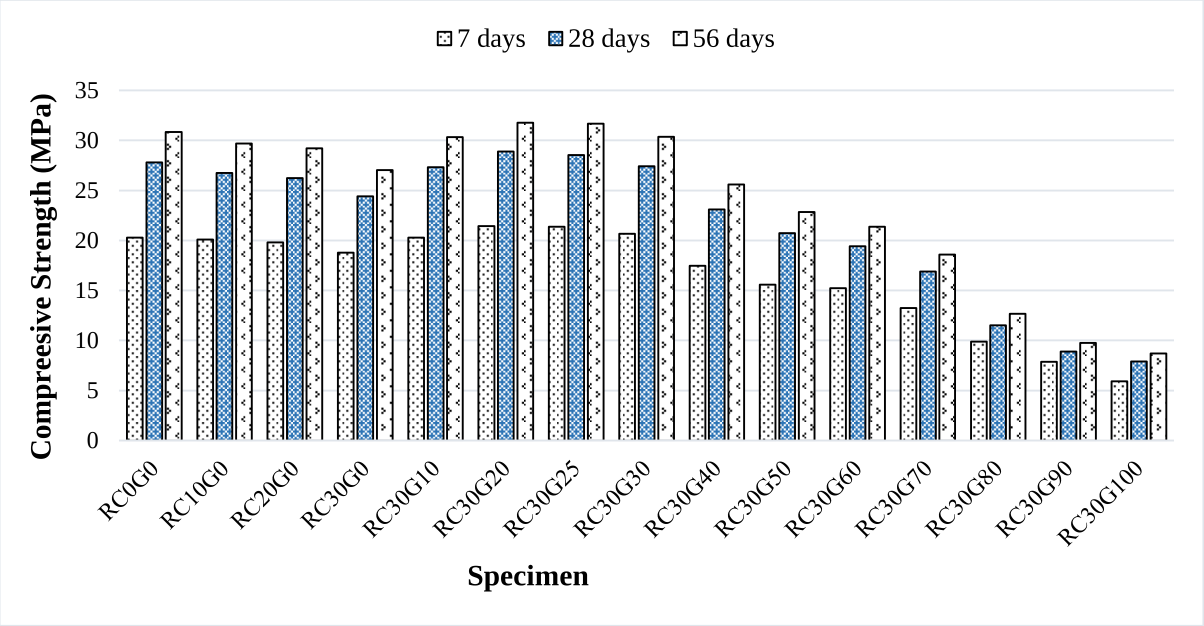


Fig. 4.5 Compressive Strength of RCG (7,28,56 days)

4.4 Splitting Tensile Strength

Numerous research has been done to ascertain the tensile characteristics of concrete formed from recycled glass concrete (RGC) using split tensile tests. Tensile strength of concrete made using RG as fine aggregate (RGFA) is less than that of typical concrete, according to several studies one (Arivalagan and Sethuraman, 2021, Rjoub and Tamimi, 2019, Ammash et al., 2009).. On the other hand, certain studies revealed that adding RGFA increased the value of tensile strength (Elavarasan, 2016, Pratheba.S, 2018, Lokesh et al., 2017).

The tensile strength of recycled concrete glass (RCG) after 28 days is shown in Fig. 4.6. The aggregate strength of brick has decreased as the percentage of recycled brick has increased. Strength fell by almost 1.3%, 2.9%, and 5.26%, respectively, from batch no. 2 ($RC_{10}G_0$) to batch no. 4 ($RC_{30}G_0$), in comparison to batch no. 1 (RC_0G_0). However, as glass content was added, the strength of the fine aggregate began to rise. Glass additions of 10% and 20% each enhanced strength by around 0.5% and 1.5%, respectively. Strength rose even for batch no. 7 ($RC_{30}G_{25}$) compared to batch no. 4 ($RC_{30}G_0$) by almost 1.8%. Starting with batch no. 8 ($RC_{30}G_{30}$), strength began to decline. In comparison to batch no. 7 ($RC_{30}G_{25}$), the strength of fine aggregates with 50% and 100% glass content was decreased by nearly 14% and 68%, respectively.

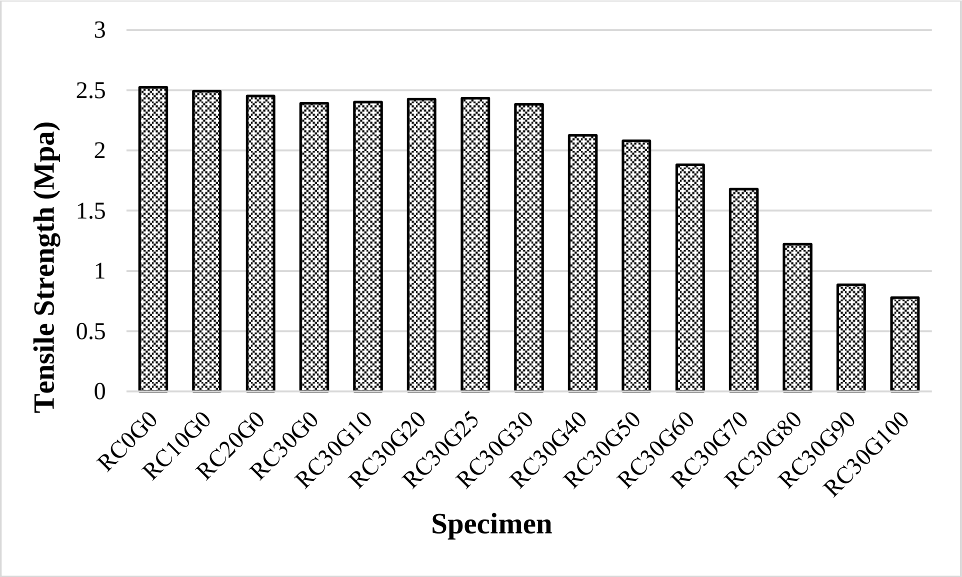


Fig. 4.6. Splitting Tensile Strength of RCG

The values for compressive strength and tensile strength after 28 days are displayed in Table 4-3. The graphic representation of the 28-day strength is shown in Fig. 4.6. Tensile strength is roughly 11%, 10.8%, 10.7%, and 10.2% of the batch's compressive strength from batch no. 1 (RC_0G_0) to batch no. 4 ($RC_{30}G_0$). Tensile strength for batches no. 5 ($RC_{30}G_{10}$) to no. 7 ($RC_{30}G_{25}$) is approximately 11.4%, 12%, and 11.7% of compressive strength for those batches. Tensile strength for batches 10 and 15 was found to be 10% and 10.2%, respectively, of compressive strength after 28 days.

Table 4-3: Compressive and Tensile strength of RCG

Batch no.	Specimen	28 days Compressive Strength (MPa)	28 days Tensile Strength (MPa)
1.	RC_0G_0	27.801	2.524
2.	$RC_{10}G_0$	26.743	2.493
3.	$RC_{20}G_0$	26.222	2.452
4.	$RC_{30}G_0$	24.412	2.391
5.	$RC_{30}G_{10}$	27.332	2.4021
6.	$RC_{30}G_{20}$	28.881	2.426
7.	$RC_{30}G_{25}$	28.543	2.434
8.	$RC_{30}G_{30}$	27.433	2.3844
9.	$RC_{30}G_{40}$	23.113	2.125
10.	$RC_{30}G_{50}$	20.732	2.081
11.	$RC_{30}G_{60}$	19.431	1.882
12.	$RC_{30}G_{70}$	16.895	1.678
13.	$RC_{30}G_{80}$	11.526	1.221
14.	$RC_{30}G_{90}$	8.883	0.885
15.	$RC_{30}G_{100}$	7.912	0.778

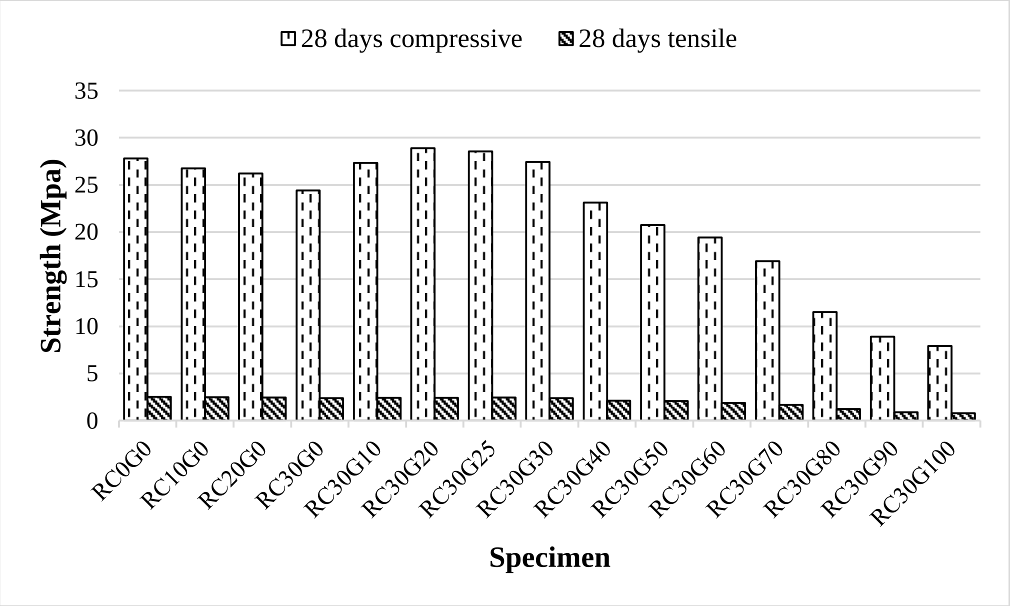


Fig. 4.7. Compressive and Tensile strength (28 days)

4.5 Flexural strength of Prism beam (without reinforcement)

To comprehend the flexural characteristics of concrete, bending strength tests must be conducted. The flexural strength of concrete made from recycled glass has been the subject of some prior research. Flexural strength is increased by up to 20% RGFA addition (Arivalagan and Sethuraman, 2021, Sunarsih et al., 2021). However, flexural strength only increased by 5% RGFA, according to another study (Lokesh et al., 2017). Some researchers shown that replacing up to 10% of the cement with recycled glass particles improves strength compared to using regular cement (Ubeid et al., 2020, Abbas et al., 2021).

Twelve batches in all were tested for flexural strength throughout 28 and 56 days. The outcome of the prism beam's flexural strength after 28 and 56 days is shown in Fig. 4.8. Here, the recycled brick proportion was changed from 0 to 100% while remaining constant at 30% from the previous example. For the replacement of glass up to 20% ($RC_{30}G_{20}$), strength has risen by over 15% as compared to the standard one ($RC_{30}G_0$). Strength began to decline from RC30G25, and by the time it reached 100% glass ($RC_{30}G_{100}$), it had decreased by around 74%. Flexural strength results after 56 days also follow the same pattern as those after 28 days. As per typical, all batches have stronger results than the 28-day results. level has increased from 2% to 4% of the previous 28-day level.

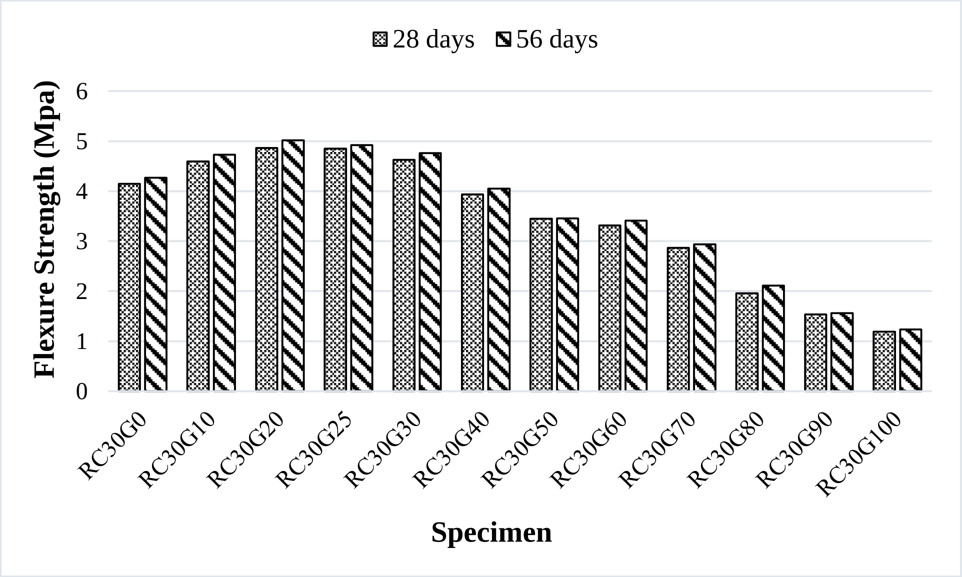


Fig.4.8. Flexural Strength of RCG (28 and 56 days)

4.6 Hardened Concrete Density

The density of hardened concrete is another factor to assess strength. A curved line in Fig.4.9 depicts the hardened density of fifteen batches. Here, density falls off as recycled brick aggregate content rises. By using 30% ($RC_{30}G_0$) recycled brick instead of the original coarse aggregate, the strength has fallen by about 8%. However, increasing the amount of recycled glass to 20% ($RC_{30}G_{20}$) revealed a value gain of roughly 10%. However, strength started to decline starting with $RC_{30}G_{25}$ and reduced by over 41% for batch no. 15 ($RC_{30}G_{100}$). The relationship between hardened density and compressive strength is depicted in Fig.4.10. Here, a nearly linear link has been established.

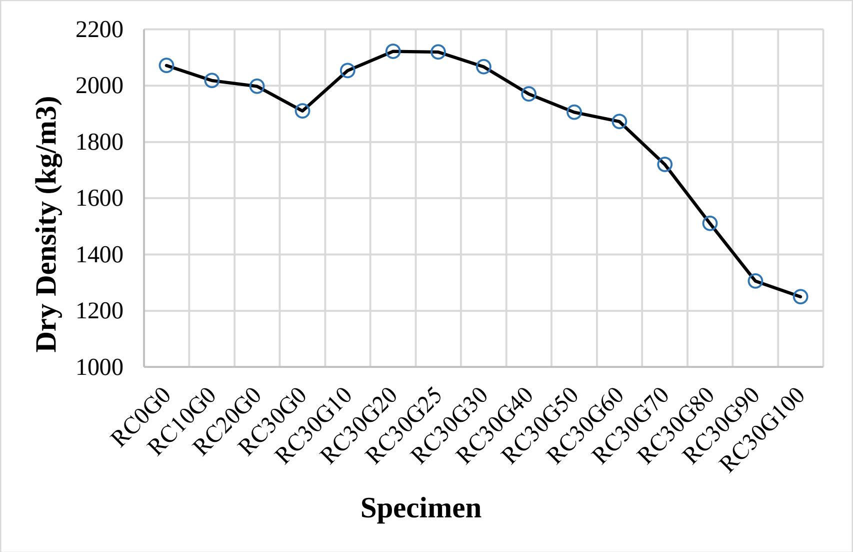


Fig. 4.9. Dry density of RCG

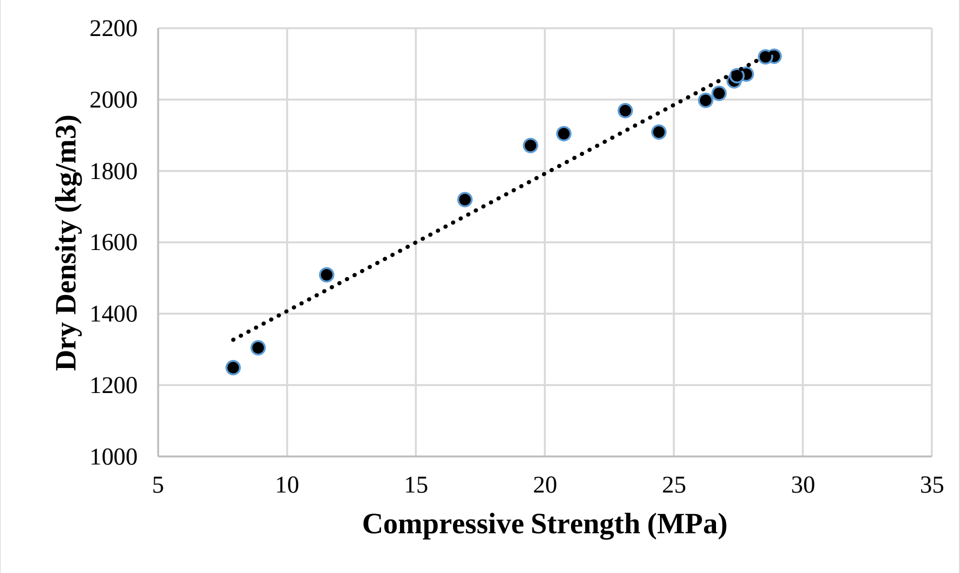


Fig. 4.10. Dry density Vs Compressive strength of RCG

4.7 Ultrasonic Pulse Velocity

In structural engineering, ultrasonic measurements are used to analyze deterioration, find flaws, and determine material qualities. Velocity is a feature of ultrasonic wave propagation that can be applied in this situation. In this instance, cylindrical samples from fifteen different batches were evaluated 28 days following casting. After 28 days of casting, fifteen batches' UPV data are shown in Fig. 4.11. As the percentage of recycled brick aggregate rises, velocity falls. Strength falls for replacement recycled brick by 10%, 20%, and 30%, respectively, as compared to the fresh one. However, percentage velocity increased once glass was added. When 20% of the original glass is replaced ($RC_{30}G_{20}$), as opposed to having no glass at all ($RC_{30}G_0$), the strength increases by around 8.4%. In comparison to batch no. 6 ($RC_{30}G_{20}$), velocity began to decline starting with batch no. 7 ($RC_{30}G_{25}$). Strength dropped by 15% and 41%, respectively, for batches 10 ($RC_{30}G_{50}$) and 15 ($RC_{30}G_{100}$), compared to batch no. 6 ($RC_{30}G_{20}$). A linear relationship between the results of the compressive strength test and UPV is shown in Fig. 4.12.

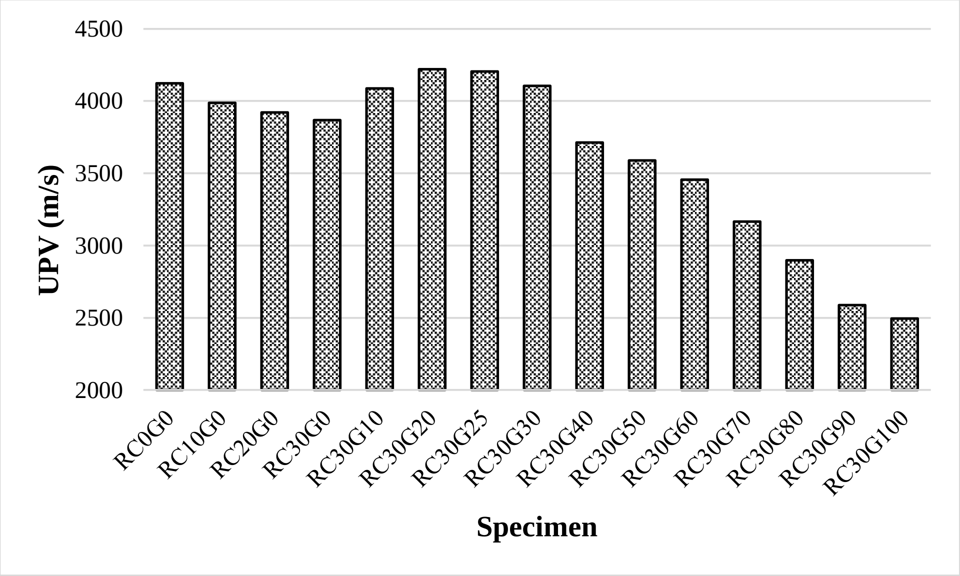


Fig. 4.11. Ultrasonic Pulse Velocity of RCG

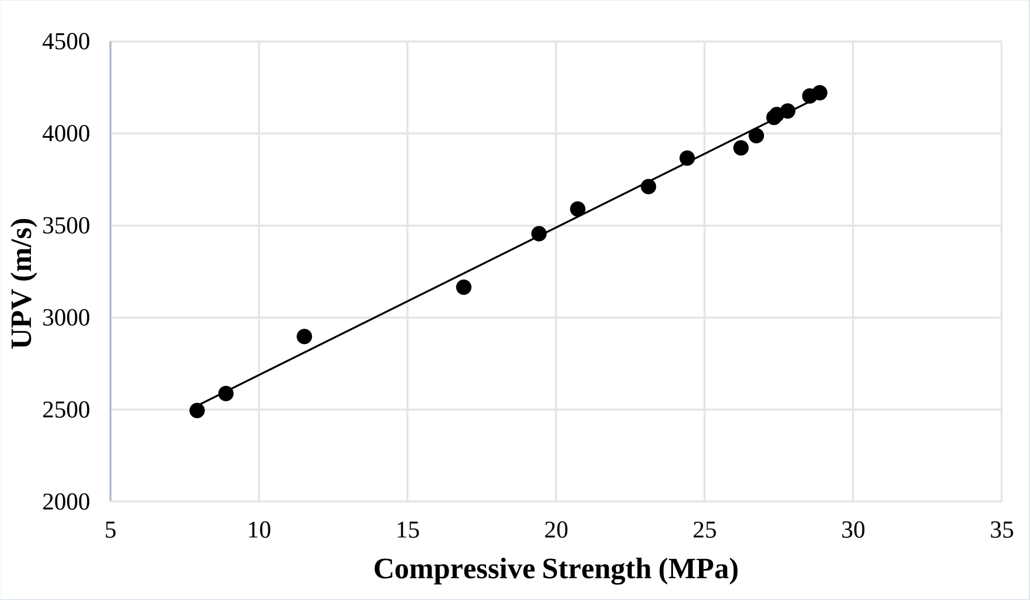


Fig. 4.12. Relation between compressive strength and UPV

4.8 Comparison with the Standard Code of Practices

Foreseeing the mechanical response of concrete using its compressive strength is possible using a variety of design criteria. The different reaction parameters of the concrete specimens are predicted in the current study using design recommendations from the ACI, fib, and Euro-code (EC2), CSA. The formulae used to calculate the strength values are displayed in Table 4-4 and come from several codes. Tensile strength and flexural strength values derived from various codes are shown in Figs. 4.13 and 4.14, respectively. As shown in Figs. 4.15 and 4.16**,** the ratio (n) between experimental and predicted values is calculated for comparative purposes; a value of n larger than 1 denotes an over-prediction, whilst a value of n less than 1 denotes an under-prediction of the outcome.

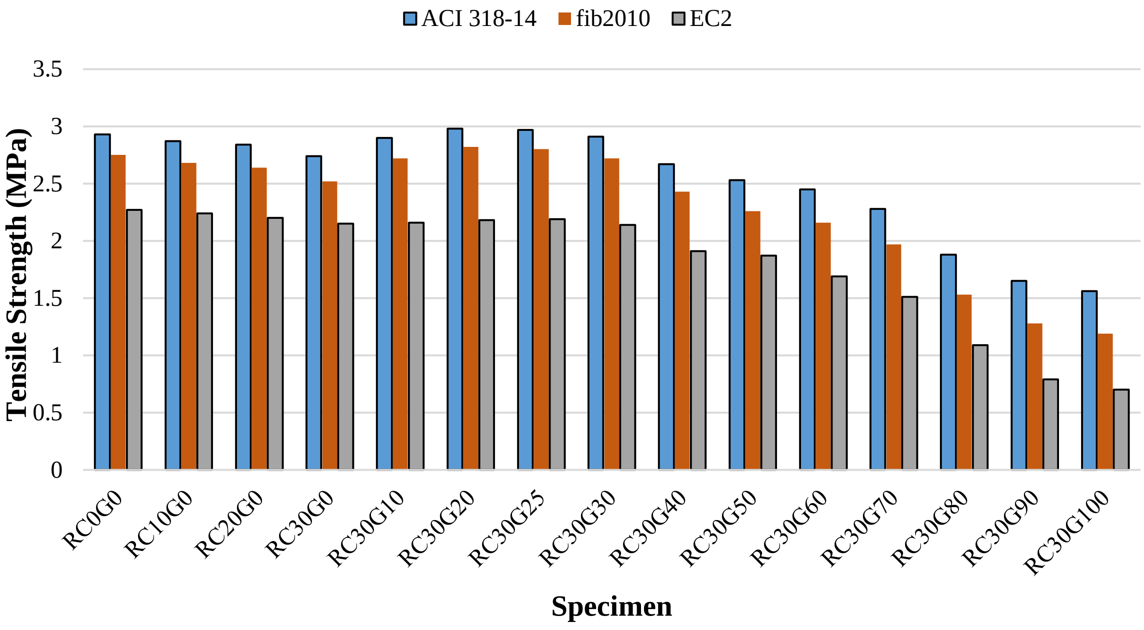


Fig. 4.13. Splitting Tensile strength values according to codes

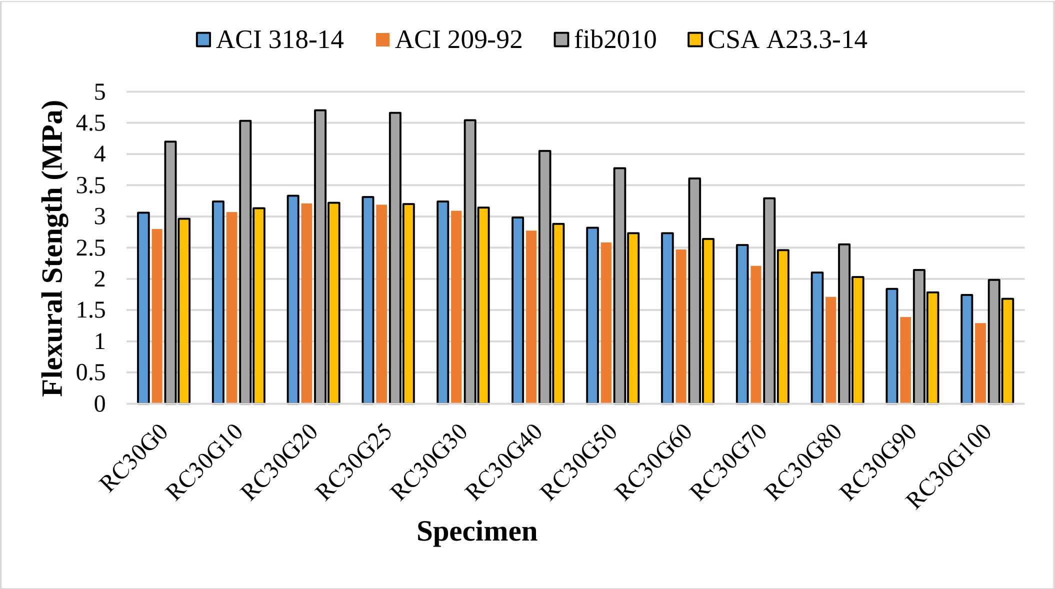


Fig. 4.14. Flexural strength values according to codes

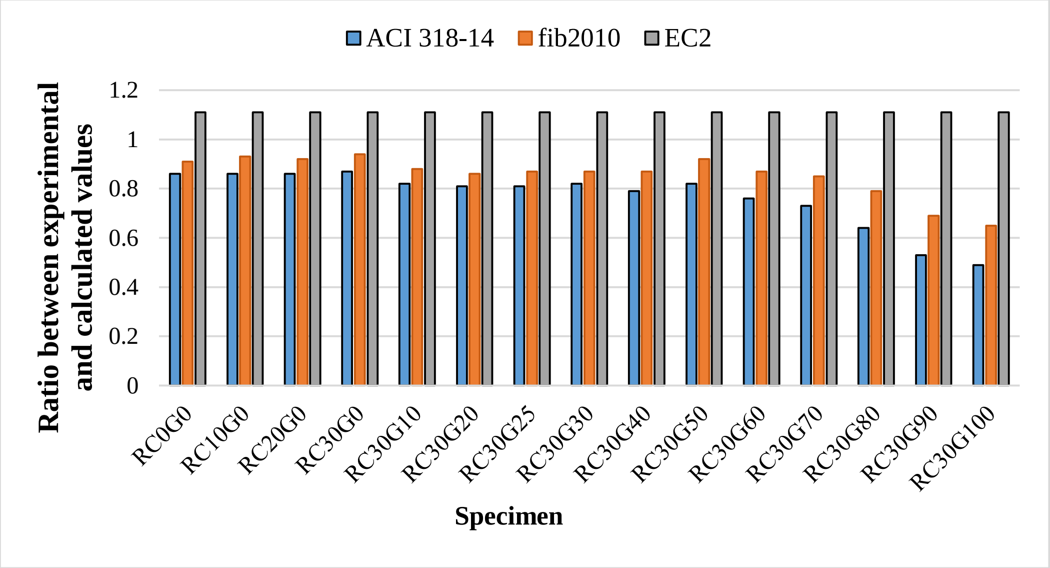


Fig. 4.15. Ratio between experimental and calculated values of Splitting Tensile strength

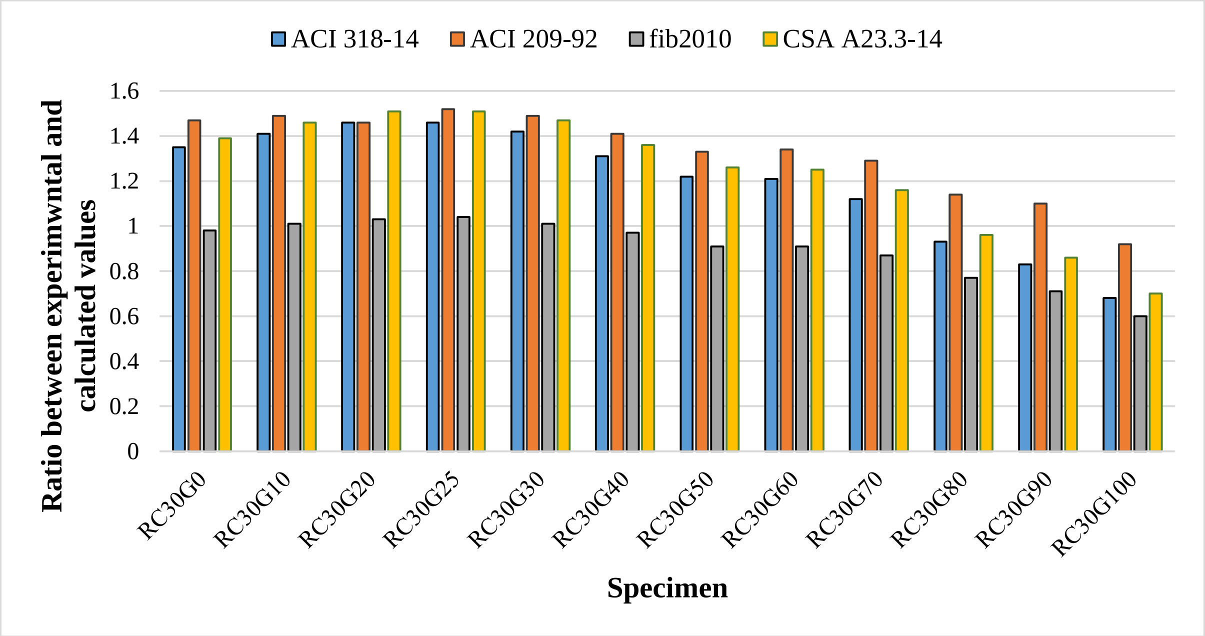


Fig. 4.16. Ratio between experimental and calculated values of Splitting Tensile strength

4.9 Failure Pattern of Concrete

The RCG concrete cylinder's failure pattern during the compressive strength test is depicted in Fig. 4.17. Here we have fifteen batches displayed. Cone and share failures are among the most typical failures. It has been found that increasing the glass content of concrete by up to 20%

improves bonding. It might occur as a result of the pozzolonic activity of glass. The failure pattern of (from left) $RC_{30}G_{100}$, $RC_{30}G_{30}$, and $RC_{0}G_{0}$ is depicted in Fig.4.18 (a). It has been noted that $RC_{30}G_{100}$ exhibits one of the weakest bonds, while $RC_{30}G_{30}$ exhibits a much stronger bond. The flexure failure of the $RC_{30}G_{40}$ specimen, which is close to the middle of the beam, is shown in Fig.4.19. Due to flexure, a similar crack pattern is shown in Fig. 4.20. Twelve specimens fail not far from the beam's centre.

Fig. 4.17. Failure pattern of RCG concrete cylinder in compression

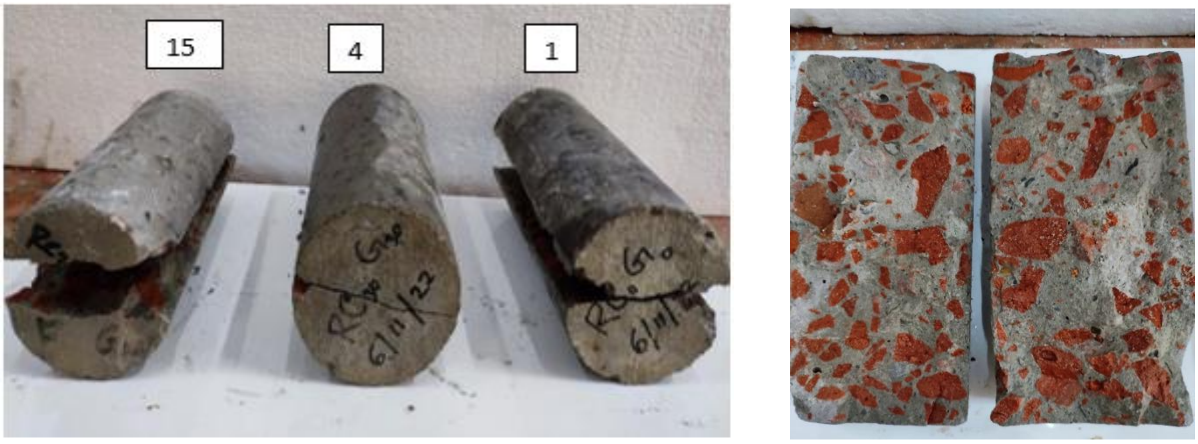


Fig. 4.18. (a) Failure pattern of RCG concrete cylinder in tension (b) cross section after failure

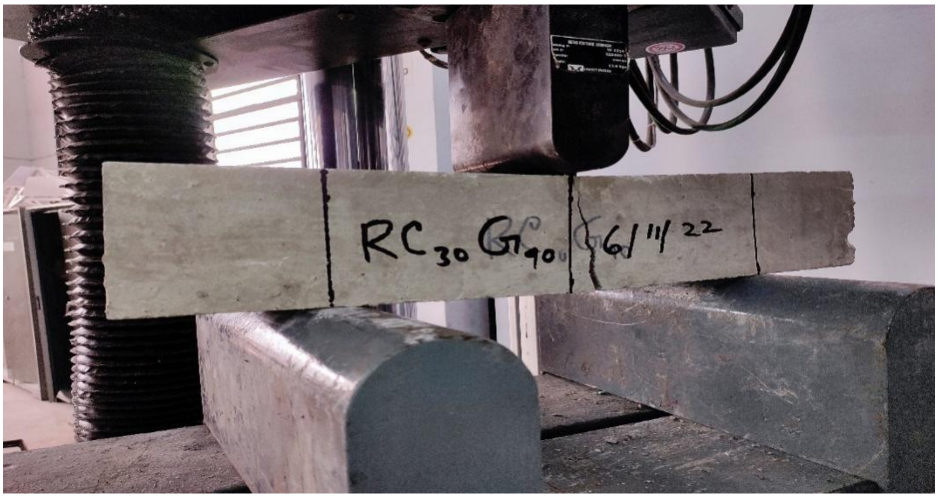


Fig. 4.19. Failure pattern of RC30G40 prism beam in flexure

Fig. 4.20. Flexural failure pattern of RCG concrete

4.10 SEM images

Scanning Electron Microscope (SEM) examination enables us to confirm how alterations are created within the sense of the material and the interfaces added to the paste, sort of a severe presence of micro-cracks within the terrain of the grains.Fig.4.21. (a-b) shows the micrographic images of large scale after 56 days of casting for the batch no.15 ($RC_{30}G_{100}$). Magnification was 659 and 2.3k and scale was 30µm and 10µm respectively. From strength result discussion it is clear that 100% replacement of sand by glass showed the lowest strength. Here lots of voids and crack and fissures are created. This may be happening lack of proper bonding with aggregates and cement and ASR reaction.Fig.4.22 shows the SEM images of $RC_{30}G_{20}$ batch which has twenty percentage glass. It has some micro cracks but much better than $RC_{30}G_{100}$ sample. Images has been taken 126 and 4k magnification and 200µm and 10µm scale respectively. As said according to strength result it gained highest strength among RCG batches. Micrographic images also indicate the lesser voids and cracks which indicates the higher strength. Due to pozzolonic action of glass it maybe happened.

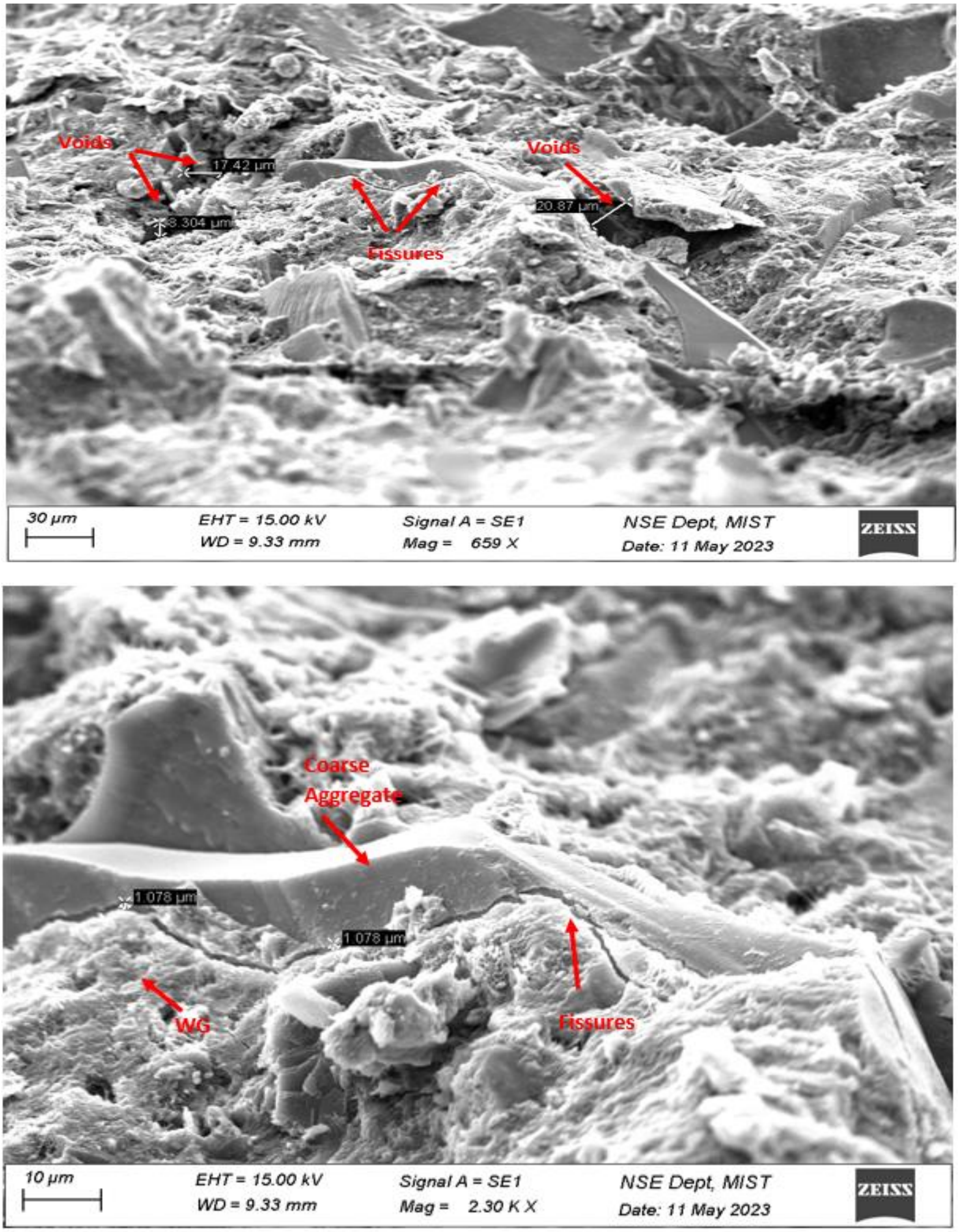


Fig. 4.21. SEM images of RC$_{30}$G$_{100}$ sample (a) 30μm (b) 10μm

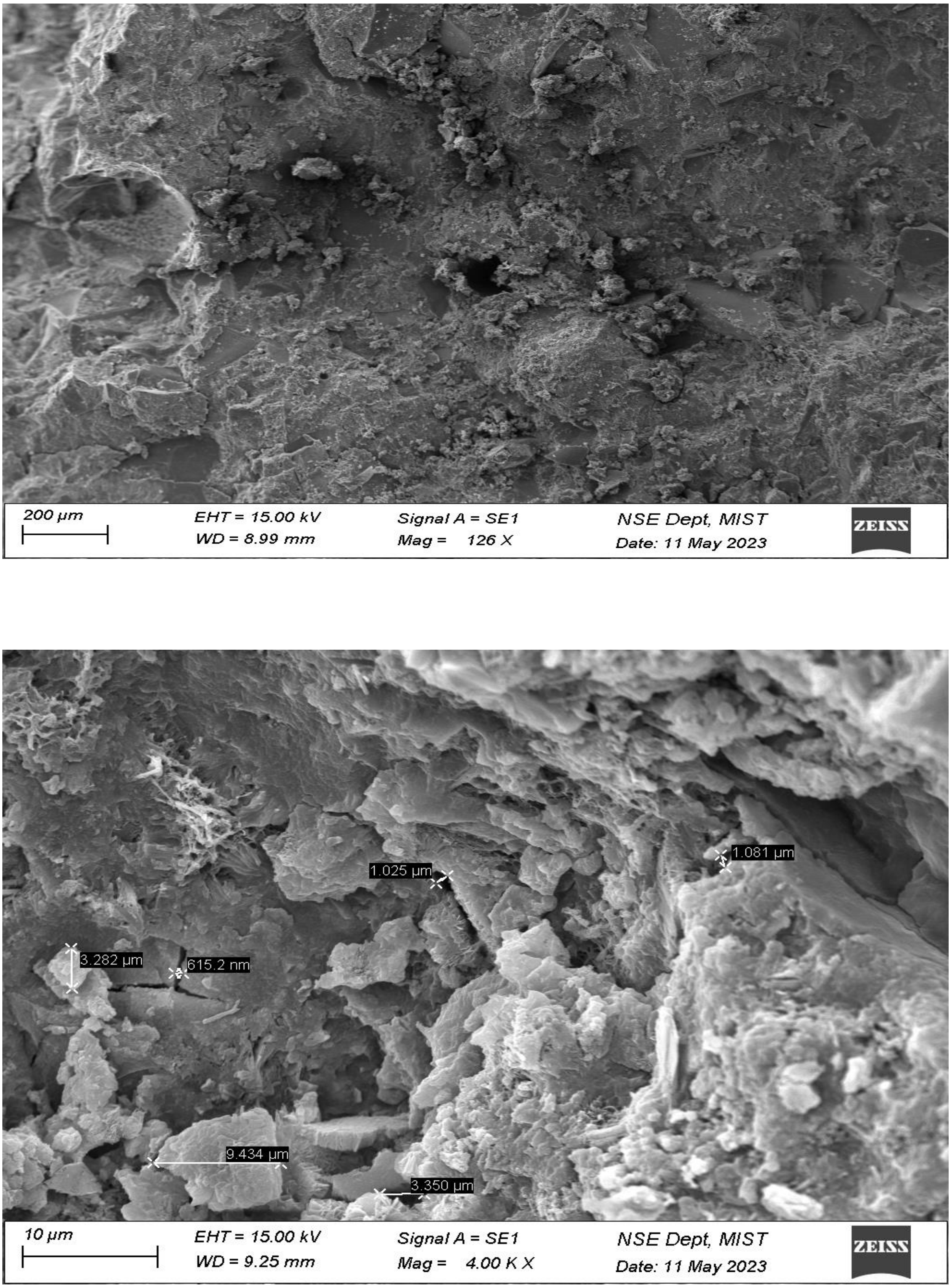


Fig. 4.22. SEM images of $RC_{30}G_{20}$ (a) 200µm (b) 10µm

4.11 Summary

In this chapter lab result of RCG especially fresh and hardened properties has been showed elaborately. Several comparisons also showed to understand the actual behavior of RCG. The test results of this chapter can be summarized below

a) Workability reduces for waste glass content replacement up to 20% ($RC_{30}G_{20}$). It then started to grow after that. The amount, kind, and shape of glass particles have an impact on how easily RCG concrete can be worked.

b) In terms of compressive strength, as usual strength decreases with the increasing percentage of recycled brick aggregate. Adding glass content up to 20% gives 12.5% more strength. But after that strength decreases with the increasing amount of glass content. Maybe for recycled tube glass, 20% is the optimum level in concrete.Almost similar trend has been followed in terms of the tensile strength of RCG. But here glass content of up to 25% ($RC_{30}G_{25}$) showed an increasing trend of strength.

c) Hardened density decreases with the increasing percentage of recycled brick aggregate. But for adding glass up to 20% density increases by almost 10% compared to the fresh one. Compressive strength maintains almost a linear relationship with hardened density.

d) In terms of Ultrasonic pulse velocity, for adding glass content up to 20% showed an increasing trend. Almost 8.4% velocity increases due to adding glass content up to 20%. Besides SEM result shows the larger voids and fissures for adding more glass content. But for up to 20% glass content SEM showed denser structure, lesser voids, and fissures. Maybe for the Alkali-Silica Reaction it happened.

e) In terms of the flexural strength of the prism beam, strength increases for adding glass content up to 20% and after that starts to decrease. Almost 15% strength has been increased by adding 20% glass content.

f) Failure pattern of cylinder specimen has no huge difference for changing glass content. The most common cone and shear failure occurred. Besides crack pattern of prism beam is as usual flexural crack.

CHAPTER 5

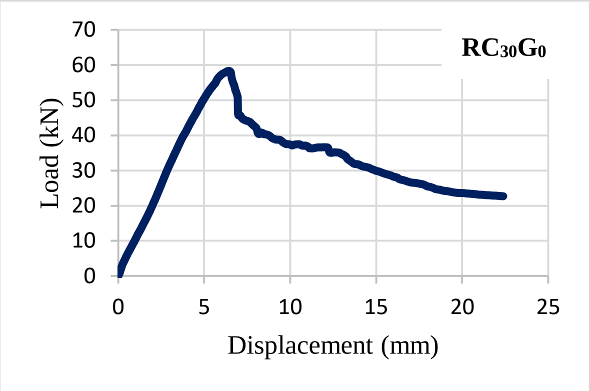
FLEXURAL RESPONSE OF REINFORCED CONCRETE BEAM

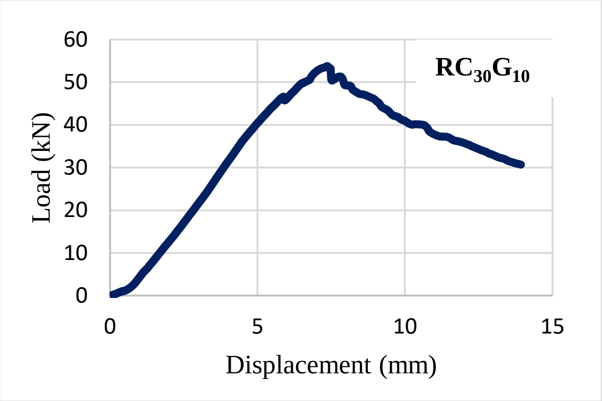
5.1 Introduction

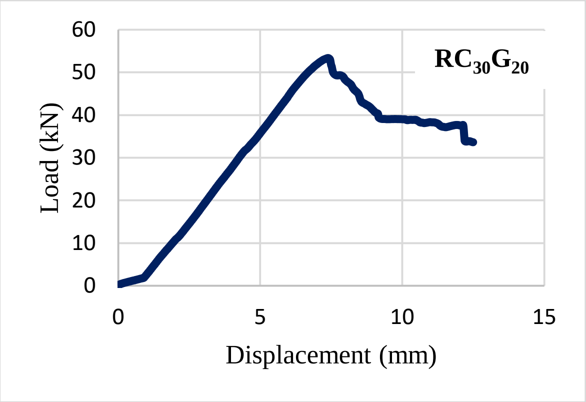
Till now, reinforced concrete structures have been the most popular choice of civil and structural engineers. They are by far considered the most successful construction materials because of their versatility, robustness, economic feasibility, and durability. This Chapter contains flexural response of reinforced concrete beam through load-deflection chracteristics, strain of steel, crack pattern of reinforced concrete beam and flexural strength of beam. Twelve varieties of reinforced concrete beam specimen is ready for the test. Load-Deflection data is recording through LVDT,UTM and also load-strain data is recording from starin gauge of steel. Besides no.of crack and pattern of crack on beam is noted in time of testing. Experimental findings have led to determinations of cracking, yielding, and ultimate moment capacity, which have been compared to the ACI-318-14 code.

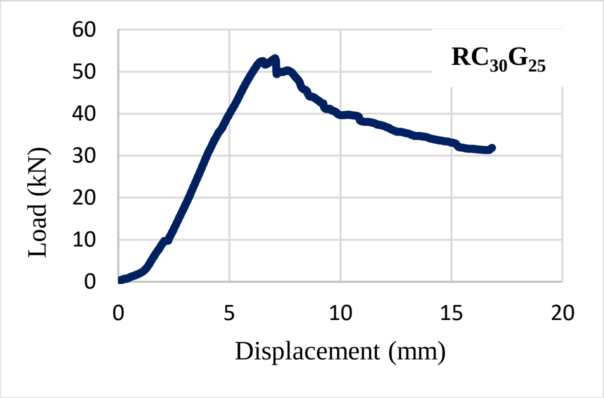
5.2 Load-Deflection Characteristics

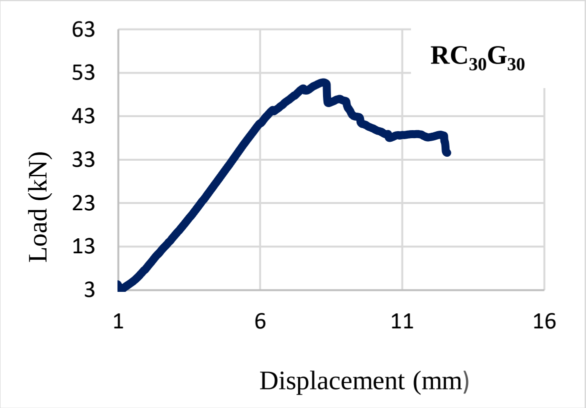
Fig.5.1 shows the load versus deflection responses at the midpoint of the tested RCG beams. Experimental results show that the load-deformation behavior of RCG beams is slightly different. For the $RC_{30}G_0$ beam, the highest load has been taken which is 58 kN with a displacement near to 6mm. After that, due to adding glass content, the slope of the load-deflection curve starts to decrease gradually with an increasing number of cracks developed in the tested beam specimens. With further increase in the applied load, the longitudinal reinforcements start to yield and then the slope of the curves significantly declines beyond the yielding point. In this stage, with a small increment in the applied load, the deflection suddenly increases and reaches the maximum load-carrying capacity when the concrete crushing takes place with an abrupt drop in the load level. On the other hand, from the load-deflection response of $RC_{30}G_{10}$, $RC_{30}G_{20}$, and $RC_{30}G_{25}$ beams, it is observed that the ability to take load decreases with the increasing amount of glass which is 7.7%%,7.8%, and 8.7% respectively. After reaching the ultimate capacity the load drops abruptly. For $RC_{30}G_{50}$ and $RC_{30}G_{100}$ load carrying capacity decreases by almost 15% and 32% respectively compared to the fresh one ($RC_{30}G_0$). In terms of displacement adding glass content doesn’t create a significant effect on concrete.

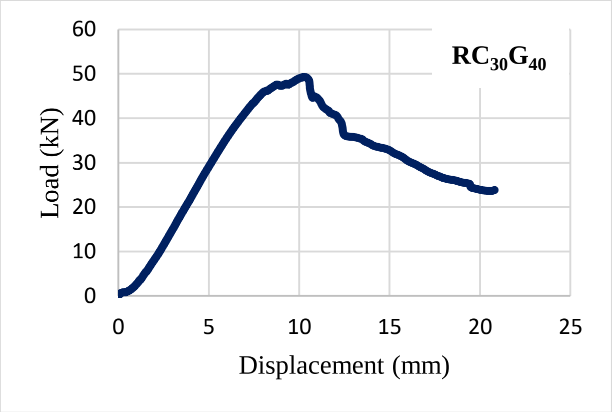

$RC_{30}G_{0}$
Load (kN)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
Displacement (mm)

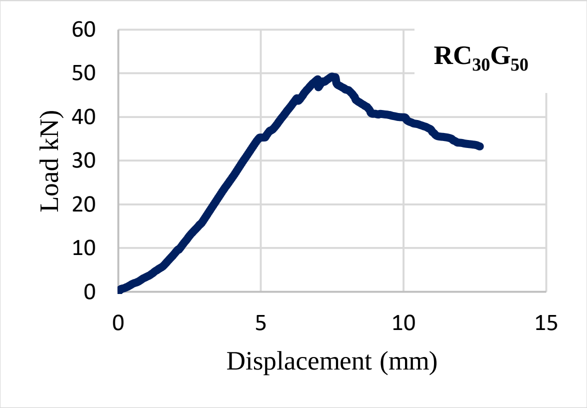

$RC_{30}G_{10}$
Load (kN)
60
50
40
30
20
10
0
0
5
10
15
Displacement (mm)

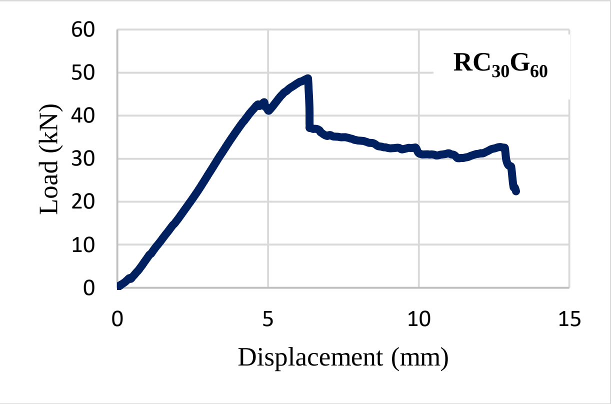

$RC_{30}G_{20}$
Load (kN)
60
50
40
30
20
10
0
0
5
10
15
Displacement (mm)


$RC_{30}G_{25}$
Load (kN)
60
50
40
30
20
10
0
0
5
10
15
20
Displacement (mm)


$RC_{30}G_{30}$
Load (kN)
63
53
43
33
23
13
3
1
6
11
16
Displacement (mm)


$RC_{30}G_{40}$
Load (kN)
60
50
40
30
20
10
0
0
5
10
15
20
25
Displacement (mm)


$RC_{30}G_{50}$
Load kN)
60
50
40
30
20
10
0
0
5
10
15
Displacement (mm)


$RC_{30}G_{60}$
Load (kN)
60
50
40
30
20
10
0
0
5
10
15
Displacement (mm)

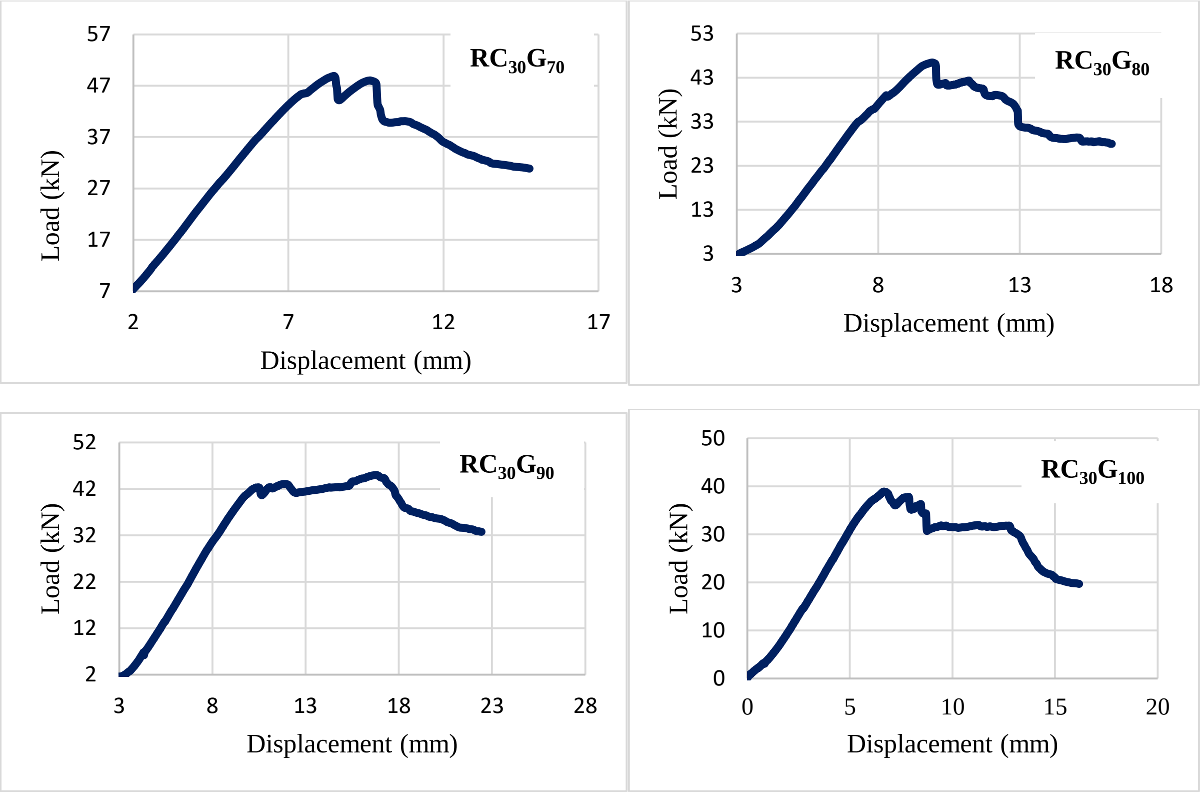
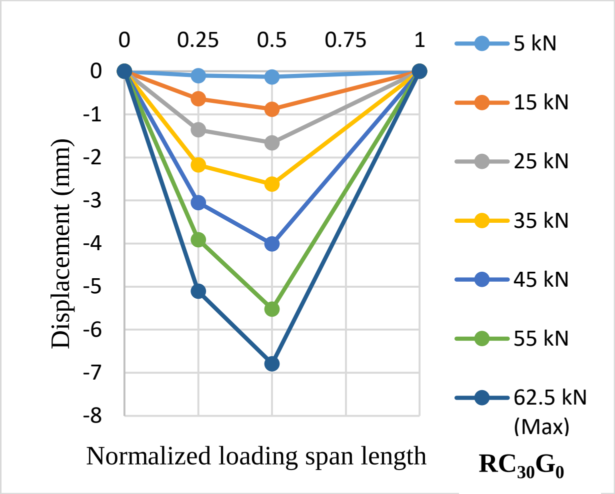
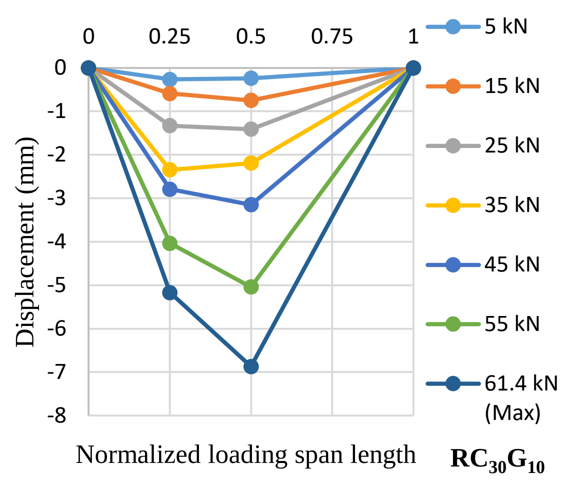


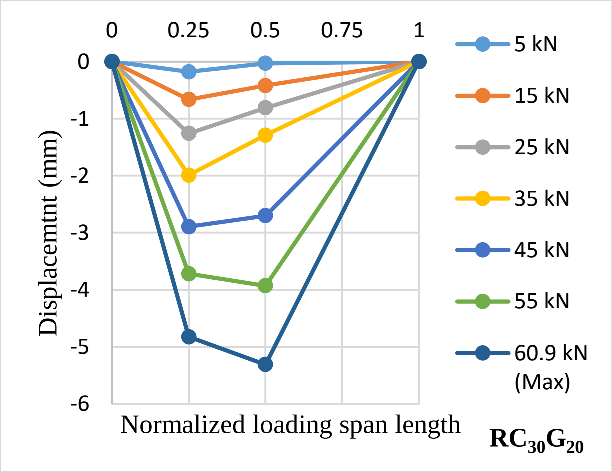
Fig.5.1 Load - Deflection behavior of RC beam

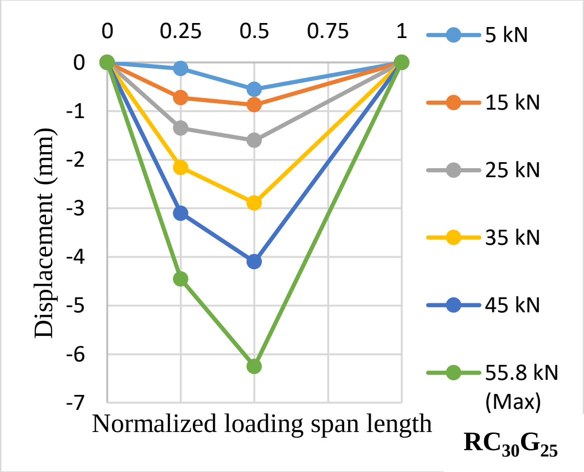
Fig.5.2 shows load and deflection data from LVDT for mid and left portions. As discussed in the methodology chapter test setup part two LVDTs have been set in times of testing. One is under the midpoint of the beam span and another one is left mid part of the beam. Almost all specimen indicates that the major failure was done by flexure and then shear failure also occurred sometime. Ultimate load carrying capacity has been decreased with the increasing percentage of glass content. Maximum deflection occurs at the mid-point or near to mid-point. Experimental results show that the load-deformation behavior of RCG beams is slightly different. For the $RC_{30}G_0$ beam, the highest load has been taken which is 62.5 kN with a displacement near 6.79mm at the mid-point. After that, due to adding glass content, the load-carrying capacity started to decrease gradually with an increasing number of cracks developed in the tested beam specimens. With further increase in the applied load, the longitudinal reinforcements start to yield and then the slope of the curves significantly declines beyond the yielding point. In this stage, with a small increment in the applied load, the deflection suddenly increases and reaches up to the maximum load-carrying capacity when the concrete crushing takes place with an abrupt drop in the load level. On the other hand, from the LVDT data $RC_{30}G_{10}$, $RC_{30}G_{20}$, and $RC_{30}G_{25}$ beams, it is observed that the ability to take load decreases with the increasing amount of glass which is 1.76%,2.56%, and 10% respectively. For $RC_{30}G_{50}$

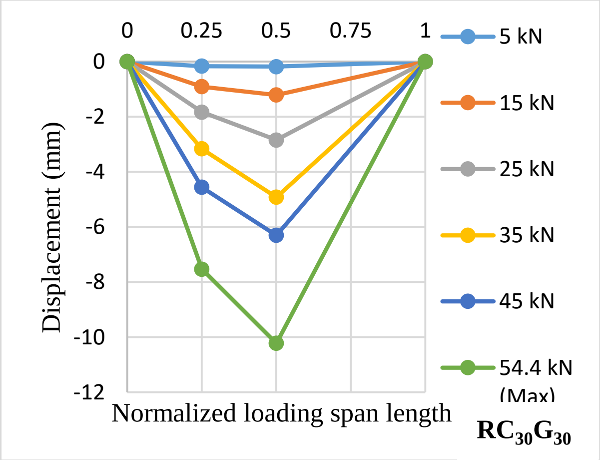
and $RC_{30}G_{100}$ load carrying capacity decreases by almost 17% and 43% respectively compared to the fresh one ($RC_{30}G_{0}$).

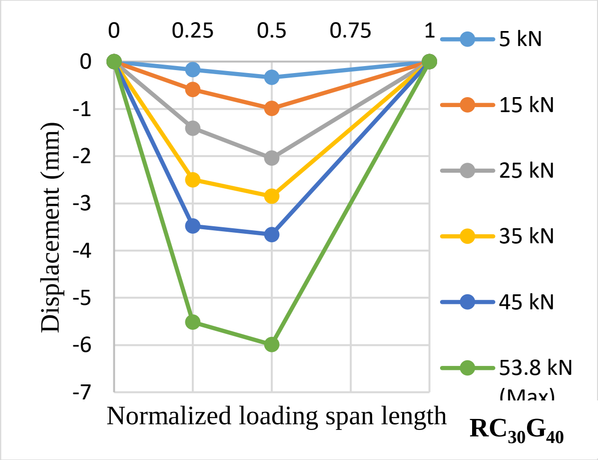












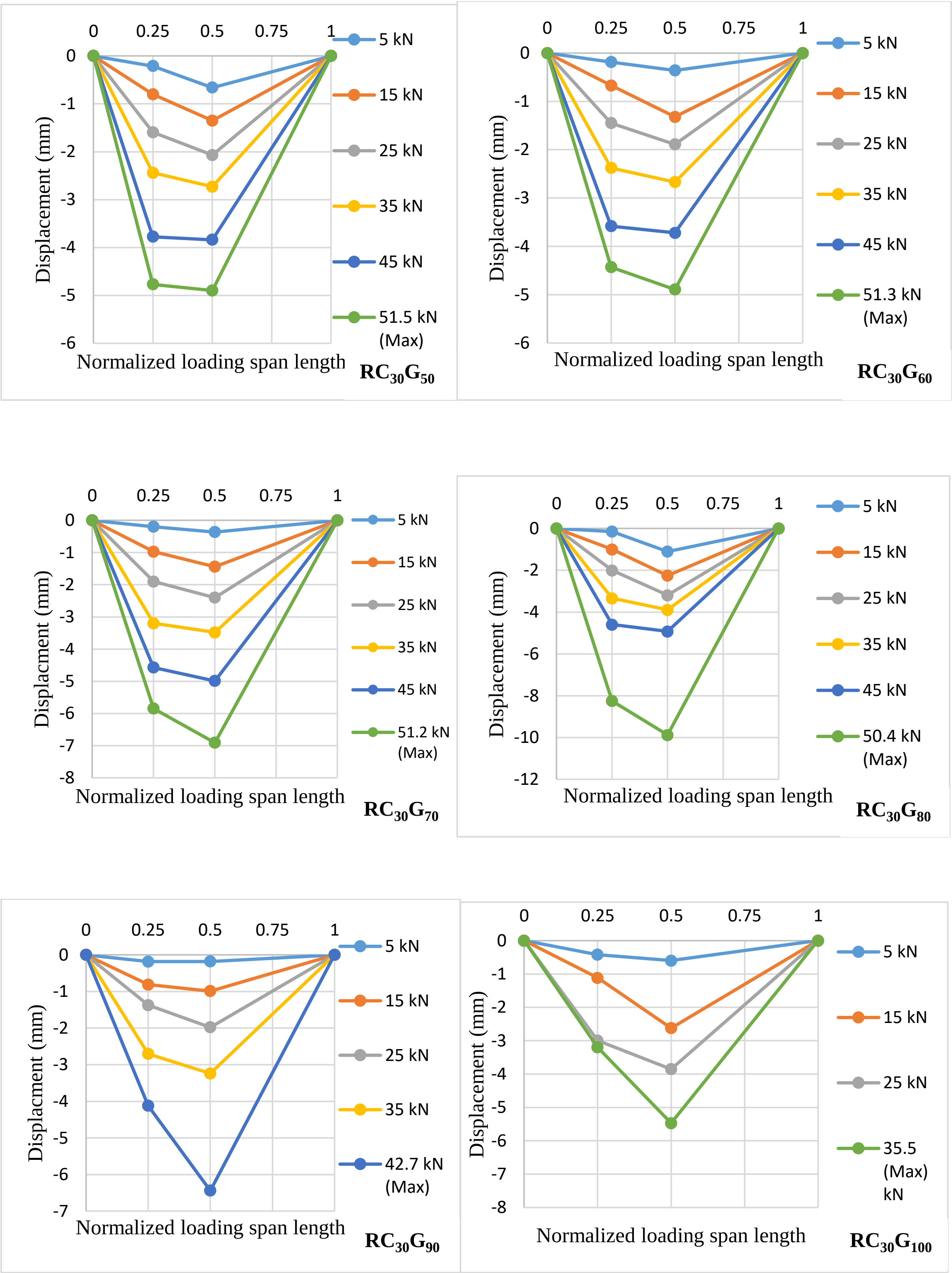
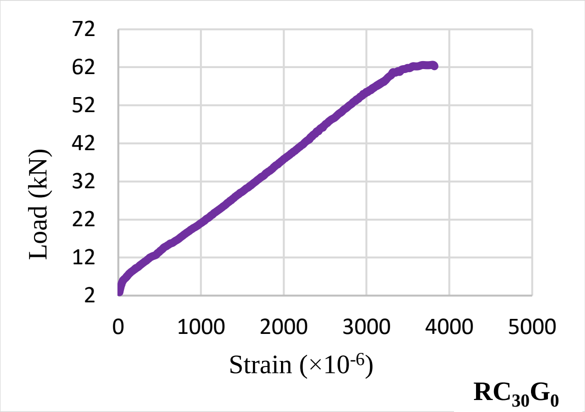
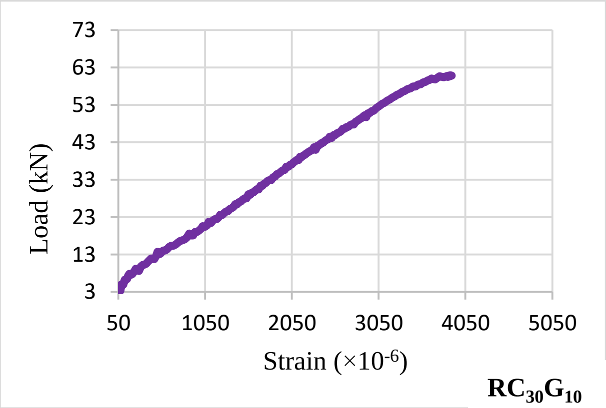


Fig. 5.2 Deflections from LVDT

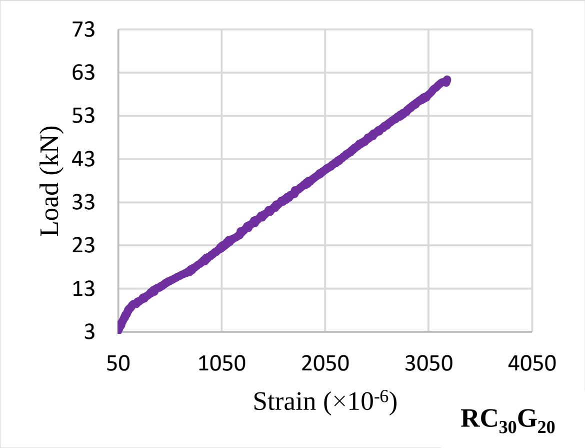
Fig.5.3 shows load and steel strain data from the strain gauge of steel. As discussed in the methodology chapter test setup a strain gauge has been set in the mid-down portion of the beam. Here Ultimate load carrying capacity has been decreased with the increasing percentage of glass content. Experimental results show that the load-strain behavior of RCG beams is slightly different. For the $RC_{30}G_0$ beam, the highest load has been taken which is 62.57 kN with a strain near to 0.004. That means steel crossed its yield limit. After that, due to adding glass content, the load-carrying capacity decreased gradually with an increasing number of cracks developed in the tested beam specimens. With further increase in the applied load, the longitudinal reinforcements start to yield and then the slope of the curves significantly declines beyond the yielding point. On the other hand, from the Strain gauge data $RC_{30}G_{10}$, $RC_{30}G_{20}$, and $RC_{30}G_{25}$ beams, it is observed that the ability to take load decreases with the increasing amount of glass which is 2.81%,3.03%, and 11% respectively. For $RC_{30}G_{50}$ and $RC_{30}G_{100}$ load carrying capacity decreases by almost 15% and 38% respectively compared to the fresh one ($RC_{30}G_0$).



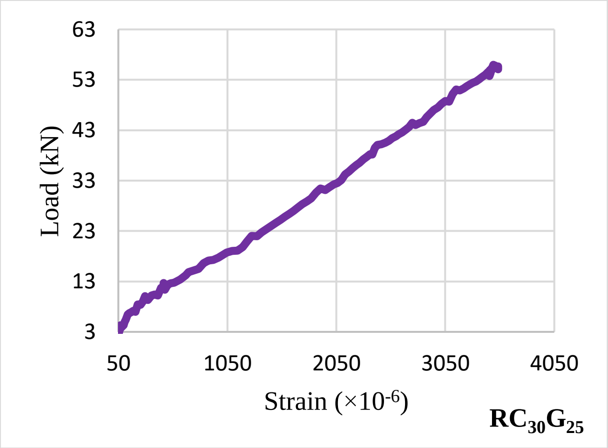
$RC_{30}G_0$



$RC_{30}G_{10}$



$RC_{30}G_{20}$



$RC_{30}G_{25}$

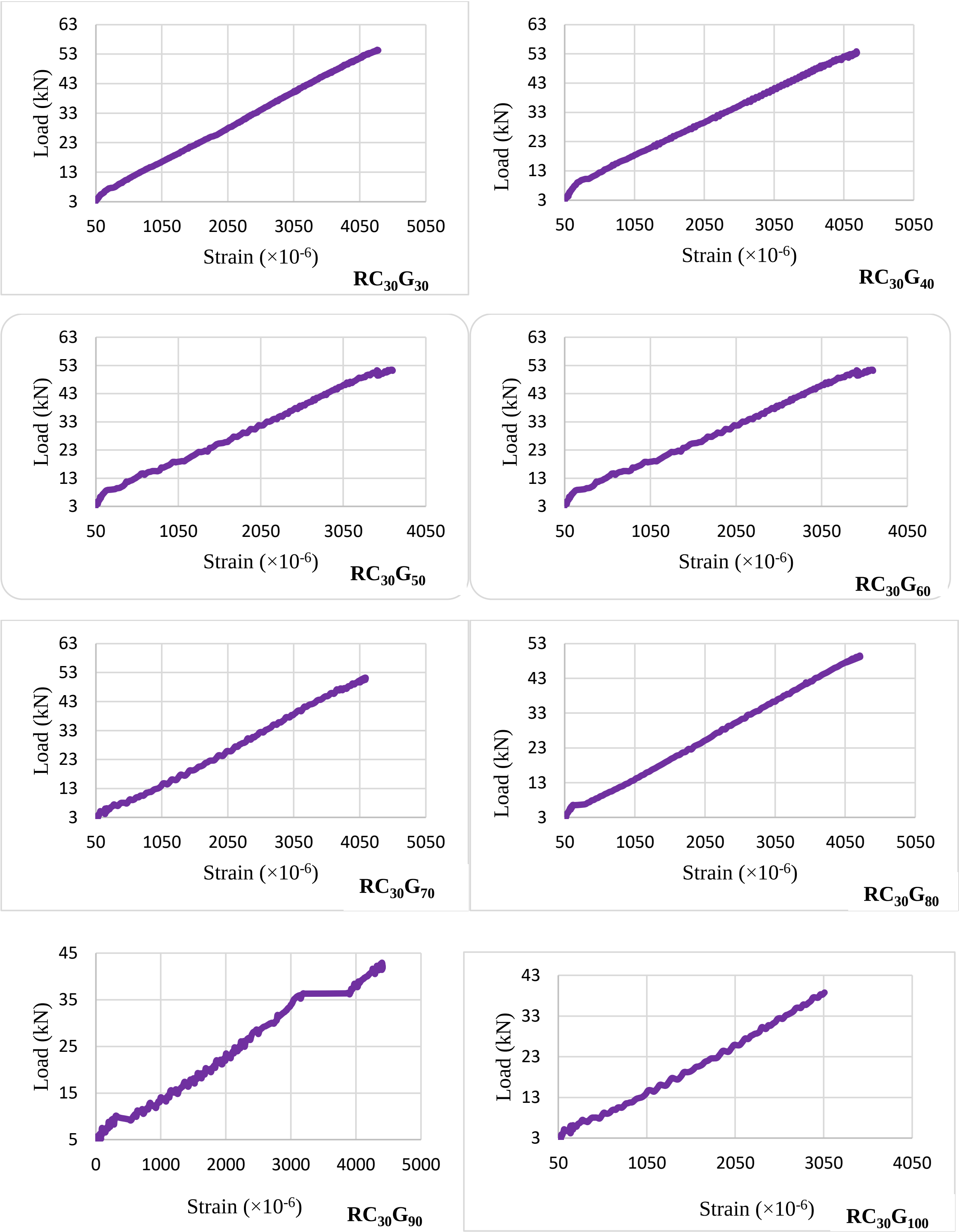


Fig 5.3. Strain Gauge data (Load Vs Strain)

5.3 Crack Pattern of RC Beam

The structural design of this beam target was to ensure the crack flexure fast and after some time finally shear crack also formed. Fig.5.4 shows the crack formation of $RC_{30}G_{80}$ specimen. Cracks no. are set serially with time in the time of formation. The first series of cracks has been marked as flexural cracks and at the last some shear cracks also formed. More or less crack pattern is almost similar for all the batches for the RCG specimen. There is no huge difference in cracks due to changing glass content. Almost similar cracks have occurred in all samples. Fig.5.5 shows the crack pattern of twelve batches.

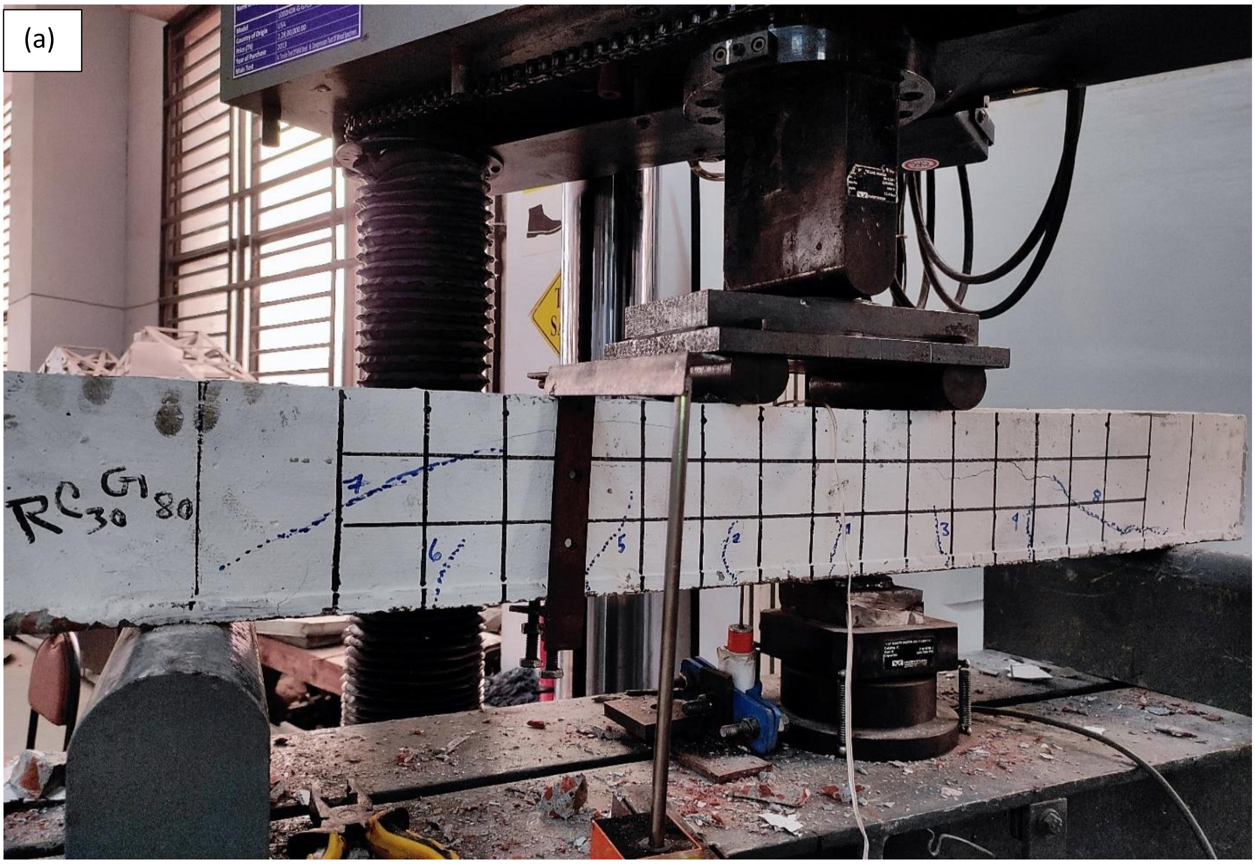


Fig.5.4 Crack Pattern of $RC_{30}G_{80}$ beam

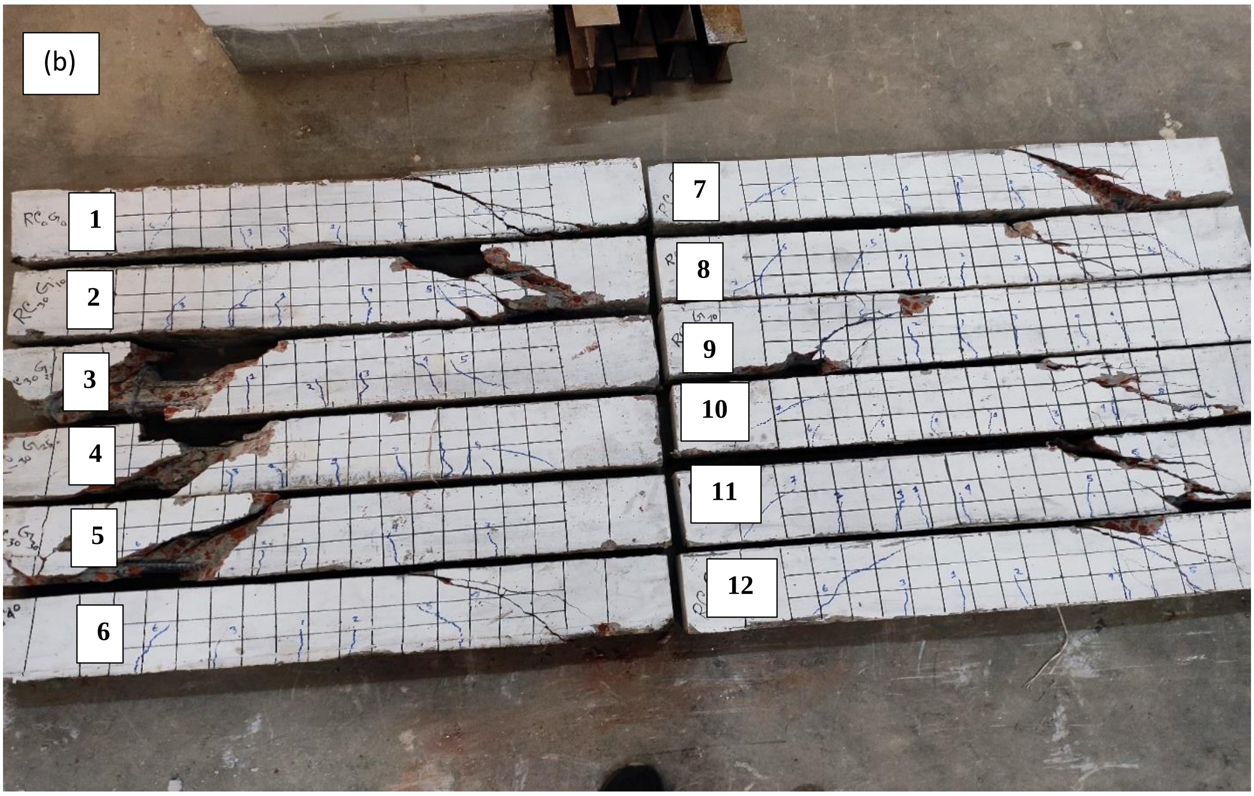


Fig.5.5 Crack of RCG beam Specimen

5.4 Flexural Strength of RCG beam

As per ASTM C 78 flexural strength of RCG beam has been done. From the experimental result of UTM and written data at the time of testing Cracking load, yielding load, and Ultimate load have been noted. From there moment is calculated. Table 5-1 shows the value of moment capacity in cracking, yielding, and ultimate according to their batch. Reinforcement is used as per the requirement of moment and shear. Here the variation of flexural capacity changing trend is quite different from the prism beam specimen. Flexural capacity decreased from the beginning of adding glass content. Ultimate capacity has decreased by 8.5%,9%, and 10% for the replacement of glass content 10%,20% and 25% respectively. For batch no.7 ($RC_{30}G_{50}$) strength has decreased 16% compared to the fresh one. Even for batch no.12 ($RC_{30}G_{100}$) strength has decreased by 33.92% compared to batch no.1. Fig.5.6 shows the trend of changing the ultimate flexural capacity of the RCG beam. Overall a decreasing trend has been shown for adding glass. Maybe the bonding between reinforcement and glass content has an effect on overall strength performance.

Table 5-2 shows the equation for calculating theoretical moment capacity according to ACI-318-14. Fig.5.7 reports the ratio of the ultimate experimental moment capacity to the ultimate moment capacity recommended by the ACI-318-14 code. The comparison reveals that the experimental ultimate moment capacity for RCG beams is near to the predicted moment capacity obtained from the ACI code. This difference may arise from the fluctuation of design concrete and steel strength from the actual strength.

Table 5-1: Flexural capacity of RCG beam

Specimen	Force, (kN)			Moment Capacity, (kN-m) ,		
	Cracking, Pcr	Yielding, Py	Ultimate, Pu	Cracking, Mcr	Yielding, My	Ultimate, Mu
RC$_{30}$G$_{0}$	17.49	43.77	58.29	3.06	7.65	10.20
RC$_{30}$G$_{10}$	14.92	39.88	53.32	2.61	6.97	9.33
RC$_{30}$G$_{20}$	14.80	39.53	52.70	2.59	6.91	9.22
RC$_{30}$G$_{25}$	14.76	39.32	52.5	2.58	6.88	9.18
RC$_{30}$G$_{30}$	13.98	38.01	50.73	2.44	6.65	8.80
RC$_{30}$G$_{40}$	13.70	36.78	49.05	2.39	6.43	8.58
RC$_{30}$G$_{50}$	13.56	36.51	48.4	2.37	6.38	8.47
RC$_{30}$G$_{60}$	13.56	36.31	48.3	2.37	6.35	8.45
RC$_{30}$G$_{70}$	13.30	35.41	47.22	2.32	6.19	8.26
RC$_{30}$G$_{80}$	12.75	34.11	45.48	2.23	5.96	7.95
RC$_{30}$G$_{90}$	12.22	33.27	44.38	2.13	5.82	7.76
RC$_{30}$G$_{100}$	10.8	28.22	38.56	1.89	4.93	6.74

Table 5-2: Ultimate moment capacity equation (ACI-318-14)

Code	Year	Equation for Mu
ACI-318	2014	$\rho_s = \frac{A_s}{bd}$; $\alpha = 0.85$ $M_u = \rho_s f_s b d^2 (1 - \frac{\rho_s f_s}{2 \times \alpha_1 f_c'})$

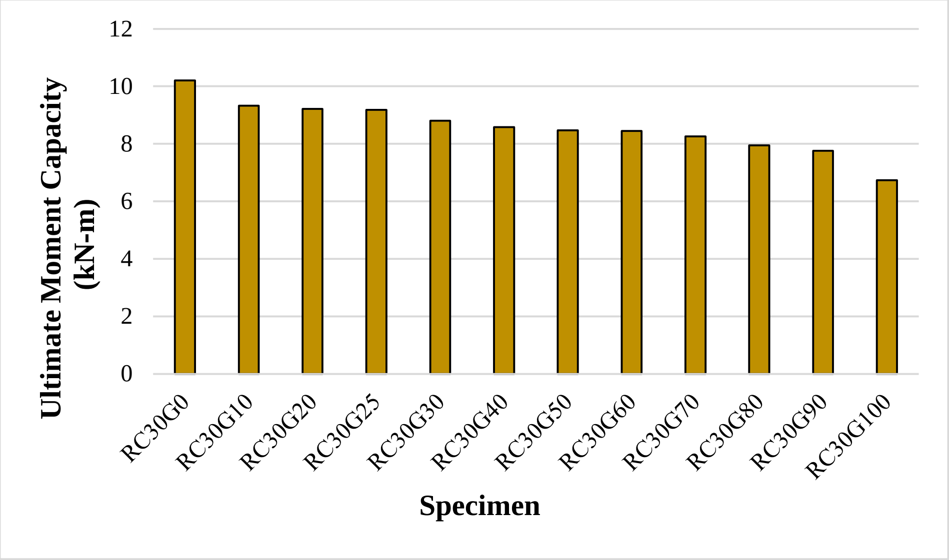


Fig.5.6 Ultimate moment capacity of RCG beam

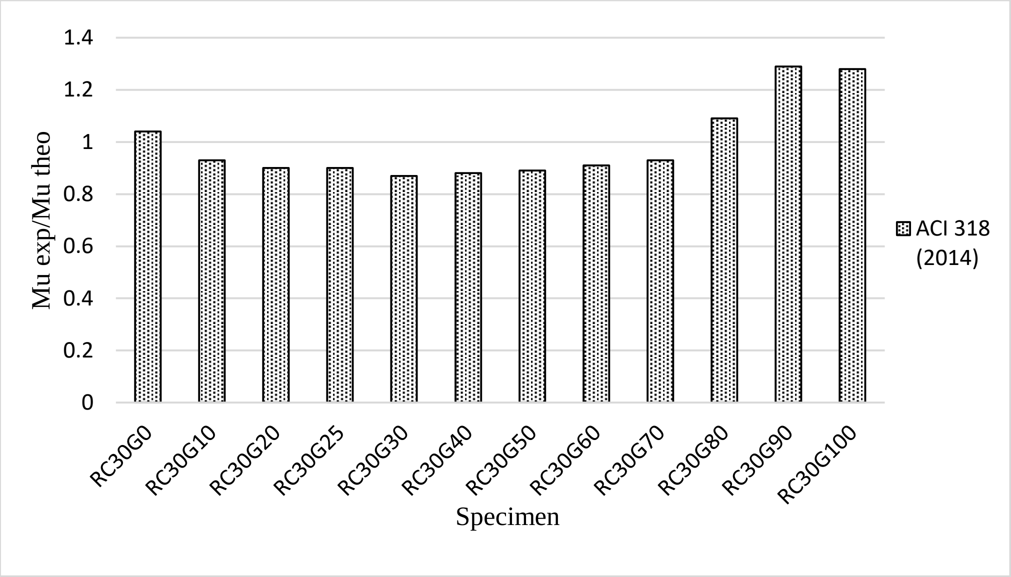


Fig.5.7 Comparison of Ultimate moment capacity of RCG beam with ACI-318 (2014)

5.5 Summary

The flexural response of the RCG beam is the main topic of discussion in this chapter. That was the last objective of this study. This data was obtained using LVDT data that was set in the mid and left-mid of the beam. A number of data points from LVDTs have been given, including displacement with distance and load changes. Additionally, the UTM data has demonstrated the behavior of the beam's load deflection. In this chapter, steel strain gauge data is also examined. From the commencement of the glass addition, strength began to decline in this section. This chapter's synopsis can be expressed as follows:

a) For the $RC_{30}G_0$ beam, the highest load has been taken which is 58 kN with a displacement near to 6mm based on UTM data. After that, due to adding glass content, the slope of the load-deflection curve starts to decrease gradually with an increasing number of cracks developed in the tested beam specimens. The bonding between the reinforcement and glass content may affect on strength.

b) For the $RC_{30}G_0$ beam, the highest load has been taken which is 62.5 kN with a displacement near 6.79mm at the mid-point based on LVDT data. After that, due to adding glass content, the load-carrying capacity started to decrease gradually with an increasing number of cracks developed in the tested beam specimens.

c) Experimental results show that the load-strain behavior of RCG beams is slightly different. For the $RC_{30}G_0$ beam, the highest load has been taken which is 62.57 kN with a strain near to 4000×10^{-6} based on strain gauge data. After that, due to adding glass content, the load-carrying capacity decreased gradually with an increasing number of cracks developed in the tested beam specimens. Most of the failure showed that steel reaches its yield point and then cracks the concrete.

d) In terms of LVDT, UTM, and strain gauge data, the load carrying capacity of RCG is reduced by 1%-8% for adding glass content up to 20% replacement. The bonding between reinforcement and glass has an effect on flexural strength.

e) In terms of the crack pattern most of the cracks are in the flexural zone and some cracks are the combination of flexural and shear crack.

f) In terms of code comparison, the experimental ultimate moment capacity for RCG beams is near the predicted moment capacity obtained from the ACI-318-14 code. Some differences may arise from the fluctuation of design concrete and steel strength from the actual strength.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 General

A mix design of a total of fifteen different mixtures is planned with a comprehensive test matrix. To fulfill the first two objectives of this research a series of experimental investigations are conducted to determine the physical mechanical and strength properties of RBA-based waste glass concrete. The physical properties of concrete such as specific gravity, workability, fineness, flow, air entrainment, and permeability tests are conducted following respective ASTM guidelines. After assessing the basic physical properties, cylindrical specimens are prepared to conduct compression, split tensile, and flexural behaviour of RBC with glass following ASTM C39, ASTM C496, and ASTM C78 respectively. A batch of control specimens is prepared and tested to compare the properties of recycled batches. The strength tests are performed at 7 days, 28 days, and 56 days. In addition, UPV tests have been conducted on each sample of different batches. Microstructural properties of RBA based WG concrete are also examined. Finally, some reinforced beam specimens are prepared for further bending tests to understand the behaviour of reinforced concrete beams following ASTM C 293 ultimately demonstrating the potential structural application of concrete containing RBCA and WGP.

6.2 Conclusions

Based on the conducted experimental investigations, the key findings of this study are as follows

a) Workability was seen to be reduced with the increased percentage of glass content (up to 20%) ($RC_{30}G_{20}$). It then started to grow after that. The amount, types, and shape of glass particles have impacts on the workability and flowability of RCG concrete.

b) Adding glass content up to 20% provides 12.5% higher compressive strength than that of without glass. However, the strength decreases with the further addition of glass content in the mix. Similar trends have been followed for the split tensile strength of RCG.

c) For the addition of glass up to 20%, an increment of density was observed as high as 10% compared to that of the control specimens.

d) According to Scanning Electron Micrographs (SEM) larger voids and fissures are shown as glass content increases. However, SEM showed a denser structure, fewer voids, and fissures up to 20% glass content. It is possible to propagate the Alkali-Silica Reaction in the hardened concrete.

e) For the $RC_{30}G_0$ beam, the highest load has been taken which is 62.57 kN with a strain near to 4000×10^{-6} based on strain gauge data. After that, due to adding glass content, the load-carrying capacity decreased gradually with an increasing number of cracks developed in the tested beam specimens.

6.3 Recommendations for Future Research

Based on the literature review and this research there is more scope of work on RCG concrete. Recommendations for future research can be:

a) Based on size, shape, texture and type of glass strength can be different for RCG. Fresh and hardened properties of concrete may vary with those properties. Those effects can be scrutinized for a wide variety of applications of waste glasses.

b) Due to some pozzolanic action of glass, it can be used as a replacement of cement up to a specific percentage. The production process of cement affects our environment and a replacement may contribute to the sustainability of the environment.

c) The effect of superplasticizers and admixtures on RG concrete can be an interesting topic to investigate. The application of admixture may open the window to add a higher percentage of waste glass in concrete with desired mechanical properties.

d) The application of RG concrete in concrete structures has not been investigated yet. The flexural and shear behavior of concrete beams or the axial response of concrete columns containing RG concrete has not been investigated comprehensively.

e) Using the existing test data, artificial intelligence can be another option to figure out the optimum percentage of RG for the best mechanical properties. In addition, individual ingredient dependencies of the strength parameter through machine learning can be a good scope of research.

f) The durability of RG concrete is a major concern as there is a major concern of alkali-silica reaction. Weather effects like salinity and snowfall on RG concrete can be a research opportunity.

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