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Exploring the Effects of the Substitution of Freshly Mined Sands with Recycled Crushed Glass on the Properties of Concrete

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Featured Application: This work provides further details on the advantages of using crushed waste glass as a substitute for riverbed sands in concrete mix design. This adds value of environmental sustainability to concrete as a construction material by replacing a mined component with waste materials that would normally have ended in landfill.

Abstract: Although many works have reported on the effects of using waste materials on the functional properties of concrete, the results are generally diverse. In this work, the effects of substitution of fresh sands with crushed waste glass (CWG) for a concrete mix design of 32 MPa concrete is explored. The mechanical properties were followed with standardised mechanical tests including compression, indirect tensile, and four-point bend tests. It is shown that the compressive strength of concrete containing 15% of CWG produced the highest compressive strength of 34.54 MPa. The splitting tensile and flexural strengths of the concrete mixtures containing CWG both exhibited a maximum strength of 3.21 and 4.90 MPa, respectively at 15% CWG content. Furthermore, it was found that a maximum of 30% CWG can be substituted without a reduction in the mechanical strength. The loss of strength with higher volume proportion of CWG is attributed to the morphological difference between the riverbed and CWG sand particles. The latter had sharp ends that at a critical content might promote stress concentration. Semiquantitative analysis by energy-dispersive spectroscopy (EDS) in a scanning electron microscope (SEM) suggests the presence of alkaline silica reaction (ASR) gel at the interface of glass particles and the mortar matrix. Further exploration of glass mortar interfaces found evidence of ASR gel-induced cracking in the vicinity of the CWG particles in mortar matrix.

Keywords: crushed glass sands; recycle glass; mechanical properties; sustainability

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1. Introduction

Concrete is a ubiquitous engineering material comprised of a mixture of fine and coarse aggregates, which are consolidated together using a hydrated cement binder that hardens over time. The estimated annual global production of concrete has now exceeded 16 billion tonnes [1]. This amount to a large consumption of cementitious and mined aggregate materials. The environmental impact of increasing extraction and consumption of naturally mined materials such as sand, gravel, and crushed rock aggregates could be mitigated by substitutions with solid wastes materials. Therefore, the exploration of the potential of alternative aggregates to reduce the quantity of quarried materials used in the production of concrete is a worthwhile endeavour.

The construction industry is widely regarded as one of the biggest consumers of natural resources, with reports stating that Australia alone extracts 130 million tonnes of aggregate annually [2]. The sustainable credentials for concrete production have long been a subject of debate, and considerable efforts have been placed into research (e.g., refs [2–7]) on the use of recyclable materials in an attempt to reduce the consumption of naturally mined components. A further step forward in achieving sustainable concrete production would be accomplished if unmined, recycled materials could be used to replace any of the components that are normally sourced from geo-formed origins. One such material of particular interest is the use of crushed waste glass (CWG) as a replacement for any of the mined components used in the compositional mixture of concrete.

Waste resource centres in Australia and many of the western world have now made many of these recyclable materials available through systematic waste processing. With new processing technologies, glass components are easily recovered, separated, and processed into CWG and graded as coarse/fine aggregates and powder when further processed to particle size of the order of 10 µm. Aggregate CWG materials are now available in quantities significant enough that a case for constant supply can be explored. In 2016 alone, it was reported that 1.1 million tonnes of glass waste was produced in Australia, with only an estimated recycling rate of 57% where the primary mode of recycling consists of lower-value products [8]. It is also reported [9] that in 2017, China produces over 20 m tonnes of waste glass with only 53% recycled, while the USA produced 11.4 million tons with only a 26% recycle rate. The average recycle rate of waste glass in EU was 73% with some countries reaching more than a 90% recycle rate. While the recycle rate may be high in the EU zone, the varying low recycle rate in the rest of the world and the low value recycle products makes a viable case for a worldwide construction materials resource in CWG.

The utilisation of waste materials as a replacement for traditional aggregates has been a key topic of research within the construction industry such that the application of CWG in concrete has been subjected to numerous studies [3,10–13]. However, the vast majority of research has produced inconsistent outcomes regarding the benefits of CWG in concrete mixes. Furthermore, the results for the optimal proportion of CWG substitutions and the subsequent effects on functional properties are too varied. In this work, we explore the use of recycled glass (CWG) as a fresh sand replacement and report the comparison between the mechanical properties of concrete containing varying ratios of CWG.

2. Waste Glass as Resource for Construction Materials

2.1. Waste Glass

The total global production of solid waste is estimated [14] to be more than 200 million tonnes with more than 13% projected to end up as glass wastes. This makes available a vast potential resource in abundance and availability such that the potential use of unrecycled waste glass in construction materials has attracted many recent reviews [14–16]. Generally, there has been mixed outcomes on the beneficial reports of substituting glass materials with the traditional constituents of concrete. Nonetheless, the benefit resides mostly in the fact that waste glass that might eventually end up as landfill can now be functionally utilised. The substitution for replacing any mined materials also brings in a latent value in its contribution to environmental impact and improved suitability of making concrete.

The main concern for the inclusion of siliceous aggregate in concrete is the susceptibility of silica-based content to undergo alkaline silica reaction (ASR). These are found [7,14,15] when siliceous materials come into alkaline mix of the binder materials. The gel from ASR when in contact with water could expand and has been implicated as a source of cracking in some applications of waste glass substitutions. The effects of ASR and its formation become significant when substitutions exceed 50% where expansions have been reported to be about 0.7%. For much smaller volume proportion substitutions, typically, expansion due to ASR gel formation has been shown [7] to be lower than 0.2%.

There are several types of glasses that may end up as waste glass, and these have been categorised as [14]:

- Sodium lime glasses (packaging glass)
- Borosilicate glasses
- Leaded glasses

- Barium glasses
- Aluminosilicates.

Potentially, any of these could end up in waste system; however, the most common in the waste collection are the sodium lime glass from food and beverage packaging. Although these come in different colouration, the major components essentially are [14,17,18]:

- SiO_2 70–72%
- CaO 9–12%
- $Na_2O + K_2O$ 8–10%
- Others Al_2O_3, Fe_2O_3, MgO.

Since most of the waste glass come in combined colours, there has been no evidence that colour makes any difference in property outcome, but the chemical and physical properties are similar irrespective of colour, which may be varied due to different compositions of minor concentrations of transition metal oxides.

Generally, the use of waste glass in concrete substitutions is either to replace cementitious binder or to replace aggregates.

2.2. Glass Wastes as Cementitious Substitutions

Cement production is known as a contributor to greenhouse gas, and efforts to reduce its use in construction materials rely on the ability of substitutes that have the chemical potential to undergo pozzolanic reactions [19]. Pozzolanic reactions occur when vitreous siliceous materials in the presence of a binder paste react with excess $Ca(OH)_2$ to form a C-S-H compound that strengthens the concrete. The pozzolanic reaction from silica can generally be represented by the equation [15]:

$$Ca(OH)_2 + SiO_2 + H_2O \rightarrow CaO\ SiO_2\ H_2O.$$

CWG powders with particle size less than 140 µm are known [20,21] to exhibit pozzolanic reactions in cement, and they have been investigated as substitutions for general purpose cement in concrete. CWG substitution for pozzolanic activity plays a key role in water absorption of concrete, with a record of higher water absorption at early ages [22]. Another report [5] recorded a lower water absorption for late age where a CWG pozzolans concrete mix suggests slower rates of pozzolanic reaction compared with hydration reaction. Although the siliceous pozzolanic reactions caused increase strength, 100% substitutions of glass powder for cement cannot be achieved, since SiO_2 on its own does not undergo the hydration reaction required for the cement binding action. Substitutions of 10 to 40% have been reported [20,23–25]. It is found that for substitutions higher than 10%, compressive strengths in early ages decrease with an increasing proportion of substitution of glass powders. However, late ages strength of concretes with siliceous pozzolans either matched or surpassed the mechanical strengths of control mixes. The late development of full strength can largely be explained by the slower rate of the pozzolanic reactions compared with the normal hydration reaction in a fully cementitious paste.

The potential CWG powders to form ASR in a cementitious mix have been investigated, and it is generally agreed that the high specific surface attending the micron-size powders promotes the formation of pozzolanic reaction ahead of ASR. Therefore, further studies [26–28] have shown that glass particles with less than 1.0 mm are less susceptible to undergo ASR in concrete mix.

2.3. Glass Wastes as Aggregate Substitutions

The use of CWG as aggregate materials (typically larger than 1.0 mm) has been widely investigated. Several studies reported a reduction of workability with the usage of CWG aggregates in the highest percentage proportion of substitution [12,29,30], while some other reports indicated there was no significant difference in the workability through a slump test [31,32]. Although it is difficult to find agreement on the outcomes of several reports, there is somewhat of an agreement that partial glass substitution improved the binder action of cement, although there is no clarity on the relative effects of substituting coarse and fine aggregates [17,33].

The outcome of compression strengths of concrete with CWG will be the interplay between a glass's bond strength with the binder cement matrix. The influence of the recycled glass addition on the compression strength is rarely a straightforward explanation [34]. Some studies carried out on the compressive strength concluded that there are no significant effects or changes due to the usage of 20–30% recycled glass in the concrete [35]. However, a decrease in compressive strength was reported [23,36] and was attributed to the weakening of the aggregate paste bond due to the addition of waste glass instead of coarse aggregate [36,37]. On other hand, some other works [5,38–40] indicated increased later age strength with partial substitutions of aggregates with CWG, although the early age strength is lower.

Flexural strength of the glass substitutions for aggregates in concrete shows a similar trend with that of its compressive strength. It is found that flexural strengths increase to the maximum with the optimum addition of glass powder [10,32,39]. Generally, it is recorded that 4–11% higher flexural strength resulted with the 10–20% substitution of fine and coarse aggregates of CWGs [41]. A similar trend in splitting strengths is also reported on the effects of CWG substitutions for aggregates. It is found that splitting strengths increase by 4–12% with the CWG additions up to 20% [25]. The variability that accompanies the numerous reports of the effect of substitution on mechanical properties of concrete demands further clarification. In this work, we focus mostly on the effects of substituting fine aggregates with CWG sourced from a local waste processing plant.

3. Materials and Methods

3.1. Materials

The gravel used in the concrete mixes was natural crushed gravel locally procured, sorted, and graded to achieve a maximum nominal size of 20 mm. Natural river sand with a maximum size of 4.75 mm was used as a fine aggregate in the concrete mixtures.

The recycled waste glass used was from local waste processing collection centres in Australia. It contained a mixture of flint, amber, and emerald green glass that was processed to remove the amalgamated constituents before being crushed to fine aggregates. Both riverbed sands and CWG fines were subjected to sieve analysis to determine the relative particle size distribution as well as their morphologic characteristics.

3.2. Scanning Electron Microscopy

Samples of fines from riverbed sands and CWG were subjected to scanning electron microscopy and energy-dispersive spectroscopy (EDS). Samples to be examined were mounted on aluminium stub with the aid of a double-sided carbon tape. The conductivity of the samples was ensured by depositing a thin layer of carbon in an evaporation chamber. In order to follow the morphology of the CWG in concrete, a small section of mortar taken from broken compression test samples was prepared for SEM and EDS analyses.

3.3. Concrete Mix Design

The concrete mixes design used in this study was based upon the design guide published [42]. The control mixture with a water-cement ratio (*w/c*) of 0.5 is designed to meet the compositional strength of 32 MPa at 28 days. The effects of substitutions of riverbed sands (with a measured specific gravity of 2.65) with CWG (with a measured specific gravity of 2.4) were followed for 10–100% substitutions. The mixes for the various substitutions are given in Table 1.

The concrete was poured into the moulds, and a vibrating rod was used to consolidate the concrete by removing the entrapped air and ensuring that the mixture conforms to the boundary of the mould. After cast concrete was hard enough to be demoulded, curing was completed in a temperature-controlled water bath.

Table 1. Mix proportion in batches for the various crushed waste glass (CWG) substitutions 32-MPa concrete.

Composition	Cement	Coarse Aggregate	Sand	Recycled Glass
Replacement %	**Kg**	**Kg**	**Kg**	**Kg**
0	320	1280	800	0
10	320	1280	720	80
15	320	1280	680	120
30	320	1280	560	240
50	320	1280	400	400
100	320	1280	0	800

3.4. Wet Concrete Properties

3.4.1. Slump Cone Test

The workability of the concrete mixture was evaluated through the slump test conducted following the Australian standard AS 1012. The standard metal slump cone with an internal diameter of 100 mm and 200 mm at each end and a height of 300 mm was used, as depicted in Figure 1.

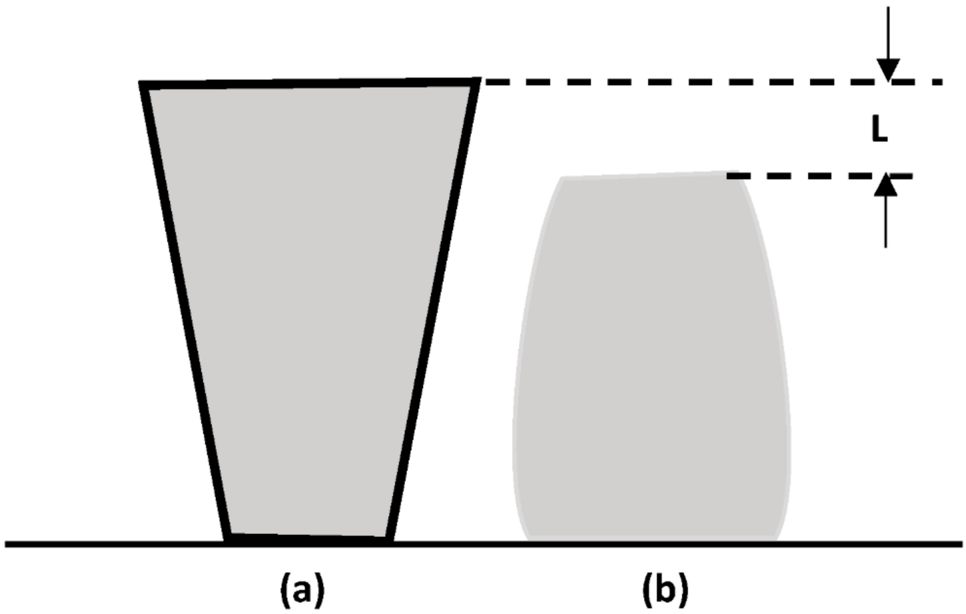


Figure 1. Schematic representation of the slump test: (**a**) Slump cone, (**b**) Concrete slump.

3.4.2. Density Measurements

The density of the concrete mixtures was determined using cylindrical samples of diameter by height of 100 mm × 200 mm. The specimen was removed from the water tank and wiped to remove excess water from the outer surface. Samples were weighed in air and when completely immersed in water to compute density in accordance with Archimedes principle.

3.5. Physical and Mechanical Properties

3.5.1. Water Absorption and Porosity

The water absorption and porosity of the concrete were determined following the AS 1012.21 specifications. A sectioned cylindrical sample with a diameter and height of 100 mm × 50 mm respectively was dried and placed in a ventilated oven at a temperature of 110 °C for 24 h. After 24 h, the weight of each specimen was measured and recorded.

Then, the freshly dried cylindrical samples were placed into plastic containers that were filled with water, covering approximately 10 mm above the sample. Once full saturation was achieved, the specimen was placed in a small container filled with water and weighed again.

3.5.2. Compressive Strength

The compression testing was conducted in accordance with the Australian standard AS1012.9. Cylindrical samples with a diameter and height of 100 mm × 200 mm respectively were used in the compression testing. The individual dimensions of each specimen were measured and recorded. An aluminium cap containing a layer of foam on the inner surface was placed on the troweled end of the specimen to dampen the effect of the surface variation. The machine exerted a uniaxial compressive force on the top and bottom surface of the specimen at a rate of 20 ± 2 MPa per second until failure. The maximum force exerted on the specimen was recorded. An average compressive strength across three tests was taken to determine the compressive strength. The fracture pattern of each mixture was recorded to and compared to determine the type of failure experienced by the specimen.

The Splitting tensile strength testing was in accordance with AS1012.9. Cylindrical samples with a diameter and height of 100 mm × 100 mm respectively were used in the tensile testing. The individual dimensions of each specimen were measured and recorded. The loading configuration is illustrated in Figure 2, and the splitting strength is calculated as specified in AS1012.9.

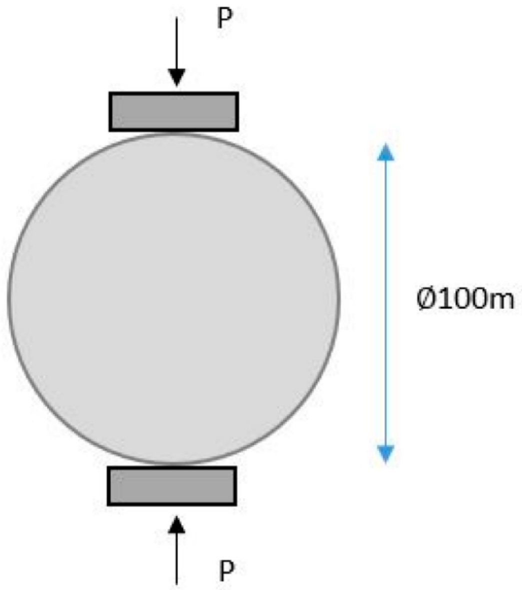


Figure 2. Schematic illustration of splitting test for concrete samples.

3.5.3. Flexural Test

The flexural strength (modulus of rupture) of the concrete samples was determined following the AS1012.9:2014 specifications. Rectangular beams with breadth, depth, and length of 100 mm × 100 mm × 300 mm respectively were used for the flexural testing.

The four-point bending test was set up as illustrated in Figure 3. The maximum force to failure was used to compute the flexure strength in accordance with the specifications of AS1012.9.

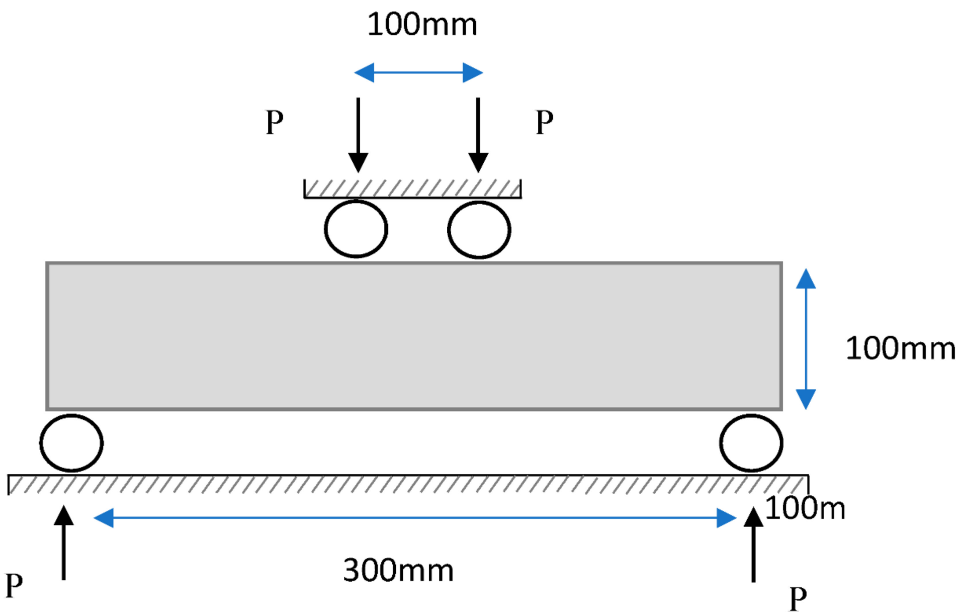


Figure 3. Schematic illustration of four-point bend test.

3.5.4. Modulus of Elasticity

Elastic modulus values were calculated from compression data obtained from elastic compressive loads applied on compression cylindrical samples with a diameter and height of 100 mm × 200 mm. The loads were applied using a 100 kN Shimadzu AG-X Plus testing apparatus that was equipped with a video extensometer. The test samples were sprayed with dark-coloured paint to provide a background contrast of light-coloured reference points marked with light colour for video tracking used in strain calculations. The test configuration is shown in Figure 4, and a video extensometer measurement is schematically illustrated in Figure 4c. As the loads were applied, the accompanied strain was automatically calculated and stored. The stress load data were fitted to determine the elastic modulus.

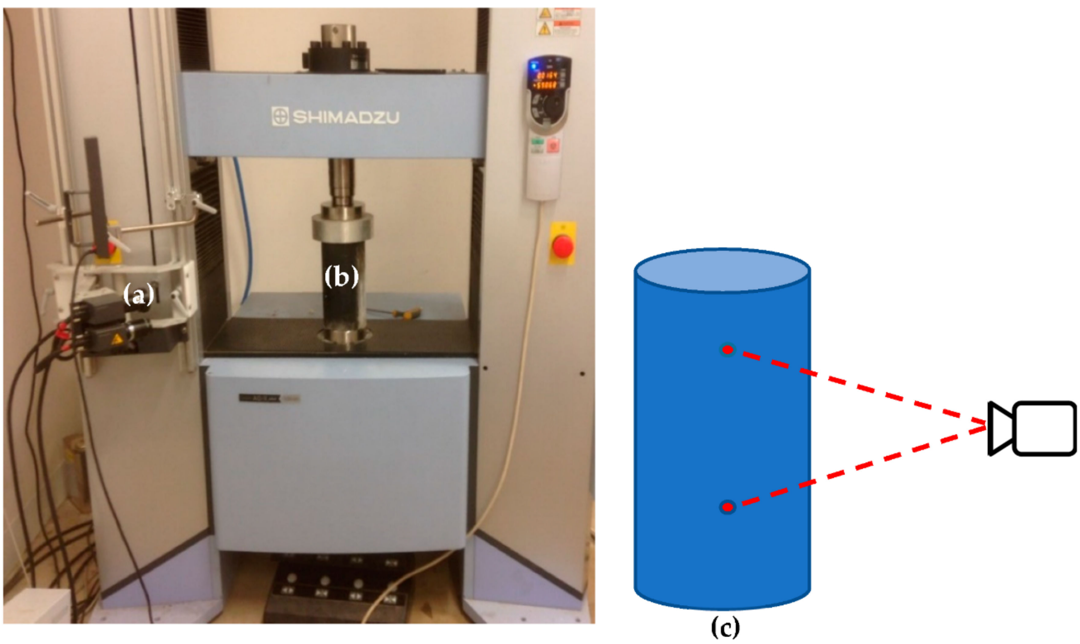


Figure 4. Set up for measuring of elastic modulus: (**a**) Video tracker, (**b**) Sample under load, (**c**) Schematic illustration of video tracking from two reference points.

4. Results and Discussion

4.1. Sieve Analysis of Raw Materials

The sieve analysis of the coarse aggregates used shows that the size of the material was primarily distributed around 19 mm and 13.2 mm and is consistent with normal practice expected in coarse aggregates. The particle size distribution curve for riverbed sands and the CWG sands are shown in Figure 5. It can be seen that the recycled glass sands peaks just above the upper bound of the recommended grading specifications. This shows that the crushed glass particles are comparatively smaller than the riverbed sand particles. The crushed glass attained a higher fraction of fine particles, with a fineness modulus of 3.29 compared with a fineness modulus of 5 observed for normal sand particles. The median particle size of the recycled glass is 300 µm, while that for normal sands was over 1.0 mm. Figure 5 shows that nearly 50% of the fresh sand aggregates lies outside the recommended lower bound size, resulting in much coarser sand with a median size of 1.8 mm. Therefore, the mixing of CWG sands and riverbed sands would be expected to provide a combined distribution effect with a particle size range that lies closer to that of the recommended range in Figure 5.

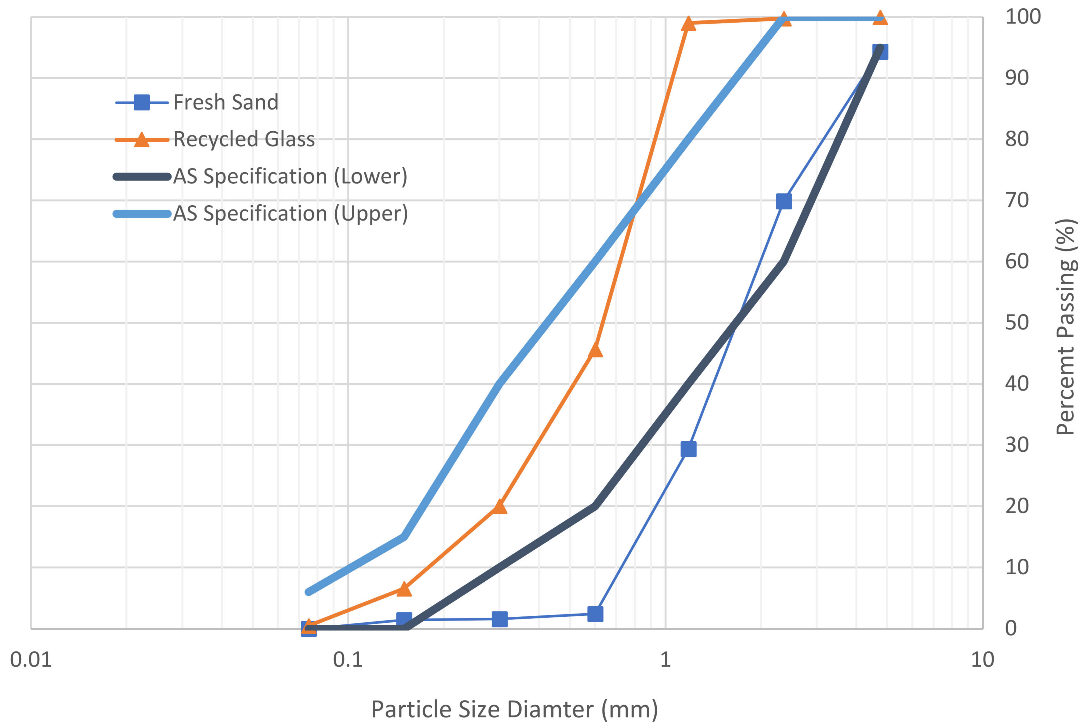
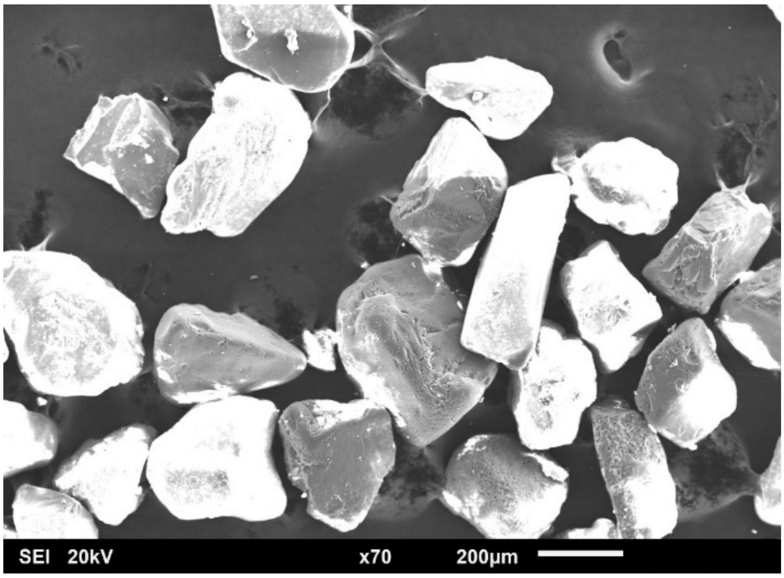


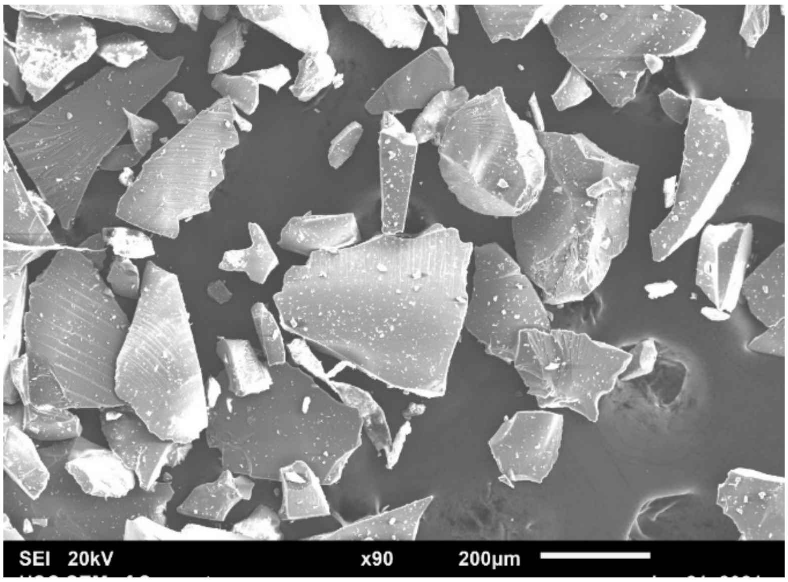
Figure 5. Size distribution curve for the fine aggregates used. Limits according to Australian Standards (AS 1141) indicated.

CWG glass with particle sizes smaller than 140 µm are known [43] to contribute to pozzolanic activity and result in an increased compressive strength of concrete. In this case, only a fraction of the CWG substitutes falls below the 140 µm size limit, and there is little evidence that there is a significant pozzolanic contribution because a significant proportion of these CWG particles are too large.

The SEM image analysis for the riverbed and glass sands is shown in Figure 6. The riverbed sands are more uniform, rounded edges with dimensions ranging from 0.3 to 1.0 mm consistent with particle size distribution curve in Figure 5. On the other hand, the glass sands present a different morphology with irregular sizes and about 90% ranging from 10 µm to 1.0 mm. The surfaces of glass sands were faceted presenting many sharp edges. This implies that the specific surface of the glass sand on the average is much higher than that of the natural sands because of smaller size distribution and because of the faceted morphology.



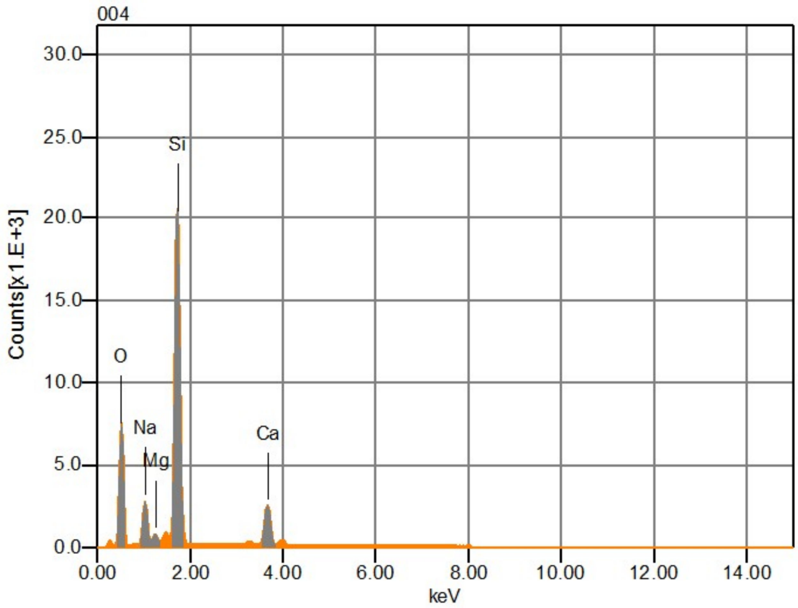
(a)



(b)

Figure 6. SEM microscopy showing morphology of fine aggregates: (**a**) Riverbed sand, (**b**) Glass sand.

Energy-dispersive spectroscopy (EDS) of the glass sands was taken to identify the glass type. The EDS is shown in Figure 7, and the semi-quantitative analysis indicated that the chemical composition of an averagely randomised sample was SiO2, 78.2%; Na_2O, 9.75%; CaO, 9.98%; and MgO, 2%. This composition is consistent with that of soda lime glass [14,17], thus suggesting that this CWG comes mostly from glass recycled from food packaging.



Chemical formula	mass%	mol%	Cation	Sigma	Net	K ratio
O						
Na2O	9.75	9.32	2.53	0.06	76839	0.0569774
MgO	2.01	2.95	0.40	0.04	17416	0.0079329
SiO2	78.27	77.18	10.45	0.19	724880	0.3625773
CaO	9.98	10.54	1.43	0.06	114350	0.0897823
Total	100.00	100.00	14.81			

Figure 7. Energy-dispersive spectroscopy (EDS) semi-quantitative analysis showing glass sand composition consistent with soda lime glass.

4.2. Fresh Concrete Properties

4.2.1. Slump

The effect of glass sand substitution on the workability of fresh concrete is followed by measures of slump. Figure 8 shows a change in slump with glass substitutions for the sand component. It is shown that generally, there is a drop in slump with glass sand proportion in the mix. The slump dropped from 75 mm to well below 60 mm for mixes containing more than 15% substitutions reaching below 50 mm for 100% replacement of glass for natural sand. It could be stated that the workability would be reduced slightly for modest substitutions up to 30%, representing about a 22% loss in workability. The role of glass components in concrete mixes has generally been reported [17] to decrease workability. Although the glass particle sizes fall within the acceptable size limit required by standards, the faceted nature of the glass particles and the irregular shapes would provide more resistance to the dynamic response of wet concrete mix to load and thus affect its flowability. This would explain the significant drop in slump for mixes with a higher proportion of sand substitutions.

4.2.2. Fresh Density

The effect of glass sand proportions on the fresh density for each of the freshly cast concretes is illustrated in Figure 9. The fresh density of the mixtures containing recycled glass aggregates decreased with the increase in the percentage of glass content. The percentage drop in density is generally modest, falling below 1% drop for mixtures containing more than 15% recycled glass. The factors that affect the density of concrete typically include the density of the aggregates, air content, and the ratio of water and cement within the mixture. Therefore, as the *w*/*c* ratio within the varying compositional mixtures remained the same, the decrease in density can be attributed to the lower specific gravity of the glass particles when compared to that of fresh sand [44]. The difference in the fresh density between the control mixture and the highest composition replacement of fresh sand is 4.2%. The trend in unit weight of freshly cast concrete reported in this study is consistent with other results reported in the published literature [39].

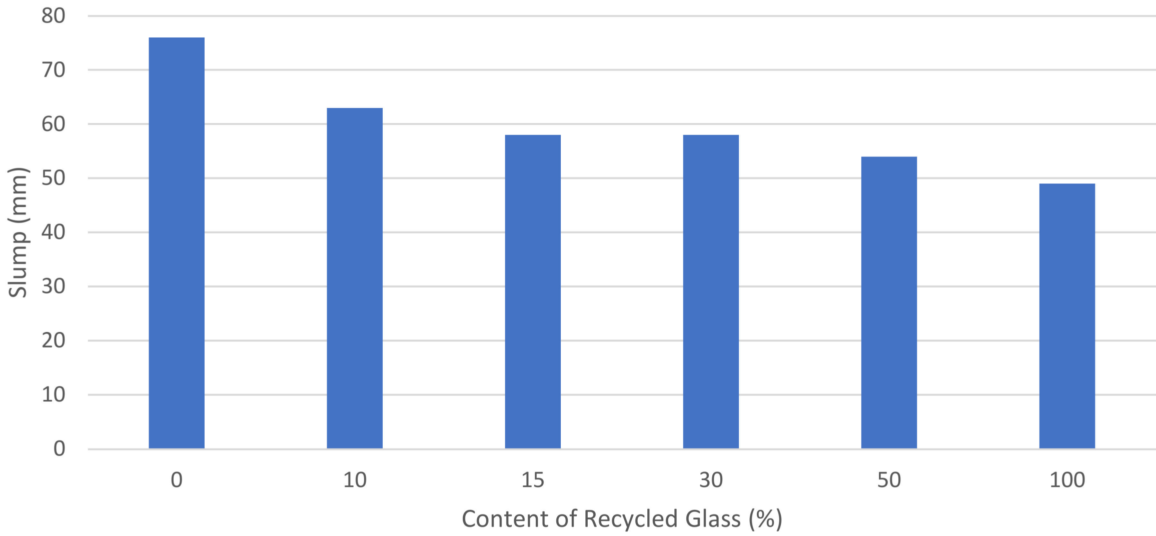


Figure 8. Effect of percentage glass waste substitutions for sand on the workability by slump.

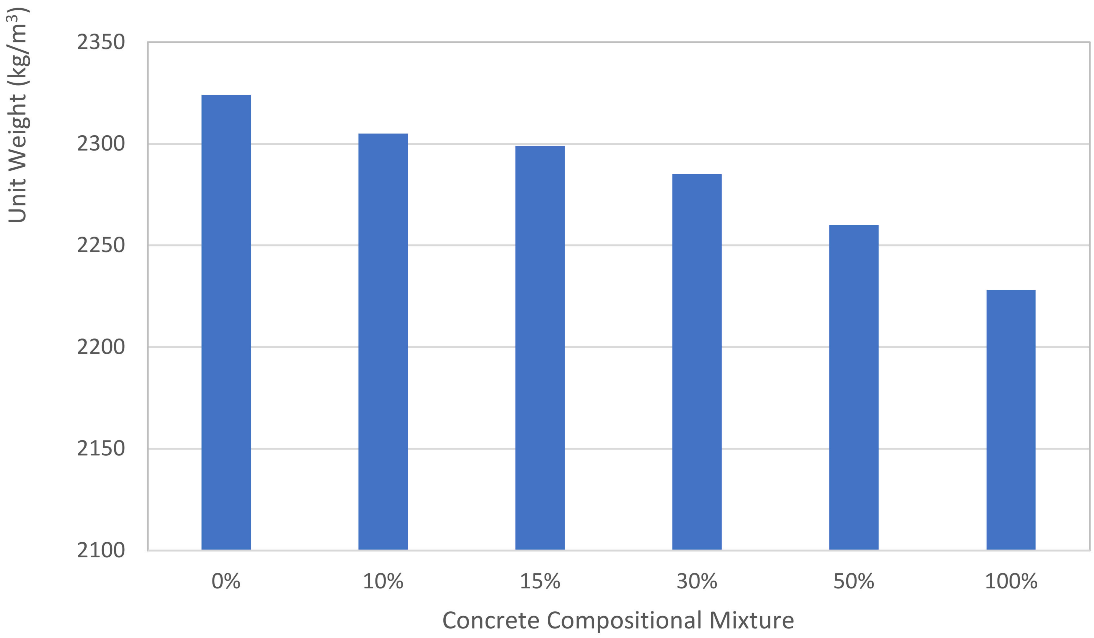


Figure 9. Effect of the proportion of glass sands on the fresh density of concrete.

4.3. Hardened Concrete Properties

4.3.1. Density

The hardening of concrete with curing age is followed by density measurements. The values of density with age are presented in Figure 10. For all compositional mixes, densification increases with age and started to plateau by day 28. The density of the respective mixtures increasing with age is a result of the continuing hydration of the cement binder. The time to peak density may be slightly delayed with glass substitutions. The 28-day density of each of the concrete mixtures shown in Figure 10 indicates a decreasing trend with increasing content of CWG. This trend is consistent with the composite effect of rule of mixtures dictated by the relatively lower specific gravity of glass.

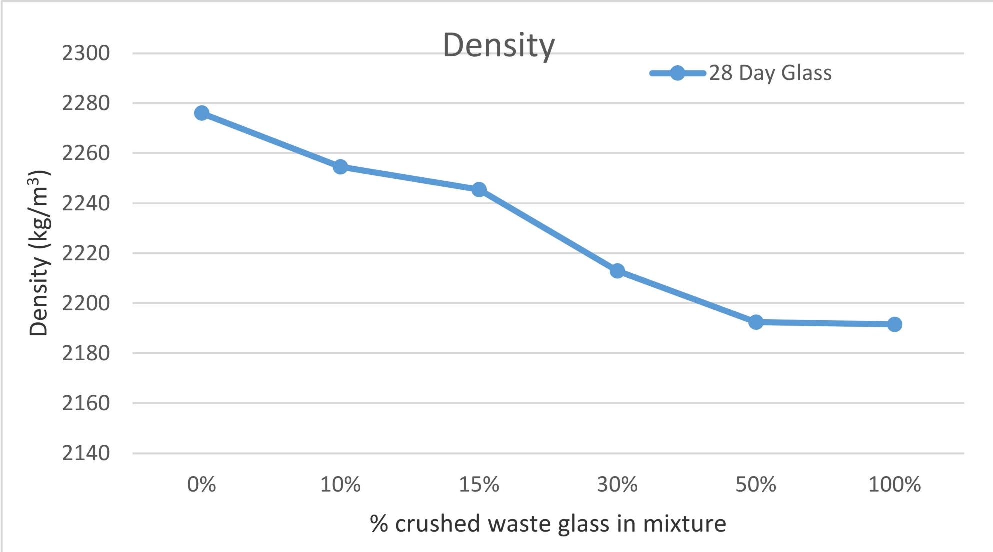


Figure 10. Effect of the proportion of glass sands on the 28-day hard density of concrete.

4.3.2. Water Absorptivity and Porosity

The water absorptivity for each compositional mixture at the curing age of 7–28 days is presented in Figure 11. It is shown that the relative absorptivity of the respective concrete mixtures decreases with the age of the concrete. This can be attributed to the relative progression of the hydration reaction at the varying stages, allowing the voids between the cement and aggregate particles to shrink with time [39]. Figure 11 shows the effect of CWG substitutions for 28-day cured samples. A 13% drop in water absorption was recorded at 15% CWG substitution. Substitutions beyond 15% did not affect the water absorption any further. The drop in water absorption is thought to be related to the improvement in packing arising from the smaller size of the glass particles and their faceted morphology. The reduction in water absorption has implications for durability, as it translates to increased resistance to the diffusive mechanisms for mass transport in the concrete microstructure [5].

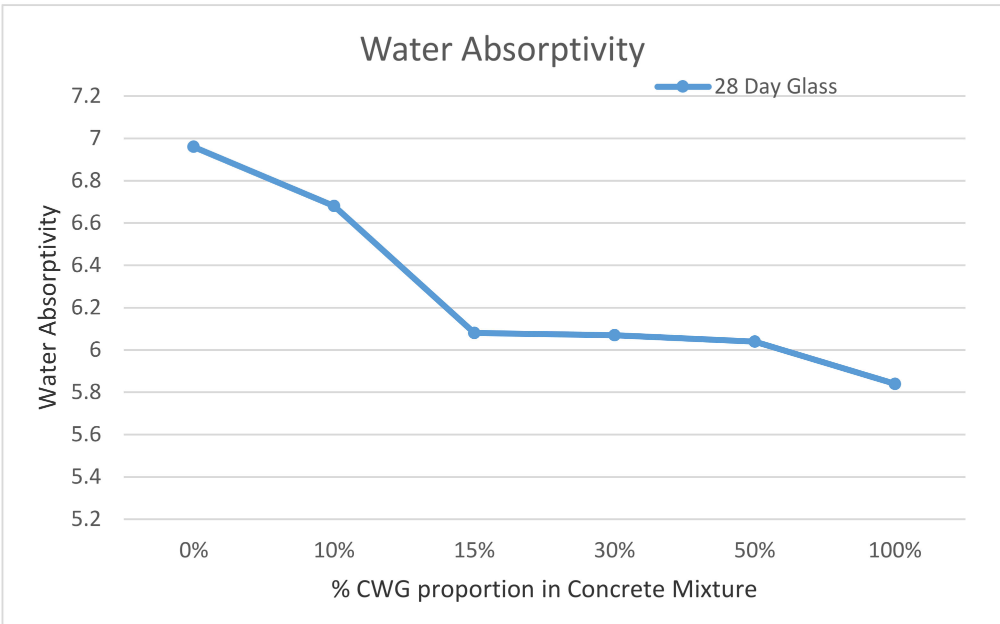


Figure 11. Effect of the density of concrete samples.

4.3.3. Compressive Strength

The compressive strength values obtained for concrete samples with CWG are presented in Figure 12. The compressive strength as expected increased with age in conformity with the time-based hydration reaction. It is not clear from the present experimental data whether glass substitution affects the time to reaching peak strength as in all cases; as shown in Figure 12, there was a gradual increase in compression strength with curing age nearly plateauing at 28 days. The 28-days strength for the control mix was 31.07 MPa, which is consistent with the mix design. There is a gradual increase in peak strength with glass substitution peaking at 34 MPa for 15%. However, when reaching 30% of the fresh sand replacement, the compressive strength dropped to 31.5 MPa and continued to drop with increasing glass substitution reaching 25.81 MPa for 100% CWG sands. This behaviour could be a combination of factors. The faceted glass particles provided increased specific surface for adhesion and would account for increased strength for small substitutions. In addition, the finer glass particles may also provide increased compaction that fills gaps in the sand. However, the relatively smooth surface of the recycled glass aggregates and the sharp edges would amount to lower adhesion between the cement paste. The possibility of glass exhibiting pozzolanic activity would strengthen the concrete [30]; however, the ability of glass particles to act as effective pozzolans requires very high specific surface that can only be achieved in glass particles with an average diameter less than 140 µm. The glass sands employed here with a particle size of 0.1–1.0 mm are less likely to offer much pozzolanic contribution.

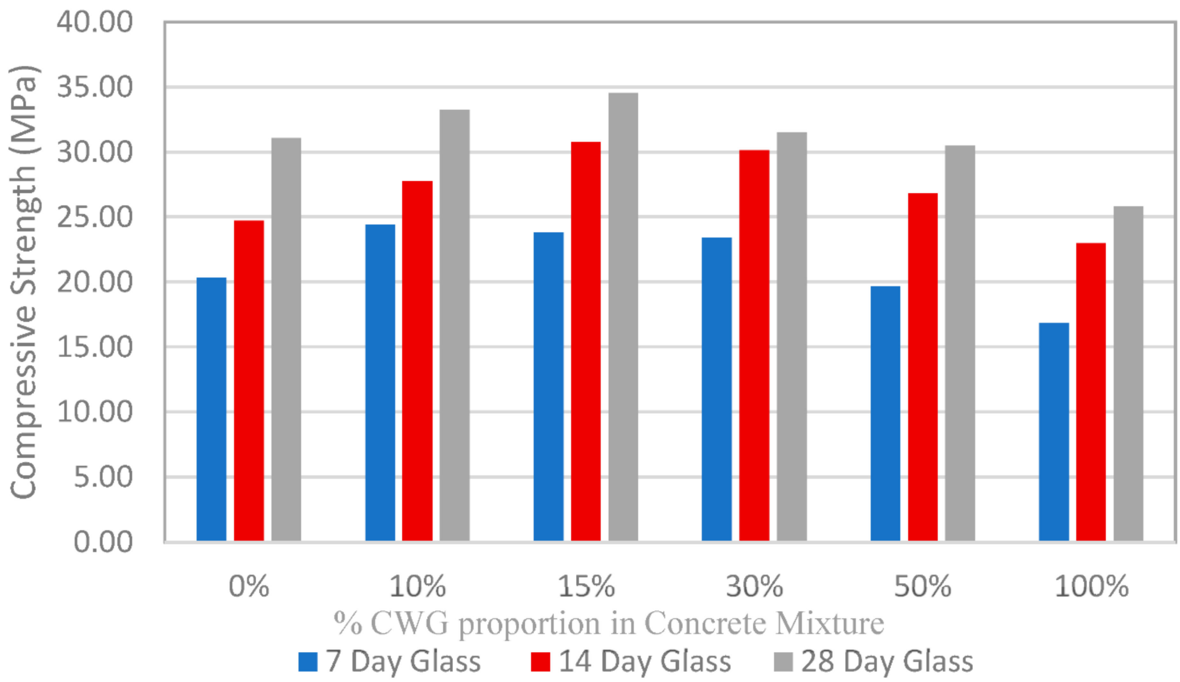


Figure 12. Effect of glass content on compressive strength concrete samples.

The fracture pattern of compression tests followed mostly ASTM type c, as shown in Figure 13 for all compositions. The possibility exists that the difference in density might have led to segregation and non-uniform distribution of glass sand that would cause a differentiation of fracture pattern for different levels of substitution. The similarity in fracture pattern suggests that the glass sand substituted was uniformly distributed for all proportions of glass sands.

Figure 13. The typical fracture of the cylindrical concrete specimens.

4.3.4. Splitting Tensile Strength

The splitting tensile strength of the concrete specimens containing recycled glass aggregates is of particular importance, as it can be an early indication of the occurrence of the alkali-silica reaction. The alkali-silica gel present within concrete containing glass aggregates can expand if sufficient moisture is present, creating tensile stress that can result in the formation of cracks within the concrete structure [45,46]. The splitting tensile strength for each of the concrete mixtures aged 7, 14, and 28 days is presented in Figure 14. It followed a similar trend as the compression strength with 15% substitution showing the highest 28-days strength of 3.2 MPa. It is shown that with glass substitutions, the early days strength was smaller, which may be an indication of a slight delay in reaching the peak strength. Nonetheless, the highest strength of 3.2 MPa recorded for 15% substitution may suggest that such a delay in reaching peak strength is not that significant for small volume proportions of glass sand. This study indicated that glass substitution up to 30% of sand could produce mechanical strength equivalent to the control mix. However, with the further increase in recycled glass content, the tensile strength of the respective mixtures was significantly reduced. The relative increase in strength at 28 days can be attributed to a further developed stage of the hydration process as a result of the decreased permeability of the glass in earlier stages [14,47]. It is known that the bond strength at the interfacial transition zone is improved for a small proportion of substitution of recycled glass and decreased at higher proportions of substitutions [45].

4.3.5. Flexural Strength

The flexural strength for each of the concrete mixtures aged 7–28 days is presented in Figure 15. The concrete mixture with 15% recycled glass content exhibited the highest flexural strength of 4.90 MPa, which corresponds to an increase of 15.4% when compared to the control mixture. The trend in the flexural strength with age is also indicated in Figure 15. This trend follows that of the compression and tensile strength.

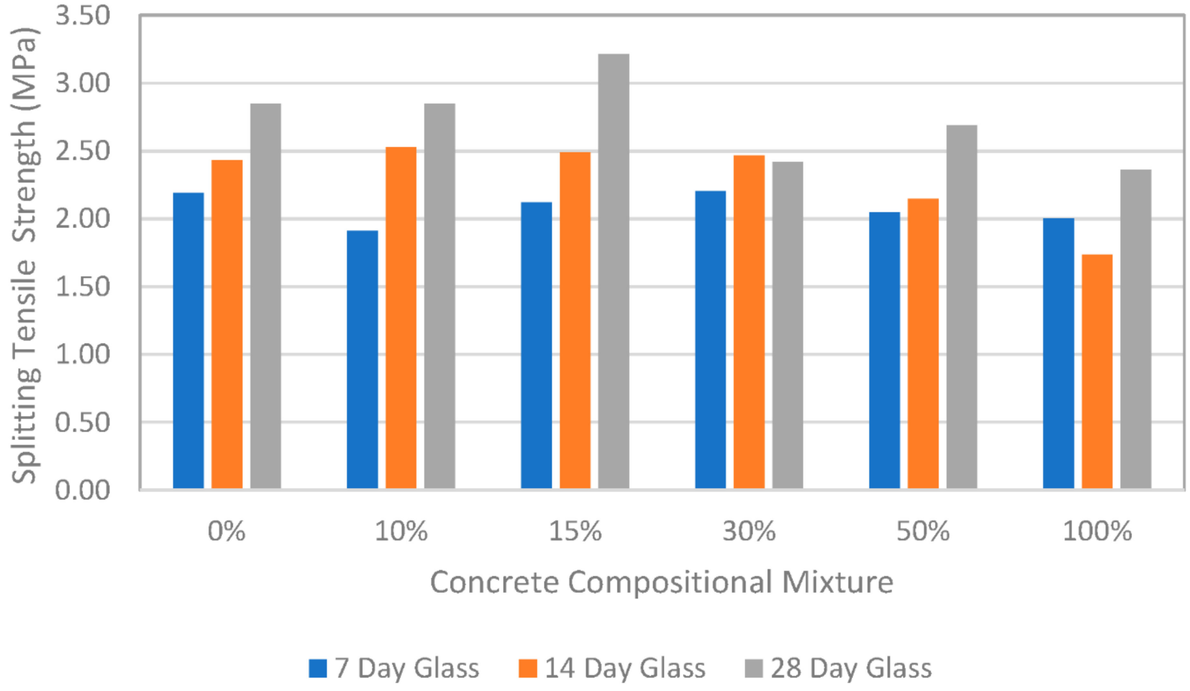


Figure 14. Effect of proportions CWG on splitting tensile strength of concrete samples.

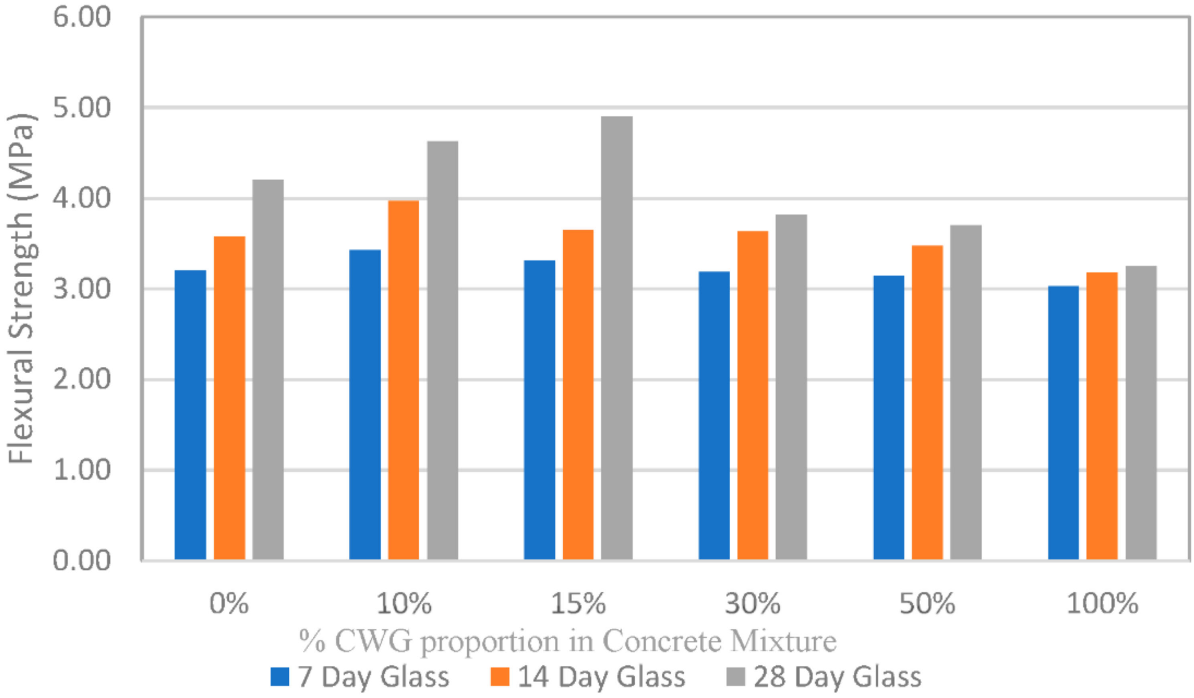


Figure 15. Trends in the flexural strength of concrete samples with percentage of CWG.

4.3.6. Modulus of Elasticity

The stress versus strain curve for the concrete samples containing recycled glass aggregates at 28 days were obtained via video extensometer. Typical stress-strain video extensometer data are shown in Figure 16. The modulus of elasticity (MoE) is determined by fitting the linear portion of the data. The values of MoE so determined are given in Table 2. It is shown that the elastic modulus of the respective mixtures ranged from 20 to 24 GPa. Although mixtures with glass substitutions tend to have slightly higher values, there is no clear trend in glass sand substitutions with the elastic modulus, since the values measured are still within the expected values of MoE corresponding to the recorded compression strengths. Largely, it could be inferred that adding CWG has no significant effect on the elastic modulus. This is an important observation, because the design of concrete structures relies mostly on elastic constant for design calculations.

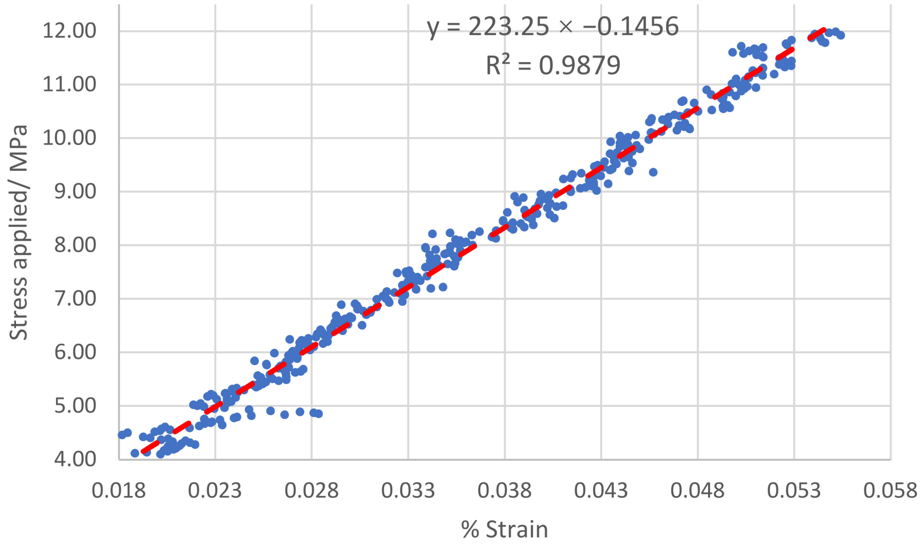


Figure 16. Representative stress-strain data from video extensometer for 15% glass substation, indicating modulus of elasticity (MoE) to be 22.3 GPa.

Table 2. Values of MoE in GPa.

Mixture	28 Days
0%	20
10%	23
15%	22
30%	20
50%	23.3
100%	24

4.4. SEM Analysis and Effects of Glass Substitution on Mechanical Properties

It is shown that the replacement of glass sand for normal riverbed sands generally provided acceptable mechanical properties for up to 30% substitution. This is generally attributed to the physical factors associated with the geometrical effects arising from the smaller particle size and the faceted morphology of the glass sands. The interaction of glass sands with the matrix was followed by scanning electron microscopy. A typical microstructure observed for glass particles in mortar is shown in Figure 17. The acicular and sharp edges found in glass particles are potential sources of stress concentration that could cause a premature failure and weakness. For small volume proportion, the contributions from such stress concentrators was not enough to weaken the concrete; hence, acceptable strength was observed for substitutions less than 30%. However, as the volume proportion of glass sands exceed 30%, the lower strength observed could be attributed to increased stress concentrating effects of sharp cornered CWG sand substitutes where the advantage from the increased specific surface is nullified.

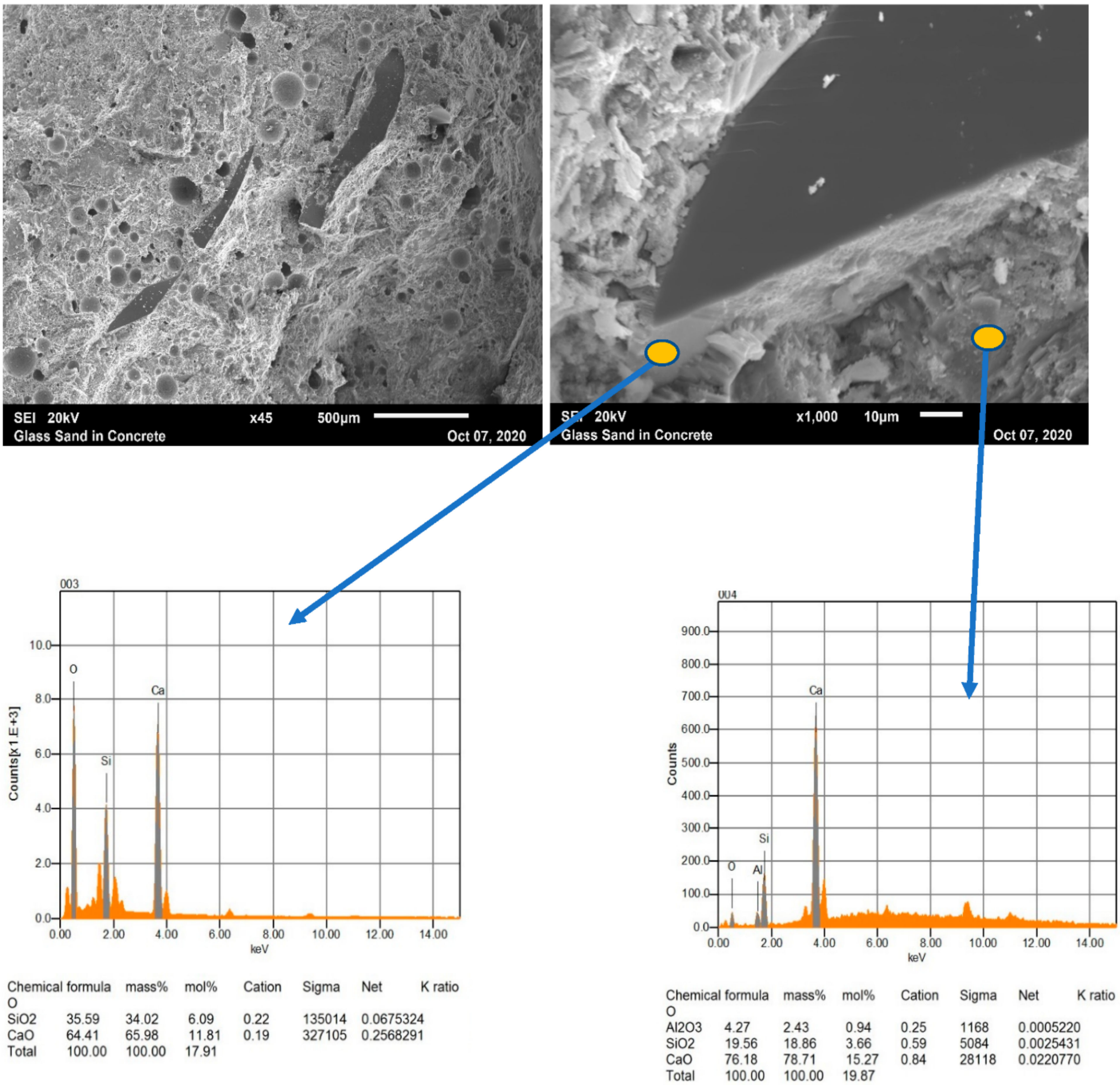
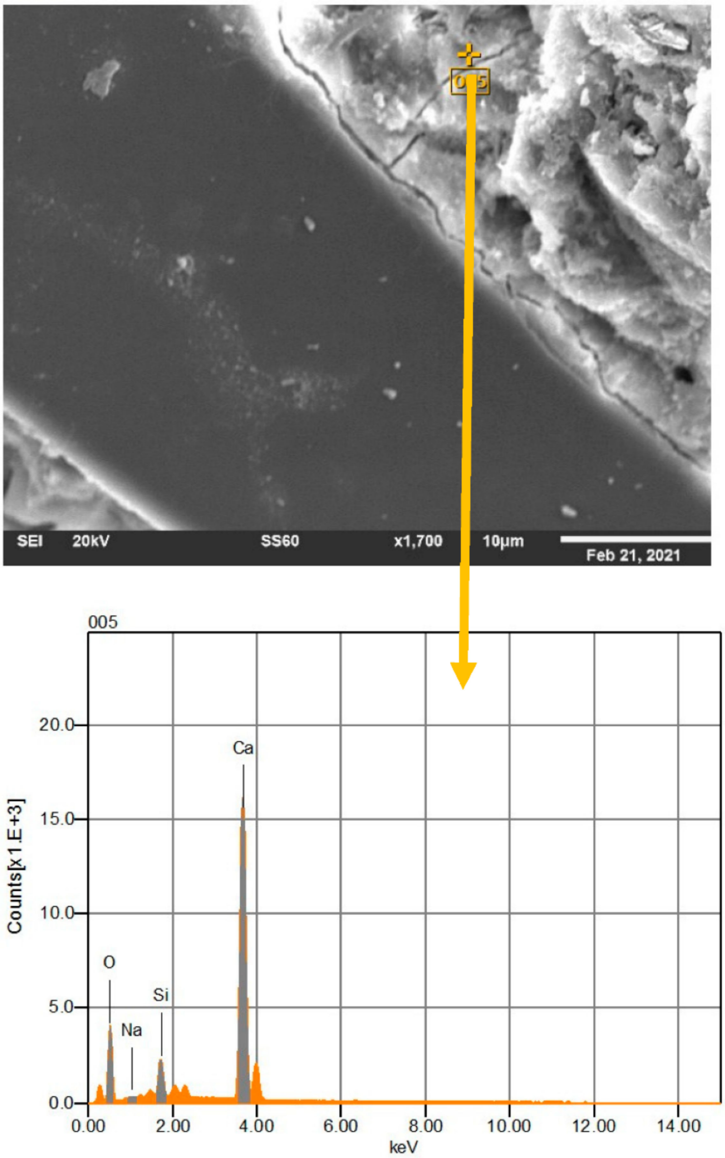


Figure 17. Glass-mortar interfacial zone with alkaline silica reaction (ASR) cracking. Accompanying EDS point probe indicate an Na-Si-Ca ratio consistent with compositions of ASR in lime glass.

The formation of ASR gel has been generally implicated with the use of soda lime glass in cement mix. Evidence exists in the present that shows the formation of ASR around the sharp edges of glass particles. Normally, it has been proposed that ASR by siliceous particles in cement binder is particle size-dependent and is prone to forming around sharp corners and cracks that have high specific surface. The EDS around glass particles showed compositions with a CaO/SiO_2 ratio consistent with ASR gel compositions [48]. However, the fine glass particles with an average diameter less than 100 µm are known to exhibit pozzolanic activity that would normally preclude the formation of ASR gel.

Evidence exists along some embedded glass particles where cracks were found at the boundary of the glass mortar matrix, as shown in Figure 18. Chemical probe by EDS indicated an Na-Ca-Si ratio suggestive of ASR gel. It is known that the Na/Si ratio determines the hydrophilic nature of ASR gels and their potential to cause cracking. It is no surprise that the Na/Si ratio would be higher in the vicinity of glass particles, and the potential for expansive cracks is high for high volume substitution.



Chemical formula	mass%	Atom%	Sigma	Net	K ratio	Line
O	53.23	73.32	0.14	93435	0.1300870	K
Na*	0.36	0.34	0.03	2777	0.0020595	K
Si	3.47	2.72	0.03	64970	0.0324974	K
Ca	42.94	23.61	0.08	761697	0.5980515	K
Total	100.00	100.00				

Figure 18. Glass-mortar interfacial zone with ASR cracking. The accompanying EDS point probe indicates that the Na-Si-Ca ratio is consistent with compositions of ASR in lime glass.

5. Conclusions

The substitutions of crushed waste glass for mined sands can be achieved in 32 MPa for up to 30% substitutions without significantly changing the primary mechanical and physical properties. However, the use of recycled glass in concrete mixtures has a significant effect on the workability that can be attributed to additional resistance to flow from the more faceted shape of the glass particles. The slight increase in mechanical properties at 15% glass proportion was attributed to geometrical effects that may arise from the increased compaction related to increased surface from smaller particles and the faceted morphology of the CWG particles. In a higher proportion of substitution, the sharp particulate advantage is lost as the gain is offset from mismatch and stress concentration effects from the less rounded glass particles. The possibility of pozzolanic contribution to strength was considered to be less likely because the average glass particles sizes are much larger than the 140 µm minimum required diameter for pozzolanic reaction.

The probe of the boundaries of glass particles in matrix suggests the formation of ASR gel and that there are cases where this would form near the sites of the glass particles. Some evidence of microcracks exist, indicating that an Na-Si ratio similar to ASR gelation with hydrophilic activity could induce cracks near the tips of the glass mortar matrix. It was concluded that a low proportion replacement of sand with CWG is less likely to have ASR-related degradation in mechanical properties.

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