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Characteristics of Sustainable Concrete with Partial Substitutions of Glass Waste as a Binder Material

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Abstract

Manufacturing waste has been quickly increasing over time as a result of the fast-rising population as well as the consumption of foods that are thrown away dishonestly, resulting in environmental contamination. As a result, it has been suggested that industrial waste disposal may be considerably reduced if it could be integrated into cement concrete manufacturing. The aim of this study is to analyze the properties of concrete employing waste glass (WG) as a binding material in proportions of 5%, 10%, 15%, 20%, 25%, and 30% by weight of cement. The fresh property was assessed using a slump cone test, while mechanical performance was assessed using flexural, compressive, splitting tensile, and pull-out strength after 7, 28, and 56 days. Furthermore, microstructure analysis was studied by scan electronic microscopic (SEM), Fourier-transform infrared spectroscopy (FTIR) and thermo-gravimetric analysis (TGA) test. The results reveal that the addition of discarded glass reduces the workability of concrete. Furthermore, mechanical performance was increased up to a 20% substitution of waste glass and then gradually declined. Waste glass can be employed as a micro filler or pozzolanic material without affecting the mechanical performance of concrete, according to microstructure research.

Keywords: waste glass, split tensile strength, flexure strength, compressive strength, bond strength, scan electronic microscopic

1 Introduction

Concrete is used as a building material all over the world due to its outstanding stability and compressive strength (Sankh et al., 2014). Cement concrete-related sustainability has become significant in engineering projects, and several views have arisen to lessen the impact of contemporary building industries on the environment (Isler,

2012). The cement industry is under pressure as energy supply costs grow to reduce carbon dioxide emissions, and the supply of unprocessed materials is of poor quality (Benhelal et al., 2013). Worldwide production of cement is increasing constantly shown in Fig. 1. Concrete it is the world's second most consumed product after water. The business is quickly expanding, particularly in emerging nations, such as China and India, where there is a large need for cement for building and infrastructure. (Ahmad, Zaid, et al., 2021).

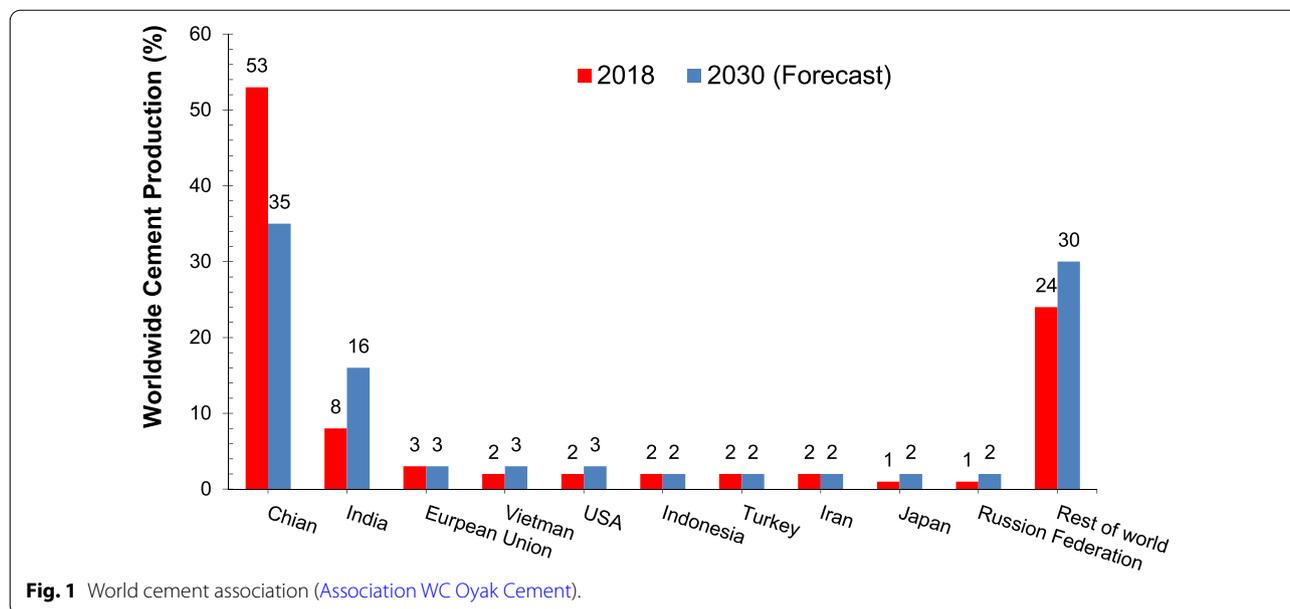
According to an International conference of cement review, Pakistan made more than 41 million tons of cement (Armstrong et al., 2013). The cement industry has now built the capacity to generate 59.5 million tons in expectation of potential demand for developing infrastructure. The World Cement Association expects

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Pakistan to produce 85 million tons, 2% of the world's cement production in 2030. In the short time of 10 years, the cement cost has raised to almost 150% (Mirza et al., 2009). Therefore, it is important to use some supplementary cementations materials instead of cement.

Sustainable construction usage means management which is responsible for and the production of a beneficial environment seeing ecology and development of resources (Plessis, 2007). Being inexpensive and better performance, cement concrete is just pointed into major construction materials globally; however, it has effects on the ecosystem (Naik, 2008). Producing cement which is a major ingredient of concrete is a major source of discharges of greenhouse gases CO₂. Each year the world presently makes about 3.6 billion metric tons of the material (Humphreys, 2013). In 2030 the volume is expected to increase to more than 5 billion metric tons (Imbabi et al., 2012; Müller & Harnisch, 2008). Even though status is different from each country, yearly about half of the world's OPC is used to produce 11 billion metric tons of concrete; the rest is used in screeds, mortars, soil stabilization, coatings, and other applications (McEwan, 1988; Smith et al., 2002). To reduce such an amount of CO₂, it is important to incorporate waste materials in concrete instead of cement.

Presently, the manufacturing of cement causes more than 5% of global CO₂ emissions (Oh et al., 2014). CO₂ emissions can be decreased by substituting OPC with cementations materials (Kurad et al., 2017; Mehta, 2002; Mohseni et al., 2015). Several industrial wastes are utilized effectively in binding material which also involves waste marble, waste foundry sand, and fly ash (Bakharev,

2006; Imbabi et al., 2012; Mwititi et al., 2018). Various researches presented to make concrete by supplementary material to decrease cost and shortage of standard materials (Vigneshpandian et al., 2017). The practice of waste stuff in concrete becomes economical and reusing of wastes is the greatest environmental choice for taking on care of the problem of garbage dumping (Metilda et al., 2015).

In contrast, the quantity of waste produced by industry has risen over time due to growing demand and product use. Only a tiny portion has been used, and the rest has been discarded carelessly, producing environmental issues. The massive increase in the amount of waste that must be thrown, the scarcity of disposal sites, and the rapid rise in transportation and disposal costs all have a negative impact on the environment, putting a halt to sustainable growth. Trash cleanup is getting increasingly difficult (Felixkala & Partheeban, 2010). Since 2005, The total global glass waste preparation estimate has been 130 Mt, with China, the United States, and the European Union generating around 32 Mt, 20 Mt, and 33 Mt, respectively (Agency & Agency, 2007). Because glass is naturally non-biodegradable, disposing of it in a landfill poses environmental challenges and can be costly (Binici et al., 2007; Ryou et al., 2006; Soroushian, 2012). Waste glass is plentiful, has no economic value, and is regularly landfilled. (Byars et al., 2003). Glass waste was also investigated for use as aggregate in the production of concrete (Rashad, 2014; Taha & Nounu, 2009). Glass pozzolanic characteristics was observed at the particle sizes less than 100 and less than 300 microns m, respectively (Shi et al., 2005). Glass powder, according to the research's,

enhances the mechanical properties of concrete (Anwar, 2016; Lee et al., 2018; Šahmenko et al., 2009). Grinding has the potential to boost the pozzolanic reactivity of SCMs (Alexander, 1960; Vizcayno et al., 2010). Pozzolanic cement mixtures are resistant to thermal cracking because of their low hydration temperatures (Amin et al., 2020; Berrocal et al., 2016; Khan et al., 2017). A good pozzolanic attempt to both avoid alkali–silica interaction and use lime to significantly reduce efflorescence (Rashad, 2014).

Although a lot of investigation is carried out on waste glass as a partial substitution in concrete. However, a review paper shows that research carried out on waste glass as a partial substitution in concrete is still scarce and further research was recommended to investigate the characteristics of concrete with the incorporation of waste glass (Rashad, 2014). Furthermore, there is no study in the open literature to improve bond strength and flexure characteristics with the incorporation of WG. This research studied the possibility of glass waste as a binding material to make sustainable concrete. Experimental lab work was done on the glass performance (at the levels of 5%, 10%, 15%, 20%, 25%, and 30% by mass of cement. From the results, it has been found that the substitution of waste glass up to 20% by weight of cement significantly enhanced the performance of concrete.

2 Materials and Methods

2.1 Materials

2.1.1 Cement

In this investigation, OPC (Ordinary Portland cement) was used as binding material to produce concrete for all batches in accordance with ASTM C150 (Cement AP ASTM C150 of the following type: 1. Concr which will be contact with Sew Type II, Moderate Sulfate Resist 2). Various tests were depicted to assess its qualities, which are listed in Table 1.

2.1.2 Aggregate

Ordinary natural fine aggregate (sea sand) was utilized as fine aggregate (F.A), and standard weight crush stone aggregate with a maximum particle size of around 25 mm was employed as coarse aggregate. Saturated dry surface conditions were employed for both fine and coarse aggregate (SSD). Table 2 shows different properties of aggregate used in this study. According to ASTM C33/C33M-13 (ASTM C 33 & C33M, 2008), Figs. 2 and 3 display the fine aggregate and coarse aggregate gradation curve.

2.1.3 Waste Glass

The locally available waste glass was used in this study. The chemical structure of glass was obtained using X-ray

Table 1 Properties of cement.

Chemical property	Percentage (%)	Physical property	Results
CaO	60.7	Size	≤ 75μ
SiO ₂	26.9	Fineness	93%
Al ₂ O ₃	5.4	Normal Consistency	31%
Fe ₂ O ₃	2.7	Initial Setting Time	38 min
MgO	2.5	Final Setting Time	431 min
SO ₃	0.5	Specific surface	325 m ² /kg
K ₂ O	0.4	Soundness	1.50%
Na ₂ O	0.9	28-day compressive Strength	42Mpa

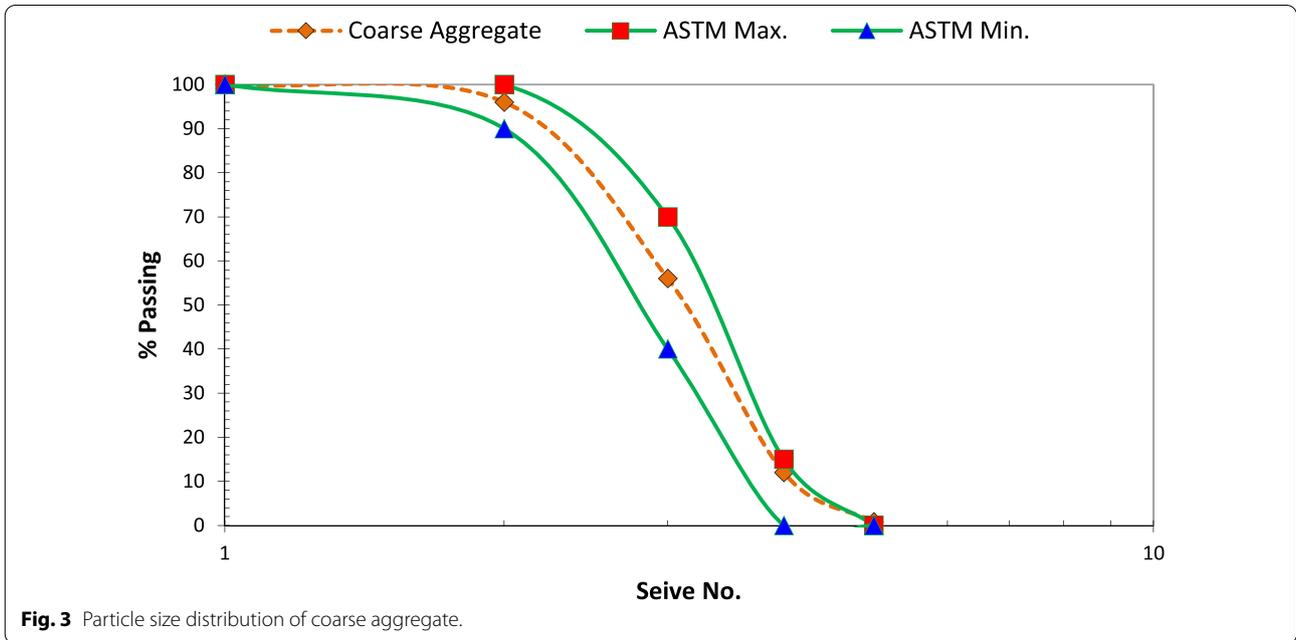
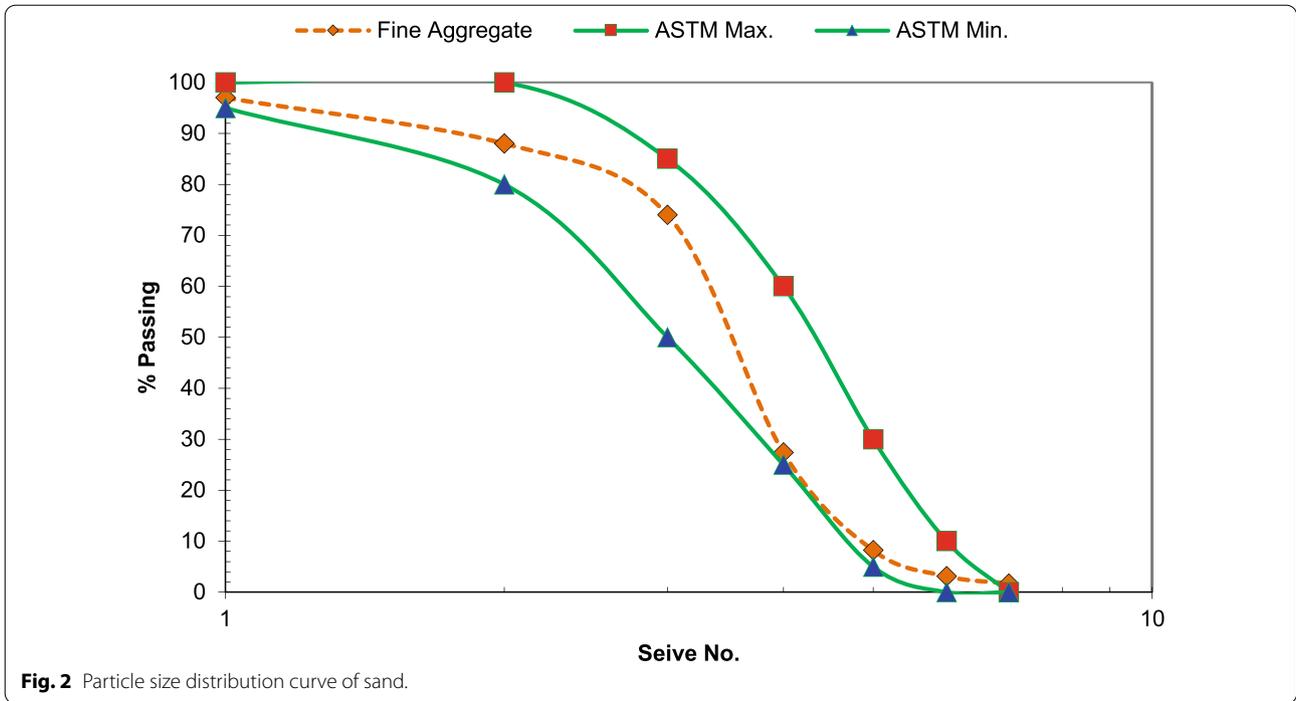
Table 2 Properties of aggregate.

Physical name	Sand	Coarse aggregate
Min. nominal size	0.075 mm	4.75 to 75 μm
Max. nominal Size	4.75 mm	25 to 4.75 mm
Absorption Capacity	5.28%	2.18%
Moisture Content	3.8%	0.45%
Bulk density (kg/m ³)	1646	1580
Fineness Modulus	2.63	5.7
Aggregate crushing value (KN)	-	165

fluorescence (XRF). The waste glass was ground in the council of scientific and industrial research (PCSIR) laboratory in Peshawar, Pakistan. Chemical composition and physical characteristics of waste glass used in this study is given in Table 3.

2.2 Concrete Mix Proportion

ASTM C 31 (Specimen CT ASTM C 31) process was utilized to make concrete samples and compaction was done by hand with a tamping rod at three distinct levels, giving each level 25 blows. For all batches, a constant water-to-cement ratio of (0.6) was employed. Seven mixes were prepared with varying percentages of glass powder (0, 5%, 10%, 15%, 20%, 25%, and 30% by weight of binder), as shown in Table 4. Instead of beginning the mixing operation, the needed quantity of raw ingredients was weighed using the weighing equipment. For ingredient mixing, the mixer speed is set at 30 revolutions per minute. The coarse aggregate was first placed in the drum, followed by the sand, and each component was thoroughly blended before a sufficient quantity of cement, water, and additives were combined over time, with the maximum time being around 10 min for all batches.

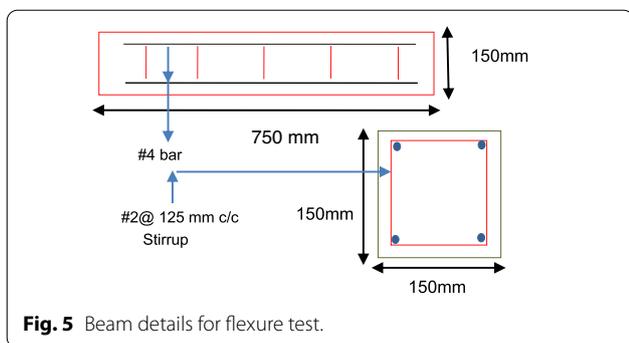


2.3 Testing Setups and Procedure

2.3.1 Slump

Vertical settlement of freshly prepared concrete, sinking in height and flowing to the sides without any support is known as a slump. Slump indicates the workability of concrete. A concrete is believed to be flowable only if it can be easily placed and compacted and provide a

smooth surface. Slump cones should be filled in three layers and compacted each layer with a tamping rod of 25 blows and then the mold is left vertically from concrete as per ASTM standard as ASTM C-143 (Grout FSTAM). The test was only valid if it yielded a “true” slump. Another sample was taken when the slump test of concrete yielded an unsymmetrical slump. After two



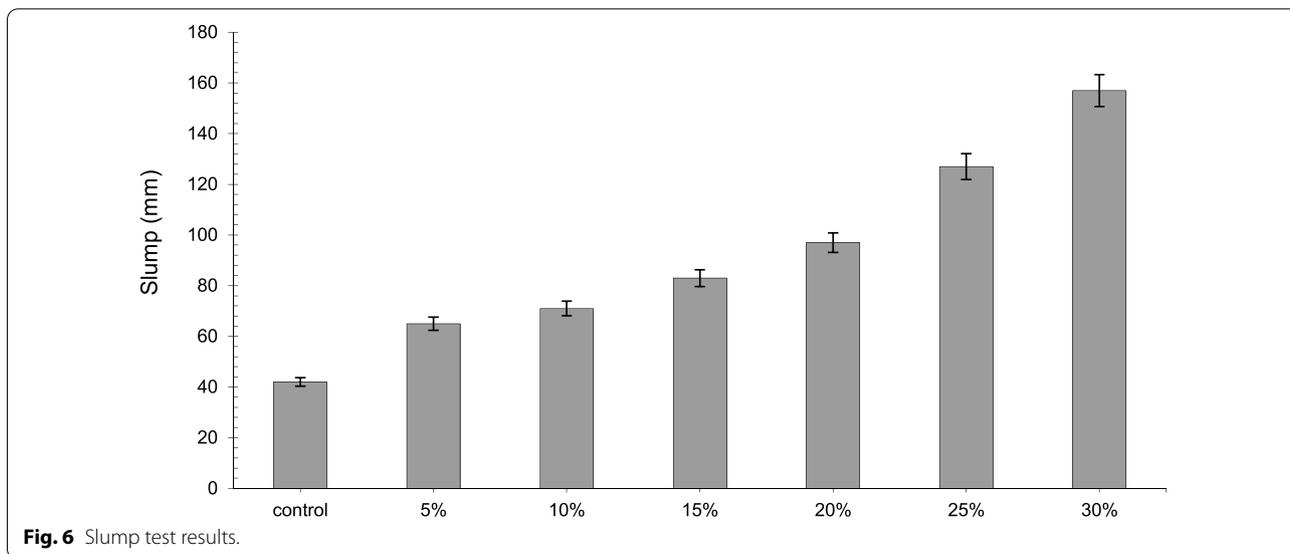
it has been concluded that slumps value rise as the percentage of glass waste increased as compared to the control mix. Slump value were 42, 65, 71,83, 97,127 and 157.5 mm for concrete containing waste glass in proportions 0%, 5%, 10%, 15%, 20%, 25% and 30%, respectively. A maximum slump was obtained at 30% replacement of waste glass's which was almost 275% higher than reference concrete. This can be credited to the glass's low water absorption. The greater amount of free water available improves the flowability of the concrete by reducing internal friction between the aggregates. A similar pattern of increase in slump value due to the incorporation of glass powder was observed by earlier researchers (Nassar & Soroushian, 2012; Vasudevan, 2013). Although it has been also reported that workability decreases with the incorporation of glass due to rough surface texture which increases internal friction between aggregate, leading to less workable (Federico & Chidiac, 2009). In addition, the increase in workability with the incorporation of waste glass is due to micro filling voids. The finer the waste glass, the better will be micro filling effects.

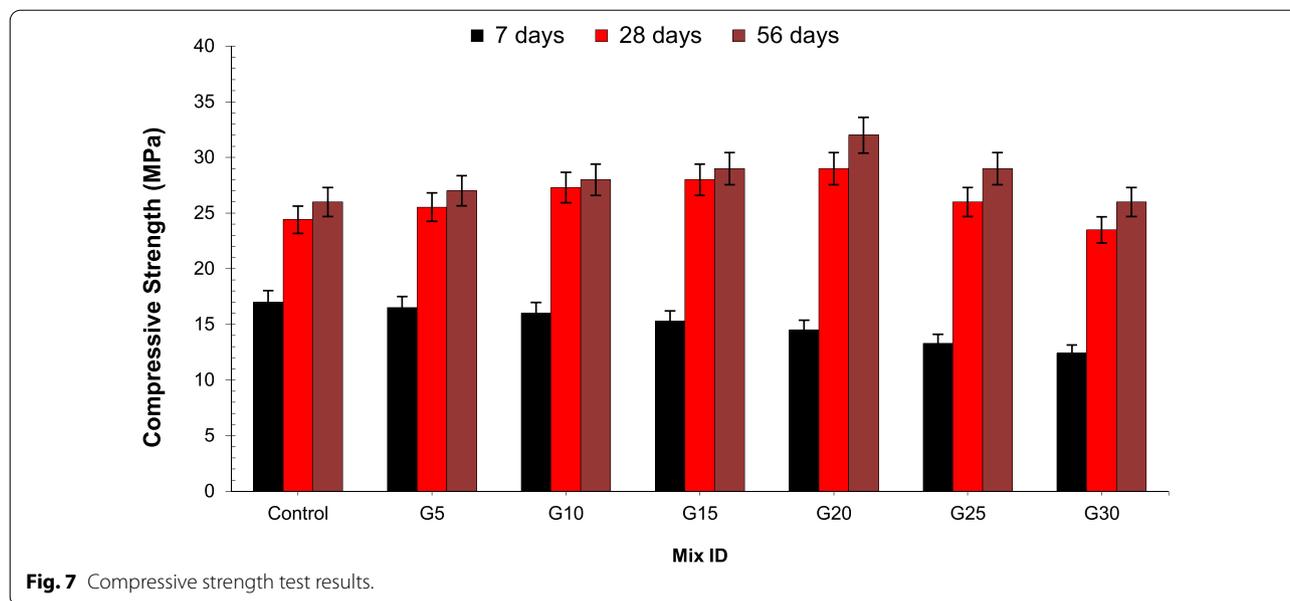
This study used waste glass (less than 38 μ) finer than past studies which show opposite results in terms of workability.

3.2 Harden Property

3.2.1 Compressive Strength

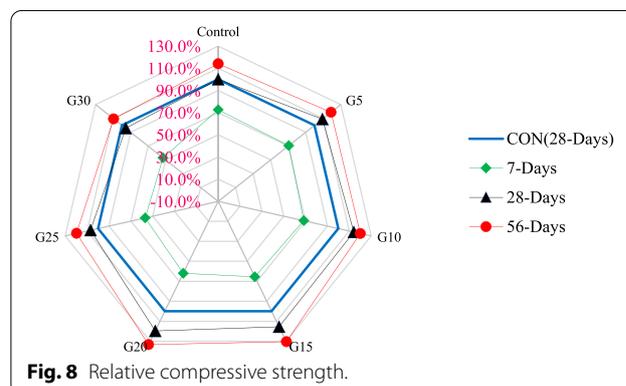
The compressive capacity of concrete increases when the proportion of glass enhances replacement of up to 20% of the glass and additional addition of glass goes to reduce as presented in Fig. 7. It can be observed that after 7 days, no clear improvement in compressive strength was observed. However, the improvement of strength gets better at 28 and 56 curing. The positive impact on the compressive strength of concrete is the chemical reaction of glass that seems to balance this tendency after the age of strengthening and As a result, the compressive capacity is increased at 28 and 56 days. It is well-known that pozzolanic reaction proceeds slowly, does not give strength at an early age (Okeke & Adedeji, 2016). Similar results were also reported by Rahma et al. (2017); Metwally, 2007). The greatest compressive capacity was obtained on a 20% substitute of glass and minimum strength was obtained at 30% replacement of the waste glass, as shown in Fig. 7. This may be because of the physical and pozzolanic property of waste glass. First and foremost, glass is the best of all components for filling spaces between concrete elements due its fineness, resulting in more dense concrete (Jin et al., 2000; Korjakins et al., 2012; Šahmenko et al., 2009; Shao et al., 2000; Wood, 2008). On the other hand, glass is a pozzolanic material containing amorphous silica that reacts with calcium hydrates (CH) that comes from the hydration of cement and converts it into calcium silicates (CSH)





gel which provides additional binding property leading to more strength (Aly et al., 2012; Nassar & Soroushian, 2011; Soroushian, 2012; Tamanna et al., 2016). However, a decrease in strength was observed beyond 20% replacement. Even at 30% replacement of glass shows strength less than control due to dilution effect. So that the total available amount of calcium hydrate (CH) is consumed by some of the glass particles and the rest of CH remains un-reactive, forming weak pockets in concrete which result in decreased strength (Subramani & Ram, 2015). The positive effect on compressive strength is because of the pozzolanic reaction of SiO₂ in glass with CH creating an extra binding gel (CSH). The extra binder created by the waste glass as a result of the interaction with accessible lime enables it to develop strength over time. However, at a higher dosage of waste glass (30% substitution) compressive strength decreases due to the dilution effect which causes alkali-silica reaction because of a large amount of non-reactive silica accessible due to excessive amount of glass. In addition, at higher dosage waste glass (30% substitution), bleeding was observed which causes more voids in hardened concrete due to evaporation of water leaves free spaces which cause lower compressive strength.

A relative assessment was executed in which 28-day compressive strength of blank mix is considered reference strength, from which concrete of varying percentage of waste glass is compared at age of different days of curing, as shown in Fig. 8. At 20% substitution of waste glass, compressive capacity is about 23% smaller than the blank batch after 7 days. For the same substitution of glass (20%), compressive strength is almost 19% higher than



the reference mix after 28 days. At long-term compressive strength (56-day curing), for the same substitution of glass (20%), compressive strength is almost 34% higher than the reference mix.

The compressive strength of concrete of various days of curing was measured using Eq. (1), certified American concrete institute (ACI) (Deluce & Vecchio, 2013):

$$f_c(t) = f_{c28} \left(\frac{t}{4 + 0.85t} \right) \tag{1}$$

where $f_{c(t)}$ is the compressive strength at days, f_{c28} is the 28 day compressive strength. The computed compressive strength is given in Table 5.

The co-relation among laboratory work and predicted from Eq. (1) is displayed in Fig. 9. It can be noted that the regression model among laboratory work and predicted from Eq. (1) is deemed to be straight. The regression line

Table 5 Concrete mixed proportion.

Mix	Experimental compressive strength (MPa)			Predicted Compressive Strength by ACI 209 (MPa)	
	7 days	28 days	56 days	56 days	180 days
Control	26	27	28	26.3	27.8
G5	26	24	26	26.3	27.8
G10	27	25	27	27.5	29.1
G15	28	27	28	29.4	31.1
G20	29	28	29	30.2	31.9
G25	32	29	32	31.3	33
G30	29	26	29	28.0	29.6

depicts a strong co-relation among laboratory work and predicted from Eq. (1) having an R² value of more than 90 percent.

3.2.2 Split Tensile Strength

Split tensile strength outcomes are given in Fig. 10. The notable enhancement in concrete tensile strength is up to 20% glass at 28 days and 56 days. However, at 7-day curing, significant improvement in tensile strength was not observed at 20% glass identical to outcomes of compression strength. Upon changing the dosage of glass, outcomes of tensile strength are manipulated likewise to the compressive strength. Tensile strength optimum values are obtained at 20% glass having maximum split tensile. This may be credited to the development of hydration products and reduction in the pores of glass mixed concrete, and the perfect bond strength among the neighboring cement paste and glass as reported by an earlier study

(Abdallah & Fan, 2014). Also reported that maximum tensile capacity of concrete is at 20% substitute of glass instead of cement (Chikhalikar & Tande, 2012). They have also noted the same conduct of tensile and compressive strength with different doses of glass.

A relative assessment was executed in which control concrete tensile strength (28 days) was considered as reference strength, from which concrete of varying percentage of waste glass is compared at age of different days of curing, as shown in Fig. 11. At 20% substitution of waste glass, split tensile strength is only 44% lower than the reference mix after 7 days. For the same substitution of glass (20%), split tensile strength is almost 15% higher than the reference mix after 28 days. At long-term split tensile strength (56-day curing), for the same substitution of glass (20%), split tensile strength is almost 32% higher than the reference mix.

The relationship of compressive strength versus split tensile strength is given in Fig. 12. The regression model between compressive and split tensile strength is seemed to be straight. The regression line depicts a strong co-relation among compressive strength versus split tensile strength having an R² value of more than 90 percent.

3.2.3 Pull-Out Strength (Bond Strength)

Based on work results, the bond strength of all mixes with varying percentages of waste glass at all ages is shown in Fig. 13. It is detected that similar to compressive strength, bond strength declines with incorporation waste glass at 7-day curing but at 28 and 56 days, bond strength enhanced up to 20% substitute of glass. It is due pozzolanic activity of waste glass that increases the concrete surrounding to reinforcement resulting in more

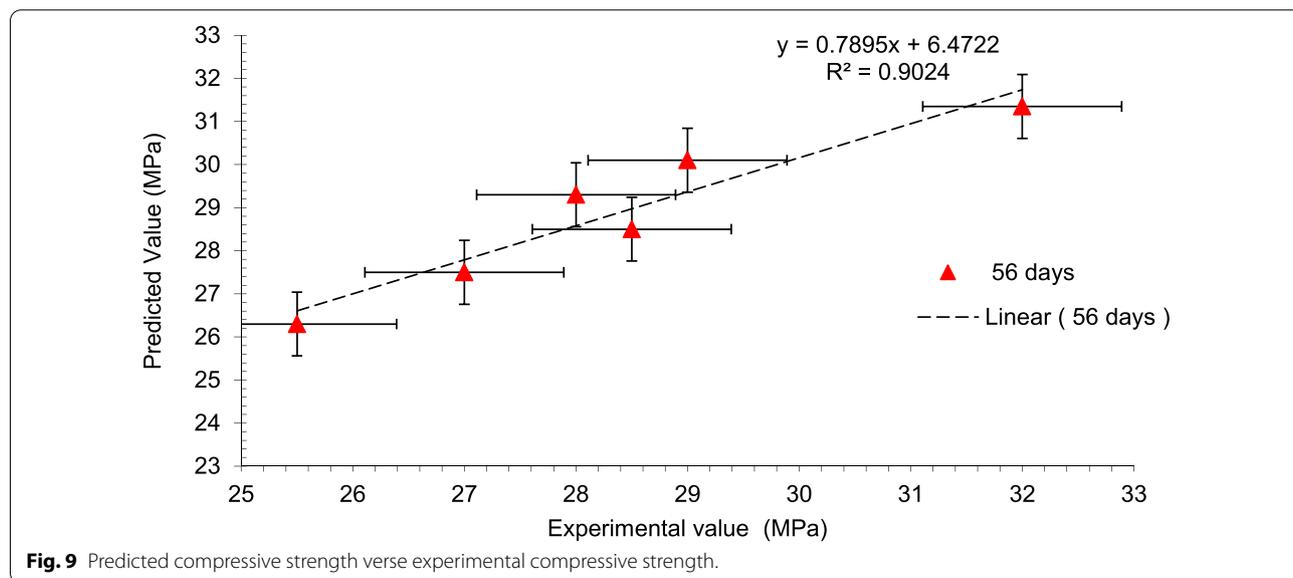


Fig. 9 Predicted compressive strength verse experimental compressive strength.

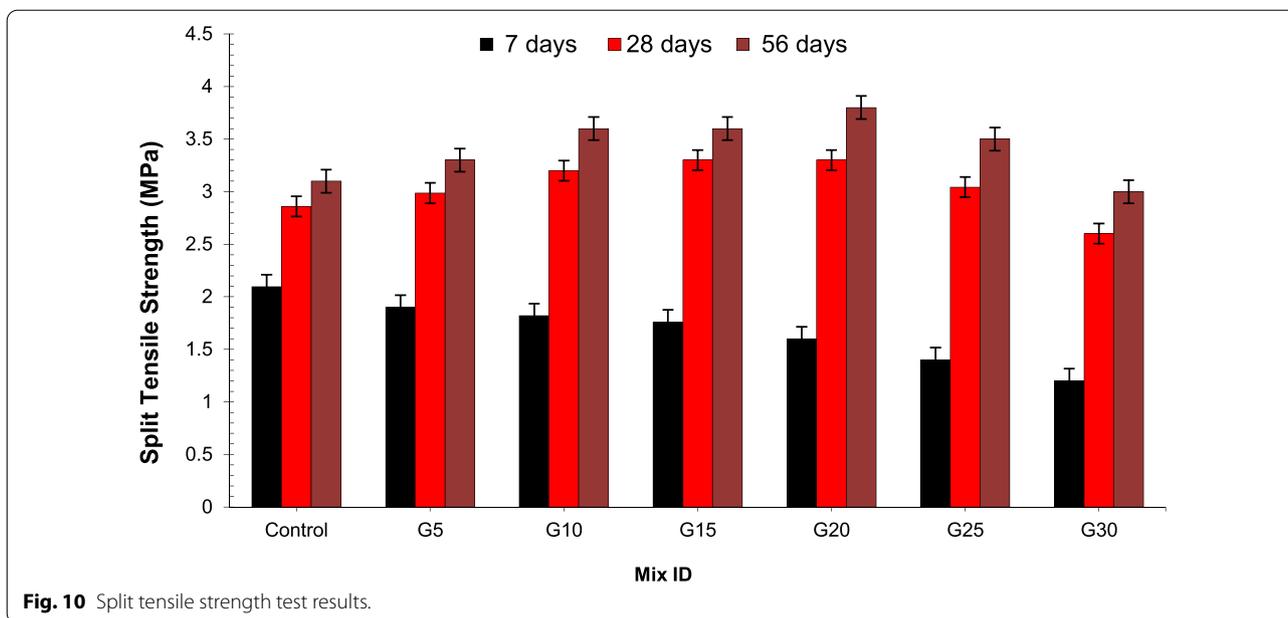


Fig. 10 Split tensile strength test results.

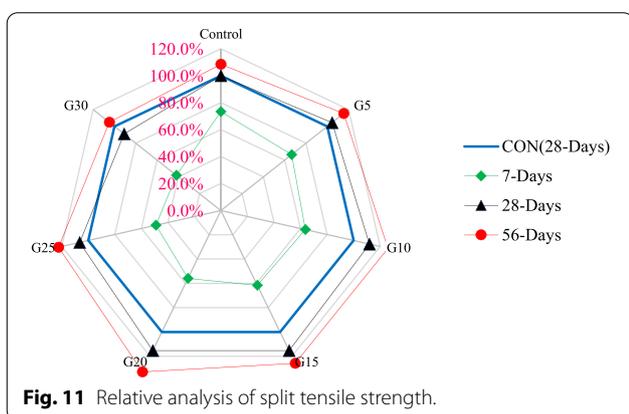


Fig. 11 Relative analysis of split tensile strength.

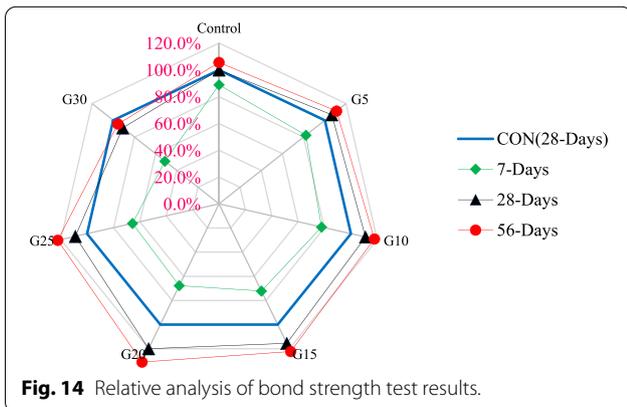
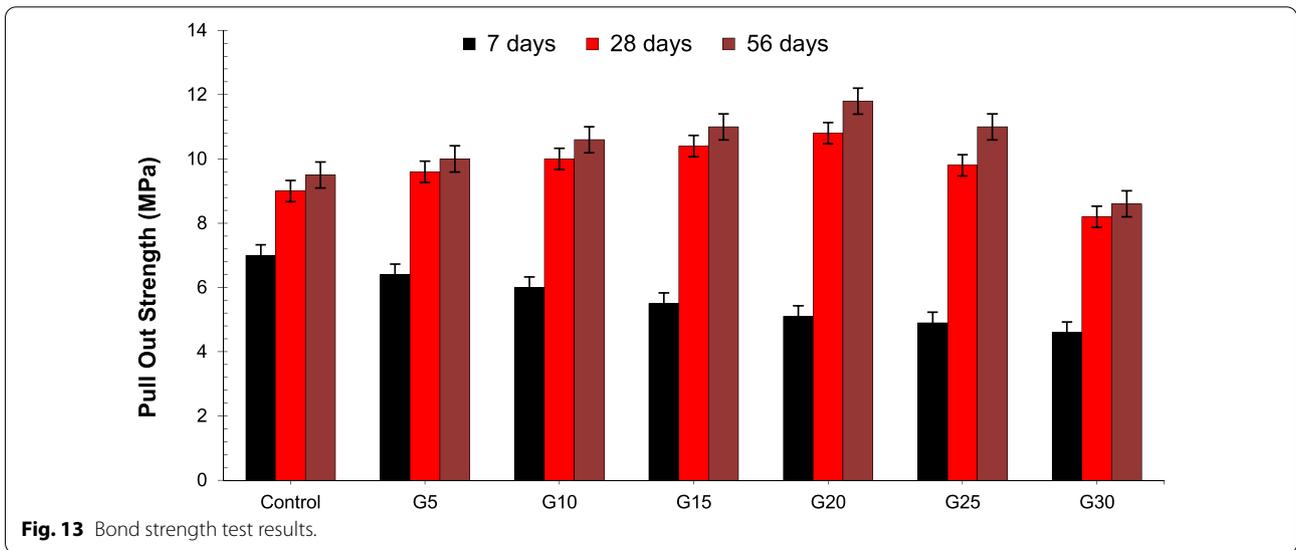
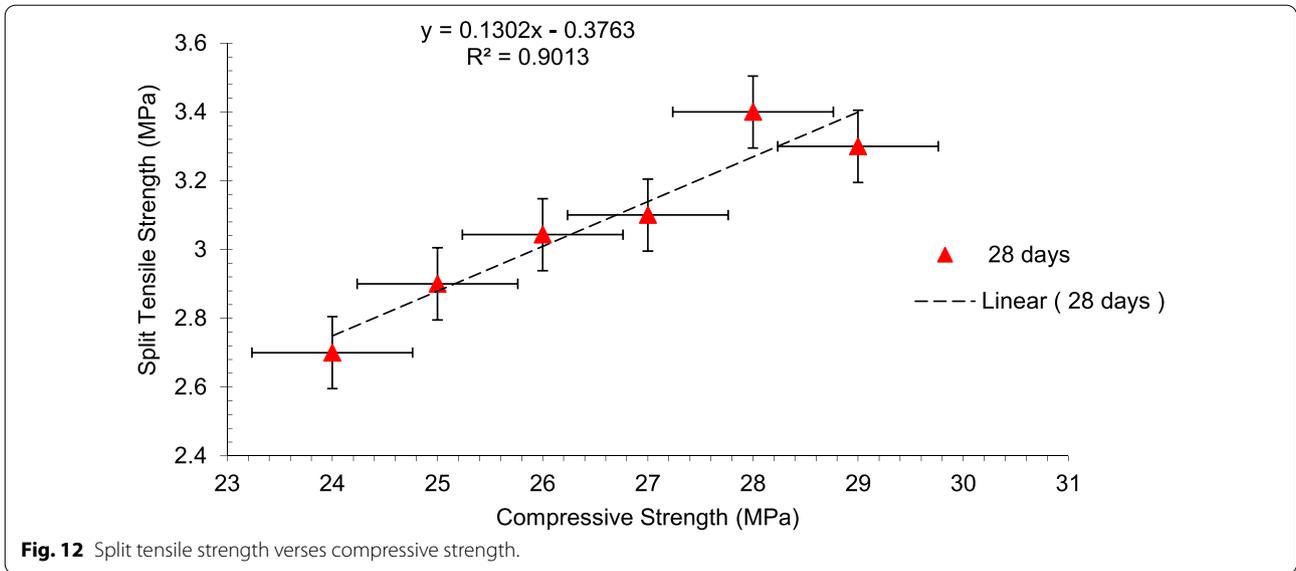
force being required to pull-out reinforcement and hence bond strength is increased. However, beyond 20% substitution of waste, bond strength starts to decrease. Even at 30% substitution of waste glass show a bond less than reference concrete (blank mix). It is because glass does not attract water which causes bleeding particular at higher dosages (30% substitution of waste glass). Concrete had maximum bond strength when glass powder content was 20 percent by weight of cement and minimum bond strength when the substitution rate is 30%. It has also been observed that owing to the pozzolanic activity of glass, which provides dense mass, and the confinement effect, the bonding between reinforcing bar and surrounding concrete enhanced (Ahmad et al., 2020). The bond between is considerably improved if the strength of concrete surrounding concrete is improved.

A relative assessment was executed in which control concrete pull-out strength 28 days was considered as a reference strength, from which concrete of varying percentage of waste glass is compared at age of different days of curing, as shown in Fig. 14. At 20% substitution of waste glass, bond strength is only 33% lower than the reference mix after 7 days. For the same substitution of glass (20%), bond strength is almost 20% higher than the reference mix after 28 days. At long-term bond strength (56-day curing), for the same substitution of glass (20%), bond strength is almost 31% higher than the reference mix.

The relationship of compressive strength versus bond strength is given in Fig. 15. The regression model between compressive and bond strength seems to be straight. The regression line depicts a strong co-relation among compressive strength versus bond strength showing an R^2 value of more than 90 percent.

3.2.4 Flexural Strength

Fig. 16 shows flexure strength with varying percentages of waste glass. Similar to compressive strength flexure strength at the initial stage (7 days) declines with the incorporation of waste glass. According to past research show that pozzolanic reaction proceeds slowly (Pereira-de-Oliveira et al., 2012). Early strength decreases with the incorporation of glass (Metwally, 2007). However, in the long-term strength (28 and 56 days), the flexure strength increased up to 20% substituting the glass and then decreased. Similar to earlier study show that



flexure strength increases up to 20% replacement of glass (Soroushian, 2012). Minimum flexural strength was obtained at 0% substitution of waste glass, while the highest strength is attained at 20% alternative of glass. It is due to fact that glass shows pozzolanic activity if the grain range is smaller than 75 microns. It is also reported that the pozzolanic activity of glass increases as the particle size decrease (Tamanna et al., 2016). The positive effect on bending strength is due to the pozzolanic activity of SiO₂ in glass with Ch of OPC giving additional binding gel. However, at a higher dose of glass (30%) the strength decreases owing dilution effect. In addition, at higher dosage waste glass (30% by weight of cement), the

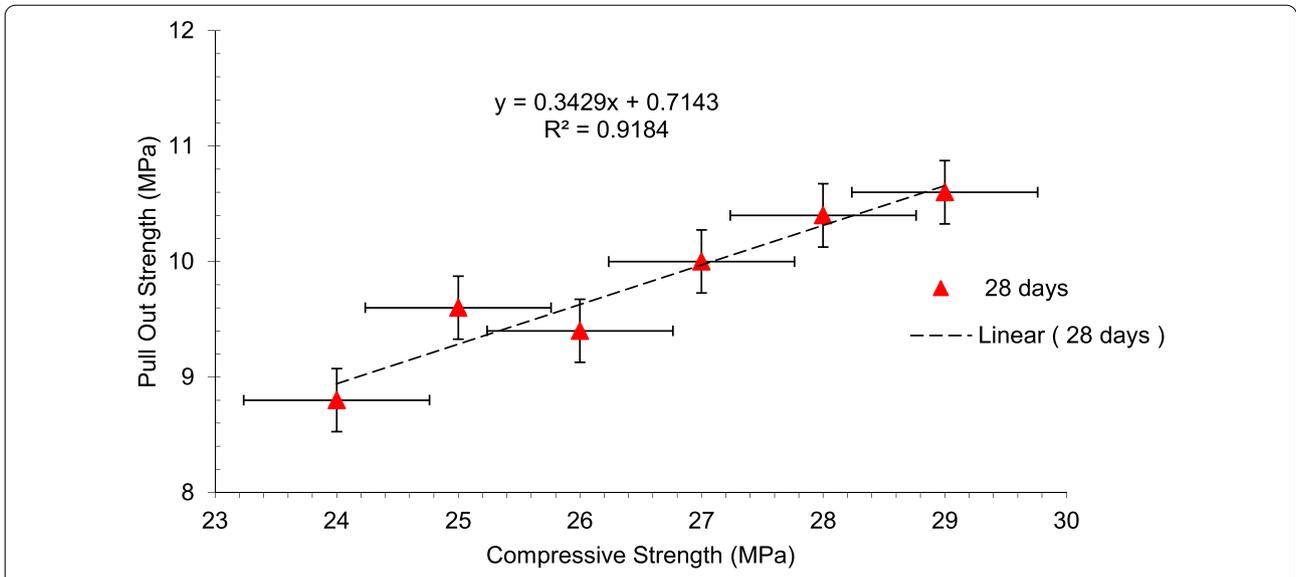


Fig. 15 Co-relation bond strength and compressive strength.

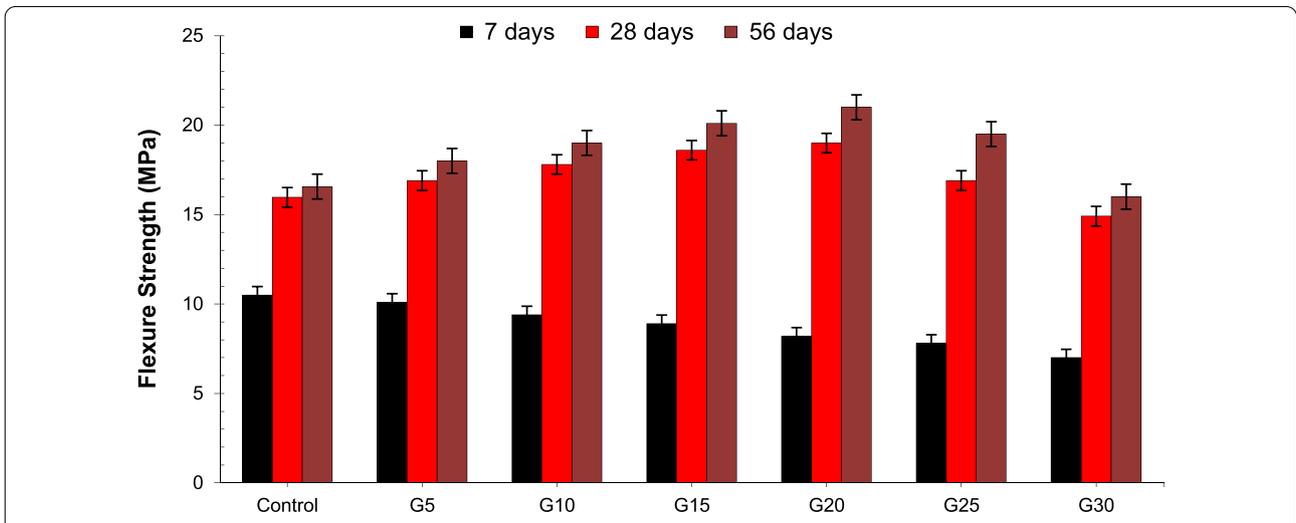


Fig. 16 Flexure strength test results.

compaction procedure becomes further complicated due to lack of flowability which causes increased compaction efforts resulting in pores in hardened concrete causing lower flexure capacity.

A relative assessment was executed in which control concrete flexure strength at 28 days was considered reference strength, from which concrete of varying percentage of waste glass is compared at age of different days of curing, as shown in Fig. 17. At 20% substitution of waste glass, flexure strength is only 49% lower than the reference mix after 7 days. For the same substitution of glass (20%), flexure strength is almost 19% higher than the reference mix after 28 days. At long-term flexure strength

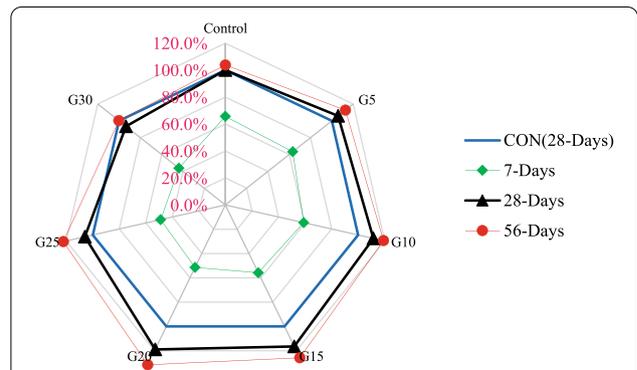


Fig. 17 Relative analysis of flexure strength test results.

(56-day curing), for the same substitution of glass (20%), bond strength is almost 32% higher than the reference mix. It can be concluded that glass improves strength over time (later age strength, i.e., beyond 28 days).

The relationship of compressive strength versus flexure strength is given in Fig. 18. The regression model between compressive and flexure strength is seemed to be straight. The regression line depicts a strong co-relation among compressive strength versus flexure strength having an R^2 value of more than 90%.

3.2.5 Young's Modulus of Elasticity (E)

Young's modulus of elasticity (E) is an extra index that measures the mechanical properties of concrete. E is a method of stability of an elastic matter and is used to connect the elastic property of objects when they are stretched or condensed. E is a very valuable parameter for any type of structural design. According to the author's best information, no researchers have evaluated the modulus of elasticity (E) on waste glass concrete in which waste glass is substituted by waste binding material in concrete production.

Fig. 19 shows modulus of elasticity with varying percentages of waste glass starting from 0% up to 30% by weight of cement in increment of 5.0%. E value was calculated after 28 days of curing concrete. E value is increased up to 20% addition of waste glass. It is reported, that the E value increase with the incorporation of waste glass (Ahmad, Tufail, et al., 2021). In addition, the E value is depending on the compressive strength of concrete, i.e., higher the compressive strength higher will be the modulus of elasticity and vice versa. Various experimental and

hypothetical relationships are existing that display that the E value depends on the compressive strength of concrete (Garcia, 2005).

The waste glass concrete E value can be directly calculated from the compressive strength of concrete using Eq. (1) given by ACI (Prabhu et al., 2014). In which f_c' is the compressive strength, while E is the young's modules. In which f_c' is the compressive strength, while E is the young's modules.

$$E = 5000x \sqrt{f_c'} \tag{2}$$

The relationship of the experimental values of E versus the predicted value of E is given in Fig. 20. The change among the experimental value of E versus predicted value of E using equation was approximately comparable. The regression model between the experimental value of E versus the predicted value of E using the equation is seemed to be straight. The regression line depicts a strong co-relation among the experimental value of E versus the predicted value of E using an equation having an R^2 value of more than 90 percent.

4 Scan Electronic Microscopy (SEM) Results

Scan electronic microscopy (SEM) is used to analyze the internal structure, as per ASTM C1293 267 test (Liu & Mukhopadhyay, 2016). Scanning Electron Microscope images of concrete samples with the presence and absence of waste glass after curing of 28 days, to describe the microstructure of waste glass concrete, as shown in Fig. 21. Fig. 21a shows the reference sample microstructure which presents the large cracks (interfacial transition zone). Voids and hairline cracks are also observed that

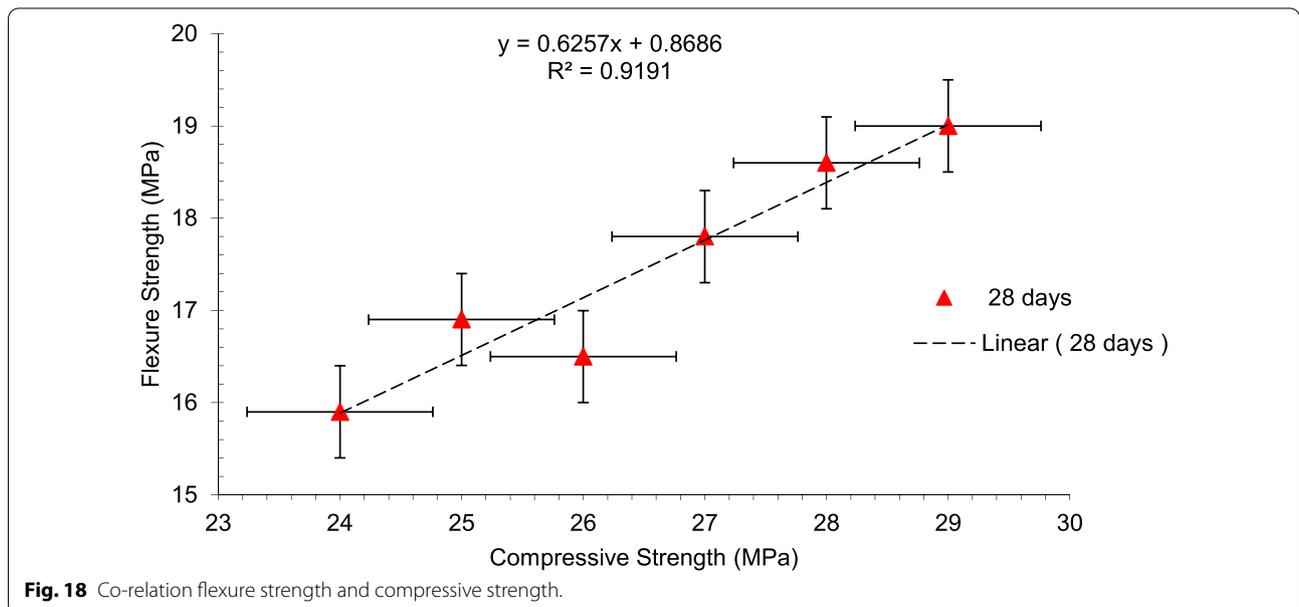
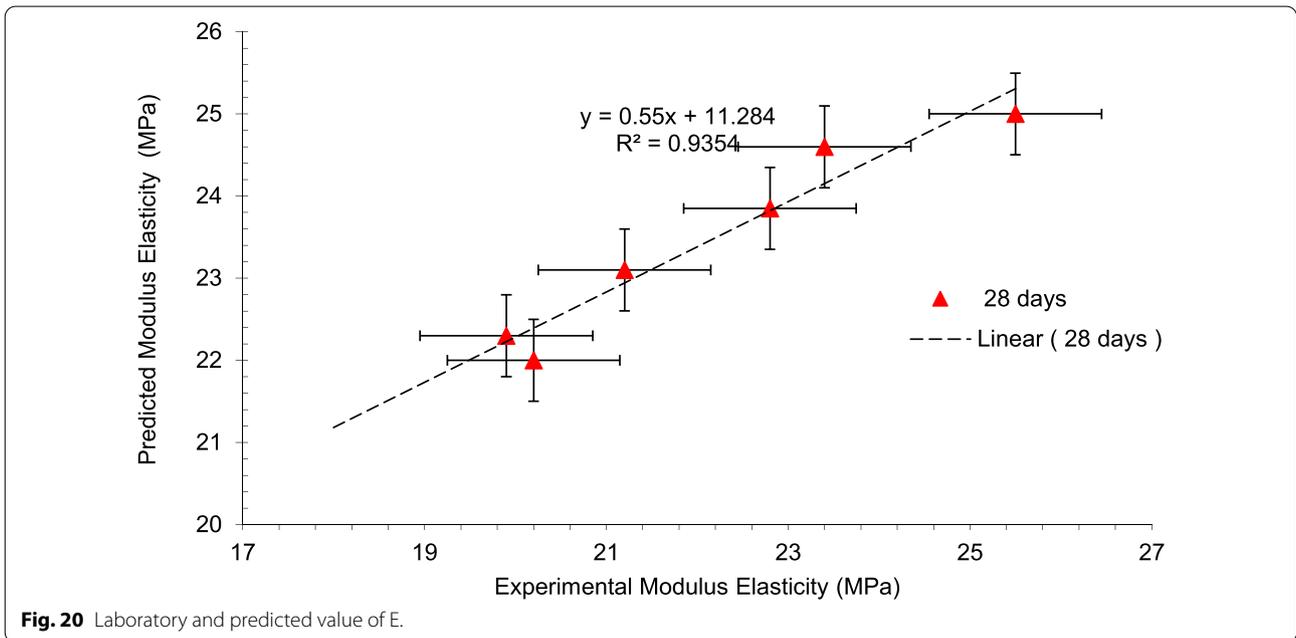
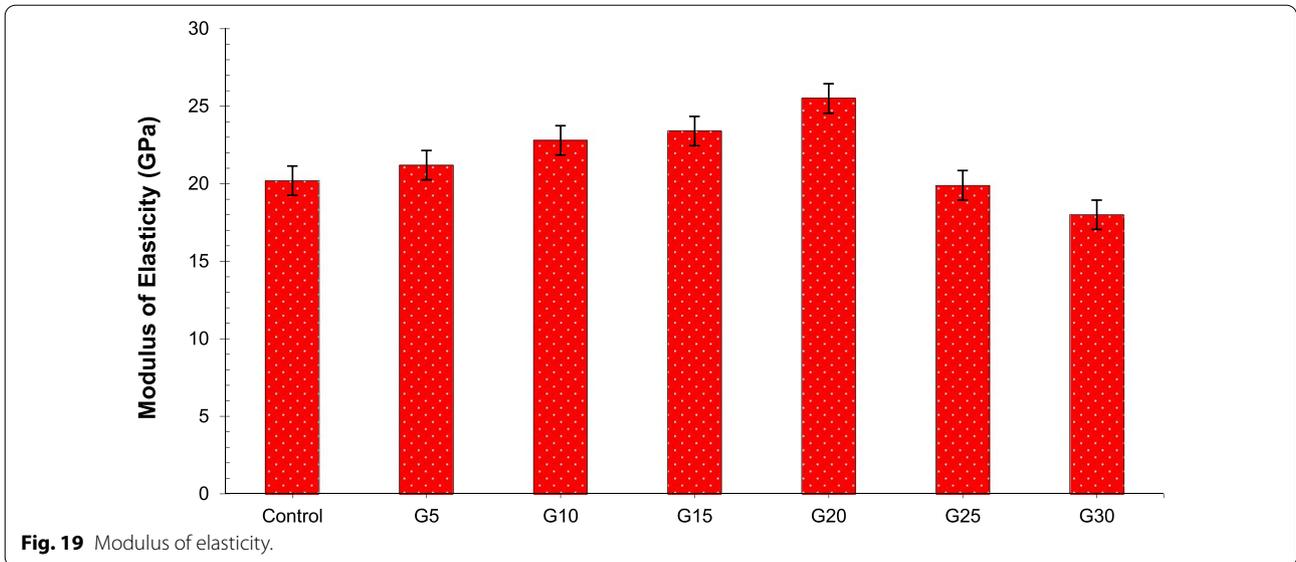


Fig. 18 Co-relation flexure strength and compressive strength.



passed through these interfaces. The addition of waste glass as a replacement for cement in concrete portrays the generation of a dense matrix. Particles of waste glass were spread appropriately throughout the binder matrix. Fig. 21c displays a dense interface which leads to enhanced concrete strength concrete (optimum dose). The increase in strength of concrete can be due to the micro filling and pozzolanic reaction of SiO₂ in glass by calcium hydrate (CH) of cement giving extra binding gel (Baboo et al., 2011). The additional binder produced by the waste glass due to reaction with available lime allows it to continue

to gain strength over time. Waste glass show pozzolanic property by converting CH (calcium hydrate) which is a by-product form during the hydration process of cement into CSH (calcium silicate hydrate) gel. In addition, due to the microfilling, effects of waste glass give more dense concrete, as shown in Fig. 21c. However, at a higher substitution of glass (30%) strength decrease due to bleeding observed which results more voids in harden concrete, as shown in Fig. 21d. In addition, I study show that, a higher dose of pozzolanic materials cause decreased in strength due to dilution effect which results in ASR (alkali-silica

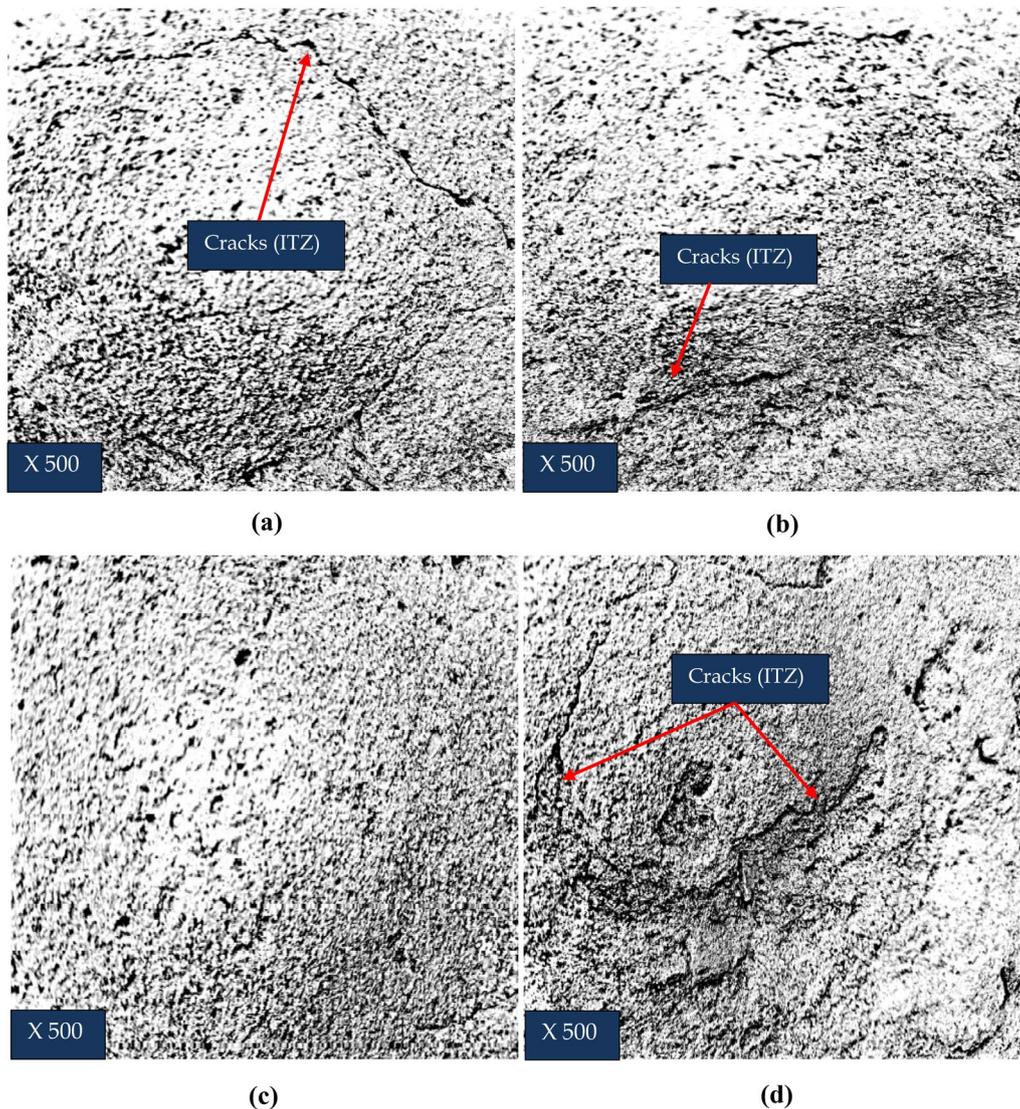


Fig. 21 a 0% Waste glass, b 10% waste glass, c 20% waste glass and d 30% waste.

reaction) due to the large quantity of non-reactive silica available due to high amount of glass ref.

4.1 Fourier-Transform Infrared Spectroscopy (FT-IR)

Fig. 22 depicts the use of Fourier-transform infrared spectroscopy to study the bands of chemical groups found in concrete samples in the presence and absence of waste glass after 28 days. The FTIR spectrum may be divided into four peaks. These peaks were observed at 1000 cm^{-1} , 2000 cm^{-1} , 3500 cm^{-1} , and 4500 cm^{-1} . These bands are classified based on the presence of molecular groups, such as calcium hydrate $\text{Ca}(\text{OH})_2$, carbonate (CO_3^{2-}), free water (OH), calcium silicate hydrate (C-S-H), and free silica (SiO_2). Increase in

the content of waste glass as a replacement of cement, free water decreases due to consuming this water, which delays the hydration process. It can be observed that the concentration of Calcium Silicate Hydrate (C-S-H) as the percentages of waste glass increased having maximum calcium Silicate Hydrate (C-S-H) at 30% substitution of waste glass. It is because waste glass is a pozzolanic material that gives secondary Calcium Silicate Hydrate (C-S-H). Calcium Silicate Hydrate (C-S-H) forms due chemical reaction of SiO_2 glass with CH form during hydration of cement. Calcium Silicate Hydrate (C-S-H) gel process binding results to enhance the mechanical performance of concrete.

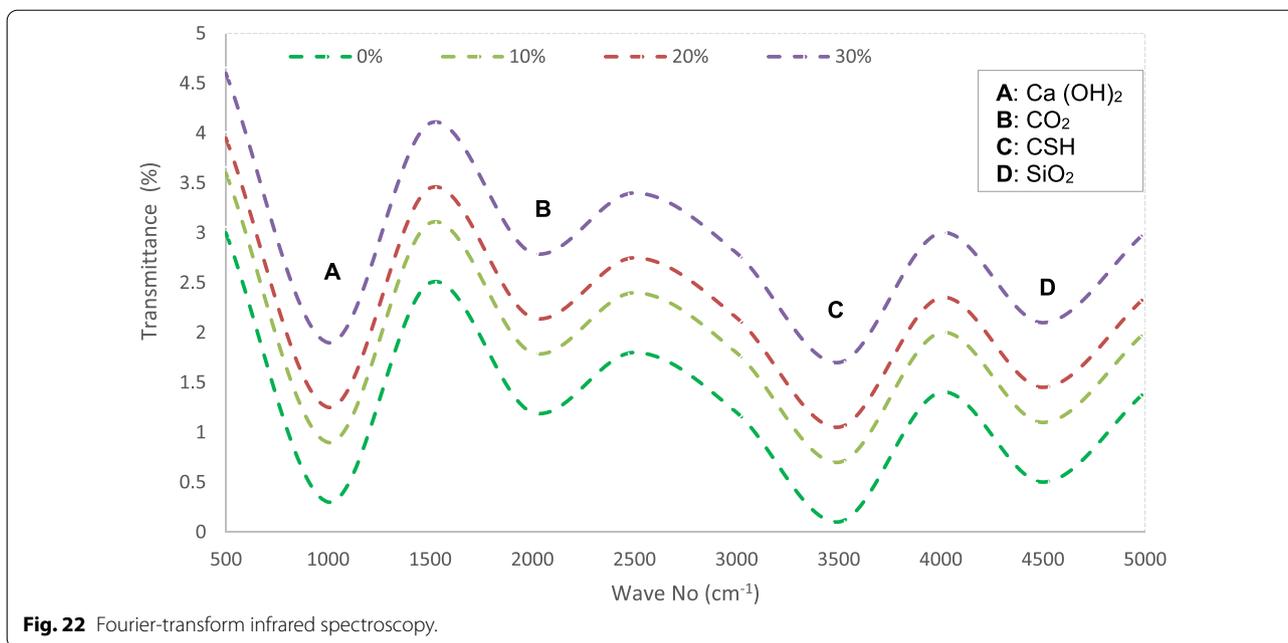


Fig. 22 Fourier-transform infrared spectroscopy.

4.2 Thermogravimetry (DTG)

Thermo-gravimetric analysis (TGA) determines a material's mass loss as a function of temperature. Fig. 23 shows the derivative thermogravimetry (DTG) with different waste glass doses (Control, G-10%, G-20%, and G-30%) at a curing age of 28 days. A free water peak was seen at roughly 100 °C, and three major peaks were discovered at various temperatures. The first was about 200 °C, which is connected to ettringite dehydration. The

dihydroxylation of calcium hydroxide Ca(OH)₂ caused the second peak to be noticed at 600 °C. The decarbonization of CaCO₃ caused the third significant peak to be detected at roughly 800 °C. The peak of CaCO₃ increased significantly as the percentages of waste glass increased, whereas the peak of Ca(OH)₂ decreased as the percentages of waste glass increased, with a minimum peak at 30 percent substitution of waste glass at 28 days due to

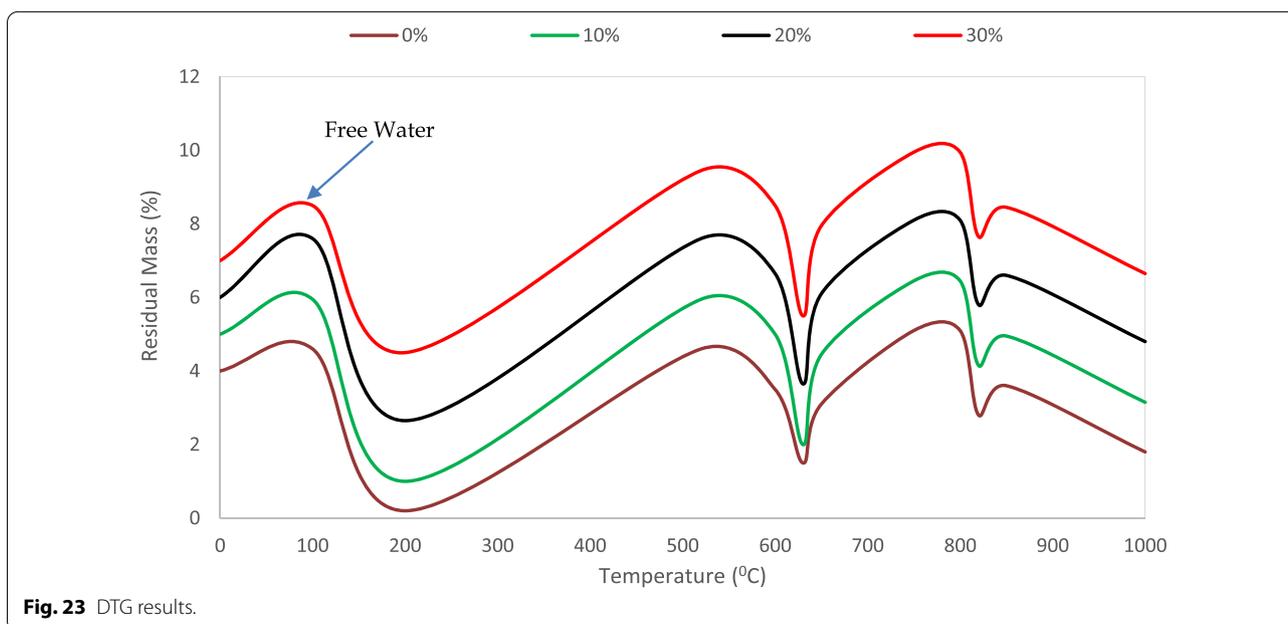


Fig. 23 DTG results.

cement reduction and the potential pozzolanic reaction of waste glass, as shown in Table 6. The hydration process results in the formation of Portlandite, which contains up to 30% waste glass. With a comparable degree of polymerization, the shaped Portlandite transforms into Calcium Silicate Hydrate (C–S–H) gel. C–S–H resulted in a dense matrix, which eventually increased the strength of the concrete.

5 Conclusions

The current study investigates the use of waste glass as a binding material in cement concrete. The best dose of replacement was observed at 20% substitution of binding material with waste glass. The following findings are based on the current study.

- The flowability of concrete increases as the proportion of waste glass is enhanced. It is because less water absorption of waste glass and micro filling of voids hence more cement paste is available for lubrication to reduce the internal friction between aggregate particles.
- At 7-day strength (compressive, flexure, split tensile and pull-out strength) reduces with the incorporation of waste glass. It is due to the pozzolanic activity of waste glass. However, as the curing days increased (28 and 56 days), the strength of concrete increased up to 20% replacement of cement by WG and then decrease.
- At higher dosage (at 30% substitution), strength (compressive, flexure, split tensile and pull-out strength) reduces due to the dilution effect which causes alkali reaction.
- Microstructure analysis displayed good interfacial bonding among aggregates and binder paste. At the interface, voids and hairline cracks were also observed, which cause a decrease in strength at higher replacement levels of waste glass.

Finally, the overall study indicated that waste glass may be successfully utilized in concrete up to 20% substitution by weight of binder without negative effects on

Table 6 Ca(OH)₂ content at 28 days.

Mix ID	Ca(OH) ₂ content (Wt%)
Control	10.50
G10	7.76
G20	6.50
G30	4.32

the mechanical or durability performance of the concrete. Although, waste glass significantly enhanced the mechanical performance of concrete, yet concrete is still weak in tension, resulting in brittle collapse without warning (deformation). This is an unsatisfactory condition for any structural components. As a result, more study was suggested to use fibers in waste glass concrete to improve the tensile capacity of waste glass concrete to avoid undesirable brittle failure.

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Authors' contributions

JA: Paper writing, Experimental work, Methodology, RMG: Supervision, Conceptual. SA: Software work, Revision. JDPG: Data Analysis, Software work. TA: Proof reading, Formatting, Software work. KI: Revise paper, Grammatical improvement.

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