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REVIEW

Strength and Durability Properties of Waste Glass Based Self Compacting Concrete: A Review

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Abstract
Self-compacting concrete (SCC) also uses a wide variety of resources, which makes it unsustainable. Currently, a lot of experts are concentrating on using valuable industrial or agricultural waste as the main raw material for the building industry. These wastes, on the other hand, are affordable and readily accessible everywhere, making them ideal for commercial use while also contributing to the reduction of environmental degradation. Waste glass (WG) is a kind of industrial waste that has the potential to be utilized in concrete. Many researchers are focused on utilizing WG in concrete and stated encouraging responses. However, the information is scattered, and no one can judge easily the benefits of WG which restrict its use. Therefore, a details review is required of WG as construction materials which provide an easy path for the reader. Furthermore, some researchers successfully conduct a review on WG as a concrete ingredient. However, according to the author's best knowledge, fewer studies focus on the utilization of WG in SCC. This review aims to deliver a concise summary of the already research carried out on WG as SCC ingredients to identify the benefits, mechanisms, and current researcher progress. Chemical compositions and physical properties of WG, strength properties, durability properties, and environmental benefits are the main aspects of this review. In addition, the review assesses future researcher guidelines for SCC with WG to improve its performance.

Keywords Self-compacting concrete · Waste glass · Compressive strength and durability

1 Introduction

In recent years, Self-Compacting Concrete (SCC) has emerged as one of the top high-performance concretes. SCC is a kind of concrete that can be laid down and consolidated using its weight [1, 2]. Even in severely structural components, it may fill reinforcing holes and spaces, and it flows without segregation [3, 4]. SCC reduces noise because it creates a vibration-free atmosphere, but it also improves the quality of concrete by reducing the need for human involvement in workability tasks. This concrete has recently been widely used in several nations for a variety of purposes [5]. Although using SCC has several technical benefits, the expense of delivery may be 2 or 3 times more than that of traditional concrete [5] depending on the mix design and concrete production quality control.

Therefore, an effort is being made to lower the cost of SCC manufacturing by substituting cheaper resources, particularly waste compositions, for the material mixes. Additionally, many nations are seeing a significant expansion of the building sector, which entails the utilization of natural resources for the building of infrastructure. The scarcity of accessible natural resources endangers this expansion. Worldwide, there is a shortage of natural resources, while at the same time, industrial waste generation is sharply rising [6–8]. Utilizing unconventional and cutting-edge materials as well as recycling trash are all part of sustainable growth for the building industry [9–11]. This helps to make up for the reduction of environmental resources and seeks out other methods of environmental preservation. Many amenities for humanity have been produced by modernization and industry. However, owing to the generation of waste materials and the release of dangerous gases, urbanization has resulted in several ecological problems, including contamination, the destruction of natural resources, and difficulties with waste disposal [12–15].

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SCC mixes include cement, coarse aggregate, fine aggregate, water, and additives, just like regular concrete [16–19]. Nevertheless, more sand must be added at the expense of less coarse material for improved viscoelastic qualities [20, 21]. SCC, in contrast to conventional concrete mixtures, comprises a high composition of fillers as fillers to enhance the transport qualities of concrete. Using a large quantity of cement as the sole powder component is not only economically unfeasible but also has negative environmental effects. Due to this, scientists have begun to substitute other powder substances, such as fly ash, silica fumes, and blast furnace slag, for a part of the cement in concrete, which lowers the cost of the material while simultaneously enhancing its performance [22]. To lower the quantity of cement and heat of hydration, improve rheological properties and longevity, and delay the setting time. Fillers like limestone powder are used as pozzolanic materials. Additionally, superplasticizer is used to lessen yielding stress and improve resistance to segregation [23].

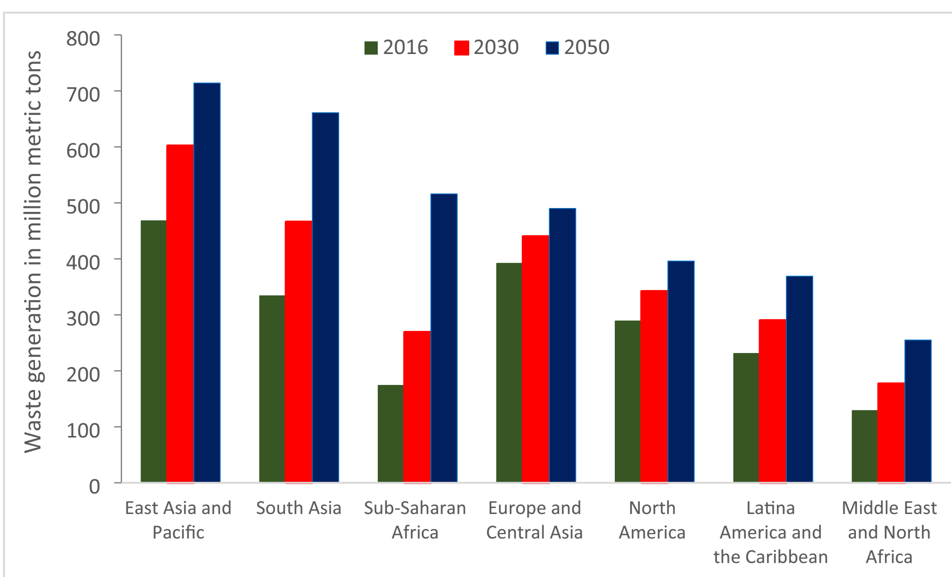
Due to pollution, rising consumerism, and a rise in waste materials, the globe is now dealing with numerous major environmental concerns. Figure 1 depicts global garbage production and projections. Additionally, the ecological demand is to implement eco-friendly methods for reusing and utilizing this garbage to save environmental assets and lower Carbon dioxide CO_2 discharges [24]. Rising living standards, industrialization, and urbanization resulted in a growing quantity of garbage that is creating dumping issues.

Additionally, out of 25 million tons, 17.5 million tons were dumped carelessly [25]. Recycling garbage is thus seen as the best option since it lessens environmental degradation and facilitates the recovery of power generation processes. Due to its nonbiodegradability, which leaves it less ecologically beneficial, and the fact that landfill capacity is being reached, glass garbage is unattractive for disposal [26]. As a result, WG has significantly increased the load on dumps across the globe. Every time the quantity of WG grows and the landfill's area is at a premium, disposing of it becomes more difficult [27]. Therefore, it is crucial to develop a sustainable substitute so that this substance may be reused and recycled.

The fact that glass is mostly used for single-use items like beverage bottles is a major issue. It is projected that WG produced 5% of the world's municipal solid trash in 2016 [28]. Glass products are being used much more often, which has produced vast amounts of WG. Glass production is projected to total 209 million tonnes yearly worldwide [29]. Europe's glass recycling rate was 71.48 percent in 2017, ranging from 98 percent (Slovenia and Belgium) to 9 percent in individual nations (Turkey). In 2017, the United States had a glass recycling rate of 26.63 percent, sending 52.9% of glass containers to landfills [29]. Glass garbage is not biodegradable and takes up precious landfill space indefinitely. Poor recycling processes result in the dumping of glass trash in landfills, increasing the need for natural resources and decreasing supplies like beaches to make additional glass. Landfill tax is projected to increase as landfill space becomes more in demand, encouraging improved recycling practises. Finding more affordable ways to recycle waste may reduce disposal costs while preserving landfills and natural resources. Due to the rising need for landfill space and environmental assets as well as the increased focus on lowering the carbon footprint of the building sector, the management of WG became a significant environmental challenge.

Glass is a special, inert, and perfect substance that can be reused endlessly without losing any of its chemical

Fig. 1 Worldwide waste production and prediction: Source (https://bit.ly/3DKYVqj)



characteristics [30]. Due to high WG dumping prices and environmental laws, the use of WG as concrete ingredients has recently received new study attention [31, 32]. The first man-made materials are composed of glass. It is created in a variety of shapes, such as flat glass, bulb glass, cathode ray tube glass, packaging, container glass, and so on. Each of these shapes has a finite life span. Glass must thus be reused to prevent the environmental concerns that might arise if it is accumulated or landfilled. Glass is a substance that is 100% recyclable and may be recycled continuously without losing quality [33]. The use of broken glass as aggregates was the subject of much laboratory investigation. They discovered that with 100% crushed glass as aggregates, 80% ASTM Type III Portland cement, 20% metakaolin as cementitious, and the right quantity of plasticizer, a fairly workable concrete could be created [32]. In the creation of concrete, WG may be utilized as a cement substitute or as an aggregate. Nevertheless, the outcomes are dependent on the WG particle size, replacement rate, and chemical makeup, all of which must be taken into account while designing the mix. The function of WG in concrete is shown in Fig. 2.

Concretes with up to 30% WG as a cementitious material achieve the maximum compressive strength (CS) and least permeability. The CS decreases above this replacement level (30%) [35]. Some other studies found that the strength of 45 MPa control concrete increased up to a substitution rate of 10% whereas the CS of 33 MPa control concrete decreased when more than 5% of the binder was supplanted by WG [36]. Workability improves with increasing WG content, according to a study that mortar samples with WG of about 15 mm at 0%, 10%, and 20% cement replacements [37]. The impact of WG fineness on various SCC qualities was explored. For concrete produced using WG with smaller particle sizes, improved strength, and durability characteristics have been reported [38]. A study that used 13 mm WG as additional cementing material in concrete found that adding WG slightly increased the slump, possibly because of the non-water absorption nature of WG [39].

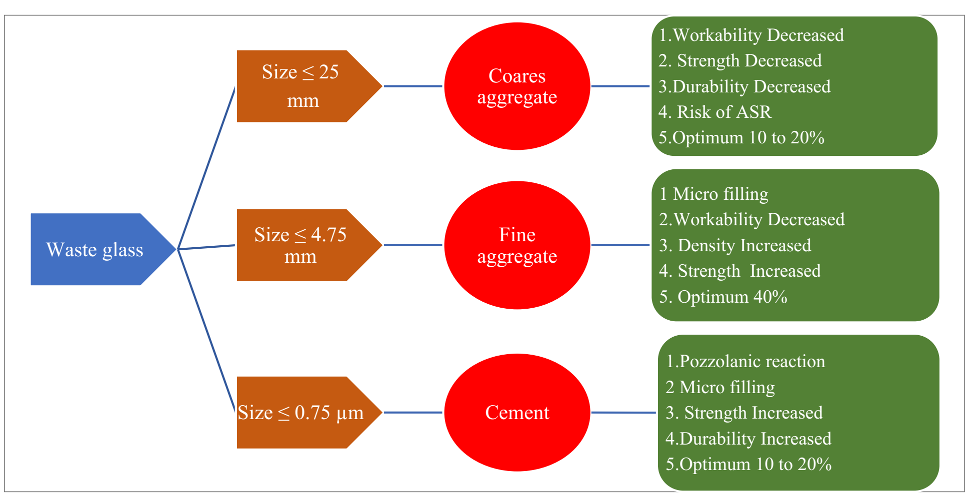
A short review of the literature reveals that many researchers are committed to using WG in practical ways and have seen success. However, there is a lack of knowledge and difficulty in evaluating the advantages of WG, which limits its application. To provide a simple route for the reader, a detailed overview of WG as building materials is necessary. Additionally, several researchers have effectively reviewed WG as a concrete ingredient. The authors' best information, however, indicates that little study has been done on WG as self-compacting concrete. The objective of this study is to provide a succinct overview of the prior research on WG as SCC constituents to highlight the advantages, mechanisms, and ongoing research developments. The key topics of this review are the chemical make-up and physical characteristics of WG, strength characteristics, and durability characteristics.

2 Physical and Chemical Properties of the Waste Glass

The bulk specific gravity of the WG was 2.49, which is less than that of cement (3.0), and its fineness modulus was 4.25, with a water absorption of 0.36. The grading of the glass aggregates met the requirements of BS 882 [40] for aggregates. According to an investigation, WG has an average surface area of 2120 g/cm2 and a PH value of 10.8 [41, 42]. About 40% of the mixture is made up of clay and dust [43]. Figure 3 depicts the WG before and after crushing.

According to Table 1, the primary components of WG powder are SiO_2, Na_2O, and CaO. Nevertheless, the amounts of these fundamental substances vary depending on the kind of glass being produced. Most glass varieties listed in the literature have a substantial quantity of SiO_2 (70%). According

Fig. 2 Role of WG in concrete [34]



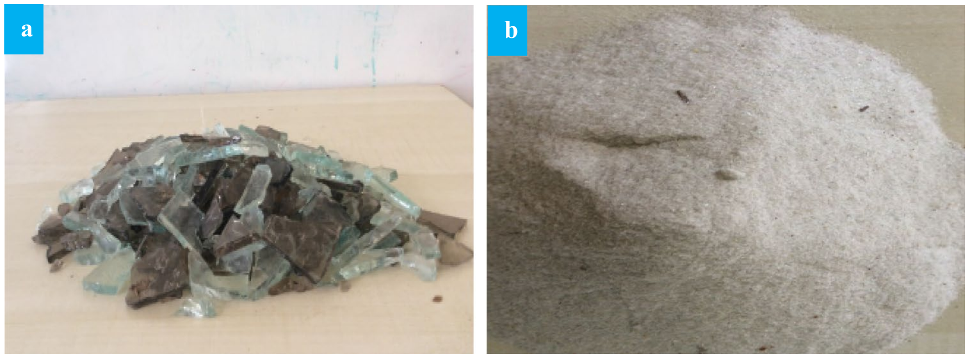


Fig. 3 WG (**a**) before crushing and (**b**) after crushing [44]

to ASTM C 618, cementitious material's pozzolanic activity must be at least 70 percent $SiO_2 + Al_2O_3 + Fe_2O_3$ to be classified as Class F [45]. Because glass has a higher SiO_2 content than regular Portland cement (OPC), it may substitute for pozzolana when employed as an additional cementitious ingredient.

Figure 4 displays pictures of glass particles obtained using scanning electron microscopy (SEM). Glass is made up of sharp, harsh, and unevenly surfaced grain forms. Concrete's flowability was decreased by the angularity and rough surface roughness of glass particles. The components' internal resistance was increased by irregularities and harshness. According to research, fly ash particles are smooth and round, while glass particles are harsh and irregular [48].

3 Strength Properties

3.1 Compressive Strength (CS)

The compressive strength (CS) of SCC with the replacement of WG is shown in Table 2 and Fig. 5. It should be noticed that the replacement of WG lowered the CS of SCC. The research found that irrespective of substitution percentage or age, using glass as a substitute for natural sand significantly reduced CS compared to the reference blend. Additionally, it was discovered that CS was unaffected by WG substitution by up to 30%. At 28 days, there was a 1.78 percent, 2.52 percent, and 6.57 percent decrease in CS compared to the reference blends for glass substitution rates of 10%, 20%, and 30%, respectively. After additional increases in glass content, notably after a 30 percent substitution, the drop in CS became noticeable. The largest CS decrease recorded for 50% WG was 15.29 percent [2]. This decrease could be due to weaker interfacial adhesion between the cement paste matrix and glass particles, smooth grain surfaces, and decreased toughness strength against fracture [49].

According to research, using recycled glass trash instead of sand lowers the CS of SCC combinations when compared to the reference blend. It was found that the high degree of smoothness of the WG particle, causes fractures as well as insufficient adhesion between the WG and cement paste inter-phase. An increase in the quantity of glass waste used in concrete lowered the CS because the poor geometry of WG prevented a homogenous dispersion of aggregates. When compared to control mixes at various percentages of WG substitutes, the percentage of CS loss is reduced as cement rises from 350 to 450 kg/m^3. This might be explained by the pozzolanic reactions that develop as the cement rises from the addition of silica fume and the high proportion of fines generated as the amount of WG rises [43]. According

Table 1 Chemical composition of WG powder (WGP)

Reference	[41]	[43]	[46]	[47]	[42]
SiO_2	61.51	67.72	71.91	70.50	74.3
Al_2O_3	1.53	1.20	-	2.60	0.15
Fe_2O_3	1.67	1.20	0.01	-	0.08
MgO	2.41	6.0	7.30	2.90	3.91
CaO	10.56	6.90	7.30	5.70	8.79
Na_2O	8.65	5.35	9.59	16.30	11.6
K_2O	-	5.35	0.53	1.20	0.03

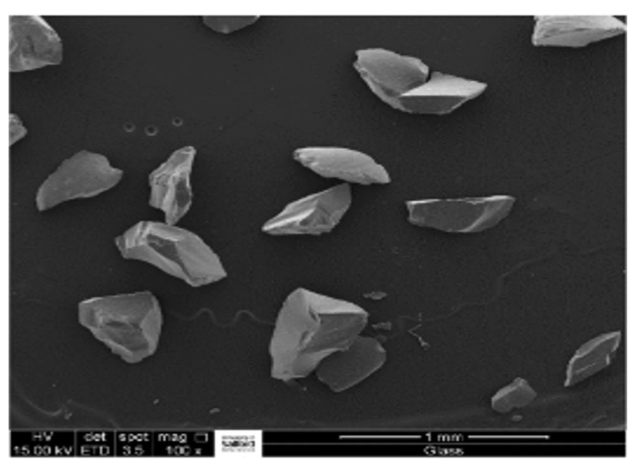


Fig. 4 SEM of WG particle [37]

Table 2 Summary of strength characteristics of SCC with substitution WG

Ref	WG as a concrete ingredient	Other Material	Percentage Range of WG	W/C	Flowability	Days	Min and Max Compressive strength (MPa)	Min and Max Tensile Strength (MPa)	Min and Max Flexural Strength (MPa)	Remarks
[41]	Cement	-	0–15	0.40	Declined	7	20.21—29.48	-	2.65—3.12	Increased
						14	22.56—27.15		4.34 -3.56	
						28	29.54—44.56		4.25 – 5.34	
[43]	Fine Aggregate	-	0–50	0.40	Increased	7	26.9—35.3	3.2–4.7	4.2–5.5	Declined
						28	35.6—46.3			
[46]	Fine Aggregate	-	0–100	0.35	-	28	53—67	3.4–5.0	2.9–5.4	Declined
[47]	Fine Aggregate	-	0–50	0.52	Increased	7	35.86 – 39.69	-	-	Declined
						14	41.88 – 44.71	-	-	
						28	44.52 – 48.51	2.92 – 3.10	4.05 – 3.44	
[40]	Fine Aggregate	-	0–30	0.37	Increased	7	42.2 – 47.3	-	-	Declined
						28	61.1 – 67.4	3.03 – 3.42		
						90	68.5 – 75.4	3.71 – 4.18		
[42]	Cement	Steel slag	0–40	0.50	Declined	28	20.2 – 21.8	2.10 – 2.94	2.66 – 3.34	Declined
[50]	Fine Aggregate	Metakaolin	0–50		-	7	30 – 35	-	-	Increased
						28	50 – 60			
						90	60—75			
[2]	Fine Aggregate	-	0–50	0.40		7	41.79 – 52.70	-	7.91 – 8.91	Declined
						28	43.13 – 53.21		8.73 – 9.38	
						90	48.33 – 57.05		9.02 – 10.22	
[51]	Fine Aggregate	Zeolite	0–80	0.40	Increased	7	47 -49	-	-	Increased
						28	48 – 55			
						90	55—62			
[52]	Fine Aggregate	-	0–45	0.40	Increased	7	24 – 27	2.4 – 2.6	1.7 – 2.7	Increased
						28	27 – 37	3.2 – 4.6	2.7 – 3.6	
						90	27—38	3.4 – 5.2	2.7 – 3.7	
[53]	Cement	-	0–30	0.60	Declined	7	11.21 – 23.17	-	-	Declined
						14	12.14 – 27.26		-	
						21	15.39 – 28.52		-	
						28	15.48 – 33.28		6.61 – 7.63	
[54]	Fine Aggregate	-	0–2.5	-	Increased	7	22.0 – 25.6	1.6 – 2.2	2.9 – 7.0	Increased
						28	45.0 – 49.2	2.9 – 3.5	5.5 – 8.0	
[55]	Cement	Fly Ash	0–20	0.40	Declined	28	61.37—72.33	-	8.7—13.7	Increased
[56]	Cement	-	0–30	0.35	Increased	7	13.95 – 35.31	-	-	Increased
						28	15.85 – 40.13			
[4]	Cement	-	0–15	-	Declined	28	30 – 38	-	3.6—3.9	Declined
[57]	Cement	Foundry Sand	0–50	0.50	-	7	17.77 – 22.66	1.98 – 2.51	2.82 – 3.35	Declined
						28	21.33 – 26.22	2.41 – 2.90	3.94 -4.69	
[58]	Fine Aggregate	Nano Silica	0–50	0.40	-	7	20 -28	-	-	Declined
						14	21 – 35		-	
						28	58 -68		6.3 – 8.2	

to Park et al. [27], adding 30% of WG to concrete resulted in a 4 percent reduction in CS when compared to control mixes.

Natural aggregates were substituted with WG at replacement levels of 0 percent, 20 percent, 40 percent, 60, 80, and 100 percent by the total volume of aggregate. One can argue that the use of WG as a whole or partial substitute for natural aggregate has a negative impact on the values of CS. The greatest drop in strength was seen with a 100% WG substitution ratio. The proportional decrease in strength was somewhere between 26 and 43 percent. Additionally, the CS values varied between 53.0 and 65.2, 51.7 and 63.1, and 46.6 and 62.0 MPa. In addition to the WG particles' smooth surface, the free water that is not absorbed by glass particles may build up there, which might reduce ITZ strength by creating a weak link between them and cement particles. The decreasing trend was more obvious at high substitution levels. As a result, the range of CS was suitable for different applications of structural concrete [46].

The result demonstrates that the CS of SCC mix was lower than the control at all test ages when glass was used in substitution of sand and 10 mm coarse aggregate. Accordingly, the 28-day strength of glass with a 15 percent, 30 percent, and 45 percent substation was reduced by 1.5 percent, 4.2 percent, and 8.5 percent, respectively [40]. Additionally, according to research, the strength of concrete created using WG was only marginally stronger than that of regular concrete [27]. This may be explained by a weaker link between the cement particles and the glass as well as a rise in the fineness modulus of the natural rive sand, which reduced the density of the concrete. Nevertheless, research find that WG concrete had a greater CS value than regular concrete. At 10%, 40%, and 60% of WG substitution levels, the authors observed a boost in the value of CS [59]. Inherent fissures in glass particles and excessive bleeding of SCC mixes including glass aggregate should also be mentioned as having a harmful influence on the strength [60]. Glass aggregate's higher CS and greater angularity, when compared to natural aggregate, might be seen as contributing elements that can raise the CS [61]. Comparable CS of blends including glass aggregate and blends created without substituting natural aggerate with glass aggregate may be achieved under the combined impact of these favorable and unfavorable variables [51]. A study substituted 10%, 20%, 30%, 40%, and 50% of WG as natural river sand in SCC. The results show that the replacement of WG lowered the CS of SCC. Recycled glass SCC blends have a decrease of 2.93 percent, 0.36 percent, 2.735 percent, 1.3 percent, and 3.17 percent, respectively, after 28 days of CS. This is comparable to earlier concrete ages. The researcher concluded that, for practical applications, the CS of glass-based SCCs is about equivalent to the mix without the WG component. Therefore, replacing less than 50% of the WG with sand yields acceptable CS results. In comparison to its control combination, it was discovered that adding 50% of WG to SCC as fine aggregate reduced CS by 8% [43].

The research examined the combined effects of two industrial effluents, namely WG and steel slag, as replacements for cement and sand in SCC. The results show that when 20% of the cement is replaced by WG, CS increases compared to the reference concrete for all substitution levels of fine aggregates made of steel slag. However, when WG content is raised further, CS declines. Concrete's compressive strength (CS) rises with an improvement in steel slag content at a constant level of WG concentration. When 20% glass powder was substituted as a binder and 80% steel slag was substituted as sand, the highest boost in CS (11%) was noted as compared to the reference mix. On the other hand, the CS of concrete slightly decreases when the amount of WG increases while the amount of steel slag remains constant. The minimal CS is specified as 40% cement substitute and 40% sand substitute for concrete including WG and steel slag, respectively showing CS 5.7 percent less than the reference mix [42].

According to research, the CS of 30 percent (10 m) WG was comparable to 30 percent fly ash at all ages. However, the CS values for mixes of 20 percent (10 m) and 40 percent (10 m) WG were lower as compared to the fly ash-based concrete. The possibility of replacing cement with WG is confirmed by the CS of 30% (10 m), which matched the intended concrete strength at 545 days. Even the coarsest glass utilized in this investigation had at least a minor pozzolanic impact that persisted after 90 days of curing, according to the ongoing strength growth in all glass mixtures [48]. It was found that the failure pattern of concrete cube specimens including glass was comparable to that of standard concrete cubes, which normally have their failure line parallel to the direction of the applied stress as presented in Fig. 6.

Compressive strength aging relation is depicted in Fig. 7, where 28 days' CS was chosen as the reference strength from which other WG doses are compared at various curing days. When 10 percent of WG is substituted for reference concrete, the CS of concrete after 7 and 28 days is equal to the reference concrete's (control concrete's CS after 28 days), but after 90 days, the CS is 6% more than reference concrete. The pozzolanic reaction of WG is responsible for the increase in CS after 28 days since it develops more gradually than cement hydration. Similar research revealed that the pozzolanic process moves more slowly than cement hydration [62–64].

When 20 percent of WG is substituted for reference concrete, the CS of concrete after 7, 28, and 90 days are equal to the reference concrete's (control concrete's CS after 28 days). When 40 percent of WG is substituted for reference concrete, the CS of concrete after 7 and 28 days is 15 and 11% less than the reference concrete, but after 90 days, the CS is equal to reference concrete. Therefore, WG up

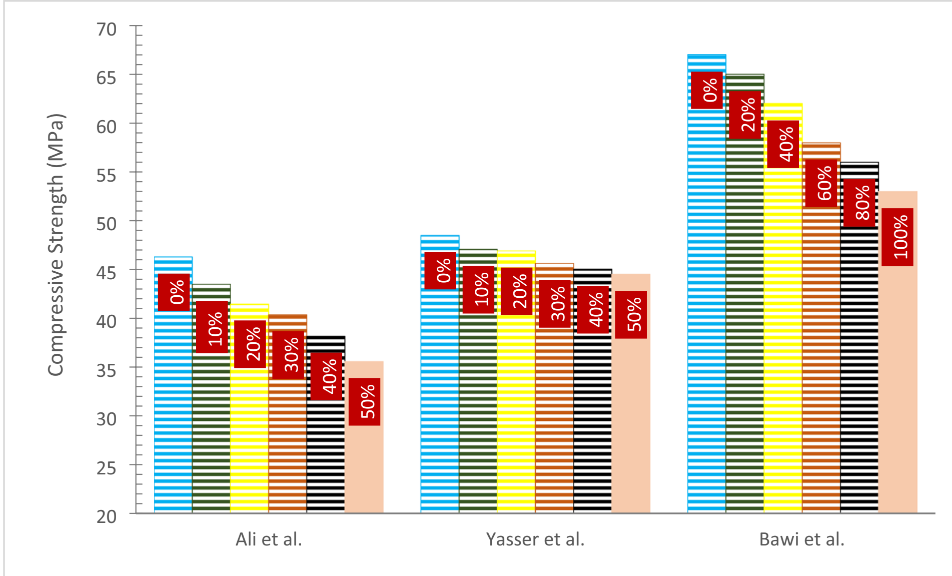


Fig. 5 Compressive strength [43, 46, 47]

to 40% can be utilized without any negative effect on CS. However, a considerably decreased in CS was observed at 50% substitution of WG due to lack of flowability which results in more voids in concrete. Also, a study claimed that the higher WG adversely affects the CS of concrete due to the dilution effect [63].

3.2 Tensile Strength (TS)

Table 2 and Fig. 8 show the TS of SCC with the substitution of WG. It should be observed that the replacement of WG caused decreased the CS of SCC. According to research, the TS of concrete including WG as sand replacement showed a tendency to decline with an increment in the WG mix proportion. The TS of WG decreases by 5% after 28 days when WG contributes 60% as fine aggregate [27]. Corresponding to this, WG was employed in research as a partial replacement for cement in amounts ranging from 0 to 30% by weight of cement. The findings demonstrate that concrete's tensile strength improved up to a 20 percent replacement of waste and further substitutions of WG reduced TS owing to poorer flowability. They may also assert that because of the higher cement matrix strength, WG improved TS more effectively than CS [63]. Additionally, it has been shown that low cement matrix strength results in less TS in concrete [64]. The TS of concrete was improved by substituting WG which forms secondary C-S–H, which increased cement matrix strength [63].

As the glass particle size grew, the TS of SCC adding WG typically decreased. The increased particle size is blamed for a generally weaker pozzolanic reaction, which results in a lower TS for 30% glass (40 m). But after 90 days, the glass powder mixtures, especially the ones with 30% glass (30 m) and 30% glass (20 m), demonstrated superior or comparable

Fig. 6 Failure of SCC (**a**) Compression and (**b**) Tensile [44]

TS to plan concrete. Parallel to CS data, the TS dropped as the degree of glass replacement rose. For mixtures of 20 mm glass powder at various replacement amounts and ages, research was conducted using TS. It's important to notice that after 90 days, the TS for concrete with 20 percent glass (20 m) is greater than reference concrete [48]. This could be caused by the smaller dilution factor and the denser microstructure created by the pozzolanic reaction of the glass powder [65]. In general, it can be concluded that the TS of concrete is not adversely affected when up to 30% of the cement is replaced with glass particles [48].

In general, as the glass particle size increased, the TS of SCC incorporating WG decreased. The bigger particle size, which results in a generally lower pozzolanic reaction is responsible for the lower TS for 30% glass (particle size 40 µm). But after 90 days, the WG mixtures of 30% glass (particle size 30 µm) and 30% glass (particle size 20 µm) showed greater or comparable TS to reference concrete. With an increase in the degree of glass replacement, the TS declined in accordance with the CS information. For mixtures of 20 mm WG at various replacement levels and ages. It's noteworthy to notice that after 90 days, reference concrete has a higher TS than a mix with 20 percent glass (particle size 20 µm) [48]. This could be the consequence of the denser microstructure and smaller dilution factor produced by the pozzolanic reaction of the WG, respectively [66]. The TS of concrete does not seem to be significantly affected by the substitution of up to 30% of cement with WG [48]. Furthermore, the research found that the combined effects of WG and calcined zeolite improved the TS of the concrete. The inclusion of the calcined zeolite has reduced the brittleness brought on by the WG and increased strength as a consequence. At all ages, more WG replacement was associated with higher TS as compared to the reference SCC. Increased interfacial transition zone strength has also led to a decrease in bleeding and shrinking [52].

The researcher examined the combined effects of WG and steel slag, as replacements for cement and sand in SCC. The results show that when 20% of the cement is replaced by WG and 80% of the sand is replaced by steel slag, the highest improvement in TS of 13.2% was recorded compared to the reference mix. The minimum strength of the concrete mix is also highlighted which is 5.6 percent lower than that of the control mix and contains 40% sand replaced by WG and 40% replacement cement. [42]. According to research, the smooth surface of the glass caused a 5 percent reduction in TS when used as an aggregate replacement with 50%. However, TS was greatly reduced by roughly 30 percent when glass was used in place of coarse aggregate in concrete [67]. Similar findings were made by another investigation, which showed that all mixes with glass aggregate had lower TS than control concrete [68]. Decreased TS was 1.5 percent, 5.0 percent, 8.2 percent, and 15.4 percent, respectively of concrete samples containing 15 percent, 30 percent, 45 percent, and 60 percent WG. These findings suggest that, because of the glass's natural tendency to microcrack when crushed, the loss in TS increases with the replacement percentages. Consequently, the glass and cement paste fail to adhere well together. A study substituted 10%, 20%, 30%, 40%, and 50% of WG as a fine aggregate. The results revealed a small reduction in strength was observed for mixtures with more than 20% WG substitution as sand. The test findings show that a 50% substitution of WG for sand causes a 5 percent reduction in TS at 28 days when compared to the reference batch [43]. Similarly, the findings show that the TS of glass-based SCC mixes was less than that of the reference mix at 28 and 90 days [69].

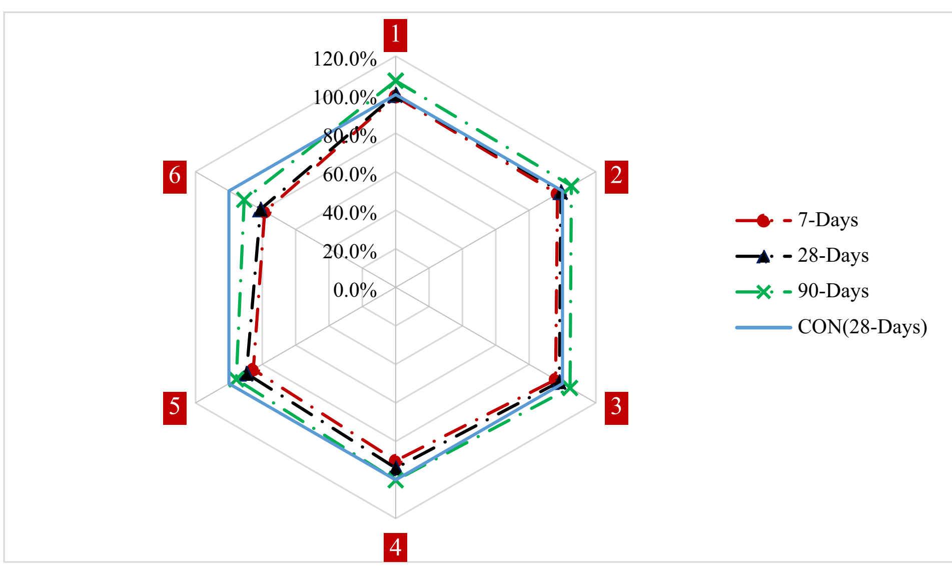


Fig. 7 Relative compressive strength

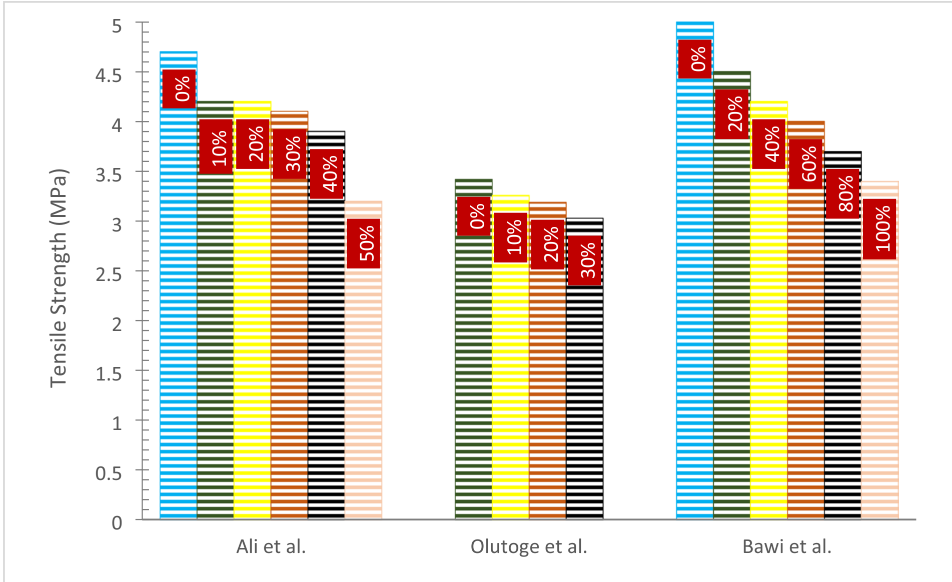


Fig. 8 Tensile strength [43, 46, 53]

3.3 Flexural Strength (FS)

The flexural strength (FS) of SCC with the replacement of WG is shown in Table 2 and Fig. 9. It should be noted that the replacement of WG caused decreased in FS of SCC. however, a study found that the pozzolanic processes that occur when WG powder is used as a cement substitute in SCC increase FS [70]. However, with larger replacement percentages, the strength steadily declines. At larger doses, the strength decreases by about 8.36 percent, 11.9 percent, and 19.33 percent for replacement percentages of 20 percent, 25 percent, and 30 percent, respectively. The FS of concrete normally improves with a 5 to 15 percent substitution of WG [71].

Research substituting 10, 20, 30, 40, and 50% of WG for fine aggregates. In comparison to the control, except for Mix 2, which had 10% glass substitution, the FS tends to decline as the proportion of WG substitute in the concrete mix increases. The adhesion between the glass and cement paste may be increased by substituting a small amount of glass for sand. However, when more glass is substituted for sand, the high degree of smoothness of the glass reduces the binding strength between the glass and cement particles. According to the flexural data, the SCC FS decreased by 15% when 50% of the sand was replaced with recycled glass as a comparison to the control mixture [43]. Instead of using fly ash, more glass powder was utilized, which resulted in a greater FS. Comparing it to reference concrete, the FS of 20% glass replacement is enhanced by 57.47%. Glass powder, contains more active silica than fly ash [55] which results in more CSH, leading to more FS of SCC.

The research examined the combined effects of WG and steel slag, as replacements for cement and fine aggregate in SCC. Results show that FS increases when steel slag content rises while WG content remains the same and FS reduces when WG content rises while steel slag content keeps the same. The highest FS, which is 19.3 percent greater than that of the control mix, is reported for concrete that substitutes 20% WG and 80% steel slag for cement and fine aggregate. In contrast, the minimum FS for concrete that substitutes 40% WG and 40% steel slag for cement and fine aggregate is reported and is 11.3% lower than that of the control mix [42]. The creation of SCC that incorporates WG aggregate as a partial replacement of fine aggregate 0 percent, 10 percent, 20 percent, 30 percent, 40 percent, and 50 percent is examined by the researcher. Results show a pattern resembling the CS findings. However, For FS, the impact of WG was less noticeable than it was for CS. Experimental findings show that for WG of 10%, 20%, 30%, 40%, and 50%, respectively results FS tends to drop by 1.38 percent, 2.52 percent, 5.97 percent, 9.40 percent, and 11.70 percent at 28 days [2].

However, the research found that, compared to reference concrete, SCC containing WG, and calcined zeolite had higher FS at all ages. For achieving the desired FS, a mixture of 30% WG and 20% calcined zeolite is thought to be ideal. Even with large percentage replacements of WG as fine aggregate, the SCC including calcined zeolite produced greater FS than FS of control SCC. In SCC, the inclusion of WG and calcined zeolite produced a considerable filler effect. At all percentage replacement levels of zeolite in the SCC, the calcined zeolite effect in conjunction with the glass powder improves the flexural behavior. The strength of the concrete was improved with the use of glass powder and raising replacement levels by using calcined zeolite. The Concrete's bond was strengthened by the addition of 30 percent zeolite, making it less susceptible to the effects of

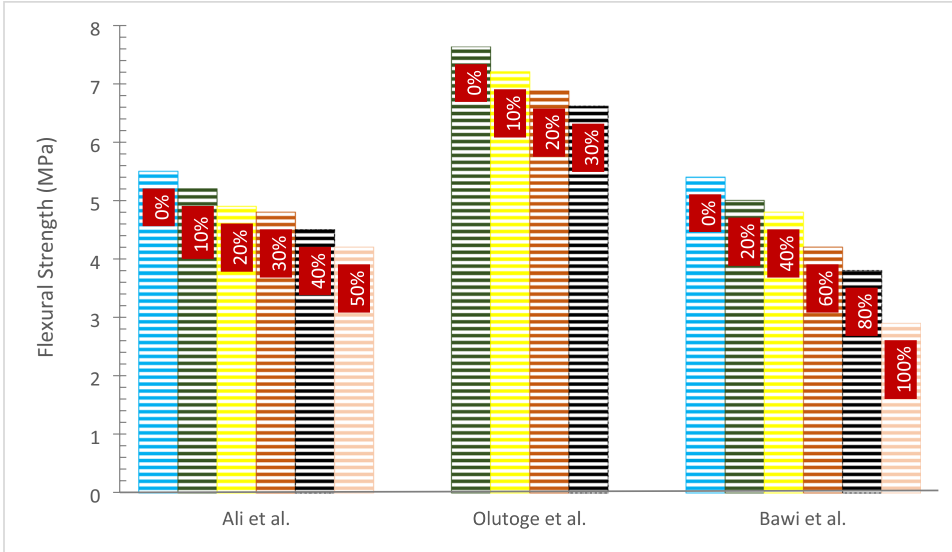


Fig. 9 Flexural strength [43, 46, 53]

flexural failure [52]. Furthermore, research shows that when 5%, 15%, and 20% WG replacements are applied, respectively, the FS of concrete rises by about 3.54 percent, 5.03 percent, and 8.92 percent after 28 days owing to pozzolanic reactions [72].

According to research, zeolite, and glass powder's pozzolanic reactivity also led to the creation of hydrate CSH gels, which increased the strength of the concrete. The addition of zeolite, which may offer extra water for the transformation of CH into CSH owing to its internal curing ability, significantly reduces the water required by the self-compacting concretes to build strength [73]. The decreased quantity of pores in zeolite brought on by the calcination effect and the replacement of the zeolite with glass powder, which prevented particle aggregation in the self-compacting concrete, may also be to blame for the increased strength. The glass powder's ability to fill pores and subsequently demonstrate pozzolanic activity contributed to the concrete's increased strength as it aged. The reduction in the quantity of water absorbed by the zeolite when combined with glass powder significantly decreased the amount of free evaporable water in the concrete, which may be the primary factor in the enhancement of the mechanical strength qualities of the SCC.

3.4 Elastic Modulus (EM)

Figure 10 shows the findings of the EM with the substitution of WG as aggregate after 28 days. In comparison to control mixes, the proportion of WG substitute in the concrete increase causing a reduction in the EM. The findings show that the 28-day EM values were found to have reduced by 3%, 5.3%, 6.6%, 9.2%, and 12.3% at cement contents of 350 kg/m^3 for substitute ratios of 10%, 20%, 30%, 40%, and 50%, respectively [43].

Research also asserted that when the amount of WG increases the EM drops as compared to the reference EM [40]. The EM of the concrete dropped as the particle size and glass substitution amount increased. The diluting factor's dominance over the positive benefits offered by the pozzolanic reaction of glass powder is the cause of the decreased EM for concrete at greater glass substitution levels. Additionally, a reduced total EM might be caused by the sort of hydration products produced during the pozzolanic process [48]. Another research found that the stiffness of the fine and coarse aggregate, which make up a significant component of the matrix, has a significant impact on the EM of concrete. Due to its higher paste composition, SCC may have a somewhat lower elastic modulus than standard concrete [74]. However, a study found that the EM for concrete containing 5% WG reached its peak value within 14 days of curing. Furthermore, concrete containing 20% WG shows EM reached its peak value on day 28 of the curing process [72].

The type of aggregate had a major effect on the EM of concrete via the elastic deformation of such aggregate, which only slightly influenced concrete deformation. Thus, the EM findings were lowered by substituting WG for aggregate, especially at high doses. For instance, the value of EM decreased by 23.7 percent while utilizing 100% WG. The cellular microstructure in the ITZ area and the poor interlocking in WG concrete produce microcracking within the concrete structure, resulting in a lower EM value than similar reference concrete even though WG has a greater EM than aggregate [46]. However, compared to other mechanical features, the impact of glass on concrete's EM value is thought to be the least significant [75]. According to earlier reports, the availability of mixing water may have increased porosity production, which might potentially be a factor in the reduced elastic behavior.

3.5 Fracture Energy

Figure 11 depicts the various fracture energies with the substitution of WG, or the energy needed to form a crack. For the reference concrete, the fracture energy value was 160.2 N/m and it steadily decreased until it was between 116.1 and 155.7 N/m. The greatest decrease could be seen at a level of fine glass aggregate substitution with a natural aggregate of 100 percent, which is 27.5 percent lower than the reference concrete.

Past studies highlighted that the cement paste-aggregate interfacial connection and the concrete's microstructural heterogeneity were connected to the fracture energy of the material [76]. High porosity, simple fracture penetration, and a weaker ITZ area than reference concrete were the effects of using WG in concrete. These elements had a negative impact on the fracture energy value and lowered it, which indicated less brittle behavior. Stress concentration increases near aggregates because of the weaker link between glass particles and cement paste, which lowers the ITZ of such concrete. As a result, fractures may form through the aggregates, causing the fracture process zone to compress, and the behavior of the concrete may become more ductile [77]. The decrease in brittleness of WG concrete is caused by the weak paste-aggregate contact and nonhomogeneous microstructure. Therefore, the fracture pattern differs from that of the reference concrete.

It may be inferred that there were few articles available that discussed the impact of WG on fracture characteristics. Due to the high brittle tendency of WG concretes', which is directly correlated with the strength qualities of concrete, when compared to the reference, WG concrete was more fragile. This phenomenon was ascribed to aggregate phase fractures, which changed the fractal dimensions of the concrete. Furthermore, when the failure line is directly through the aggregates, the lowest fractal dimension, and smoother fracture surface are seen [78]. As a result, the assessment recommends more research into the fracture properties of WG-based concrete.

4 Durability

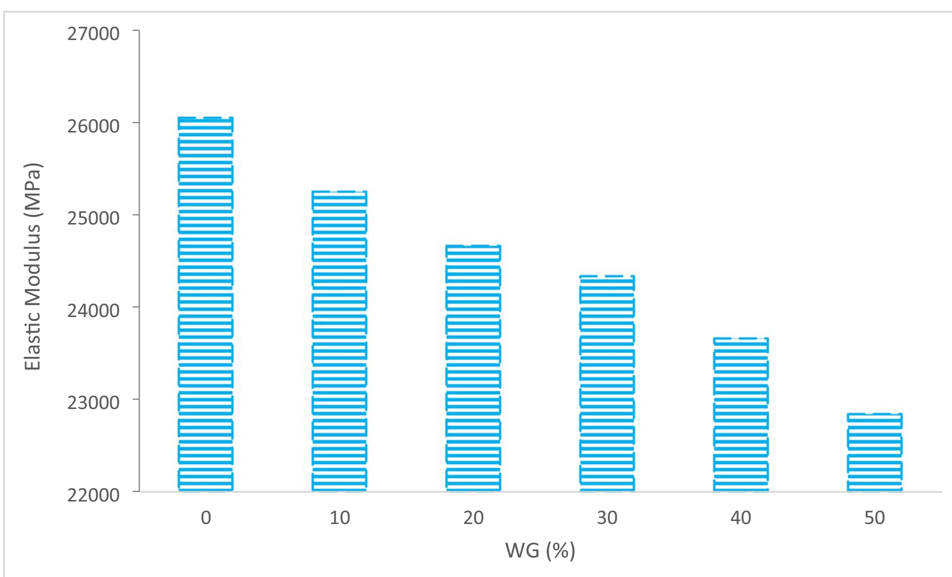
4.1 Bulk Density

Figure 12 displays the samples with glass aggregate's hardened bulk density after 28 days. Comparing specimens with natural river sand to specimens having glass aggregate, the hardened density of the glass aggregate specimens is considerably lower. This decrease in density could be caused by the fact that the glass aggregate utilized in this study exhibited particle densities that were 1.3% lower than those of natural river sand. All specimens exhibited densities that ranged from 2347 kg/m3 to 2386 kg/m3. Additionally, the bulk density of the hardened samples containing 50% glass aggregate was reduced by 1.6% in comparison to the reference [2].

4.2 Water Absorption and Porosity

Figure 13 compares the water absorption and porosity values of SCC containing WG and calcined zeolite to control concrete at various ages. The concrete samples exhibited lower water absorption at all concrete ages when WG was added. The combined effects of calcined zeolite and WG were primarily responsible for the decreased water absorption values of SCC. The SCC porosity is decreased

Fig. 10 Elastic modulus [43]



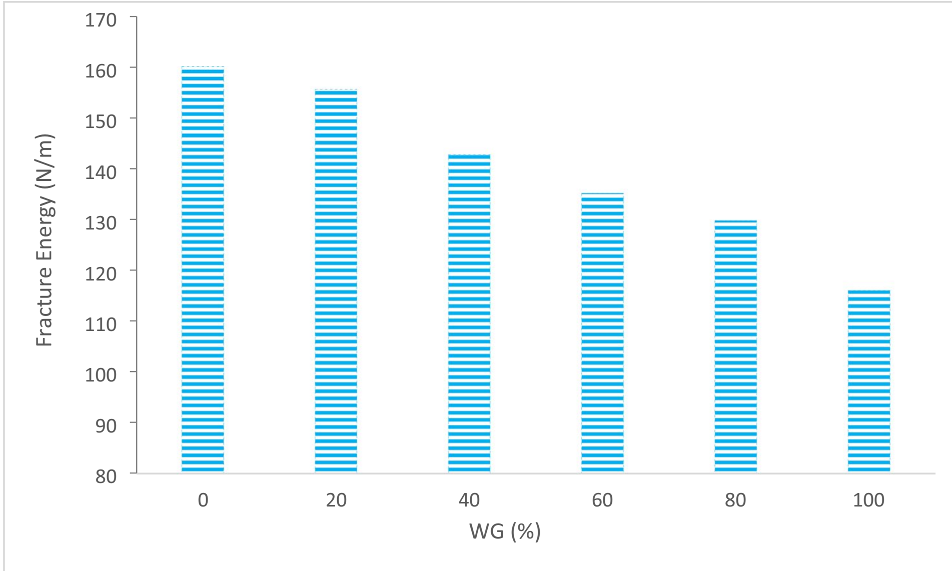


Fig. 11 Fracture energy [46]

because of the decrease in water absorption. Calcined zeolite can fill holes and fine glass powder also can fill gaps between particles to create SCC that is tight with few water-accessible pores. The decreased in.

First, as a consequence of a chemical interaction between natural pozzolans and CH in hydrated cement paste that consumes lime and produces calcium silicate hydrates (CSH) gel, cement paste's binding ability is improved, leading to a more compact mass with reduced water absorption and SCC porosity. Second, since the pozzolanic material's grains are smaller than those of cement, it may provide a more compact mass by micro-filling voids, which reduces the amount of water absorption [79, 80]. Furthermore, studies showed that bentonite clay substitutes might lower WA by up to 30% [81]. Additionally, one study found that SCM decreased water absorption due to micro filling, which increased concrete's density and decreased water absorption. Nevertheless, at higher dosages, a rise in WA was seen due to a lack of flowability, which increased compaction and led to porous concrete, which ultimately increased the water absorption of concrete [82].

4.3 Sorpitivity

The speed at which moisture is absorbed is referred to as sorptivity. When the surface of hardened concrete is exposed to moisture or immersed in water. Concrete fissures absorb

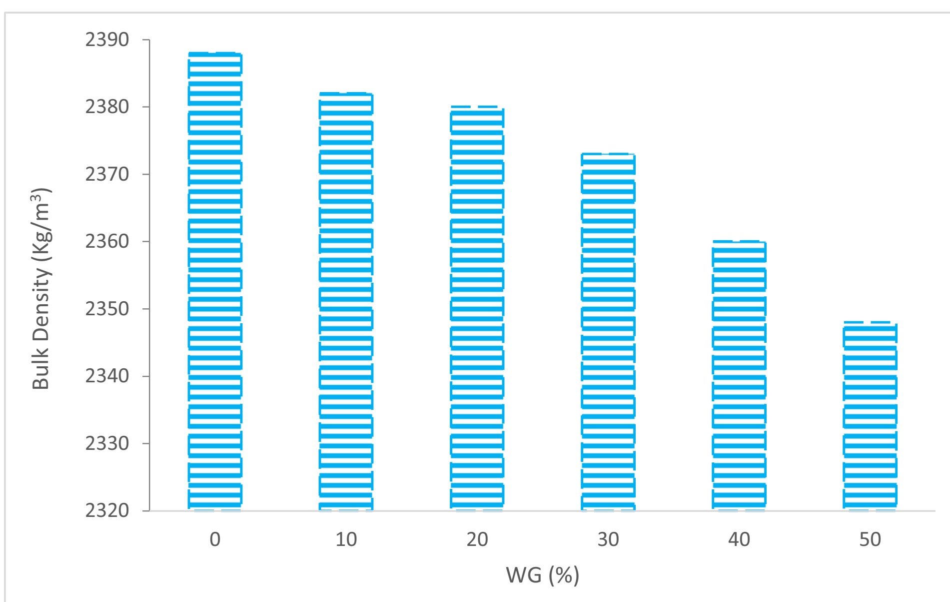


Fig. 12 Bulk density [2]

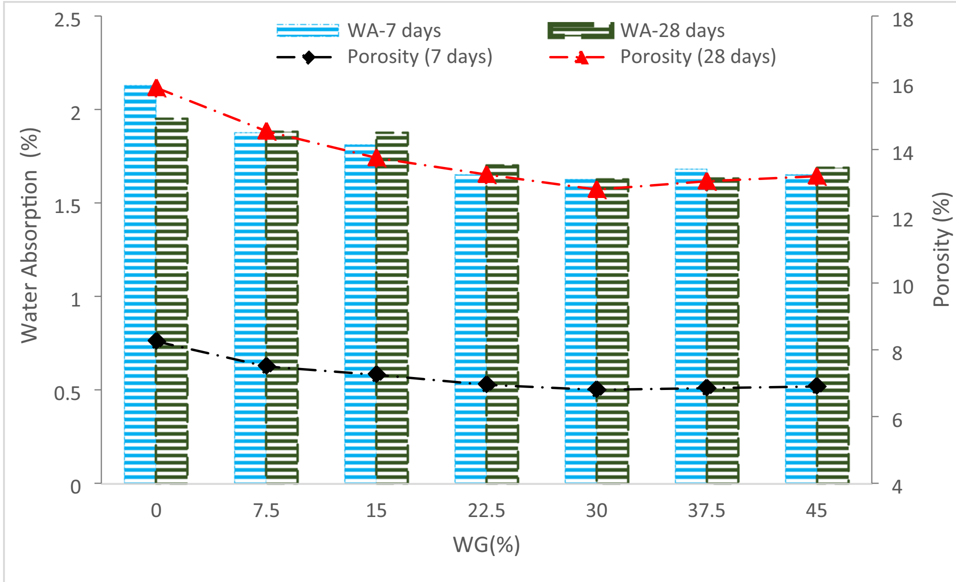


Fig. 13 Water absorption (WA) and Porosity [52]

moisture through the force of capillary suction. Concrete's sorptivity rate may be used to link durability, degradation during wet-dry cycles, and service lifespan. Figure 14 illustrates the capillary water absorption findings after 28 days of curing. The findings demonstrated that owing to glass particles' lower moisture absorption characteristics than the natural river sand, sorptivity values considerably dropped as WG concentration increased. The use of calcined zeolite together with WG in the concrete was shown to significantly lower the sorptivity values [52]. Due to their natural hydrophobicity, glass granules limit the quantity of water that concrete may absorb via capillarity [36].

According to research, durable concrete is defined as having a sorptivity value of less than 3 mm/h$^{1/2}$. For reinforcing steel bars in reinforced concrete, the recommended sorptivity value assures a minimum concrete cover of 15 mm to avoid corrosion. The sorptivity value of 3 mm/h$^{1/2}$, which ensures a minimum concrete cover, is defined as water might infiltrate to a depth of 15 mm in 24 h of rain [83]. According to research, cement concrete may use regular fine aggregate instead of WG (WG) without affecting the performance of specimens. Additionally, the use of WG as fine aggregates reduced the heat conductivity and sorptivity of cement mortars significantly [84]. Because secondary cementitious materials (CSH), which improve the mortar's

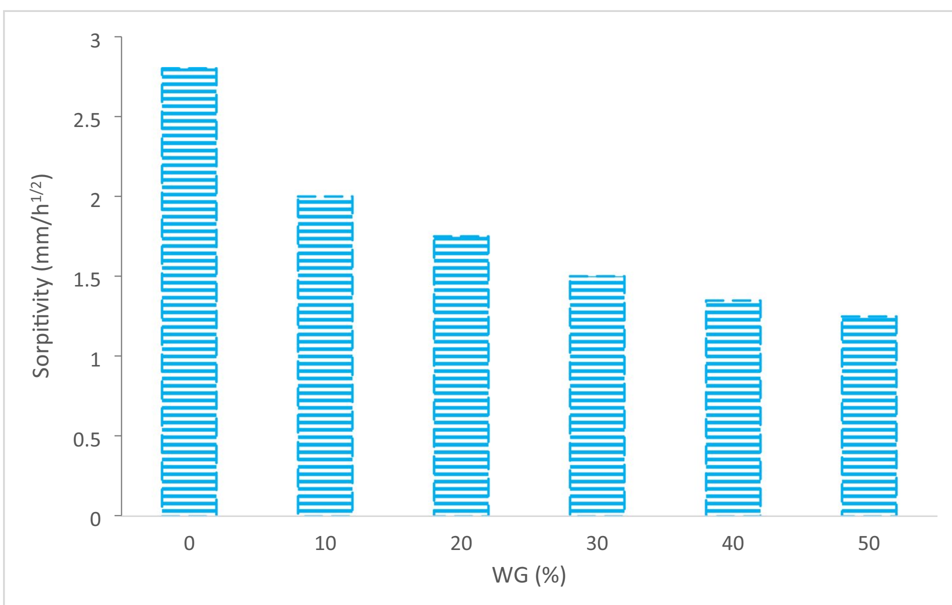


Fig. 14 Sorpitivity [2]

binding qualities and lower porosity, are produced during the pozzolanic reaction, replacing pozzolanic material reduces the porosity of concrete [82]. The 50 percent glass aggregate and reference specimens had sorptivity values of 2.83 mm/$h^{1/2}$ and 1.35 mm/$h^{1/2}$, respectively. A mixture containing 50% RGA will have a 52.3 percent reduction in sorptivity. This might be explained by the fact that the sorptivity of SCM specimens dropped owing to the impermeable nature of glass, whilst the strength of SCM specimens was reduced due to the poor interfacial adhesion between glass particles and paste matrix [2].

4.4 Electrical Resistivity

The electrical resistivity test assesses the permeability of the microstructure and the ion-transfer resistance of water-saturated concrete inferentially [66]. The material property known as particular electrical resistivity makes it evident that electrical charge transfer through the composite is a possibility. It often depends on the cementitious material's chemical make-up, the pores' type and shape, and the make-up of the pore solution [85]. Electrical resistivity is a crucial component in determining a material's ability to conduct electric current. Dry cementitious materials have extraordinarily high electrical resistivity values because of their insulating qualities. The electrical resistance of oven-dried concrete is around 109 Ω m [86].

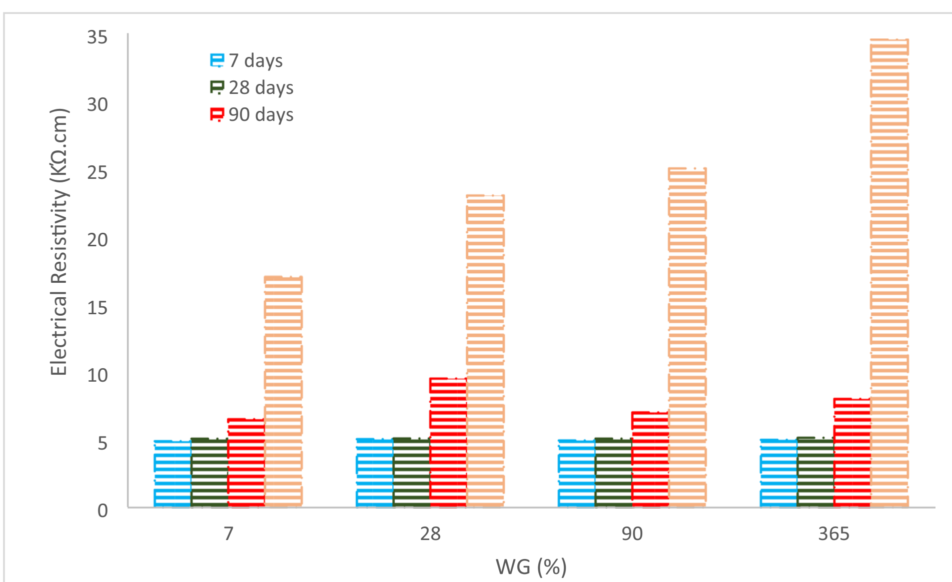
Figure 15 displays the electrical resistivity values at 7, 28, 90, and 365 days. All of the SCC groups' electrical resistivity values were near 5 KΩ-cm on day 7 and began to rise with time, which is especially noticeable for combinations containing glass aggregate. The resistivity of the SCC groups increased with glass aggregate replacement level from 7 to 365 days. The rise in resistivity of concrete mixes may have a convincing explanation for the pozzolanic response of extremely small glass particles. According to an SEM examination, research [87] found evidence of a thin layer of CSH at the glass-paste contact, probably as a result of the pozzolanic reaction of glass. Due to the interaction between the dissolved glass silica and the portlandite, Du and Tan [88] demonstrated that the glass-paste ITZ may be denser over time than the link between sand and paste.

4.5 Dry Shrinkage

Concrete shrinks because of the moisture that is lost during the drying process. Shrinkage-compensating concrete is used in its production to reduce cracking and structural instability brought on by drying shrinkage in concrete. The amount of drying shrinkage that takes place in concrete structures is governed by the materials, mixture quantities, curing period, drying environment, and limitations. According to research, aggregate prevents cement paste from moving around freely, which causes concrete to shrink [63]. Figure 16 shows the drying shrinkage values determined as a function of time. As can be observed, drying shrinkage values reduced as recycled glass content increased. This is likely because WG has a less water absorption rate than virgin glass. The drying shrinkage was far smaller than the AS 3600 [89] limit of 0.075 percent at 56 days. The temperature at which cement paste hydrates has been shown to effect shrinkage [90]. Because less heat was produced during the pozzolanic process, another study revealed that pozzolanic mortars decreased concrete shrinkage [80].

Due to a low water-cement ratio (w/c) that restricts free water evaporation, a previous study found that high-performance concrete including WG as a cement substitute had

Fig. 15 Electrical resistivity [51]



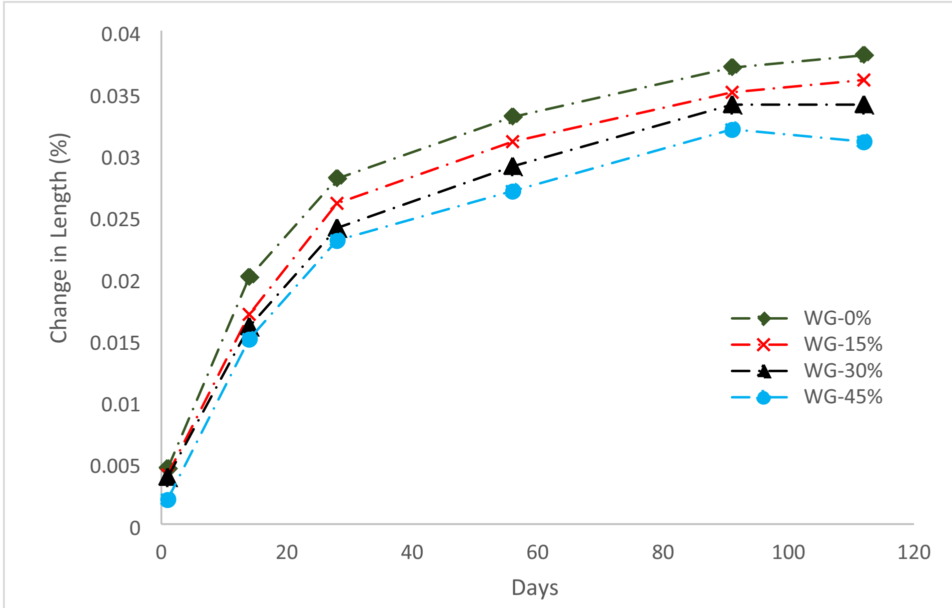


Fig. 16 Dry shrinkage [40]

lower drying shrinkage than control concrete [91]. Another research found that using WG as a 10 percent replacement for cement resulted in reduced drying shrinkage. Due to the denser matrix and WG's pozzolanic impact at 28 days, the drying shrinkage in this instance was smaller than the reference concrete shrinkage [92].

Additionally, the research found that because of pozzolanic reaction and micro filler, smaller WG grains increased concrete performance greater significantly than bigger ones [63]. Additionally, by filling up cracks in concrete materials, WG lessens drying shrinkage and increases the internal compactness of concrete, according to a study [93]. Additionally, it was demonstrated that dry shrinkage at 56 and 90 days was almost similar to shrinkage at 28 days. Additionally, it has been shown that the shrinkage rate increases in the first seven days and then declines or remains unchanged with age [94]. According to prior research, coarse aggregate inhibits shrinkage, which is mostly brought on by the movement of mortar [93]. The creation of supplementary C-S–H because of the replacement of WG enhanced the cement paste's viscosity, which decreased the paste's mobility. Additionally, the use of WG decreased the heat of hydration, which in turn shrank the pace at which water vaporized off the concrete surface, leading to fewer shrinkage cracks [63].

The cement paste binding qualities and stiffness were increased by the pozzolanic activity in combination with the micro-filling of mineral additive, which eventually reduced the dry shrinkage [80]. According to research, the drying shrinkage of cement pastes is decreased when the amount of cement in the pastes is reduced [95]. The study also discovered that the mineral additive reduced the heat of hydration, preventing the rapid loss of water from the surface of the concrete and reducing the development of dry shrinkage fractures [93]. Additionally, it has been shown that fly ash, which plugs micropores and so increases internal compactness, may greatly reduce drying shrinkage in concrete.

However, research claimed that the hydration rate rises and participates in the exothermal effect of the pozzolanic reactivity when cementitious materials with high pozzolanic reaction react with hydrated CH [96]. Because of shrinkage and the development of minute cracks, the higher hydration rate influences the longevity of mortars and concrete. According to research [97], the larger temperature rise in metakaolin blended mortars compared to control was caused by metakaolin's faster effect on cement hydration.

4.6 Alkali-Silica Reaction (ASR)

Figure 17 shows the ASR growth of SCC mixtures containing WG at various ages. Up to 14 days, the ASR growth was remarkable. The expansion at 14 days was smaller than 0.09 percent for all concrete mixes, which is marginally smaller than 0.1 percent, as stipulated by ASTM C 1260 for a benign response, demonstrating the suppressing impact of WG microparticles on ASR development. As is clear, glass has a significant alkaline content that may be leached away, causing an expansion from the alkali-aggregate. Glass particles will not cause harmful expansion on their own once they are less than 300 µm, according to research [98]. According to research [31], ASR expansion of concretes including WG (particle size 4.76 mm) increased as the amount of fine aggregate substitute enhanced.

ASR development of mortar including 100% beverage WG (size 5 mm) as fine aggregate increased, corresponding to Ling and Poon [99]. According to Park et al. [27], as the percentage of WG rise, the growth rate as measured by ASR expansion in accordance with ASTM C 1260 [100]. Using clear soda-lime glass as a fine aggregate substitute in levels ranging from 0 to 100% with a 10% increase, Jin et al. [101] examined the ASR development of mortars. The ASR became larger as the glass sand concentration rose. Topcu et al., [102] examined the ASR development of mortars using WG as a natural alternative to river sand. According to Fig. 17, the ASR development steadily reduced as the percentage of GWG microparticles rose from 0 to 5, 10, 15, 20, 25, and 30. However, expansions at all ages did not go beyond 0.20 percent, the maximum permitted by ASTM 1260 [103].

Natural river sand was a substitute for WG (size 4.75–0.3 mm). At 14 and 21 days old, the ASR expanded more due to the presence of more glass sand. In a study [104], the ASR development of mortars including 10, 30, and 100% glass sand was examined. As the glass sand content rose, ASR expansion accelerated. Crushed WG (size 4.75–0.15 mm) was utilized by Ismail and Al-Hashmi [105] to partly replace fine aggregate of 0, 10, 15, and 20%. The results showed that the existence of WG reduced ASR development. The ASR declines as the quantity of WG enhances. ASR development is significantly influenced by the amount of glass sand present. The ASR expansion shrank as glass particle size decreased. This may be because certain glasses with high active silica concentration may be categorized as reactive aggregates or pozzolanic materials [106]. It is evident that when the substitute level of WG microparticles rises, the expansion of the mortar bar reduces. The extremely reactive GWG microparticles' reaction with lime to generate CSH gel, which keeps the alkalis in the CSH, may be one cause.

Additionally, scientists discovered that at sand replacement levels up to 40%, WG with grain sizes smaller than 4.5 mm results in no surface flaws or produces any increasing ASR gel [107]. Because they create pores and hold solutions for future reactions, microcracks in the particle are undesirable because they increase ASR reactivity. This confirms that fragment size is not the primary factor influencing the ASR possibility. Other aspects affecting the development of the ASR gel include the WG concentration, the type of cement and aggregates, the mix ratio, and w/c. Therefore, it is feasible to lessen the risk of ASR created by the chemical properties of WG and by keeping an ideal level of substitution and fragment size. Due to micro filling, properly graded WG powders may reduce ASR expansion while increasing density. Additionally, the inclusion of lithium ions prevents development by changing the ASR gel composition [108].

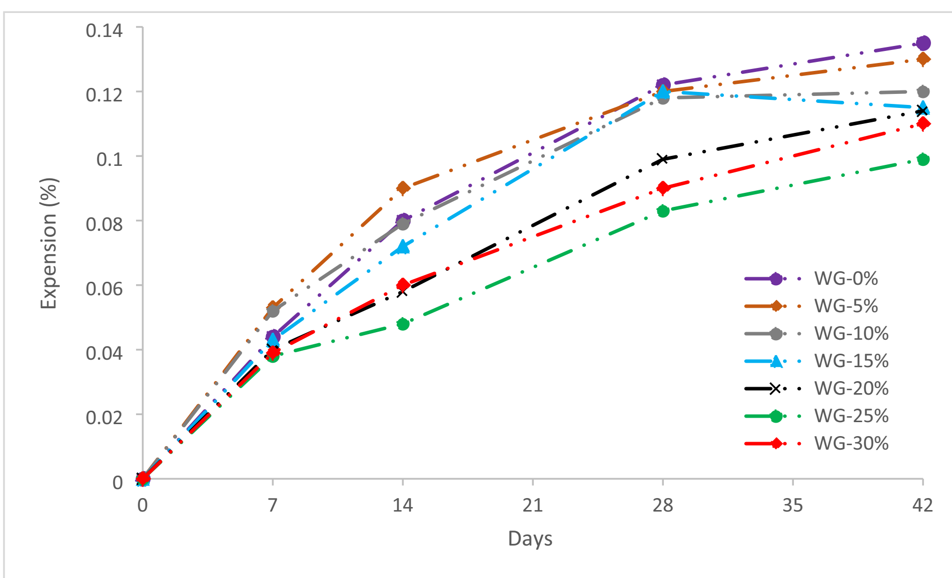
In short, the concrete specimen test showed no detrimental ASR growth, showing that ASR would not be a concern in the existence of WG microparticles. This may happen because the WG microparticles' pozzolanic interaction with the cement seemed to strengthen the binding of the alkali and prevent it from reacting in other ways.

5 Performance at Aggressive Environment

5.1 Acid Resistance

Numerous chemicals that are both naturally occurring and used in an industry constantly expose concrete buildings to harsh environmental conditions. Due to its ubiquity in drainage systems, industrial pollution, and groundwater,

Fig. 17 Expansion due to ASR [70]



sulfuric acid (H_2SO_4) is one of the most harmful substances for concrete buildings [109]. Concretes degrade and suffer damage significantly and quickly when exposed to sulfuric acid. Although cementitious materials are constantly at risk from sulfuric acid, cement type, and content are crucial variables determining performance in sulfuric acid settings [110]. According to research [111], when sulfuric acid combines with hydration byproducts like calcium hydroxide (CH) or calcium silicate hydrates, the alkalinity of hardened cement binders, which is responsible for cementitious characteristics, may be partly or fully neutralized (CSH). As illustrated in Fig. 18, the inclusion of WG in the SCC mixes reduces sample mass loss and increases sulfuric acid resistance. For each set of created mixes, the samples with a 20% WG content showed the greatest resilience.

When subjected to acid assault, SCC blends work better than traditional concrete. Concrete's calcium hydroxide (CH), which is reacted with sulfuric acid at the start of the corrosion process, may be consumed by the WG pozzolanic reaction to lessen the deteriorate under acid assault. Additionally, the CSH gel created by the pozzolanic activity of the WG refines the holes in the concrete and helps to boost durability [113]. According to research [114], the use of tiny rubber particles as fillers among the natural aggregates increases the endurance of the concrete and contributes to the higher performance of SCC with waste.

5.2 Chloride Diffusions

Among all mixtures, the reference concrete had the greatest chloride diffusion coefficient. The lowest chloride diffusion coefficient was achieved by replacing 20% of the original material with glass powder. It is obvious that glass powder is required to improve the pore structure of the concrete, however, additions beyond 20% seem ineffective. The compaction energy may have risen owing to reduced flowability. This enhanced the diffusion of chloride since there were more voids possible. According to research [115], concrete containing 30% WG reduced the chloride diffusion coefficient by 90% when compared to the reference control. Reduced diffusivity is a result of the thicker microstructure, finer pores, and poorer interconnectivity. Research [116] also found that when the amount of glass powder in concrete increased chloride penetrability decreased. Research that looked at the durability properties of mortar with cement replaced by glass powder by 10% and 20% discovered that although carbonation resistance was reduced with WG incorporation, water sorptivity was unaffected [117]. Research [116] also noted a decrease in chloride penetrability with an increase in the amount of glass powder in concrete. Research that looked at the durability properties of mortar with cement replaced by glass powder by 10% and 20% discovered that the presence of WG reduced carbonation resistance but had no effect on water sorptivity [115].

5.3 Carbonation Depth

The most critical of the many deterioration events of reinforced concrete is reinforcement corrosion, which has a substantial impact on the longevity and performance of reinforced concrete structures [118]. The carbonation depth for WG replacement at 0, 10, 15, and 20% coarse aggregate and 5% silica fume was greater than that for 5% glass powder

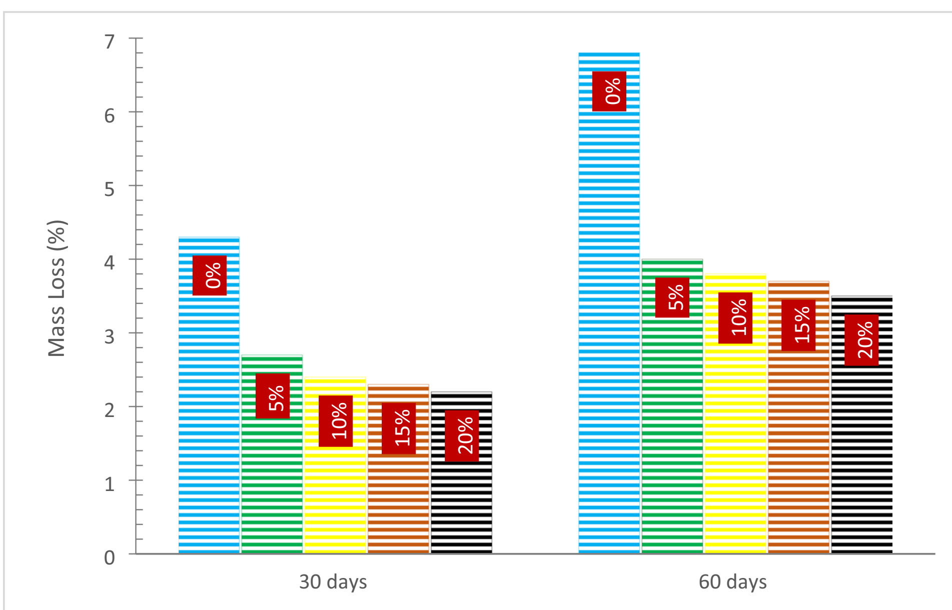


Fig. 18 Mass loss [112]

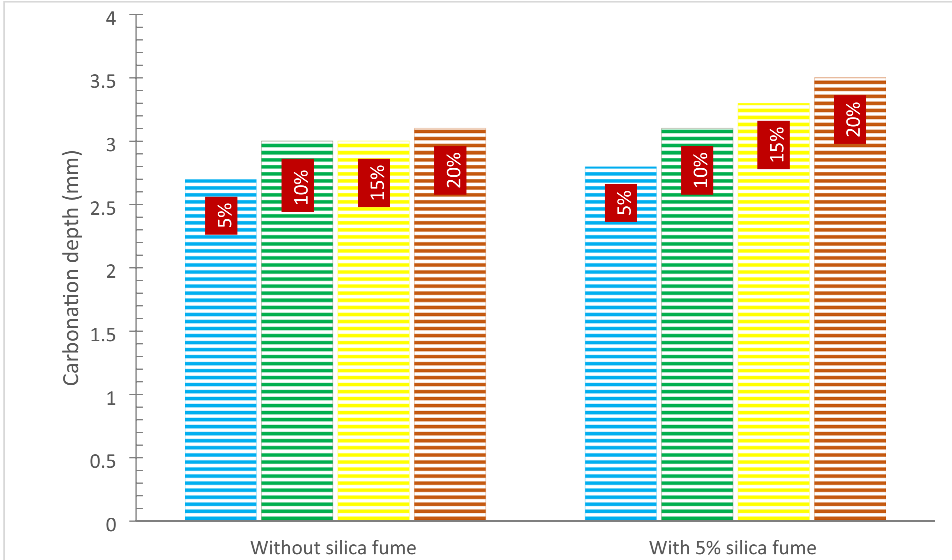


Fig. 19 Carbonation depth [119]

as shown in Fig. 19. Carbonation seems to rise in tandem with an increase in WG percentage, which is consistent with the overall tendency seen in concrete for various pozzolanic materials induced by decreasing amounts of Calcium Hydroxide (CH). This may be due to the greater reactivity of silica fume and the resultant decrease in CH compared to WG in powder form [119].

According to one research, the carbonation depth of glass containing SCC was larger than that of reference SCC. It is consistent with the pattern found in concrete for different pozzolanic materials and is most likely the result of CH reduction. Incorporating WG helps to minimize CH, which lowers the PH of the mix [120]. According to one research, the carbonation depth reduced as the fly ash concentration dropped. This might be because the cement produced more hydration products [121], resulting in high carbonation resistance. Therefore, the CO_2 transmission coefficient in concrete has been reduced. If the concrete carbonation process was regulated by CO_2 transmission in concrete, the carbonation depth of concrete was adversely connected with the concrete strength grade. At the same time, products of the interaction between hydration products and CO_2 on the concrete surface filled up certain holes, increasing the surface density of concrete and decreasing the CO_2 transmission coefficient in concrete. As a result, the carbonation response of concrete decreased.

6 Environmental and Economic Benefits

Recycling glass has a favorable effect on sustainability since it may be used as a raw material more than once. It is an appealing concept to convert into an alternate raw material without sacrificing quality [122]. A study [123] claims that recycling glass saves 0.58 t of CO_2, cuts air pollution by 20%, and decreases water pollution by 40% to 50% along the supply chain. When employing cullet rather than raw materials, a researcher claims that CO_2 emissions are reduced by 53 percent. In contrast to the typical rule that states that a 10% increase in cullet volume results in a 5% reduction in CO_2, the Italian cullet reusing scenario demonstrated a decline of 1.9 Mt of CO_2 [124]. To achieve sustainability in this business, there is a push to employ industrial garbage and byproducts. In the manufacture of one ton of cement, 0.9 tons of CO_2 are released into the environment. Additionally, the manufacture of cement results in the mild emission of NOx, SOx, and particulates [125]. Incorporating WG as a Portland cement substitute in concrete has benefits for the environment beyond lowering CO_2 emissions. Additionally, it lessens the quantity of WG dumped in landfills. Over one ton of environmental assets is saved for every ton of reused glass. Since WG is not biodegradable, sensible examination of alternate uses for the material requires a diversion away from landfill disposal locations. When utilized in the right amount, the use of WG in the manufacturing of concrete improves the concrete's efficiency (both mechanical and durability performance) as well as the ecosystem [126]. Depending on the recommendation and test results, it was determined that adding WG up to 20% might be advantageous when taking CS into account.

Hilton et al. [127] studied the ecological impacts of the plan and WG incorporating concrete. The comparison between WG and plan concrete has decreased the environmental effect by more than 13%, according to the results. Additionally, the usage of WG reduced the release of hazardous gases created by plan concrete by 20%, which significantly improved the way it related to global climate change. When utilizing concrete made of cement, glass-based cement, which emits 0.17 to 0.42 g CO_2/g, lowers CO_2 emissions by 83 percent [128]. In their study, Patel et al. [129] came to a similar conclusion. Granulated foam glass (GFG) use in concrete may greatly decrease the amount of WG and advance the recycling sector, enhancing the ecological quality [130].

According to the World Health Organization (WHO), utilizing WG in concrete rather than OPC in concrete manufacture reduces numerous environmental difficulties such as acid rain, ozone depletion, photochemical instability, and WG. The use of WG in concrete has a wide range of additional benefits. When garbage is recycled, the first benefit is a decrease in landfill issues. Second, WG is used as an additive in concrete and will be added to concrete, causing some natural material to be lost in the concrete. The usage of WG also protects the natural material. However, there are still several outstanding problems with the properties of WG cement, such as long-term serviceability, impact assessment, and carbon footprints, therefore WG base cement is not yet fully researched. Reusing recycled WG in the manufacture of cement and concrete may also provide considerable financial advantages. In the US, the dumping charge for landfills typically runs from $40 to $100 per ton of garbage, while the price of concrete aggregates is $5 to $15 per ton and the price of additional cementing supplies is $30 to 80 per ton. Depending on the amount of manufacturing, the expense of crushing may vary from $15 to $30/ton [131]. According to a survey, the cost of WG in the local Bangladeshi market is around 2 BDT/kg. Additionally, the overall cost of WG may rise by up to 2.5 BDT/kg after refining and crushing. Since a 50 kg bag of cement costs 450 BDT, replacing 10 and 20% of it with WG would result in expense declines of 7% and 14%, respectively. Cost and CS are compared in [132]. The ideal glass concentration was discovered to be 20%, for which CS was 2 percent higher than the control concrete. As can be shown in Fig. 20, the expense of cement itself will be decreased by 14 percent by adding 20 percent glass to cement. In addition, replacing 20% of the binder would cause an environmental reduction of 18% of CO_2 emissions. With this decrease in CO_2 emissions, significant amounts of NOx, SOx, and particulate matter will also be decreased.

7 Conclusions

The use of WG as a concrete component has several ecological and financial advantages, along with less soil and groundwater contamination, less dust pollution, less use of natural resources for cement clinker, and cheaper concrete building prices. The purpose of this analysis is to provide a thorough overview of current progress in the use of WG in SCC production, as well as to identify four directions for using WG in concrete production: physical and chemical properties, strength properties, durability aspects, and environmental aspects. The comprehensive conclusion is given below.

- The chemical composition of WG depicts that, it has the creditability to be used as a cementitious material.
- Strength properties such as compressive, tensile, flexural, elastic modulus, and fracture energy of SCC were reduced with the substation of WG. The decrease in strength properties of SCC is due to the poor ITZ. However, with up to 20% substitution of WG, the strength properties of SCC are comparable to control concrete strength.

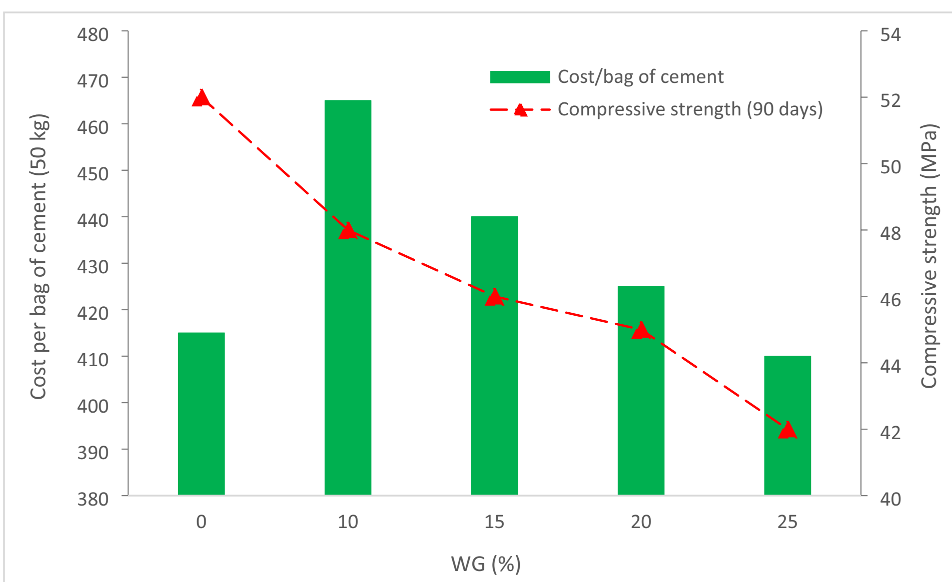


Fig. 20 Cost of glass blend cement and compressive strength [132]

- Water absorption, porosity, and sorptivity decreased with the substitution of WG due to micro-filling action which produces more compact concrete.
- Expansion due to ASR also decreased with the substitution of WG. However, it depends on the glass particle size. The risk of ASR is eliminated if the particle size is less than 100 microns.
- Decreased dry shrinkage was also observed with WG substitution as the pozzolanic reaction releases less heat as compared to the cement hydration.
- The performance of SCC improved in an aggressive environment with the substitution WG due to filling ability and pozzolanic action.
- The cost per bag of cement increased and CS decreased with the substitution of WG. However, according to the author's best knowledge, for small scale cost per cement bag increased with WG. However, for large scale, the cost will be reduced. However, a details analysis is required in this area.

8 Recommendations

Although SCC has multiple benefits over conventional concrete. However, fewer researchers focus on SCC. WG can be utilized in SCC up to some extent but before being used practically, details research needs to address the following issues.

- Less data is accessible on durability aspects particularly dry shrinkage and creeps. This study thus suggests that SCC's dry shrinkage and creep characteristics should be further investigated with the substitution of WG.
- Less data is accessible on fracture characteristics of SCC with WG substitution. Therefore, a detailed study of fracture characteristics of SCC with WG substitution should be explored.
- The strength of SCC decreased with the substitution of WG due to poor ITZ (cracks). Therefore, the review suggests adding filler materials (marble waste) to improve the IZT of concrete. Furthermore, the glass-based SCC is more brittle than the conventional SCC. Therefore, the review also recommended the addition of fiber in glass waste-based self-compacting concrete to obtain high-strength ductile durable self-compacting concrete.
- ASR is one of the challenges for WG. ASR depends on the particle size of WG. The review also suggests conducting a details study on ASR with a varying particle size of WG.
- Additionally, research on fire resistance is necessary to understand how this form of concrete responds to high temperatures.
- Environmental and economic benefits show that WG in SCC provides multiple benefits. However, the information is less and a details study through life cycle assessment is required.

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Data Availability All the materials are available in the main text.

Declarations

Ethics Approval and Consent to Participate Not applicable.

Consent to Participate Not applicable.

Consent for Publication Not applicable.

Competing Interests No conflict of interest is present among the authors.

References

1. Girish S, Ranganath RV, Vengala J (2010) Influence of powder and paste on flow properties of SCC. Constr Build Mater 24:2481–2488. https://doi.org/10.1016/j.conbuildmat.2010.06.008
2. Tuaum A, Shitote S, Oyawa W (2018) Experimental study of self-compacting mortar incorporating recycled glass aggregate. Buildings 8:15
3. Durgun MY, Atahan HN (2017) Rheological and fresh properties of reduced fine content self-compacting concretes produced with different particle sizes of nano SiO2. Constr Build Mater 142:431–443. https://doi.org/10.1016/j.conbuildmat.2017.03.098
4. Vanjare MB, Mahure SH (2012) Experimental investigation on self compacting concrete using glass powder. Int J Eng Res Appl 2:1488–1492
5. Okamura H, Ozawa K (1995) Mix design for self-compacting concrete. Concrete Library of JSCE 25(6):107–120
6. Habert G (2014) Assessing the environmental impact of conventional and "green" cement production. In: Eco-efficient construction and building materials. Elsevier, pp 199–238. https://doi.org/10.1533/9780857097729.2.199
7. Anwar A (2016) The influence of waste glass powder as a pozzolanic material in concrete. Int J Civ Eng Technol 7:131–148
8. Lenka BP, Majhi RK, Singh S, Nayak AN (2022) Eco-friendly and cost-effective concrete utilizing high-volume blast furnace slag and demolition waste with lime. Eur J Environ Civ Eng 26:5351–5373. https://doi.org/10.1080/19648189.2021.1896581
9. Siddique R (2014) Utilization of Industrial By-products in Concrete. Procedia Eng 95:335–347. https://doi.org/10.1016/j.proeng.2014.12.192
10. Turner LK, Collins FG (2013) Carbon dioxide equivalent (CO2-e) emissions: A comparison between geopolymer and OPC cement concrete. Constr Build Mater. https://doi.org/10.1016/j.conbuildmat.2013.01.023
11. Jalal M, Fathi M, Farzad M (2013) Effects of fly ash and TiO2 nanoparticles on rheological, mechanical, microstructural and thermal properties of high strength self compacting concrete. Mech Mater 61:11–27. https://doi.org/10.1016/j.mechmat.2013.01.010
12. Xiao J, Li L, Shen L, Poon CS (2015) Compressive behaviour of recycled aggregate concrete under impact loading. Cem Concr Res 71:46–55
13. Ling G, Shui Z, Gao X, Sun T, Yu R, Li X (2021) Utilizing Iron Ore Tailing as Cementitious Material for Eco-Friendly Design

of Ultra-High Performance Concrete (UHPC). Materials (Basel) 14:1829. https://doi.org/10.3390/ma14081829
14. Rajesh A, Jeevanesan R (2020) Experimental study on replacement of cement using silica fume and fine aggregate using glass powder. Int J Res Granthaalayah 7:285–293. https://doi.org/10.29121/granthaalayah.v7.i11.2020.368
15. Kumar R, Shafiq N, Kumar A, Jhatial AA (2021) Investigating embodied carbon, mechanical properties, and durability of high-performance concrete using ternary and quaternary blends of metakaolin, nano-silica, and fly ash. Environ Sci Pollut Res 28:49074–49088
16. Bouzoubaa N, Lachemi M (2001) Self-compacting concrete incorporating high volumes of class F fly ash: preliminary results. Cement Concr Res 31:413–420
17. Zeghichi L, Benghazi Z, Baali L (2012) Comparative study of self-compacting concrete with manufactured and dune sand. J Civ Eng Archit 6:1429–1434
18. Güneyisi E, Gesoglu M, Al-Goody A, Ipek S (2015) Fresh and rheological behavior of nano-silica and fly ash blended self-compacting concrete. Constr Build Mater 95:29–44. https://doi.org/10.1016/j.conbuildmat.2015.07.142
19. Rahmani Y, Sohrabi MR, Askari A (2011) Mechanical properties of rubberized self compacting concrete containing silica fume. Adv Mater Res 441–445. https://doi.org/10.1533/9780857097729.2.199
20. Diederich P, Mouret M, Ponchon F (2013) Simple tools for achieving self-compacting ability of concrete according to the nature of the limestone filler. Constr Build Mater 48:840–852
21. Nagataki S, Fujiwara H (n.d.) Self-compacting property of highly flowable concrete. ACI Symp Publ 154:301-314. https://doi.org/10.14359/960
22. Gesoğlu M, Özbay E (2007) Effects of mineral admixtures on fresh and hardened properties of self-compacting concretes: binary, ternary and quaternary systems. Mater Struct 40:923–937
23. Rizwan SA, Bier TA (2012) Blends of limestone powder and fly-ash enhance the response of self-compacting mortars. Constr Build Mater 27:398–403
24. Cai W, Liu C, Zhang C, Ma M, Rao W, Li W, He K, Gao M (2018) Developing the ecological compensation criterion of industrial solid waste based on emergy for sustainable development. Energy 157:940–948
25. Chen G, Lee H, Young KL, Yue PL, Wong A, Tao T, Choi KK (2002) Glass recycling in cement production—an innovative approach. Waste Manag 22:747–753
26. Rakshvir M, Barai SV (2006) Studies on recycled aggregates-based concrete. Waste Manag Res 24:225–233
27. Park SB, Lee BC, Kim JH (2004) Studies on mechanical properties of concrete containing waste glass aggregate. Cem Concr Res 34:2181–2189. https://doi.org/10.1016/j.cemconres.2004.02.006
28. Kaza S, Yao L, Bhada-Tata P, van Woerden F (2018) What a waste 2.0: a global snapshot of solid waste management to 2050. World Bank, Washington, DC. https://doi.org/10.1596/978-1-4648-1329-0
29. Harrison E, Berenjian A, Seifan M (2020) Recycling of waste glass as aggregate in cement-based materials. Environ Sci Ecotechnology 4:100064
30. Topcu IB, Canbaz M (2004) Properties of concrete containing waste glass. Cem Concr Res 34:267–274
31. de Oliveira LAP (2008) Mechanical and durability properties of concrete with ground waste glass sand. Artig Em Encontro Cient Int. https://ubibliorum.ubi.pt/bitstream/10400.6/588/1/oliveiraetal11dbmcpd.pdf
32. Meyer C, Xi Y (1999) Use of Recycled Glass and Fly Ash for Precast Concrete. J Mater Civ Eng 11:89–90. https://doi.org/10.1061/(asce)0899-1561(1999)11:2(89)
33. Sobolev K, Türker P, Soboleva S, Iscioglu G (2007) Utilization of waste glass in ECO-cement: Strength properties and microstructural observations. Waste Manag 27:971–976
34. Ahmad J, Zhou Z, Usanova KI, Vatin NI, El-Shorbagy MA (2022) A step towards concrete with partial substitution of waste glass (WG) in concrete: a review. Materials (Basel) 15:2525. https://doi.org/10.3390/ma15072525
35. Yang K, Yang C, Magee B, Nanukuttan S, Ye J (2016) Establishment of a preconditioning regime for air permeability and sorptivity of alkali-activated slag concrete. Cem Concr Compos 73:19–28
36. Aliabdo AA, Abd Elmoaty AEM, Aboshama AY (2016) Utilization of waste glass powder in the production of cement and concrete. Constr Build Mater 124:866–877. https://doi.org/10.1016/j.conbuildmat.2016.08.016
37. Al-Kheetan MJ, Byzyka J, Ghaffar SH (2021) Sustainable valorisation of silane-treated waste glass powder in concrete pavement. Sustainability 13:4949
38. Shi C, Wu Y (2005) Mixture proportioning and properties of self-consolidating lightweight concrete containing glass powder. ACI Mater J 102:355
39. Nassar R-U-D, Soroushian P (2012) Strength and durability of recycled aggregate concrete containing milled glass as partial replacement for cement. Constr Build Mater 29:368–377. https://doi.org/10.1016/j.conbuildmat.2011.10.061
40. Kou S, Poon CS (2009) Properties of self-compacting concrete prepared with recycled glass aggregate. Cem Concr Compos 31:107–113. https://doi.org/10.1016/j.cemconcomp.2008.12.002
41. Roy R, Kumar P (2017) Study and experiment analysis of the feasibility of partial replacement of industrial waste glass powder as cement in self compacting concrete. Int J Civ Eng Technol 1–9
42. Rehman S, Iqbal S, Ali A (2018) Combined influence of glass powder and granular steel slag on fresh and mechanical properties of self-compacting concrete. Constr Build Mater 178:153–160
43. Ali EE, Al-Tersawy SH (2012) Recycled glass as a partial replacement for fine aggregate in self compacting concrete. Constr Build Mater 35:785–791
44. Olofinnade OM, Ede AN, Ndambuki JM, Ngene BU, Akinwumi II, Ofuyatan O (2018) Strength and microstructure of eco-concrete produced using waste glass as partial and complete replacement for sand. Cogent Eng 5:1483860. https://doi.org/10.1080/23311916.2018.1483860
45. C. ASTM, 618 (2014) (n.d.) Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. ASTM International, West Conshohocken, PA, 2012
46. AL-Bawi RK, Kadhim IT, AL-Kerttani O (2017) Strengths and failure characteristics of self-compacting concrete containing recycled waste glass aggregate. Adv Mater Sci Eng 1–12. https://doi.org/10.1155/2017/6829510
47. Sharifi Y, Houshiar M, Aghebati B (2013) Recycled glass replacement as fine aggregate in self-compacting concrete, Front. Struct. Civ Eng 7:419–428
48. Tariq S, Scott AN, Mackechnie JR, Shah V (2022) Glass powder replacement in self-compacting concrete and its effect on rheological and mechanical properties. J Sustain Cem Mater 11:240–256
49. Wright JR, Cartwright C, Fura D, Rajabipour F (2014) Fresh and hardened properties of concrete incorporating recycled glass as 100% sand replacement. J Mater Civ Eng 26:4014073
50. Ouldkhaoua Y, Benabed B, Abousnina R, Kadri E-H, Khatib J (2020) Effect of using metakaolin as supplementary cementitious material and recycled CRT funnel glass as fine aggregate on the durability of green self-compacting concrete. Constr Build Mater 235:117802
51. Khalooee S, Ahmadi B, Askarinejad A, Nekooei M (2021) Tackling the issues of self-compacting concrete containing

high volume of waste glass aggregate by zeolite. Struct Concr 22:E207–E227
52. Vimalan PMAS, Lavanya G (2021) Influence of calcined zeolite on physical-mechanical properties of self compacting concrete containing glass powder. Rev Română Mater J Mater 51:25–32
53. Madhangopal K, Nagakiran B, Sraddha SR, Vinodkumar G, Thajun P, KishoreSankeerth S, Varalakshmi T (2014) Study the Influence of Waste Glass Powder on the Properties of Concrete. IOSR J Mech Civ Eng 11:34–38. https://doi.org/10.9790/1684-11263438
54. Kandoori ADR, Dongre A (2017) Performance of SCC with partial replacement of fine aggregate with waste glass powder. In: 33rd National Convention of Architectural Engineers and National seminar on" Architectural Engineering Aspect For sustainable Building Envelopes, The Institution of Engineers and Indian Association of Structural Engineers, Institution of Engineers, Khairatabad
55. Öz HÖ, Yücel HE, Güneş M (2017) Comparison of glass powder and fly ash effect on the fresh properties of self-compacting mortars. In: IOP Conf Ser Mater Sci Eng, IOP Publishing, p. 32036
56. Noorzyafiqi D, Srisunarsih E, Sucipto TLA, Siswanto B (2021) Enhancing slump flow, specific gravity, and compressive strenght material properties of self compacting concrete (SCC) with glass waste powder. In: J Phys Conf Ser, IOP Publishing, p. 12013
57. Arjun N, Vennila A, Sreevidya V (2017) Experimental Study on Self Compacting Concrete with Foundry Sand and Glass Powder. Int J ChemTech Res 10:390–395
58. Natarajan S, Udayabanu M, Ponnan S, Murugan S (2019) Performance of Nano-Silica Modified Self-Compacting Glass Mortar at Normal and Elevated Temperatures. Materials (Basel) 12:437
59. Sangha CM, Alani AM, Walden PJ (2004) Relative strength of green glass cullet concrete. Mag Concr Res 56:293–297
60. Taha B, Nounu G (2008) Properties of concrete contains mixed colour waste recycled glass as sand and cement replacement. Constr Build Mater 22:713–720. https://doi.org/10.1016/j.conbuildmat.2007.01.019
61. Mohajerani A, Vajna J, Cheung THH, Kurmus H, Arulrajah A, Horpibulsuk S (2017) Practical recycling applications of crushed waste glass in construction materials: A review. Constr Build Mater 156:443–467. https://doi.org/10.1016/j.conbuildmat.2017.09.005
62. Ahmad J, Martínez-García R, De-Prado-Gil J, Irshad K, El-Shorbagy MA, Fediuk R, Vatin NI (2022) Concrete with partial substitution of waste glass and recycled concrete aggregate. Materials (Basel) 15:430.https://doi.org/10.3390/ma15020430
63. Ahmad J, Aslam F, Martinez-Garcia R, De-Prado-Gil J, Qaidi SMA, Brahmia A (2021) Effects of waste glass and waste marble on mechanical and durability performance of concrete. Sci Rep 11:21525. https://doi.org/10.1038/s41598-021-00994-0
64. Ahmad J, Tufail RF, Aslam F, Mosavi A, Alyousef R, Faisal Javed M, Zaid O, Khan Niazi MS (2021) A step towards sustainable self-compacting concrete by using partial substitution of wheat straw ash and bentonite clay instead of cement. Sustainability 13:824. https://doi.org/10.3390/su13020824
65. Elaqra H, Rustom R (2018) Effect of using glass powder as cement replacement on rheological and mechanical properties of cement paste. Constr Build Mater 179:326–335
66. Ramezanianpour AA, Ghoreishian SAH, Ahmadi B, Balapour M, Ramezanianpour AM (2018) Modeling of chloride ions penetration in cracked concrete structures exposed to marine environments. Struct Concr 19:1460–1471. https://doi.org/10.1002/suco.201700285
67. Rajagopalan P, Balaji V, Unnikrishnan N, Haq TJ, Bhuvaneshwari P (2017) Study of bond characteristics of reinforced waste glass aggregate concrete. In: IOP Conf Ser Earth Environ Sci, IOP Publishing, p. 12006
68. Mardani-Aghabaglou A, Tuyan M, Ramyar K (2015) Mechanical and durability performance of concrete incorporating fine recycled concrete and glass aggregates. Mater Struct 48:2629–2640
69. Arabi N, Meftah H, Amara H, Kebaïli O, Berredjem L (2019) Valorization of recycled materials in development of self-compacting concrete: Mixing recycled concrete aggregates – Windshield waste glass aggregates. Constr Build Mater 209:364–376. https://doi.org/10.1016/j.conbuildmat.2019.03.024
70. Sharifi Y, Afshoon I, Firoozjaei Z, Momeni A (2016) Utilization of waste glass micro-particles in producing self-consolidating concrete mixtures. Int J Concr Struct Mater 10:337–353
71. Mallum I, Lim NHAS, Omolayo N (2022) Sustainable utilization of waste glass in concrete: A review. Silicon 14:3199–3214. https://doi.org/10.1007/s12633-021-01152-x
72. Abdallah S, Fan M (2014) Characteristics of concrete with waste glass as fine aggregate replacement. Int J Eng Tech Res 2:11–17
73. Tran YT, Lee J, Kumar P, Kim K-H, Lee SS (2019) Natural zeolite and its application in concrete composite production. Compos Part B Eng 165:354–364
74. Alexander M, Mindess S (2005) Aggregates in concrete. CRC Press. https://doi.org/10.1201/9781482264647
75. Tan KH, Du H (2013) Use of waste glass as sand in mortar: Part I-Fresh, mechanical and durability properties. Cem Concr Compos 35:109–117
76. Tasdemir C, Tasdemir MA, Mills N, Barr BIG, Lydon FD (1999) Combined effects of silica fume, aggregate type, and size on post-peak response of concrete in bending. Mater J 96:74–83
77. Beygi MHA, Kazemi MT, Nikbin IM, Amiri JV (2013) The effect of water to cement ratio on fracture parameters and brittleness of self-compacting concrete. Mater Des 50:267–276
78. Yan A, Wu K-R, Zhang D, Yao W (2001) Effect of fracture path on the fracture energy of high-strength concrete. Cem Concr Res 31:1601–1606
79. Shannag MJ (2000) High strength concrete containing natural pozzolan and silica fume. Cem Concr Compos 22:399–406
80. Ahmad J, Aslam F, Martinez-Garcia R, El Ouni MH, Khedher KM (2021) Performance of sustainable self-compacting fiber reinforced concrete with substitution of marble waste (MW) and coconut fibers (CFs). Sci Rep 11:23184. https://doi.org/10.1038/s41598-021-01931-x
81. Ahmad S, Barbhuiya SA, Elahi A, Iqbal J (2011) Effect of Pakistani bentonite on properties of mortar and concrete. Clay Miner 46:85–92
82. Ahmad J, Zaid O, Shahzaib M, Abdullah MU, Ullah A, Ullah R (2021) Mechanical properties of sustainable concrete modified by adding marble slurry as cement substitution. AIMS Mater Sci 8:343–358. https://doi.org/10.3934/matersci.2021022
83. Menéndez G, Bonavetti VL, Irassar EF (2007) Ternary blend cements concrete Part II: Transport mechanism. Mater Construcción 57:31–43
84. Sikora P, Horszczaruk E, Skoczylas K, Rucinska T (2017) Thermal properties of cement mortars containing waste glass aggregate and nanosilica. Procedia Eng 196:159–166
85. Figueiras H, Nunes S, Coutinho JS, Andrade C (2014) Linking fresh and durability properties of paste to SCC mortar. Cem Concr Compos 45:209–226
86. Fiala L, Toman J, Vodička J, Ráček V (2016) Experimental study on electrical properties of steel-fibre reinforced concrete. Procedia Eng 151:241–248
87. Rajabipour F, Maraghechi H, Fischer G (2010) Investigating the alkali-silica reaction of recycled glass aggregates in concrete materials. J Mater Civ Eng 22:1201–1208
88. Du H, Tan KH (2014) Concrete with recycled glass as fine aggregates. ACI Mater J 111:47–57. https://doi.org/10.14359/51686446
89. Standard A (2004) AS 3600 Concrete structures-incorporating AMD 1: May 2002 and AMD 2. https://scholar.google.com/scholarhl=en&as_sdt=0%2C5&q=AS+3600+Concrete+structures-incorporating+AMD+1%3A+May+2002+and+AMD+2&btnG=

90. Ahmad J, Majdi A, Al-Fakih A, Deifalla AF, Althoey F, El Ouni MH, El-Shorbagy MA (2022) Mechanical and Durability Performance of Coconut Fiber Reinforced Concrete: A State-of-the-Art Review. Materials (Basel) 15:3601. https://doi.org/10.3390/ma15103601
91. Tagnit-Hamou A, Zidol A, Soliman N, Deschamps J, Omran A (2018) Ground glass Pozzolan in conventional, high, and ultra-high performance concrete. MATEC Web Conf 149:01005. https://doi.org/10.1051/matecconf/201714901005
92. Wattanapornprom R, Stitmannaithum B (2015) Comparison of properties of fresh and hardened concrete containing finely ground glass powder, fly ash, or silica fume. Eng J 19:35–48
93. Ahmad J, Zaid O, Siddique MS, Aslam F, Alabduljabbar H, Khedher KM (2021) Mechanical and durability characteristics of sustainable coconut fibers reinforced concrete with incorporation of marble powder. Mater Res Express 8:075505. https://doi.org/10.1088/2053-1591/ac10d3
94. Ahmad J, Zaid O, Aslam F, Shahzaib M, Ullah R, Alabduljabbar H, Khedher KM (2021) A study on the mechanical characteristics of glass and nylon fiber reinforced peach shell lightweight concrete. Materials (Basel) 14:4488. https://doi.org/10.3390/ma14164488
95. Bheel N, Abbasi SA, Awoyera P, Olalusi OB, Sohu S, Rondon C, Echeverría AM (2020) Fresh and hardened properties of concrete incorporating binary blend of metakaolin and ground granulated blast furnace slag as supplementary cementitious material. Adv Civ Eng 2020:1–8
96. Sonebi M, Lachemi M, Hossain KMA (2013) Optimisation of rheological parameters and mechanical properties of superplasticised cement grouts containing metakaolin and viscosity modifying admixture. Constr Build Mater 38:126–138
97. Ambroise J, Maximilien S, Pera J (1994) Properties of metakaolin blended cements. Adv Cem Based Mater 1:161–168
98. Shi C, Wu Y, Shao Y, Riefler C (2004) Alkali-aggregate reaction of concrete containing ground glass powder. Proc 12th Int Conf AAR Concr 789–795. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Alkali-aggregate+reaction+of+concrete+containing+ground+glass+powder&btnG=
99. Ling T-C, Poon C-S (2013) Effects of particle size of treated CRT funnel glass on properties of cement mortar. Mater Struct 46:25–34. https://doi.org/10.1617/s11527-012-9880-8
100. Shon C-S, Zollinger DG, Sarkar SL (2002) Evaluation of modified ASTM C 1260 accelerated mortar bar test for alkali–silica reactivity. Cem Concr Res 32:1981–1987. https://doi.org/10.1016/S0008-8846(02)00903-1
101. Jin W, Meyer C, Baxter S (2000) "Glascrete"—concrete with glass aggregate. ACI Mater J 97:208–213. https://doi.org/10.14359/825
102. Topçu İB, Boğa AR, Bilir T (2008) Alkali–silica reactions of mortars produced by using waste glass as fine aggregate and admixtures such as fly ash and Li2CO3. Waste Manag 28:878–884. https://doi.org/10.1016/j.wasman.2007.04.005
103. Astm C (2007) 1260 Standard test method for potential alkali reactivity of aggregates (mortar-bar method). Section 4:676–680
104. Degirmenci N, Yilmaz A, Cakir OA (2011) Utilization of waste glass as sand replacement in cement mortar, Indian. J Eng Mater Sci 18:303–308
105. Ismail ZZ, Al-Hashmi EA (2009) Recycling of waste glass as a partial replacement for fine aggregate in concrete. Waste Manag 29:655–659. https://doi.org/10.1016/j.wasman.2008.08.012
106. Zhu H, Chen W, Zhou W, Byars EA (2009) Expansion behaviour of glass aggregates in different testing for alkali-silica reactivity. Mater Struct 42:485–494. https://doi.org/10.1617/s11527-008-9396-4
107. Tamanna N, Tuladhar R, Sivakugan N (2020) Performance of recycled waste glass sand as partial replacement of sand in concrete. Constr Build Mater 239:117804. https://doi.org/10.1016/j.conbuildmat.2019.117804
108. Kawamura M, Fuwa H (2003) Effects of lithium salts on ASR gel composition and expansion of mortars. Cem Concr Res 33:913–919. https://doi.org/10.1016/S0008-8846(02)01092-X
109. Committee ACI.: Code requirements for environmental engineering concrete structures (ACI 350–01) and commentary (ACI 350R-01): An ACI standard. In: American Concrete Institute. (2001). https://scholar.google.com/scholarhl=en&as_sdt=0%2C5&q=requirements+for+enviromental+engineering+concrete+structures+%28ACI+350–01%29+and+commentary+%28ACI+350R-01%29%3A+An+ACI+standard.+In%3A+American+Concrete+Institute&btnG=
110. Siad H, Mesbah HA, Khelafi H, Kamali-Bernard S, Mouli M (2010) Effect of mineral admixture on resistance to sulphuric and hydrochloric acid attacks in self-compacting concrete. Can J Civ Eng 37:441–449
111. Türkel S, Felekoğlu B, Dulluc S (2007) Influence of various acids on the physico-mechanical properties of pozzolanic cement mortars. Sadhana 32:683–691
112. Rahat Dahmardeh S, Sargazi Moghaddam MS, Mirabi Moghaddam MH (2021) Effects of waste glass and rubber on the SCC: rheological, mechanical, and durability properties. Eur J Environ Civ Eng 25:302–321
113. Siad H, Lachemi M, Sahmaran M, Hossain KMA (2016) Effect of glass powder on sulfuric acid resistance of cementitious materials. Constr Build Mater 113:163–173
114. Thomas BS, Gupta RC (2016) A comprehensive review on the applications of waste tire rubber in cement concrete. Renew Sustain Energy Rev 54:1323–1333
115. Du H, Tan KH (2017) Properties of high volume glass powder concrete. Cem Concr Compos 75:22–29
116. Kamali M, Ghahremaninezhad A (2015) Effect of glass powders on the mechanical and durability properties of cementitious materials. Constr Build Mater 98:407–416
117. Matos AM, Sousa-Coutinho J (2012) Durability of mortar using waste glass powder as cement replacement. Constr Build Mater 36:205–215
118. Neves R, Branco FA, De Brito J (2012) A method for the use of accelerated carbonation tests in durability design. Constr Build Mater 36:585–591
119. Alaraj MA (2018) Effects of waste glass as a partial replacement of coarse aggregate on concrete performance. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Effects+of+waste+glass+as+a+partial+replacement+of+coarse+aggregate+on+concrete+performance&btnG=
120. Matos AM, Ramos T, Nunes S, Sousa-Coutinho J (2016) Durability enhancement of SCC with waste glass powder. Mater Res 19:67–74
121. Golewski GL (2018) Green concrete composite incorporating fly ash with high strength and fracture toughness. J Clean Prod 172:218–226
122. Cocking R (2003) The challenge for glass recycling. In: Sustainable Waste Management: Proceedings of the International Symposium Held at the University of Dundee, Scotland, UK on 9-11 September 2003. Thomas Telford Publishing, pp 73–78. https://doi.org/10.1680/swm.32514.0008
123. Sarkis C-JL, Raich OM, Mestre J-LZ (2017) Assessment of the temperature of waterproofing membrane when a recycled crushed glass finish layer is used on flat roofs to protect from sun radiance. Energy Procedia 115:451–462
124. Larsen AW, Merrild H, Christensen TH (2009) Recycling of glass: accounting of greenhouse gases and global warming contributions. Waste Manag Res 27:754–762
125. Cattaneo JUS (2008) Glass recycling: market outlook. In: Resource conservation challenge work. https://scholar.google.com/scholar?hl=en&as_sdt=0%2C5&q=Cattaneo+JUS+%282008%29+Glass+recycling%3A+market+outlook.+In%3A+Resour+Conserv+Chall+2008+Work&btnG=
126. Joshi RC, Lohita RP (1997) Fly ash in concrete: production, properties and uses. Fuel Energy Abstr 39:26. https://doi.org/10.1016/0140-6701(98)94358-2

127. Hilton B, Bawden K, Winnebeck K, Chandrasiri C, Ariyachandra E, Peethamparan S (2019) The functional and environmental performance of mixed cathode ray tubes and recycled glass as partial replacement for cement in concrete. Resour Conserv Recycl 151:104451. https://doi.org/10.1016/j.resconrec.2019.104451
128. Menchaca-Ballinas LE, Escalante-Garcia JI (2019) Low CO2 emission cements of waste glass activated by CaO and NaOH. J Clean Prod 239:117992. https://doi.org/10.1016/j.jclepro.2019.117992
129. Dhirendra P, Yadav RK, Chandak R (2012) Strength Characteristics of Pre Cast Concrete Blocks Incorporating Waste Glass Powder. ISCA J Eng Sci 1:68–70
130. Popov M, Zakrevskaya L, Vaganov V, Hempel S, Mechtcherine V (2015) Performance of Lightweight Concrete based on Granulated Foamglass. IOP Conf Ser Mater Sci Eng 96:012017. https://doi.org/10.1088/1757-899X/96/1/012017
131. Shi C, Zheng K (2007) A review on the use of waste glasses in the production of cement and concrete. Resour Conserv Recycl 52:234–247
132. Islam GMS, Rahman MH, Kazi N (2017) Waste glass powder as partial replacement of cement for sustainable concrete practice. Int J Sustain Built Environ 6:37–44. https://doi.org/10.1016/j.ijsbe.2016.10.005