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Effect of crushed waste glass as partial replacement of natural fine aggregate on performance of high strength cement concrete

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Abstract. Disposal of industrial waste in cities where municipal authorities permitting higher floor area ratio coupled with increasing living standards, a lot of demolition waste is being generated. Its disposal is a challenge particularly in megacities where no landfills are available. The ever-increasing cost of building construction materials also necessitates consuming demolition wastes in a useful manner to save fresh natural raw materials. In the present work, the crushed waste glass is used in high-strength concrete as a partial replacement of fine aggregate. The control concrete of grade M60 was proportioned following BIS 10262-2009. The crushed waste glass has been used as a partial replacement with varying percentages of 10, 20, 30, and 40% by weight of fine aggregate. Experimental tests were carried on the fresh and hardened state of the concrete. The effect of crushed waste glass on the workability of the concrete has been investigated. Non-destructive tests, acid attack tests, compressive strength, split tensile strength, and X-ray diffraction analysis was carried out for the control concrete and concrete containing crushed waste glass after 7, 28, and 270 days of normal curing. The results show that for the same w/c ratio, the workability of concrete increases with increasing replaced crushed waste glass content. However, the decrease in compressive strength of the concrete after 28 days of normal curing and further after 28 days of acid attacks, up to 30% replacement level of fine aggregate by the crushed waste glass is insignificant.

Keywords: admixture; concrete; crushed waste glass; durability; X-ray diffraction analysis

1. Introduction

1.1 Background

The Joint Research Commission (JRT 2010) stated that the structural form of glasses is the same as liquids. At ambient temperature, they react to the impact of force and elastic deformation and behave as solids. The India Brand Equity Foundation (2019) mentioned that the glass is an inorganic material that is usually manufactured by melting a mixture of silica (sand 75%), soda (15%), and calcium compound (10%) with suggested metallic oxide and serve as a coloring agent. Major countries producing glasses are Germany, the USA, UK, China, and Japan. According to Glass Industry - FY19 update (Care Ratings Professional Risk Opinion 2018) the glass manufacturing

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companies generates yearly revenue of USD 90bn, with leading exporter being Germany, France, US, Japan, and China. The most common products of glass firms are flat glass, glass containers, fiberglass, and other products. Many industrial firms generated waste and its increment causes many environmental problems. Glass with its different varieties could be one of these waste products, classified as non-biodegradable material and impart sustainable environmental impact (Park *et al.* 2004). During the last decades, different varieties of waste in the size and form of aggregates such as recycled concrete aggregate, red bricks, ceramic tiles, and waste glass, and other solid waste has been utilized as partial or full substitution of natural aggregate in the production of concrete (Sato *et al.* 2009).

1.2 Literature review on crushed waste glass

This paper reported on the utilization of beverage glass as a partial replacement of fine aggregate in concrete. The waste glass was replaced with varying percentages of 0, 18, 19, 20, 21, 22, 23, and 24% by weight of fine aggregate. The waste glass had a specific gravity of 2.39 with 150-600 µm particle size. Crushed waste glass concrete was tested for fresh and hardened states at 7, 28, and 90 days. It was reported that workability decreased with increasing waste glass content. Replacement of fine aggregate with a crushed waste glass of 18-20% improved the compressive and flexural strength with respect to control concrete Bisht and Ramana (2018); (Bisht *et al.* 2020). This paper studied waste glass cullet and glass powder as partial replacement of fine aggregate and cement in precast concrete paving blocks of size 100 mm×200 mm×60 mm. The beverages glass was the source of this waste. The specific gravity of the waste glass was 2.48 and the size of the particle varied from 0-5 mm. Waste glass cullet replaced with varying percentages of 0, 25, 40, 55, and 70% by weight of fine aggregate, whereas, glass powder of particle size of 47.9 µm was replaced by 20% of cement weight. Density, water absorption, compressive strength, dry shrinkage, and alkali-silica reaction were tested for 7, 14, 21, and 28 days. It was reported that density and water absorption decreased with increasing glass cullet content and 20% replacement of glass powder led to the highest reduction in density as well as water absorption of concrete. The waste glass cullet with a higher dosage did not make a considerable negative effect on the compressive strength of the paving block (Lu *et al.* 2019). This paper reported on the durability of concrete with replaced heavyweight cathode ray tube waste glass by weight of fine aggregate with a specific gravity of 3 and of particles size 5 mm. Different w/c ratios of 0.35, 0.45, and 0.55 were used in this research work. Fine aggregate was replaced with varying percentages of 0, 50, and 100% by weight of crushed waste glass. Slump, air content, compressive, flexural strength, water absorption, and sulfate attack tests were carried out at 28, 56, and 91 days. It was reported that slump and air content increased, however, compressive strength and flexural strength decreased with increasing waste glass content (Kim *et al.* 2018). This paper illustrated the utilization of bottles of waste glass as partial replacement of 0, 30, 50, and 70% by weight of fine aggregate on mechanical properties of concrete. The waste glass had a specific gravity of 2.5 with 5 mm particle size. Also, styrene-butadiene rubber as an additive was utilized by weight of cement with varying percentages of 0, 5, 10, and 20%. Slump, air content, compressive, tensile, and flexural strength were found after 1, 4, and 13 weeks of casting. It was reported that the slump and air content decreased with a higher dosage of waste glass content. Compressive, tensile, and flexural strength of concrete reduced with increasing waste glass content. A dose of 10% carboxylate styrene-butadiene copolymer (SBR) latex of cement was reported most effective for strength enforcement. SBR also improved bond strength and chemical resistance (Park *et al.* 2004). This paper studied the influence of waste glass on the mechanical properties of concrete.

The source of waste glass with specific gravity 2.49 was bottled with green, brown, and clear colors. The fixed water-cement ratio of 0.69 was used in this study. Waste glass at a constant replacement level of 20% was used to substitute coarse and fine aggregate. Fly ash with 5, 10, and 20% was replaced by the weight of cement. Air content of fresh concrete, and specimens for dry density and compressive and flexural strength after 7 and 28 days were tested. It was reported that the waste glass significantly decreased the compressive and flexural strength and slightly increased the air content with and without fly ash and micro silica Almesfer and Ingham (2014). Coarse aggregate was replaced by the waste glass with varying percentages of 0, 15, 30, 45, and 60%. The specific gravity of this waste was 2.49 with particle size 4-16 mm. The source of this waste glass was soda bottles. The workability of concrete with waste glass and compressive, tensile, and flexural strength were found after 28 days. It was reported that the waste glass did not show a considerable effect on the workability of concrete. The compressive, tensile, and flexural strength of concrete decreased with increasing waste glass content Topcu and Canbaz (2004). This paper reported the mechanical properties of concrete containing waste liquid crystal display (LCD) glass as partial replacement of fine aggregate with varying percentages of 0, 10, 20, and 30% by weight of fine aggregate. LCD glass had a specific gravity of 2.45 with 3.37 mm particle size. The different water-cement ratios of 0.28, 0.32, and 0.36 were used to study the compressive strength and ultrasonic pulse velocity in self-compacting glass concrete. It was reported that the compressive strength and UPV results increased with age but decreased with increasing w/c ratio Wang and Wang (2017). The waste glass was collected from broken windows glass and crushed to the particle size of 0-1.18 mm. Fine aggregate was replaced by the weight of waste glass powder with varying percentages as 10%, 20%, 30%, and 40% for the M25 mix. Concrete specimens were tested for compressive, split tensile strength, water absorption, and density after 28 days. It was reported that 20% replacement of fine aggregate by waste glass showed a 15% increase in compressive strength at 7 days and 25% increased at 28 days. The workability of concrete increased with increasing waste glass content (Malik *et al*. 2013). This paper reported the mechanical properties of concrete containing fine waste crushed glass with a fineness modulus of 2.64. The waste glass was obtained from used windows panes. The fine waste crushed glass replaced fine aggregate by the varied percentage of 0%, 5%, 15%, and 20%. Fresh and hardened concrete was tested after 7, 14, and 28 days. The maximum Compressive strength was given by 20% replacement, whereas tensile strength decreased with increasing waste glass content. The workability of concrete increased with increasing the waste glass content with lower water absorption Abdullah and Fan (2014). Self-compacting concrete containing crushed glass obtained from glass bottles as partial replacement of river sand as fine aggregate from 0% to 50% replacement levels. The specific gravity of the crushed glass was 2.5 and 2.49 but the same particle size of 4.25 mm. It was reported that slump and air content enhanced with increasing waste glass aggregate content. However, compressive, split tensile strength, and static modulus of elasticity decreased with increasing waste glass aggregate content Kou and Poon (2009); (Sharifi *et al*. 2013). This paper reported the study on concrete with recycled glass with a specific gravity of 2.53 as fine aggregate. The recycled waste glass was utilized as sand replacement in concrete with a varied percentage of 0%, 25%, 50%, 75%, and 100%. Concrete so prepared was a test for slump and fresh density. Hardened concrete was tested for dynamic and static moduli of elasticity and drying shrinkage with three concrete grades of M30, M45, and M60 having a w/c ratio of 0.45, 0.38, and 0.32, respectively. Concrete of grade 45 was separately used to replace cement with 30% fly ash and 60% slag cement. It was reported that the glass sand had no noticeable effect on fresh and mechanical properties of concrete, only negligible reduction in fresh concrete density, a slight increase in air content, an insignificant change in a slump was observed. Waste glass sand remarkably enhanced the concrete to chloride ion penetration Du and Tan (2014). This paper reported the application of waste glass powder in the production of concrete. Container glass powder with particles finer than 75 µm and with 2.62 specific gravity was used in this research work. Waste glass powder with a varied percentage of 0%, 5%, 10%, 20%, and 25% by weight of cement was replaced. Concrete specimens of grade 33 MPa and 45 MPa were tested after 7 and 28 days respectively. It was reported that the waste glass powder played the pozzolanic role and had an insignificant effect on the setting time of cement. It was also concluded that 10% of glass powder as cement replacement enhanced the compressive strength by 9% and 15% of glass powder as cement additive increased concrete compressive strength by 16% (Aliabdo *et al*. 2016). This paper studied the recycling of waste glasses as a partial substitution of fine and coarse aggregate. Coarse aggregate was replaced with crushed green bottle glass with varying percentages of 33%, 50%, 67%, and 100% of 4.6 mm particle size. Whereas, the fine aggregate was totally (100%) replaced with a crushed waste glass of different grading. The fresh concrete was tested for the slump. Hardened concrete specimens were tested for compressive, split tensile, and flexural strength after 7 and 28 days. The slump test for all concrete mixes showed the same value of 100±30 mm. It was reported that the glass sand had slightly reduced the fresh density; air content and negligible difference in a slump. Waste glass sand as 100% replacement of fine aggregate, increased compressive, split tensile, flexural strength, and static modulus. Whereas, replacement of crushed waste glass of coarse aggregate decreased these strengths (Gerges *et al*. 2018). This paper reported the effect of LCD waste glass sand on the performance of concrete. LCD waste glass had a specific gravity of 2.46 with a 3.3 mm average particle size. Three different mixes grade of concrete of 21, 28, and 35 MPa were considered for investigation. Fine aggregate with varying percentages of 0, 20, 40, 60, and 80% was replaced by LCD waste glass. The slump and compressive strength of concrete decreased with increasing LCD crushed waste glass content Wang (2009). This paper studied the macro and micro properties of concrete containing LCD glass sand and powder. LCD glass sand had a specific gravity of 2.45 with a 3.37 mm average particle size. Cement with varying percentages of 0, 10, 20, 30, and 40% was replaced by waste LCD glass powder, and natural sand was replaced by waste LCD glass sand with 0, 10, 20, and 30%. The setting time and compressive strength increased with increasing LCD glass powder content. Slump decreased with increasing waste LCD glass sand content (Yung *et al*. 2014). This paper studied the effect of waste glass powder as a partial replacement of cement with a varying percentage of 0 to 30%. The sources of this waste were bottles, transparent glass, and scrap glass with a specific gravity of 2.5, 2.5, and 2.54, respectively. This waste had a particle size of 63, 250, and 10.9 µm. The workability of concrete decreased with increasing glass powder content. Glass powder with 30% replacement level increased the compressive strength of concrete. The glass powder improved mechanical properties similar to that of class F fly ash and gave a better result than ground granulated blast furnace slag and FFA in terms of permeability reduction (Mosaberpanah *et al*. 2018; Rahma *et al*. 2017; Zidol *et al*. 2017). White, green, and brown colors of crushed waste glass with varying percentages of 10%, 30%, and 100% by weight of fine aggregate were utilized in cement mortar to investigate its alkali-silica reaction and strength performance. It was found that ASR was marginally noticed. Crushed waste glass with 30% substitution gave similar strength to that of reference mortar. Whereas, 100% replacement of fine aggregate by waste glass exhibited a higher loss of flexural strength than compressive strength. Natural fine aggregate with various percentages of 10, 20, and 30% was replaced by windows waste glass in concrete. Concrete was tested at fresh state for workability and hardened state for water absorption and strength performances after 1, 3, 7, and 28 days of normal curing. The higher replacement level of waste glass reduced the workability. Water absorption of concrete increased with the replaced waste glass. The waste glass had an insignificant influence on strength performance (Degirmenci *et al*. 2011). Natural fine aggregate with varying percentages of 5, 10, 15, and 20% was replaced by the crushed waste glass from food, medicine, and cosmetics bottles in cement mortar. The addition of crushed waste glass declined the density of mortar. Moreover, a higher replacement level of waste glass enhanced the strength property of cement mortar (Meddah 2019). Cement was replaced by an equal amount of recycled waste glass in cement mortar. It was concluded that 20% of cement can be substituted by a waste glass of particle size 20 µm to gain a similar strength to the reference mix. A higher substitution level than 20% of waste glass caused a dilution effect on cement mortar (Małek *et al*. 2020). (Steyn *et al*. 2020) This study aimed to investigate the effect of waste glass and rubber as partial replacement of natural fine aggregate on fresh and hardened properties of concrete. Fine aggregate was replaced by waste glass and rubber with 15% and 30% by weight. It was reported that the addition of both types of waste declined the slump measurements. Waste glass improved concrete strengths. Whereas, waste rubber exhibited an equal result of 28 days compressive strength to that of reference concrete but decreased its tensile strength. The waste glass in concrete showed higher resistivity in contrast to water absorption than concrete produced by rubber. (Khan *et al*. 2021) This paper studied the alkali-silica reaction of the glass waste in alkali-activated concrete. In this study, 100% of glass waste was utilized as natural fine aggregate. ASTM C1293 concrete prism test was performed to evaluate the ASR of waste glass in AAC. It was found that one-year expansion of OPC-based concrete and ground granulated blast furnace slug-based alkali-activated concrete were found to be 0.21% and 0.13%, which exceeded the values given in the ASTM code of practice. Fly ash-based AAC and FA-GGBS based AAC enjoyed one-year expansion within the ASTM standard. (Yang *et al*. 2020) This paper assessed ASR by conducting a laboratory test on the dry-mixed concrete blocks following ASTM C1260 and ASTM C227 standards. Long-term field tests assessment showed that exterior-glass alkali-silica reacted gel was found on old blocks due to slowed rate of concrete in the field and mitigate the formation of interior-glass ASR gel in the dry-mixed concrete blocks. (Shayan 2002) In this research work, cement, fine, and coarse aggregates were replaced by waste glass powder, fine glass, and coarse glass aggregate with varying sizes of 12 µm, 4.75 mm-0.15 mm, and 12 mm-4.75 mm respectively. It was reported that the fine and coarse aggregate could be replaced by 50% to gain the

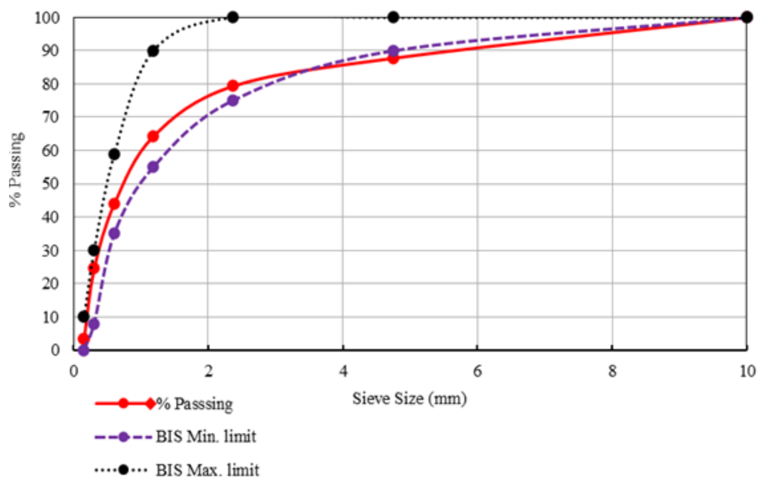


Fig. 1 Sieve analysis of natural fine aggregate

Table 1 Physical properties of OPC cement

S. No.	Property	Result		Requirements as per BIS
1	Standard consistency	30%		-
2	Initial setting time	156 minutes		Not less than 30 mins
3	Final setting time	408 minutes		Not more than 600 min
4	Specific gravity	3.1		-
5	Fineness	98%		Less than 10%
6	Compressive strength	3 days	22 N/mm^2	
		7 days	33.6 N/mm^2	
		28 days	46.6 N/mm^2	

Table 2 Sieve analysis of crushed waste glass

IS Sieve size	Weight of crushed waste glass retained				% Retained	Cum % retained	% Passing
	Sample No.						
	I	II	III	Avg			
1	2	3	4	5	6	7	8
10	0	0	0	0	0	0	100
4.75	112	123	0	117.5	11.75	11.75	88.25
2.36	96	84	0	90.0	9.00	20.75	79.25
1.18	201	186	0	193.5	19.35	40.10	60.00
600	134	130	0	132.0	13.20	53.30	46.70
300	276	288	0	282.0	28.20	81.50	18.50
150	70	74	0	72.0	7.20	88.70	11.30
Pan	111	115	0	113.0	11.30	100.00	0.00
Fineness modulus, ∑Cum % retained/100=296.1/100=2.96						296.10	-

Table 3 Physical properties of F.A, C.A and CWG

S/No.	Property	Test result		
		F.A (Zone II)	C.A	CWG (Zone II)
1	Specific gravity	2.60	2.74	2.65
2	Fineness modulus	2.96	8.90	2.96
3	Water absorption	0.80%	0.50%	0.45%
4	Moisture content	0.25%	0.30%	0.20%

acceptable limit of strength enhancement. It was also concluded that the utilization of glass in the form of powder would minimize the expansion of ASR gel in the presence of aggregate. (Sobolev *et al*. 2007) This paper studied the use of waste glass on ECO-Cement. 70% of Portland cement was substituted by waste glass powder. Flexural and compressive strength at 50% replacement level of waste glass was similar to that of normal cement mortar. SEM analysis uses to detect the densified layer around the glass particles due to partial hydration of glass and formation of an additional

(a) Waste tubular glass

(b) Crushed waste glass

Fig. 2 Waste glass and its crushed particles

calcium silicate hydrate gel. (Walczak *et al*. 2015) Waste glass was utilized in autoclaved aerated concrete (AAC) to investigate its strength property and morphology. Fine aggregate was replaced by CRT glass, glass cullet, and calsiglass with varying percentages of 5% and 10% for CRT glass and 1, 3, 5, and 10% for cullet glass and calsiglass respectively. Strength enhancement of AAC with CRT glass and cullet glass are reported of similar to the reference AAC. The presence of glass powder is the main cause of strength development. Recycled waste glass was partially utilized in concrete to study its effect on strength improvement. Fine aggregate with varying percentages of 10, 20, and 50% were substituted by the waste glass. It was reported that 10% of waste glass imparted higher strength than control concrete.

2. Materials

In this study Ordinary Portland Cement of grade 43, fresh lot of wonder brand confirming to BIS 8112 (BIS 2013) was delivered by the supplier. The cement has been tested for its physical properties, following BIS 4031 Part 4 and 15 (BIS 1995); BIS 650 (BIS 1999), and BIS 4031 Part 5 and 6 (BIS 2000). The results are given in Table 1. Natural river sand as fine aggregate has been used in this study. Sieve analysis of this fine aggregate is shown in Fig. 1. The fine aggregates of zone II as per BIS 383 (BIS 2002). Other physical properties of fine aggregate as shown in Table 3 have been found following BIS 2386 Part 3 (BIS 2002). The crushed natural stone aggregate of particle size of 20 mm and 10 mm was used as coarse aggregate. Other properties of the coarse aggregate were found out as shown in Table 3 complying with BIS 2386 Part 3 (BIS 2002). The source of the waste glass is solar water heater glass tubes made of borosilicate glass with 2 mm thickness mounted on roof top shown in Figs. 2(a) to 2(b) and the sieve analysis is given in Table 2. The dismantled glass tubes were cleaned in clear water, dried, crushed, and sieved, and further crushed to have compatible grading with the fine aggregate to be replaced by it. The results obtained from various physical tests carried out are shown in Table 3. The polycarboxylate ether-based superplasticizer (High range water reducer) which is a new category and improved version of plasticizer is used and permits the large reduction of water due to their chemical structure BIS 19103 (BIS 2004).

Table 4 Mix proportioning for control and crushed waste glass concrete

Mix designation	Cement (kg/m^3)	F.A (kg/m^3)	C.A (kg/m^3)	CWG (%)	CWG (kg/m^3)
CWGC-0%	399	778	1058	0	0
CWGC-10%	399	700	1058	10	78
CWGC-20%	399	622	1058	20	156
CWGC-30%	399	545	1058	30	233
CWGC-40%	399	467	1058	40	311

3. Experimental scheme

3.1 Mix proportion

Concrete of grade M60 was proportioned complying with IS: 10262-2009 and IS: 456-2000. In this study, high-strength concrete of grade M60 was investigated. The binder to aggregate ratio is obtained as 1:1.95:2.65 for water to cement ratio=0.35 with a suggested dosage of PC base superplasticizer (0.45% by weight of cement). For M60 grade concrete, crushed waste glass with varying percentages of 0%, 10%, 20%, 30%, and 40% were partially replaced with fine aggregate by weight and designated as CWGC-0%, CWGC-10%, CWGC-20%, CWGC-30%, and CWGC-40%. The quantity of concrete ingredients which is required and calculated for 1m^3 of concrete mix of M60 grade are given in Table 4.

3.2 Preparation of test specimens

Standard concrete specimens of size 150 mm×150 mm×150 mm were casted for compressive strength, rebound hammer, ultrasonic pulse velocity, chloride attack, and acid attack tests. Also, standard cube specimens of size 100 mm×100 mm×100 mm were casted for correlation of the compressive strength with the standard specimen of size 150 mm×150 mm×150 mm. cylinder specimens of size 150 mm diameter and 300 mm length complying with IS: 10086-2013 were casted for splitting tensile strength.

3.3 Tests conducted

The tests on concrete specimens are conducted on its fresh and hardened state. İn fresh state concrete tested for workability whereas, in the hardened state concrete further classified and tested for destructive, non-destructive, and durability, discussed below.

3.3.1 Workability of concrete

To assess the workability of control concrete and concrete containing crushed waste glass, a test complying with IS:1199-2004 was conducted for the slump.

3.3.2 Destructive test

For evaluating mechanical properties of concrete mix, concrete cube specimens of size 100 mm×100 mm×100 mm and 150 mm×150 mm×150 mm and cylinder of size 100 mm diameter and 200 mm length were tested for compressive and splitting tensile strength confirming to IS: 516-2018


(a) Marking of specimens


(b) Rebound hammer reading

Fig. 3 Rebound hammer testing on cube specimens of size 150×150×150 mm


Fig. 4 UPV test set up

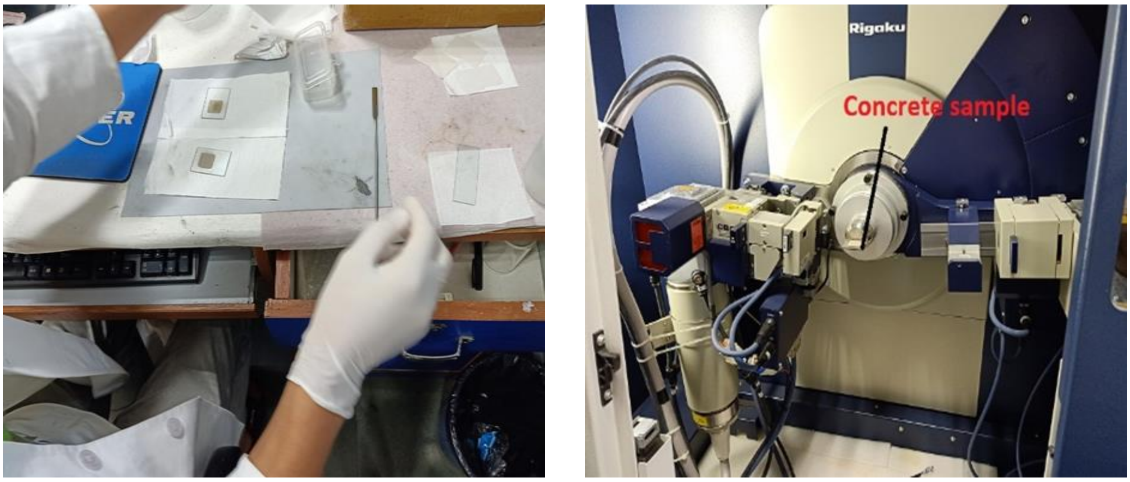
and IS: 5816-2013.

3.3.3 Non-destructive test

Non-destructive tests, namely, rebound hammer, ultrasonic pulse velocity, and X-Ray diffraction were carried out on hardened concrete specimens. The rebound hammer test is a non-destructive test that is used for assessing the likely compressive strength of concrete with the help of a suitable correlation between rebound index and compressive strength complying with BIS 13311 Part 2 (BIS 2004). In this investigation, rebound hammer tests were carried out on concrete cube specimens of size 150 mm×150 mm×150 mm for varying replacement of fine aggregate by industrial wastes used in this study. The specimens were removed from the curing tank and kept at laboratory room temperature for 24 hours, Then the specimens were marked with a grid of 3×3@37.5 mm c/c having 9 points on each of the four vertical faces with a marker. The rebound hammer results for concrete with the waste of age 28 and 270 days are discussed the test procedure are shown from Figs. 3(a) to 3(b), whereas the ultrasonic pulse velocity test assesses the quality of concrete in terms of homogeneity, presence of cracks, and voids without destructing the concrete member or structure confirming to IS: 13311 (Part 1)-2004. The specimens were removed from the curing tank and kept at laboratory room temperature for 24 hours, then pulse velocity test has been carried out on side

Table 5 Pulse velocity criterion for concrete quality grading

S. No.	Pulse velocity by cross probing (km/s)	Concrete quality grading
1.	Above 4.5	Excellent
2.	3.5 to 4.5	Good
3.	3.0 to 3.5	Medium
4.	Bellow 3.0	Doubtful



(a) (b)

Fig. 5 Samples preparation for XRD analysis

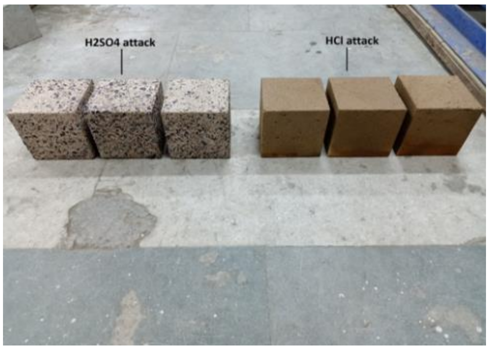
four faces of the cube specimens of size 150 mm×150 mm×150 mm, and four observations on every two opposite faces have been taken. For characterizing the quality of concrete in terms of pulse velocity, the recommendations IS: 13311 (Part 1)-2004 are given in Table 5 and the test procedure is shown in Fig. 4.

XRD analysis was carried out on both control concrete and concrete containing crushed waste glass with varying percentages of 10, 20, 30, and 40% after 28 days by Rigaku Ultima IV as shown in Figs. 5(a) to 5(b). The inner core of concrete samples was extracted and prepared in powder form passing through 90 µm IS sieve. Before the test, diffractometer operated at 40 kV, 30 mA with scan angle of 5-80 degree and scanning rate of 8 degree per minute. Match software was used to identify the crystal phase present in concrete such as quartz (SiO_2), portlandite [$Ca(OH)_2$], calcite ($CaCO_3$), alite (C_3S), belite (C_2S), and ettringite (CSA).

3.3.4 Durability test

Acid and chloride attack tests were carried out on cube specimens of size 150 mm×150 mm×150 mm after 28 days of normal curing. Figs. 19-20 show the physical appearance of control concrete and concrete containing crushed waste glass subjected to sulphate and chloride attack. From Figs. 6(a) to 6(b), it can be observed that the surface of concrete samples exposed to sulphuric acid has got severely eroded as compared to chloride attack. Calcium sulphate, a product of hydrated lime $Ca(OH)_2$ and H_2SO_4 bleaches out of exposed surfaces of concrete specimen leaving the exposed surfaces eroded. Entrapped calcium sulphate reacts with tricalcium aluminate and forms ettringite

(a)



(b)

Fig. 6 Samples immersed in H2SO4 and HCl solutions and its physical appearance after immersion

which expands and develops micro-cracks in the concrete.

Calcium chloride, a product of hydrated lime $Ca(OH)_2$ and HCl reacts with tricalcium aluminate to form calcium chloroaluminate referred to as Friedel's salt A.M. Neville (Neville 2012) is a double-layered hydroxide and capable of retaining chlorides in its crystallographic structure with concrete. This is why concrete specimens after 28 days immersion in HCl solution is almost uneroded.

The initial weight of the specimens was measured before immersion in 5% H_2SO_4 and 5% HCl solutions for an additional 28 days. The specimens were removed from the acid solutions, dried with a towel, and weighed. The percentage of loss of weight and compressive strength were measured as follows.

$$\text{Loss in weight (\%)} = \frac{W1-W2}{W1} x100 \tag{1}$$

$$\text{Loss in compressive strength (\%)} = \frac{\sigma1-\sigma2}{\sigma1} x100 \tag{2}$$

Where W1 is the weight of cube before the immersion in acid environment, W2 is the weight of cube after 28 days of immersion in acid environment, $\sigma1$ is the compressive strength of cube specimen before immersion in acid environment, $\sigma2$ is the compressive strength of cube specimen after 28 days of immersion in acid environment.

4. Results and discussions

4.1 Workability

In this study, a proper amount of polycarboxylate ether-based superplasticizer was utilized to both control concrete and concrete containing crushed waste glass aggregate. The workability of all mixes of crushed waste glass concrete with varying percentages of 0%, 10%, 20%, 30%, and 40% was determined by slump test. Fig. 7 shows the results of the concrete slump value depending on the crushed waste glass replacement ratio. From Fig. 8 it can be observed that the workability (slump) of concrete increased with increasing crushed waste glass content. The mean value of slump tests was 90, 93, 100, 105, and 110 mm for 0, 10, 20, 30, and 40% waste glass replacement ratio,

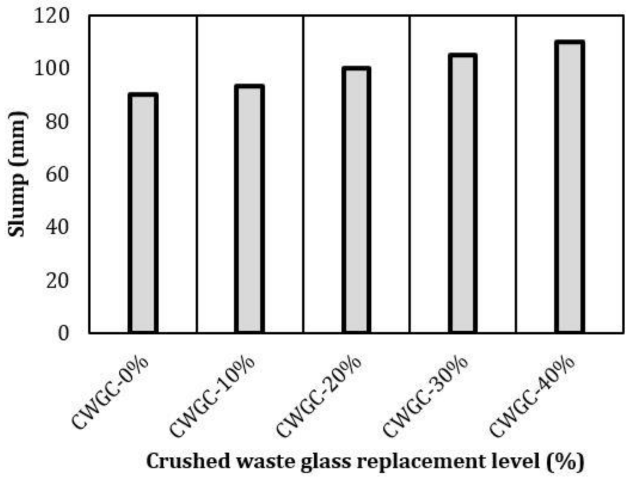


Fig. 7 Show slump value of concrete

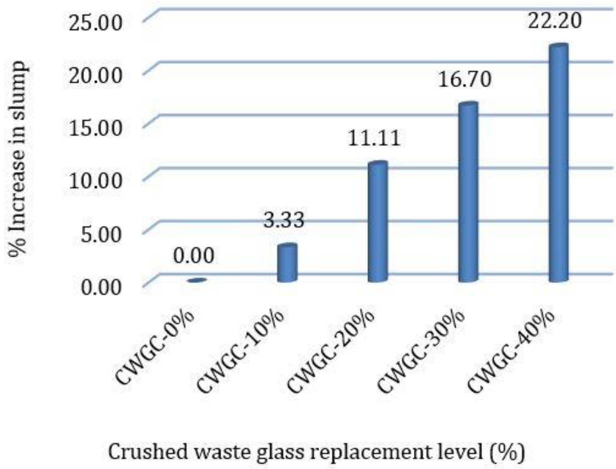


Fig. 8 Percentage increase in slump

which indicated the increase in slump value by 3.3, 11.1, 16.7, and 22.2% with comparison to concrete without crushed waste glass as shown in Fig. 8. In this study, waste glass with low water absorption and higher density as compared to natural fine aggregate was used and caused to increase the workability of concrete. The previous researcher reported that crushed waste glass as fine aggregate with lower density caused the reduction in the slump with increasing waste glass replacement content (Bisht and Ramana 2018, Park *et al*. 2004, Du and Tan 2009, Wang 2009, Wang *et al*. 2014). The reduction in a slump was attributed to the low density of waste glass with comparison to natural fine aggregate.

4.2 Dry density

The dry density of the control concrete was 2400 kg/m^3, Whereas, concrete with replaced crushed waste glass of 10, 20, 30, and 40% by weight of fine aggregate were reported as 2406, 2414, 2426,

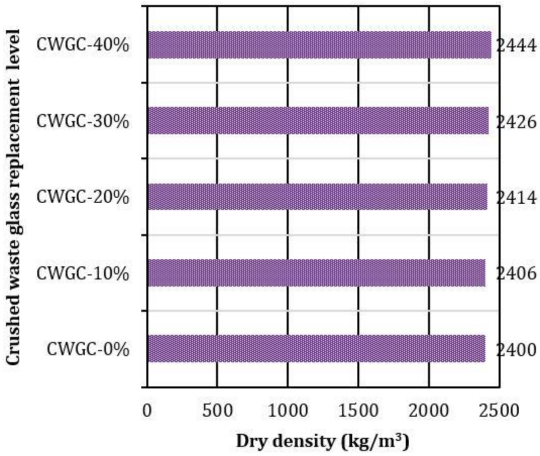


Fig. 9 Dry density of concrete

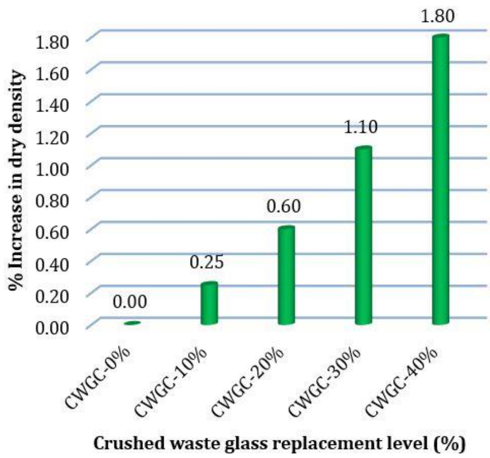


Fig. 10 Percentage increase in dry density

and 2444 kg/m^3 as shown in Fig. 9. From Fig. 10, it can be reported that the dry density of concrete marginally increased with increasing waste glass content by 0.25, 0.6, 1.1, and 1.8% as compare to control concrete as shown in Fig. 10. The marginal increased in dry density of crushed waste glass concrete can be attributed to the marginal higher specific gravity of crushed waste glass as compared to fine aggregate.

4.3 Compressive strength

Control concrete and concrete with crushed waste glass were tested for compressive strength for cube size of 150 mm×150 mm×150 mm and 100 mm×100 mm×100 mm after 7, 28 and 270 days, respectively. The compressive strength results are presented in Tables 6 and 7, and plotted in Figs. 11 and 12. The reduction of compressive strength of concrete containing crushed waste glass after 28 days is found to be 0.34, 0.84, 3.70, and 8.24% as compared to control concrete as shown in Fig. 13. The result for compressive strength after 270 days for control concrete is found as 69.4 MPa.

Table 6 Compressive strength result of cube size 150 mm×150 mm×150 mm for 7, 28 and 270 days

Mix ID	Age (days)	Samples test results (MPa)			Avg. Str (MPa)	Std. Dev	C.O.V (%)	Str. Decrease (%)
		S1	S2	S3				
CWGC-0%	7	48.1	47.5	48.4	48.00	0.46	0.96	0.00
CWGC-10%		48.7	45.7	46.7	47.03	1.53	3.25	2.02
CWGC-20%		45.8	47.6	46.1	46.50	0.96	2.06	3.13
CWGC-30%		47.9	46.5	43.8	46.07	2.08	4.51	4.02
CWGC-40%		42.7	43.5	43.1	43.10	0.40	0.93	10.21
CWGC-0%	28	59.5	60.3	58.6	59.47	0.85	1.43	0.00
CWGC-10%		58.7	60.4	58.9	59.33	0.93	1.57	0.23
CWGC-20%		58.6	58.5	59.8	58.97	0.72	1.22	0.84
CWGC-30%		58.1	57.3	56.4	57.27	0.85	1.48	3.70
CWGC-40%		55.3	54.6	53.9	54.60	0.70	1.28	8.19
CWGC-0%	270	70.2	68.7	69.4	69.43	0.75	1.08	0.00
CWGC-10%		68.1	69.9	68.8	68.93	0.91	1.32	0.72
CWGC-20%		66.7	67.4	68.1	67.40	0.70	1.04	2.92
CWGC-30%		64.7	67.2	64.0	65.30	1.68	2.57	5.95
CWGC-40%		61.8	64.1	60.7	62.20	1.73	2.78	10.41

Table 7 Compressive strength result of cube size 100mm×100 mm×100 mm for 7 and 28 days

Mix ID	Age (days)	Samples test results (MPa)					Avg. Str (MPa)	Std. Dev	C.O.V (%)	Str. Decrease (%)
		S1	S2	S3	S4	S5				
CWGC-0%	7	52.9	51.2	54.9	52.9	52.8	52.94	1.31	2.47	0.00
CWGC-10%		50.9	50.6	51.0	52.1	51.8	51.28	0.64	1.25	3.14
CWGC-20%		49.7	50.1	49.6	49.5	49.3	49.64	0.29	0.58	6.23
CWGC-30%		48.2	47.4	48.7	48.5	47.7	48.10	0.54	1.12	9.14
CWGC-40%		46.7	45.6	46.4	47.1	46.3	46.42	0.55	1.18	12.31
CWGC-0%	28	65.2	67.2	61.4	63.5	65.5	64.56	2.20	3.41	0.00
CWGC-10%		66.5	61.9	62.7	62.2	63.2	63.30	1.86	2.94	1.95
CWGC-20%		62.0	60.2	64.6	62.6	61.8	62.24	1.59	2.55	3.59
CWGC-30%		59.5	62.5	60.3	60.5	61.6	60.88	1.18	1.94	5.70
CWGC-40%		58.2	57.3	57.1	58.1	59.3	58.00	0.87	1.50	10.16

Whereas, the reduction after 270 days has been found as 0.72, 2.90, 5.91, and 10.37% as compared to the control concrete as shown in Fig. 13. The comparison of reductions in compressive strength shows that reduction in strength decreases with age ranging from 13.9% to 16.6%. By utilizing this waste, loss of compressive strength of concrete was observed.

The reduction in compressive strength can be attributed to the (i) Less water absorption of crushed waste glass than the fine aggregate makes more water available for the hydration of cement, thus increasing w/c ratio for this concrete. This could be one of the reasons as to why the strength of concrete decreased. and (iii) The percentage of crushed waste glass passing through sieve size of

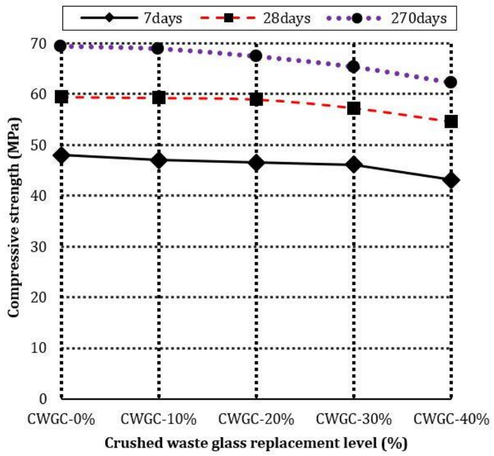


Fig. 11 compressive strength of cube size 150 mm

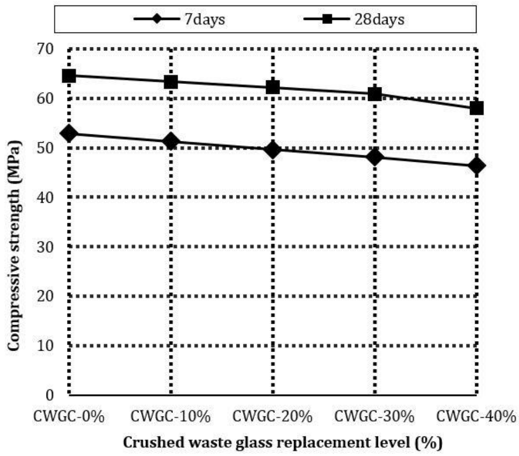


Fig. 12 Compressive strength of cube size 100 mm

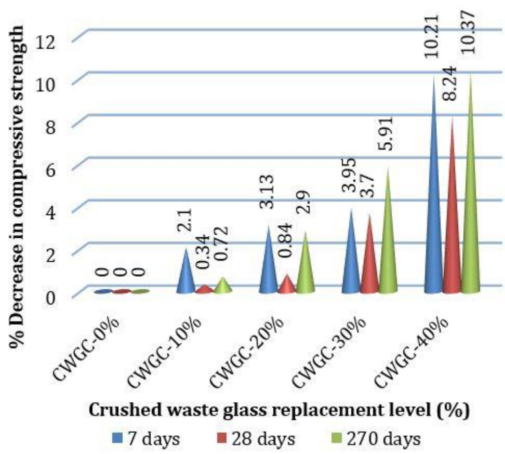


Fig. 13 Percentage increase in compressive strength

Table 8 Splitting tensile strength results after 7 and 28 days

Mix ID	Age (days)	Samples test results (MPa)			Avg. Str (MPa)	Std. Dev	C.O.V (%)	Str. Decrease (%)
		S1	S2	S3				
CWGC-0%	7	3.37	2.94	3.31	3.21	0.23	7.16	0.00
CWGC-10%		3.31	3.25	3.04	3.20	0.14	4.37	0.31
CWGC-20%		3.10	3.01	3.01	3.04	0.05	1.64	5.30
CWGC-30%		2.96	2.97	3.11	3.01	0.08	2.66	6.23
CWGC-40%		2.80	2.82	2.80	2.81	0.01	0.36	12.46
CWGC-0%	28	3.99	3.63	3.83	3.82	0.18	4.71	0.00
CWGC-10%		3.40	3.60	3.80	3.60	0.20	5.55	5.76
CWGC-20%		3.70	3.41	3.24	3.45	0.23	6.67	9.68
CWGC-30%		3.50	3.50	3.30	3.43	0.11	3.21	10.21
CWGC-40%		3.26	3.21	3.32	3.26	0.06	1.84	14.66

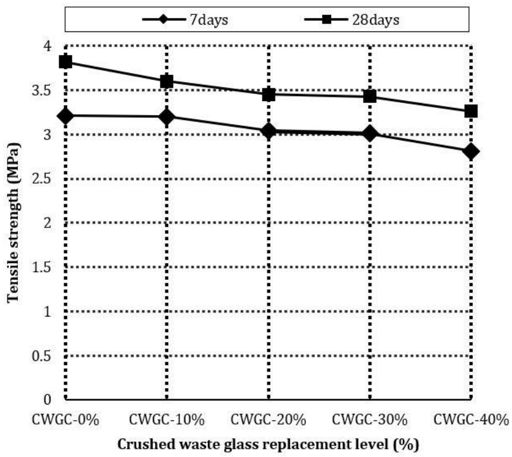


Fig. 14 Split tensile strength

150 µm was less as compared to replaced fine aggregate, thus surface area of fine aggregate in the concrete having crushed waste glass was more than control concrete. Higher surface area requiredmore water for cement hydration, thus it absorbs designed mix water and cause reducing strength. The correlation of compressive strength of cube size of 150 mm with 100 mm of control concrete and concrete with crushed waste glass with varying percentages of 10, 20, 30, and 40% were reported as 8.57, 6.75, 5.42, 6.30, and 6.20%, respectively. It means that the cube of size 100 mm would have strength of 1.054 to 1.086 times as compared to the strength of the cube of size 150 mm.

4.4 Splitting tensile strength

The 7 and 28 days splitting tensile strength results are presented in Table 8 and shown in Fig. 14. Fig. 14 shows similar trends to that of compressive strength results. By inclusion crushed waste glass, the response of splitting tensile strength was as detrimental as the compressive strength result.

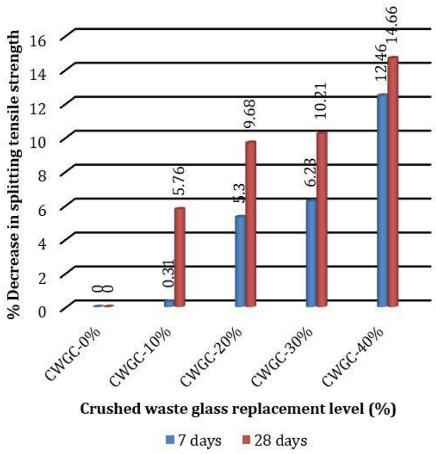


Fig. 15 Percentage decrease in split tensile strength

Table 9 Ultrasonic pulse velocity results after 28 and 270 days

Mix ID	Age (days)	UPV (km/s)			Avg. UPV (km/s)	Std. Dev	C.O.V (%)
		S1	S2	S3			
CWGC-0%	28	4.78	4.77	4.68	4.74	0.06	1.27
CWGC-10%		4.65	4.64	4.54	4.61	0.06	1.30
CWGC-20%		4.53	4.52	4.50	4.52	0.02	0.44
CWGC-30%		4.48	4.46	4.44	4.46	0.02	0.45
CWGC-40%		4.40	4.39	4.40	4.40	0.01	0.23
CWGC-0%	270	4.82	4.81	4.78	4.80	0.02	0.42
CWGC-10%		4.73	4.77	4.68	4.73	0.05	1.06
CWGC-20%		4.73	4.72	4.71	4.72	0.01	0.21
CWGC-30%		4.68	4.65	4.65	4.66	0.02	0.43
CWGC-40%		4.60	4.56	4.57	4.58	0.02	0.44

The split tensile strength decreased with increasing waste glass content. The tendency of decreasing tensile strength can be attributed similar to that of compressive strength. Previous studies (Kim *et al*. 2018) and (Gerges *et al*. 2018) conducted for partial replacement of the crushed waste glass with fine aggregate and reported that the splitting tensile strength decreased with increasing waste glass content. This is mainly conveyed due to the weak bond strength between smooth surfaces of waste glass with cement paste. Also, Abdullah and Fan (2014); Kou and Poon (2009) attributed to the difference in densities between the recycled glass and natural sand. The decrease in splitting tensile strength is shown in Fig. 15.

4.5 Ultrasonic pulse velocity results after 28 and 270 days

Control concrete and concrete containing crushed waste glass were tested for ultrasonic pulse velocity after 28 and 270 days. The results for UPV are presented in Table 9 and shown in Fig. 16. Results for UPV after 28 days show that control concrete and the concrete with 10 and 20%

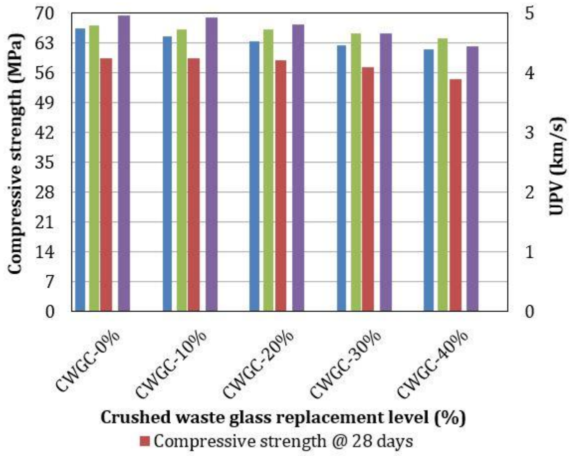


Fig. 16 Relation between crushing strength and UPV

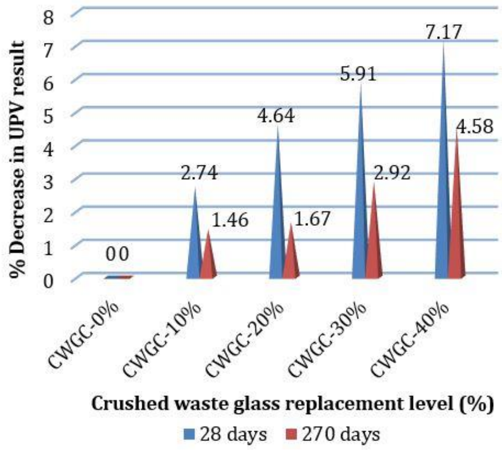


Fig. 17 Percentage decrease in UPV

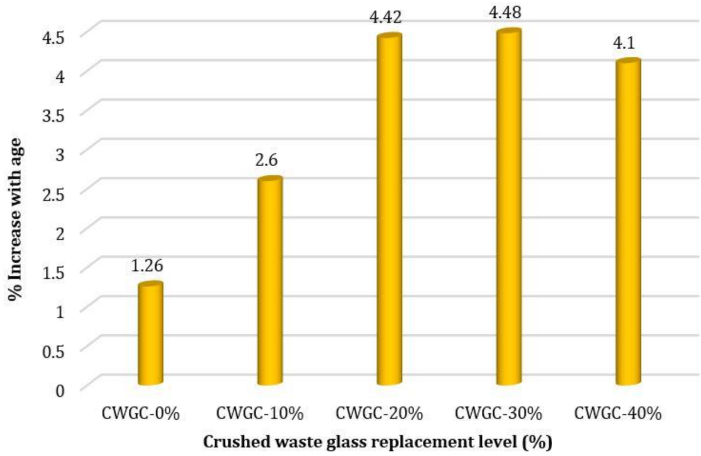


Fig. 18 Percentage increase with age

Table 10 Ultrasonic pulse velocity results after 28 and 270 days

Mix ID	Age (days)	Rebound number			Avg. RN	Std. Dev	C.O.V (%)
		S1	S2	S3			
CWGC-0%	28	52.4	52.3	52.8	52.5	0.26	0.50
CWGC-10%		52.5	51.9	50.8	51.7	0.86	1.66
CWGC-20%		52.1	50.9	50.2	51.1	0.96	1.88
CWGC-30%		50.9	49.9	48.8	49.9	1.05	2.10
CWGC-40%		45.7	46.5	47.3	46.5	0.80	1.72
CWGC-0%	270	63.5	63.1	63.9	63.5	0.40	0.63
CWGC-10%		60.6	58.6	59.9	59.7	1.01	1.69
CWGC-20%		59.9	59.3	58.9	59.4	0.50	0.84
CWGC-30%		57.9	58.5	58.2	58.2	0.30	0.52
CWGC-40%		55.1	55.8	54.8	55.2	0.51	0.92

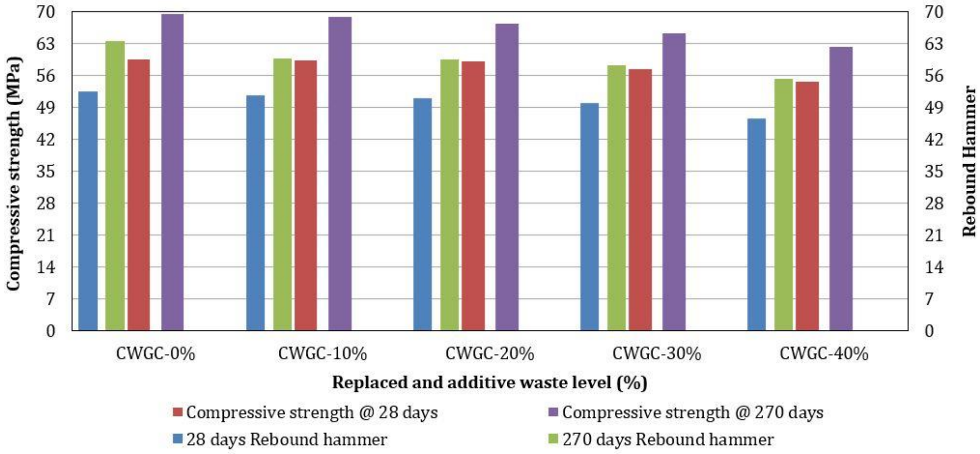


Fig. 19 Relation between compressive strength and R.H

replacement of fine aggregate by crushed waste glass are of excellent quality. Whereas, concrete with 30 and 40% of crushed waste glass is of good quality. The reduction in ultrasonic pulse velocity can be ascribed due to the lesser value of ultrasonic pulse velocity through glass than concrete as shown in Fig. 17. It is important to note here that the control concrete and concrete with crushed waste glass with 10, 20, 30, and 40% by weight of fine aggregate after 270 days UPV testing are increased by 1.27, 2.60, 4.42, 4.48, and 4.1% as compared to 28 days as shown in Fig. 18. This shows that the quality of concrete improves with age. Improvement of quality of concrete of higher age of curing is due to the densification of dicalcium silicate, C2S.

4.6 Rebound hammer results after 28 and 270 days

The results for control concrete and concrete with replaced crushed waste glass by weight of fine aggregate are presented in Table 10 and plotted in Fig. 19. Results after 28 days for surface hardness of concrete with replaced crushed waste glass by weight of fine aggregate are found decreasing

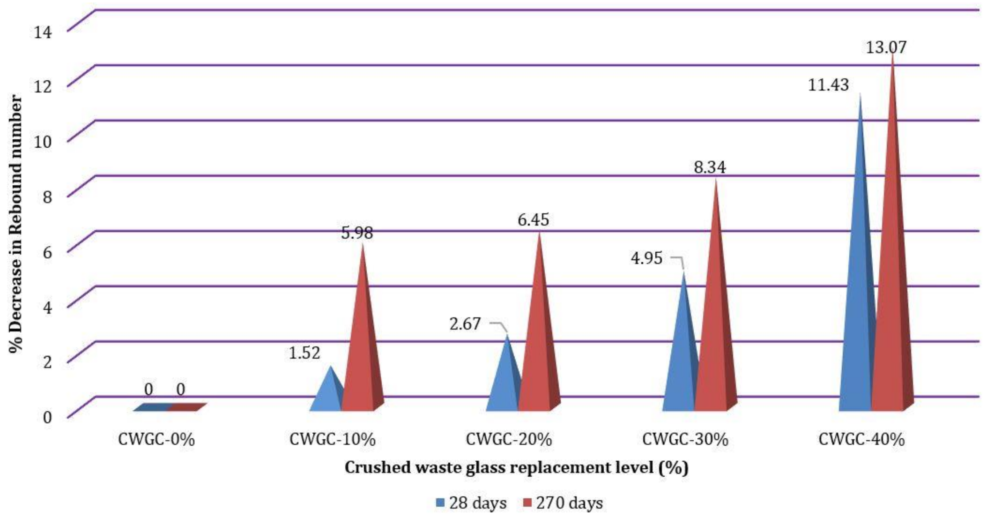


Fig. 20 Percentage decrease in rebound hammer

Table 11 Loss in weight and compressive strength of concrete cubes due to 5% solution of H_2SO_4

Mix ID	Wt. before immersion @ 28 days (kg)	Wt. after immersion @ 28 days (kg)	% loss in wt. @ 28 days	Strength (MPa) after immersion	% loss in strength. @ 28 days
CWGC-0%	8.07	7.86	2.60	42.2	29.08
CWGC-10%	8.12	7.90	2.71	41.6	29.85
CWGC-20%	8.12	7.89	2.83	40.1	32.03
CWGC-30%	8.19	7.95	2.93	38.6	32.64
CWGC-40%	8.25	7.98	3.27	36.5	33.15

Table 12 Loss in weight and compressive strength of concrete cubes due to 5% solution of HCl

Mix ID	Wt. before immersion @ 28 days (kg)	Wt. after immersion @ 28 days (kg)	% loss in wt. @ 28 days	Strength (MPa) after immersion	% loss in strength. @ 28 days
CWGC-0%	8.10	8.01	1.11	53.7	9.75
CWGC-10%	8.13	8.03	1.23	52.5	11.47
CWGC-20%	8.15	8.05	1.23	52.1	11.69
CWGC-30%	8.21	8.10	1.34	50.4	12.04
CWGC-40%	8.26	8.14	1.45	47.3	13.37

respectively by 1.52, 2.67, 4.95, and 11.43% as compared to control concrete as shown in Fig. 20. It is important to note here that the concrete with 0, 10, 20, 30, and 40% replacement of fine aggregate by crushed waste glass after 270 days surface hardness testing by rebound hammer are of higher values by 20.95, 15.50, 16.24, 16.63, and 18.71% as compared to 28 days values. This shows that the strength of concrete with a higher percentage of replacement of crushed waste glass than 40% is almost constant that is approximately 16% for 10, 20, and 30% replacement at 270 days of age. Densified and hardened dicalcium silicate, C2S might be responsible for the improved surface hardness of concrete of higher age.

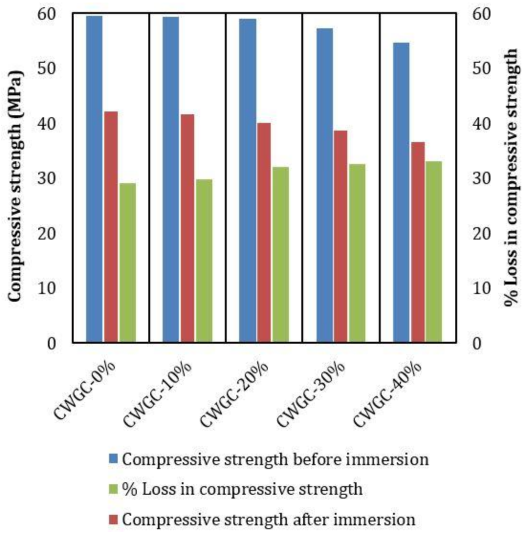


Fig. 21 Percentage loss due to 5% solution of H_2SO_4

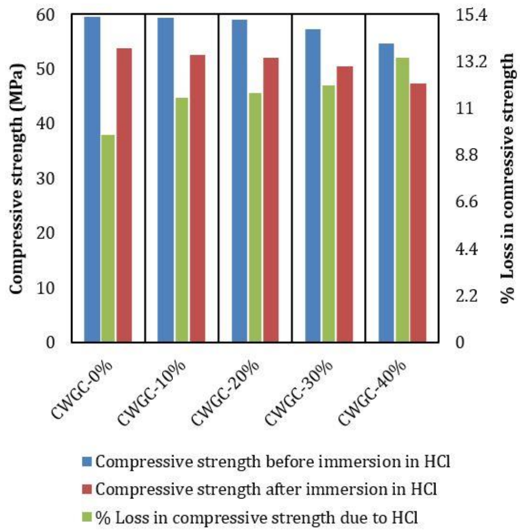
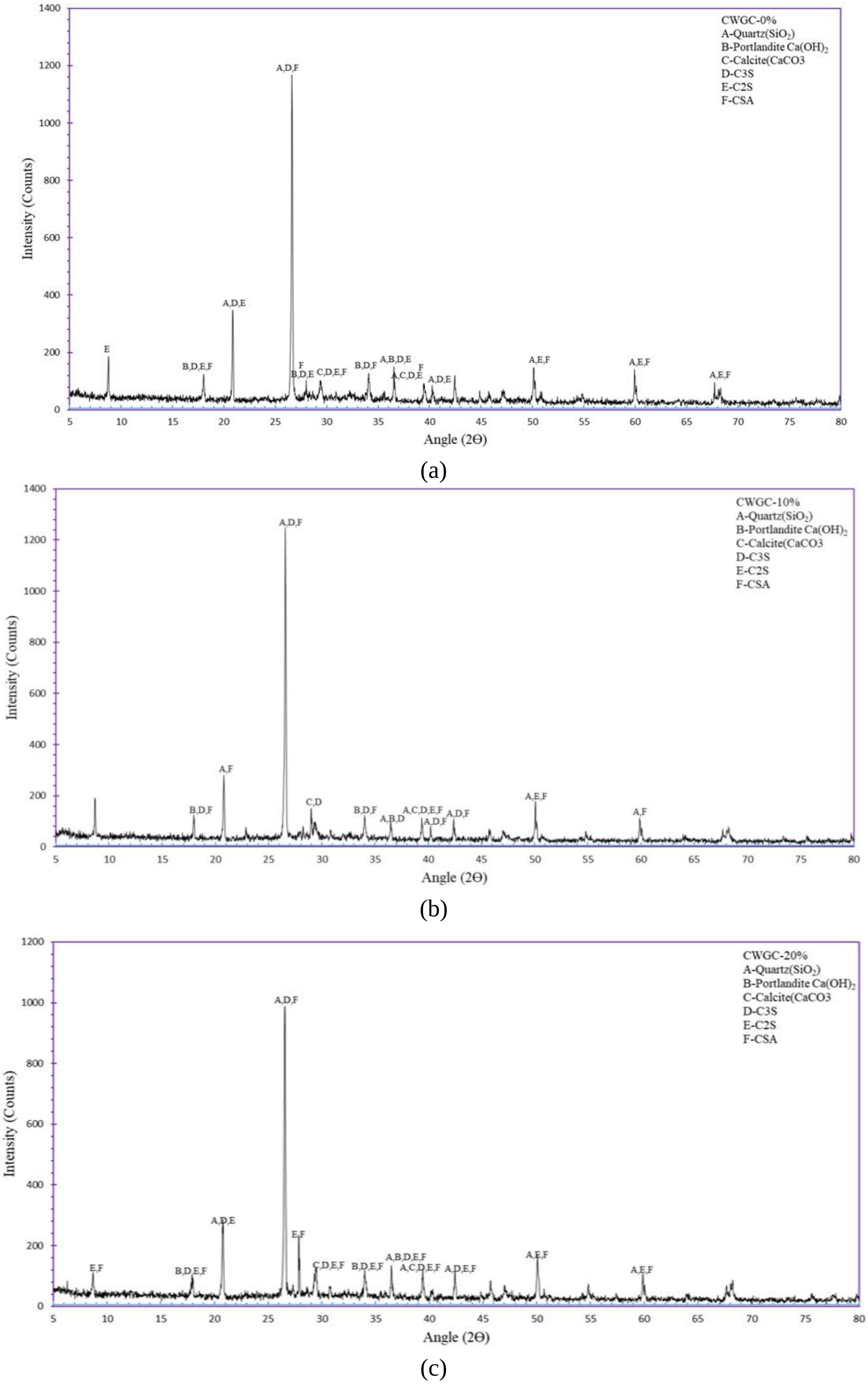


Fig. 22 Percentage loss due to 5% solution of HCl

4.7 Acid and chloride attack on concrete

The percentage of loss of weight and compressive strength were measured are presented in Tables 11 and 12 (Figs. 21 and 22). The percentage loss of weight due to H_2SO_4 attack for 0, 10, 20, 30, and 40% crushed waste glass concrete specimens was 2.60, 2.71, 2.83, 2.93, and 3.27% respectively. Whereas for chloride attack the loss of weight was marginally low by 1.11, 1.23, 1.23, 1.34, and 1.45%. The difference in a percentage weight loss of 0% and 10% CWGC specimens in H_2SO_4 and HCl solutions is almost equal of average value 1.485, and of 20% and 30%, CWGC specimens are also equal of an average value of 1.595. This difference is the highest of value 1.82 for 40% CWGC

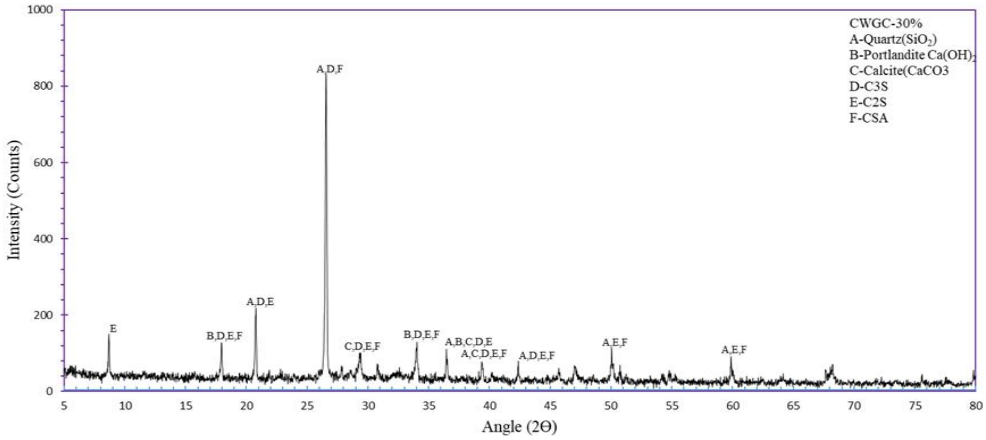


(a)

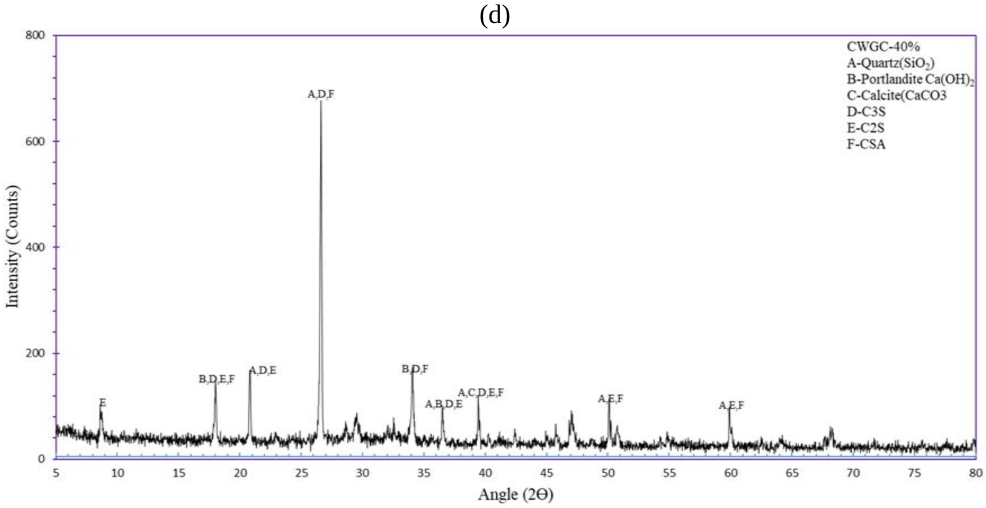
(b)

(c)

Fig. 23 XRD analysis for control and concrete containing crushed waste glass



(d)



(e)

Fig. 23 Continued

specimen.

The percentage loss of compressive strength due to sulphuric acid attack was found as 29.08, 29.85, 32.03, 32.64, and 33.15% for 0, 10, 20, 30, and 40% CWGC specimens, and the percentage loss of compressive strength due to HCl attack was found to be 9.75, 11.47, 11.69, 12.04, and 13.37%, respectively.

The percentage loss in strength after 28 days immersion in sulphuric acid environment for control concrete and concrete containing crushed waste glass varies from 29 to 33%, while for HCl attack it varies from 9.75 to 13.15% minimum for control specimen and maximum for 40% CWGC specimen.

4.8 X-ray diffraction analysis

Based on the XRD analysis, it had been found that the quartz (SiO_2) is the major crystal present in control and crushed waste glass concrete. The quartz (SiO_2) is the major crystal to produce C_3S and C_2S for imparting the strength. Thus, quartz, tricalcium silicate, and ettringite were found with equal peaks of 1161, 1245, 983, 833, and 677 for crushed waste glass of varying percentages of 0, 10, 20, 30, and 40%, respectively. The peaks of these compounds were detected at 2Θ angle of 26.6°. The peak intensity of quartz for the control concrete was counted more as compare to crushed waste glass concrete. The two major chemical compounds of cement namely C_3S and C_2S, responsible for imparting strength to the concrete. When water is added to the cement, they undergo hydration and the reaction release the calcium hydroxide. Carbon dioxide from the air reacts with $Ca(OH)_2$ in concrete and form calcium carbonate ($CaCO_3$) which is responsible for mechanical strength of concrete and is detected at 2Θ angle of 29.3° and 39.4°. whereas, $Ca(OH)_2$ detected at 2Θ angle of 18.04°, 28° , 34.1°, and 36.5° for all replacement ratio. The XRD analysis are shown in Figs. 23(a) to 23(e).

5. Conclusions

In this research work, natural fine aggregate was replaced by the crushed waste glass with varying percentages of 0%, 10%, 20%, 30%, and 40% in concrete. Based on the experimental tests carried out on the concrete, the following conclusion can be drawn.

• The workability of concrete increased with increasing replaced crushed waste glass content. The dry density of concrete marginally increased with increasing waste glass content by 0.25, 0.6, 1.1, and 1.8%.

• By utilizing crushed waste glass, loss of compressive and split tensile strength of concrete was observed. The reduction of compressive strength after 28 days curing is found to be 0.34, 0.84, 3.70, and 8.24% as compared to control concrete.

• The UPV for control concrete and the concrete with 10 and 20% replacement of fine aggregate by crushed waste glass are of excellent quality. Whereas, concrete with 30% and 40% of crushed waste glass is of good quality.

• The control concrete and concrete with crushed waste glass with 10, 20, 30, and 40% by weight of fine aggregate after 270 days curing, UPV results increased by 1.27, 2.60, 4.42, 4.48, and 4.1% as compared to 28 days.

• The surface hardness of concrete with replaced crushed waste glass by weight of fine aggregate after 28 days are found decreasing respectively by 1.52, 2.67, 4.95, and 11.43% as compared to control concrete.

• The concrete with 0, 10, 20, 30, and 40% replacement of fine aggregate by crushed waste glass after 270 days curing, surface hardness is of higher values by 20.95, 15.50, 16.24, 16.63, and 18.71% as compared to 28 days values. This shows that the increase in strength of concrete with higher than 10% of replacement by crushed waste glass is about 16%.

• The percentage loss of weight due to H_2SO_4 attack for 0, 10, 20, 30, and 40% crushed waste glass concrete specimens was 2.60, 2.71, 2.83, 2.93, and 3.27% respectively. Whereas for chloride attack the loss of weight was marginally low by 1.11, 1.23, 1.23, 1.34, and 1.45%.

• The percentage loss in strength after 28 days immersion in sulphuric acid environment for control concrete and concrete containing crushed waste glass varies from 29 to 33%, while for HCl attack it varies from 9.75 to 13.15% minimum for control specimen and maximum for 40% CWGC specimen.

• The quartz (SiO_2) is the major crystal to produce C_3S and C_2S for imparting the concrete

strength. Thus, quartz, tricalcium silicate, and ettringite were found with equal peaks of 1161, 1245, 983, 833, and 677 for crushed waste glass of varying percentages of 0, 10, 20, 30, and 40% respectively. The peaks of these compounds were detected at 2ϴ angle of 26.6°. The maximum peak intensity was given by 10% CWGC specimen and this could be due to the absence of C_2S.
• The peak intensity of quartz for the control concrete was counted more as compare to crushed waste glass concrete.

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