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Utilization of Crushed Waste Glass as a Partial Replacement for Sand in Cement Mortar for a Sustainable Environment

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Abstract: The disposal of non-biodegradable waste glass poses a serious environmental threat as it can cause soil, water, and air pollution when not properly discarded in landfills. The use of glass in construction has shown promising results in enhancing various properties of concrete and improving overall sustainability. This study investigated the mechanical properties of mixed colored glass, comprising green and brown hues, and clear glass in mortar, to explore the feasibility of using colored glass as a replacement for sand and to determine how the addition of color affects the mechanical properties of mortar. The incorporation of waste glass as a partial replacement for sand resulted in a 2.7% increase in flow table values when 5% of Mixed Colored Glass Sand (MCGS) was utilized in place of sand, as compared to the control mix (CM). Conversely, a 5.4% and 4.7% decrease in flow table values were observed when 15% of clear glass (CGS) and MCGS were used as a substitute for sand respectively. When 15% of MCGS and CGS were replaced with sand, compressive strength increased by 60% and 42.6% respectively, compared to the control mix, when 5% MCGS, 10% MCGS, 5 CGS, and 10% CGS were observed. After 28 days of curing, a 10.6% and 10% increase in strength was observed when 10% of MCGS and CGS were replaced. At 7 days, a 3.3% increase in flexural strength was found when 5% of MCGS was replaced with sand was observed. The fire resistance test showed reduced mass and compressive strength of specimens at different temperatures. No significant expansion of ASR was recorded throughout the test period. The use of waste glass as a substitute for sand has shown improvements in environmental sustainability and economics. When 10%WGS and 15%WGS were utilized, 20% and 30% of waste glass sand was replaced with sand, respectively. Incorporating waste glass into construction enhances the mechanical properties of concrete and promotes the conservation of natural resources and environmental sustainability. This study examined the economic advantages of replacing sand with waste glass and found that CM has the highest cost of 90.64 Tl. At replacement of 5%, 10%, and 15% MCGS showed 1.07%, 1.96%, and 2.95% savings compared to the control mix, respectively. Moreover, replacing 5%, and 10% of natural sand with clear glass sand could bring about savings of 1.91%%, and 3.63%, respectively. Replacing 15% CGS showed the highest savings of 5.45% compared to the control mix. The study compared the use of colored and clear glass as a partial replacement for sand and found that there were slight differences in the results, but overall they were similar.

Keywords: Alkali-silica reaction, Fire resistance, Mechanical properties, Sand replacement, Waste glass

Introduction

Around 20 million metric tons of waste glass are produced yearly, and the recycling rate is worrying. Approximately 60% of waste glass is landfilled, with less than 20% recycled. Even though there is less landfill capacity, the amount of waste glass that is landfilled is predicted to increase dramatically (Agboola Shamsudeen Abdulazeez et al., 2020). . Glass is not biodegradable, it takes up many landfill areas and pollutes the air, water, and soil. In heavily crowded places, there is also a problem with a shortage of appropriate landfill space. To

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solve these challenges, the reuse of waste glass should be prioritized. Recycling glass saves landfill space, saves energy, and decreases prices while safeguarding natural resources (Borhan, 2012).

Waste glass has been utilized as a partial substitute for coarse aggregate, sand, and cement in the production of concrete and mortar. Since the 1960s, scholars have explored the potential of utilizing waste glass with a size greater than 4.75mm as a replacement for coarse aggregate in concrete (Yu et al., 2016). Nevertheless, using coarse glass aggregate reduced compressive strength as the concentration of glass increased. Additionally, there were contradictory results about the impact of glass aggregates on the workability of concrete.

Several studies have explored utilizing recycled crushed glass as a viable alternative to coarse glass aggregates to mitigate detrimental cracks (Afshinnia & Rangaraju, 2016; Chen et al., 2006; Jani & Hogland, 2014). Utilizing glass sand in concrete enhances its properties due to its sleek surface and less water absorption (Topcu & Canbaz, 2004). The mechanical and durability characteristics of hardened concrete are not compatible with variations in glass magnitude (De Castro & De Brito, 2013; Adaway & Wang, 2015). This can lead to the formation of microscopic fissures at the edges of glass particles when they are crushed. When there is moisture, can the damaged surface of aggregates develop ASR (Alkali Silica Reaction) expansion gels, which results in concrete cracking (Adaway & Wang, 2015)

Studies have demonstrated that ASR expansion can also happen when a higher proportion of glass material is used as a substitute for sand. The non-biodegradable characteristic of waste glass poses a significant challenge when disposing of it in landfills since it significantly contributes to soil, water, and air pollution. The glass waste will have accumulated so much that the landfills will not take in any other kind of waste as they will be at their peak, primarily because of the enormous human population. Conversely, the thrown-away glass may take tens of millions of years before it decays, thus worsening the complications in landfills. Recycling the discarded glass items would, therefore, ensure that reduced amounts of glass are disposed of in the landfills and result in energy conservation and natural resource conservation since the production of new glass items usually requires the mining of sand used to make new glass. It is an admirable approach as the processing of reusing the fragmented glass mitigates particular environmental challenges about landfills while safeguarding the existence of our planet's clutter for future generations.

Materials and Methods

Research Design

The study is based on experimental research and aims to look into using crushed waste glass as a partial replacement for sand in cement mortar. The study was designed to determine the suitability of waste glass in place of sand in cement mortar. It will comprise laboratory experiments to test glass waste's physical and chemical properties, establish the optimum particle size of crushed waste glass, and develop optimum cement mortar mixes using waste glass. This research also deals with the different properties of mortar (fresh and hardened) that use clear glass and colored glasses (green and brown).

Materials

Cement

Ordinary Portland cement (Type I) (42.5 R) was used for the study (ASTM C 150 – 07) which was obtained locally.

Fine Aggregate

The fine aggregate used for this study was artificial sand, represented by crushed stones. As a glass replacement, clear and colored (green and brown) glasses of quartz sand have been replaced for 15% of the total volume in both fresh and hardening properties of mortars. Sieve analysis has been used to obtain well graded sand. In this study, an attempt has been made to analyze the effect of partial replacement of glass with sand on the properties of mortar. The implications of this research could be in developing improved material for construction and could exploit the findings to understand the mortar's behavior better.

Waste Glass

The waste glass was collected from different bars, most of which sell drinks, and a few glass recycling sites. The glass collected was divided mainly into three types: green, brown, and clear, depending on its source. The waste glasses were cleaned separately by removing all traces of impurities, sugars, or alcoholic deposits. The glass was crushed through abrasive Los Angeles to the required size. This crushed glass was sieved to ensure the collected glass size was uniform and impure-free. All in all, the collection and overall recycling of the waste glass was very comprehensive. Table 1 shows the chemical composition of waste glass used in previous studies.

Table 1. Chemical composition of waste glasses

Chemical components (%)	Liu et al., (2022) Waste glass	Zhao et al., (2013)	Green glass (Y. Wang et al., n.d.)	Clear glass (Y. Wang et al., n.d.)	Brown glass (Y. Wang et al., n.d.)
SiO_2	68.3	76.1	65.97	68.43	70.69
Na_2O	14.6	11.3	11.08	10.97	10.22
MgO	1.3	0.91	1.11	0.91	1.32
Al_2O_3	1.2	3.37	3.33	2.21	3.63
Cao	11.9	5.8	11.85	11.79	10.79
K_2O	0.7	0.72	0.35	0.32	1.86
Fe_2O_3	0.36	0.02	0.62	0.17	0.52
LoI	1.34	0.4	-	-	-

Clear Glass Sand (CGS)

Figures 1 and 2 show clear glass and it is crushed for within the fine aggregate size respectively.

Figure 1. Clear glass used

Figure 2. Clear glass sand size (CGS)

Mıxed-Colored Glass Sand (MCGS)

Green and brown glasses given in Figures 3 and 4 respectively, were used to replace fine aggregate. Figure 5 and 6 are their crushed forms.

Figure 3. Green glass

Figure 4. Brown glass

Figure 5. Green glass sand size (GGS)

Figure 6. Brown glass sand size (BGS)

Water

Water is an essential material for concrete, as the cement needs water for hydration, and the workability of the mix also requires water. Tap water was used to mix the materials (ASTM C1602/C1602M – 22). Water/ Cement ratio used for this research was 0.485 as per ASTM (C109/C109M).

Mix Design of Mortar

For optimal results, the typical mortar demands a precise combination of ingredients, with a proportion of 1 part cement to 2.75 parts graded standard sand by weight (ASTM C109/C109M). When Portland cement is utilized, a water/cement ratio of 0.485 is employed, determined by the total weight of cement incorporated. Table 2 shows materials amounts used in different mixes.

Table 2. Mix design of mortar (1m^3)

Different Mixes	Cement (g)	Sand (g)	Clear Glass Sand (CGS) (g)	Mixed Color Glass Sand (MCGS) (g)		Water (ml)
				Brown	Green	
CM	500	1375	0	0	0	242
5 % MCGS	500	1305	0	35	35	242
10 % MCGS	500	1235	0	70	70	242
15 % MCGS	500	1165	0	105	105	242
5 % CGS	500	1305	70	0	0	242
10 % CGS	500	1235	140	0	0	242
15 % CGS	500	1165	210	0	0	242

Results and Discussion

Fresh Properties of Mortar

Flow Table

Flow table test have been performed for all mixes according to ASTM (C 1437 – 07) Multiple empirical research published in scientific journals has demonstrated that substituting fine aggregate with recycled glass modifies the characteristics of freshly mixed concrete. Multiple studies have demonstrated that the reduction in slump can be achieved by increasing the quantity of discarded glass. Additionally, as (Afshinnia & Rangaraju, 2016) support, the irregular angular shapes of these glass particles are another factor that activates the reaction in performance. This gives less fineness modulus and a lesser amount of cement paste because of the geometry of this shape, which provides low fluidity for the mixture. Small glass particles within the waste glass sand and plastic properties may cause adverse effects on the texture, shape, and even consistency of the concrete. This mainly pertains to aspects such as objects that have smooth surfaces and sharp edges. (Afshinnia & Rangaraju, 2016) ascertained that if a high percentage of recycled glass is incorporated into concrete, it may lead to a slump reduction compared to other variants. However, different types of surveys regarding this issue have presented divergent results. For example, after the study, it was found that it led to a slight increase in slump value and heightened its replacement level using coarse particles (Taha & Nounu, 2008). In this light, the authors used high-range water reducers to determine if the effect after the control mixture would be good enough. Others have discovered positive correlations between slight increases in a slump and a high level of replacement (Batayneh et al., 2007; De Castro & De Brito, 2013; Ibrahim, 2017; Park & Lee, 2004; Sharifi et al., 2013; Terro, 2006; Topcu & Canbaz, 2004; Yu et al., 2016) have reported that the flexural strength of concrete decreases with increased glass sand.

Figure 7 outlines these findings under the flow table values for the different mixes tested as the test progressed. An interesting trend was observed regarding the material variety affecting the flow table values, as shown in Figure 7. The replacement of 5% MCGS with sand induced an increase in the flow table values by 2.7%, thus proving that the sand may improve the flowing capabilities of the mixture. However, 10% MCGS or 10 % CGS replaced decreased by 0.91% and 2.3% in the flow table, respectively, suggesting that these materials may not be ideal for enhancing flowability. Substituting the sand in place of CGS 5% showed a very nominal reduction in the flow table values by 0.34%. Hence, the effect of such substitution was also found insignificant. Finally, when the adoption of 15% MCGS or CGS as a sand replacement is adopted, there is a significant decrease in flow table values by 4.7% and 5.4%, respectively. It can be seen from the result that the waste glass sand replacing up to 15% of the volume of sand does not have a significant effect on the flow table of mortar. This is when clear and mixed-colored glass sands are replaced by normal sand. The increase in glass replacement led to a rise in slump value due to the formation of a denser granular structure. Chen et al. (2006) state that glass grains, being smaller than natural sand, can efficiently fill coarse aggregate. Terro (2006) conducted an additional study to investigate the influence of including waste glass in combinations and its correlation with an increase in slump. From this, waste glass sand, as a partial substitute for the normal sand in the mortar, justifies its use without deleteriously affecting its flow table performance. Replacing clear and mixed-colored glass sands with normal sand in the mortar justifies its use without deleteriously affecting its flow table performance.

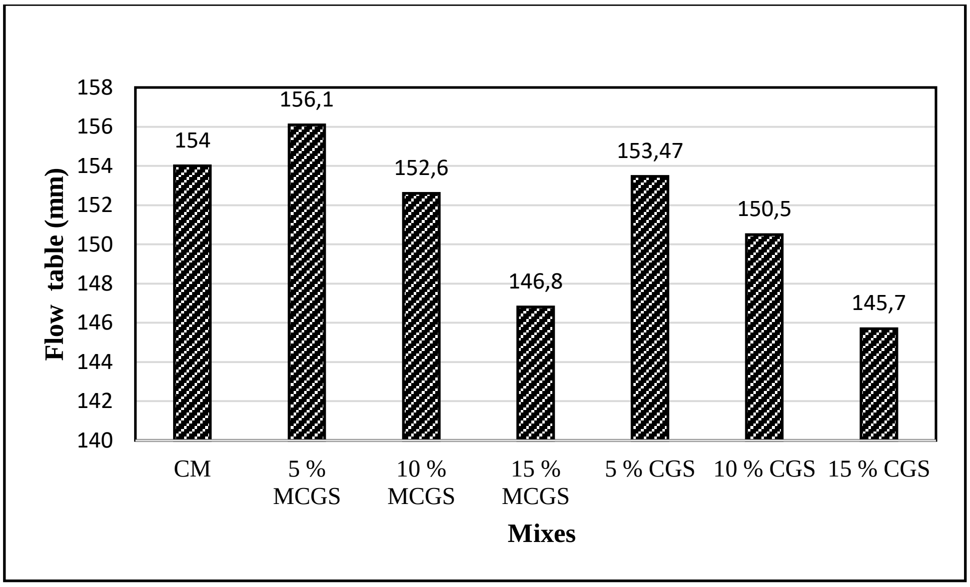

Figure 7. The flow table values of mixes

Fresh Density

Several studies have demonstrated that including waste glass as a fine aggregate in fresh concrete reduces its density. The aforementioned studies include (Chen et al., 2006; De Castro & De Brito, 2013; Du & Tan, 2014; Adaway & Wang, 2015; Topcu & Canbaz, 2004). The likely cause for this is the reduction in concrete density resulting from the addition of glass, as glass particles possess a higher density compared to conventional sand. According to De Castro and De Brito (2013), increasing the water-to-cement ratio reduces the density and increases the porosity of the mixture when water is introduced. Studies conducted by Ismail & AL-Hashmi, 2009; Topçu & Canbaz 2004 and H.-Y. Wang, 2009) have demonstrated that the dry density of concrete can be reduced by increasing the proportion of recycled glass sand to fine aggregate. According to (Ling & Poon, 2012), there is a direct correlation between the higher specific gravity of lead in funnel glass and its higher dry density. Research conducted by Yu et al. (2016) revealed that incorporating steel slag into concrete increased its density. Studies have observed that the fresh density of concrete decreases with an increase in waste glass used as a fine aggregate replacement (De Castro & De Brito, 2013; Mardani-Aghabaglou et al., 2015).

The mortar samples' fresh density reduced as the glass sand percentage increased. This is because the glass's density is lower than that of sand. The values of the fresh density of mortar samples are presented in Table 3. When 15% of clear glass sand was replaced with sand, the fresh density of mortar decreased by 2.78% compared to the control mix at a 2446 kg/m3 value. Clear and light glass sand is found to be denser compared with mixed-colored glass sand. However, there was no significant difference between the two glass sand types. These results show that the glass sand used significantly in mortar production, be it ground or powder form, only slightly affects the changes in fresh density within 7 days.

Table 3. The fresh density of mixes

Mix	The fresh density of mortar (kg/m^3)
CM	2516
5 % MCGS	2490
10 % MCGS	2480
15 % MCGS	2446
5 % CGS	2496
10 % CGS	2490
15 % CGS	2450

Hardened Properties of Mortar

Dry Density

Various studies have shown that adding waste glass sand into the concrete contributes to a decrease in the density of the obtained concrete mix. The scholars Du and Tan (2014) and Topcu and Canbaz (2004) show that waste glass tends to reduce the thickness of mortar. According to Ling and Poon (2012), there is a direct correlation between the higher specific gravity of lead in funnel glass and its higher dry density. Research conducted by Yu et al. (2016) revealed that incorporating steel slag into concrete increased its density. Conversely, incorporating shattered glass into the mixture may decrease the ultimate density of the concrete.

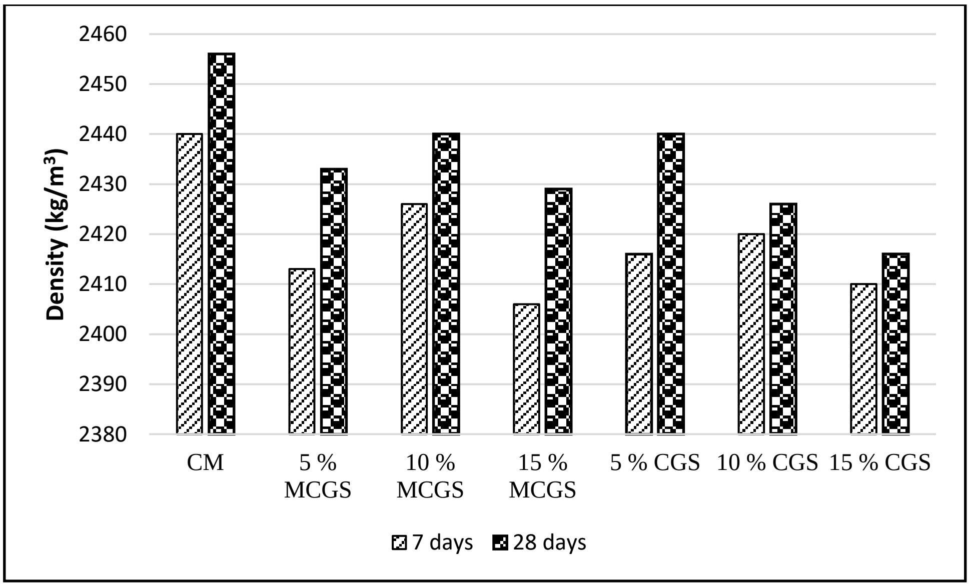

Figure 8. Dry density of mixes

According to Du and Tan (2014), the presence of less glass resulted in a reduced amount of air. Nevertheless, when the particle morphology exhibited greater amorphousness, an increased concentration of glass led to a higher proportion of air and enhanced control over air voids. From Figure 8, it can be observed that at 7 days, mixes with 5%, 10%, and 15% of MCGS, as well as 10% and 15% CGS, showed a decrease of less than 2% as compared to the mix without MCGS or CGS. Similarly, after 28 days, the hardened density of the mortar showed a minimal decrease compared to the control mix. The results imply that although the waste glass sand in concrete may lead to small reductions in density, this will be relatively minimal and will not make the concrete objectionable for general use.

Compressive Strength

Compressive strength test of specimens was done according to ASTM (C109/C109M). Several research have investigated the influence of waste glass, a finely ground material, on the compressive strength of concrete. Multiple studies (Batayneh et al., 2007; Ismail & AL-Hashmi, 2009; Wang, 2009) have demonstrated that incorporating recycled glass sand into concrete leads to an enhancement in its compressive strength. With the addition of RGS, the compressive strength exhibited a consistent increase until it reached the desired ratio. It peaked and thereafter declined. The observed decrease in strength at greater percentages can be attributed to a potential deficiency of cement paste in the combination. This phenomenon arises due to the formation of minuscule voids and the obstruction of robust bonds inside the concrete (Adaway & Wang, 2015). The drop in strength is attributed to an increase in friability, a decrease in density, and enhanced surface smoothness. The researchers discovered that, under specified conditions, the strength of the concrete they examined was equivalent to that of the reference concrete (Terro, 2006). However, as the quantity of glass exceeded the predetermined threshold, the strength of the concrete began to diminish. Studies have shown that fractured glass possesses considerable strength (Afshinnia & Rangaraju, 2016). Shattered glass should be avoided in high-alkali concrete mixes due to the potential for detrimental expansion resulting from the interaction between alkali and aggregate. Shayan and Xu (2004) found that the performance of regular concrete was considerably inferior to a blend of 80% coarse waste glass sand and 20% fine crushed waste glass sand. Conversely, a study done by Shayan and Xu(2004) demonstrated that combining fine and coarse fragments of glass in equal proportions resulted in a declining pattern. Similarly, Chen et al. (2006)discovered that the compressive strength of a material is significantly influenced by both the duration of the curing process and the ratio of replacement.

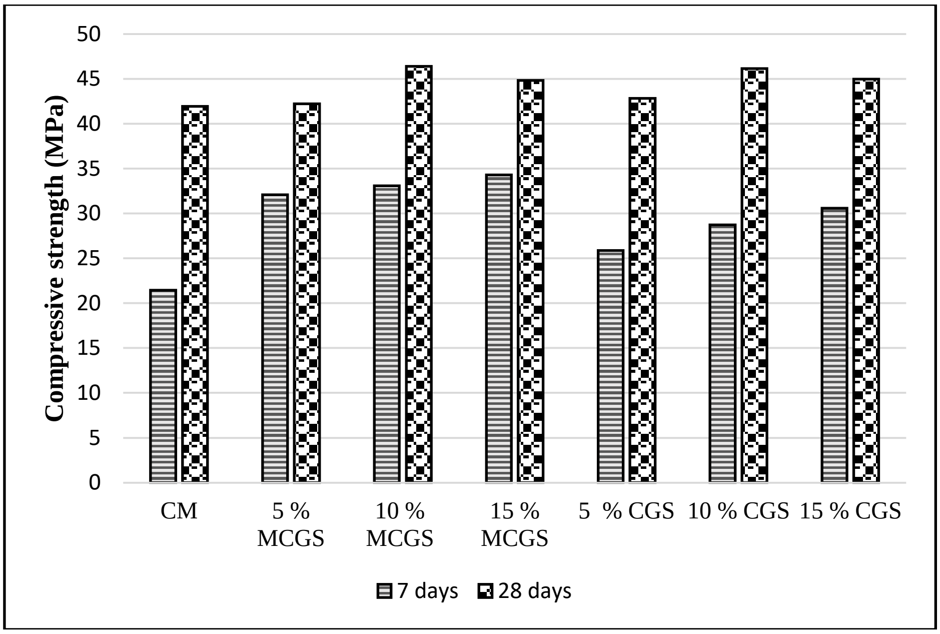

Figure 9. Compressive strength of mixes

The compressive strength of the concrete was significantly higher than that of the control concrete, even after a period of 91 days. In addition, it continued to increase up to the one-year mark (Chen et al., 2006). The combination of cement adhesive with crushed waste glass sand can produce pozzolanic reactions, hence improving the microstructure at the line transition zone (Park & Lee, 2004). The compressive strength test is a critical measure to assess the mechanical properties of mortar. In Figure 9, the 7 and 28 days compressive strength tests were performed to examine the effect of Mixed-colored Glass Sand (MCGS) and Clear Glass Sand (CGS) on the cement mortar strength. It was observed from the results that with the replacement of sand by 5% MCGS in 7 days, there is an enhancement of about 49.6% in the compressive strength of mortar. Similarly, after

7 days, the compressive strength increases by 20.7% on 5% replacement of CGS in place of sand. It was also observed that as the replacement percentage rose to 10 and 15 % MCGS in place of sand, the strength of mortar proportionally increased. The compressive strength of MCGS replacement increased to 54.29% and 60% after 7days at 10 and 15%, respectively. When CGS was replaced by 10 and 15% sand, the compressive strength increased to 34% and 42.58 %, respectively.

The substitution of 10% and 15% MCGS by sand enhanced the compressive strength by 10.6% and 10%, respectively, concerning the control mix after the 28 days test period. At the replacement of 10% CGS and 15% CGS with sand, there was an increase in the compressive strength by 10% and 7.2%, respectively. There was a negligible increase of 0.67% and 0.87% in compressive strength at 5% MCGS and 5% CGS, respectively. These results imply the potential for enhancing mortar strength by incorporating MCGS and CGS in the mortar mixtures, focusing upon varying the substitution percent, bringing forward the same significant changes in cement mortar strength development at early ages. For example, high-rise compressive strength can be cited for 7 days in the case of Mixed-colored Glass sand specimens. Chen et al. (2006) and Ling and Poon (2012) discovered that substituting crushed glass for sand in mortar resulted in a reduction in compressive strength. An observable reduction occurred when the water-cement ratio was increased. Ibrahim (2017) found that the addition of waste glass (WG) at various concentrations increased the compressive strength of concrete. This increase in strength was greater than that observed in concrete without WG. The maximum dosage of WG that has been identified is 15%. Introducing a waste glass ratio of 15% resulted in a significant 25% improvement in the compressive strength of the concrete, as compared to the control mix. The incorporation of recycled glass in concrete at a rate of 5% to 40% led to incremental improvements in compressive strength of 2.07%, 3.79%, 24.47%, 17.13%, 13.11%, 12%, 6.89%, and 5%, respectively.

Flexural Strength

Sharifi et al. (2013) discovered that adding a small amount of glass to ordinary concrete increased its flexural strength. This occurred due to the glass enhancing the adhesive properties of the cement mixture. Supported by empirical research conducted by Ismail and Al-Hashmi (2009). Utilizing recycled glass, which has pozzolanic properties and increases over time, at a replacement rate of up to 20% greatly reduces the curing time. The concrete's strength remained unaltered even after replacing all of the original components with recycled glass. To examine the flexural strength of the mortar ASTM (C 348 – 08) was followed, it was tested over two durations of 7 and 28 days. It was noted during testing that the replacement of MCGS by sand at 5% at7 days registered a significant increase of 2.7% in the case of flexural strength. The strength had increased by 0.51% for the 7th day by raising the percentage replacement to 10%. The flexural strength had been decreased for the percentage replacement of 15% MCGS by 1.02%. Replacement of the CGS with sand by 5%, 10%, and 15% reduces the flexural strength as follows: approximately 1.02%, 2.04%, and 3.6%, respectively. Usually, the study showed that with 5% MCGS used after 28 days, the flexural strength was higher by 2.6% of the control mix (CM).

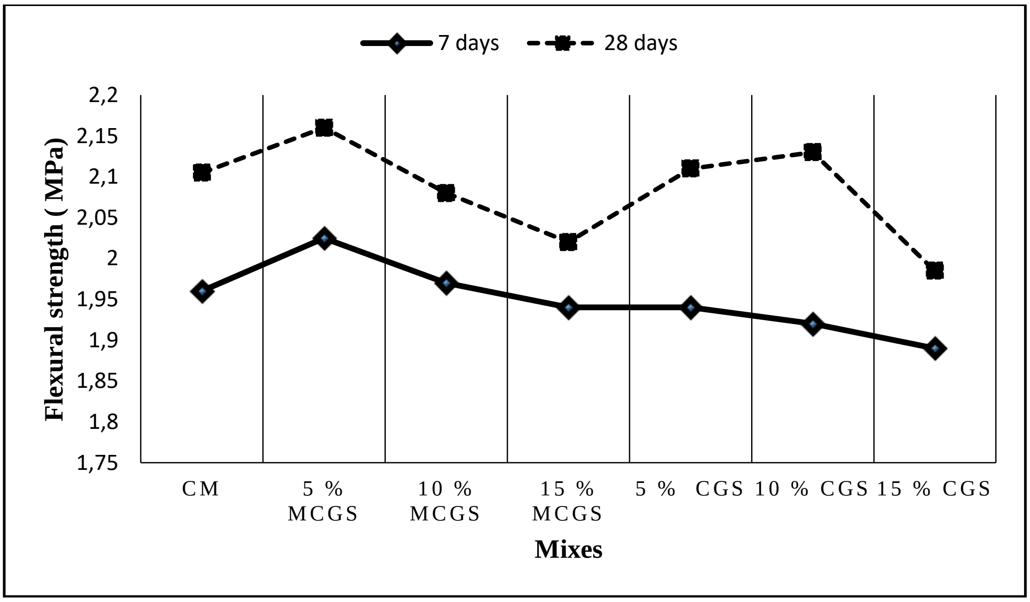

Figure 10. Flexural strength of mixes

However, replacing sand with 10% and 15% MCGS reduced flexural strength to 2.6% and 4.03%, respectively. Moreover, this research also demonstrated how 5% and 10% CGS delivered higher flexural strength compared to the control mix at 7 days with positive increments of 0.24% and 1.2%, respectively, at 28 days. However, when 15% CGS was used as a replacement, a decrease of 5.7% in flexural strength was found. In summary, results show that using MCGS and CGS as partial replacements for sand may have different effects on the flexural strength of the control mix, in which 5% MCGS and 10% CGS are shown to improve flexural strength. In contrast, a higher percentage of MCGS or CGS can slightly decrease flexural strength.

Durability Properties of Mortar

Fire Resistance

The fire resistance properties of the specimens were tested using standard test methods for fire tests of building construction and materials ASTM (E 119 – 20). The results are presented in Table 4, which clearly shows the specimens' mass decrease when exposed to temperatures of 200℃, 400℃, and 600℃ for 90 minutes. It was found that all specimens exhibited a decrease in mass with an increase in temperature. Notably, the control mix reduced 1.6%, 3.2%, and 4.4% of the mass at 200℃, 400℃, and 600℃, respectively. When 5% MCGS was replaced with sand, the mass was reduced by 0.41%, 3.06%, and 5.7% compared to the actual mass before the fire. Similarly, a reduction of 0.76%, 3.8%, and 4.8% of the mass was observed when 10% MCGS was replaced with sand at 200℃, 400℃, and 600℃, respectively. When 15% MMCGS, 5% CGS, 10% CGS, and 15% CGS were placed in 600℃, a decrease of 5.24%, 5.8%, 4.8%, and 5.33% of mass was observed, respectively. These results demonstrate the impact of temperature on the specimens' mass and the different materials' effectiveness in reducing mass loss at different temperatures.

Table 4. Mass of specimens in (g)

	Mass of Specimens Before Fire Test	Mass (g) after 200 ℃	Mass (g) after 400 ℃	Mass (g) after 600 ℃
CM	291.5	286.8	282.2	278.5
5 % MCGS	290.9	289.7	282	274.3
10 % MCGS	288.2	286	277.2	274.8
15 % MCGS	288.1	286.2	278.7	273
5 % CGS	290.9	288.7	282.5	274
10 % CGS	292.5	288.5	281.3	278.5
15 % CGS	290.8	289.2	280	275.3

The results presented in Figure 11, indicate specimens' residual compressive strength after a fire test. Notably, a significant increase in compressive strength was observed at 200℃; however, at 400℃ and 600℃, there was a decrease in compressive strength compared to the control mix. At 200℃, specimens containing 5%, 10%, and 15% MCGS showed an increase of 6.5%, 12%, and 8% in compressive strength compared to the control mix.

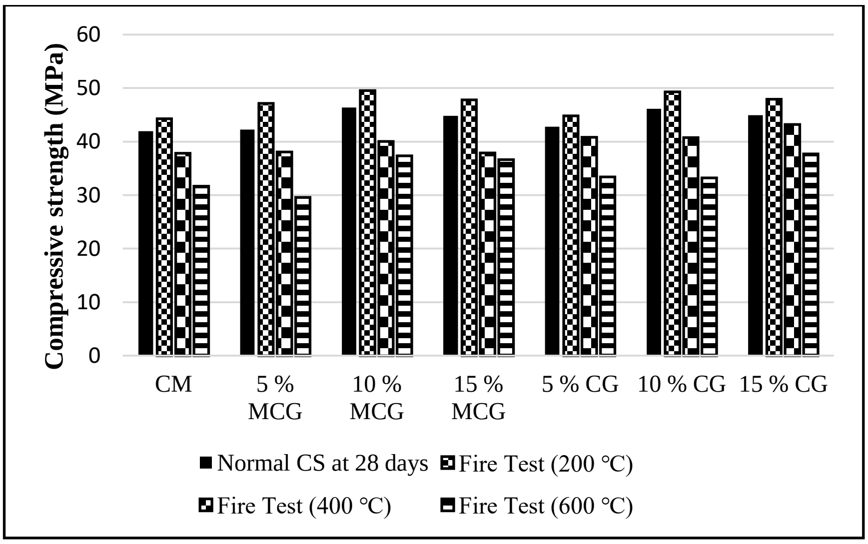

Figure 11. Residual compressive strength after fire test

Furthermore, an increase of 11.3% and 8.2% was found when 10% and 15% CGS were replaced compared to CM. When the temperature was increased to 400℃ and 600℃, the adhesive forces between cement, water, and aggregates weakened as the water evaporated from the samples, thus compromising the mortar's ability to resist compression force. However, at 400℃ and 600℃, 15% CGS showed an increase of 15% and 19% in residual compressive strength compared to the control mix, respectively. In addition, when 15% MCGS was replaced with sand, an increase of 15.6% was found in compressive strength at 600℃ compared to CM. Interestingly, the replacement of waste glass sand with natural sand showed an improvement in its ability to endure high temperatures compared to the control mix.

Water Absorption

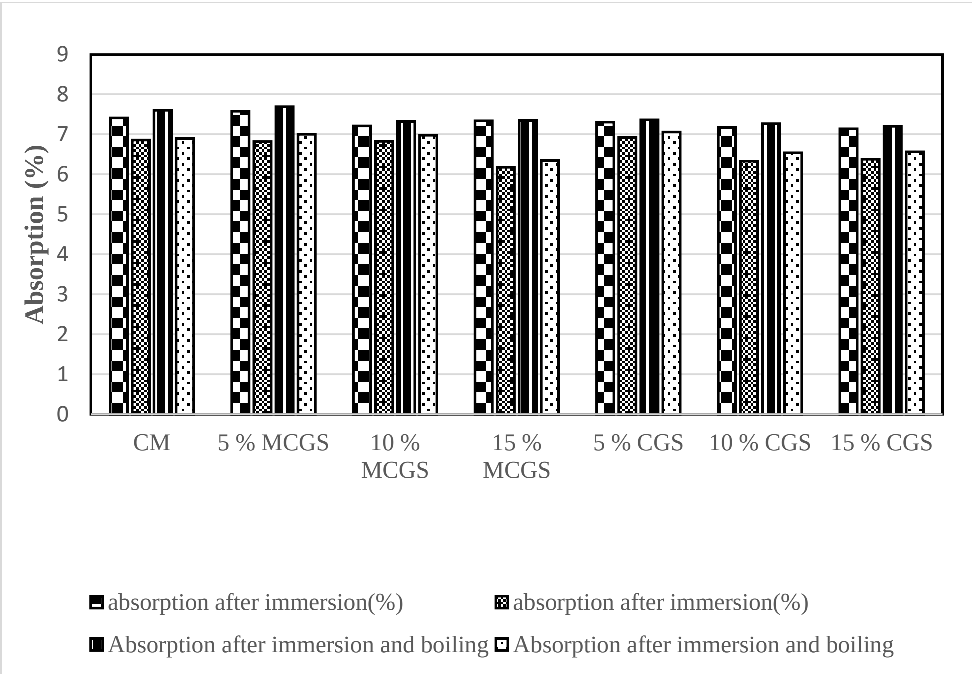

Figure 12. Water absorption (%) of mixes

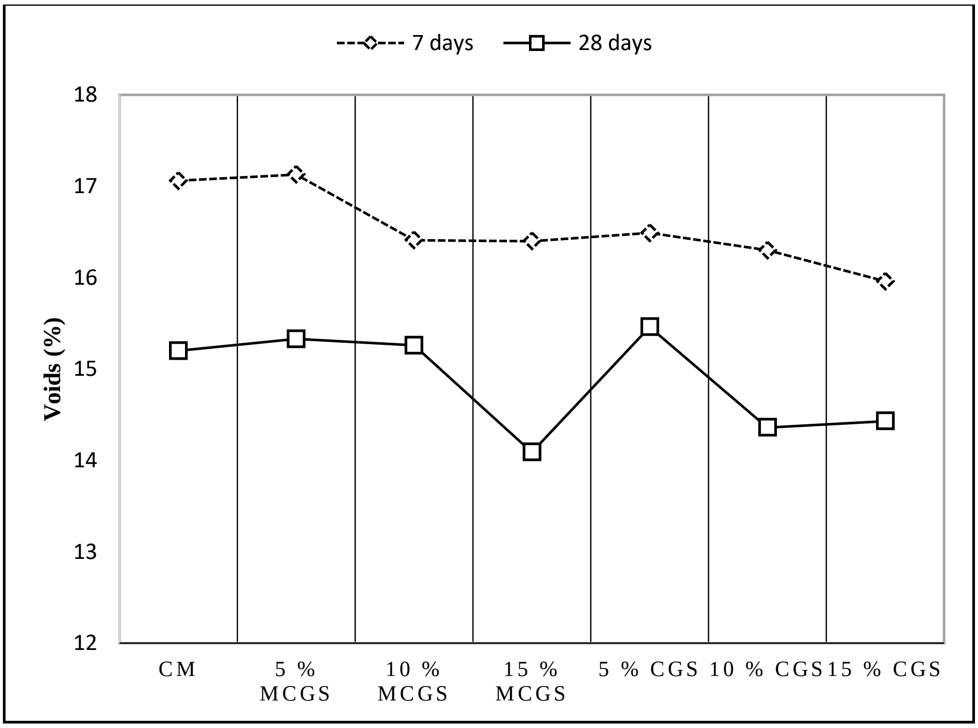

Figure 13. Percent voids of mixes

Water Absorption test was conducted as per ASTM (C – 642) The study found that using more glass aggregate in mortar mixes resulted in lower water absorption at all curing stages. This is a common phenomenon known as the reduction in water absorption over time, as the hydration process continuously occurs and forms concrete with lower porosity. As hydration products fill the pores between cement particles and aggregates, the average pore diameter decreases. However, the decrease in water absorption observed with an increase in waste glass replacement can be explained by the impenetrable nature of glass aggregates compared to sand and the uneven shape of waste glass. The irregular geometry of waste glass may provide greater opportunities for the deposition of hydrated concrete products. Figure 12 shows the percentage water absorption of samples after immersion and water absorption of specimen after immersion and boiling. 5% CGS and 5% MCGS, showed a minimal increase in water absorption at 7 days and 28 days. Where other mixes showed less decrease in water absorption. The boiling of specimens increased the absorption of specimens, the CM showed an increase of 0.60% comparing the result WA after immersion and WA after immersion and boiling. Figure 13, indicates that an increasing percentage of replacement of waste glass by sand showed a decrease of the percentage of voids. It was found that the % voids of CM were 17.1% at 7 days and 15.2% at 28 days. 15% CGS showed the minimum percent voids among the specimens at 7 days.

Table 5. Densities for water absorption

	Bulk density, Dry g_1 (g/cm^3)		Bulk Density after Immersion (g/cm^3)		Bulk Density after Immersion and Boiling (g/cm^3)		Apparent Density, g_2 (g/cm^3)	
mix	7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days
CM	2.24	2.2	2.41	2.35	2.42	2.35	2.71	2.59
5 % MCGS	2.23	2.19	2.4	2.34	2.4	2.34	2.69	2.59
10 % MCGS	2.24	2.19	2.4	2.34	2.41	2.34	2.68	2.58
15 % MCGS	2.23	2.22	2.4	2.35	2.4	2.35	2.67	2.58
5 % CGS	2.24	2.19	2.4	2.34	2.41	2.34	2.68	2.59
10 % CGS	2.24	2.2	2.4	2.34	2.4	2.34	2.68	2.56
15 % CGS	2.25	2.2	2.41	2.34	2.41	2.34	2.8	2.57

Table 5, shows the bulk density of specimens after immersion and bulk density after immersion and boiling, the overall results were quite similar. Bulk density was found to be less than other densities where immersion of water/boiling was considered. The increase of waste glass sand showed a decrease of density compared to CM, but the decrease was found to be insignificant.

Alkali-Silica Reaction Test

According to Du and Tan (2013) and Park and Lee (2004), the size of the glass sand is directly proportional to the increase in ASR. The smallest increase in ASR occurs at 0.150 mm, while the most significant increase occurs at 2.36 mm. The pozzolanic treatment reduces the ASR expansion from 2.36 mm to 0.150 mm. The pozzolanic reaction is initiated by the reaction of silica in fine-grained glass sand with Ca $(OH)_2$ due to cement hydration. The low SiO2/CaO ratio in the pozzolanic process does not cause swelling. The formation of ASR gel is due to the heightened occurrence of apparent internal fissures in particles with larger sizes. According to Du and Tan (2014), the expansion of green glass sand in ASR reaches a peak of 1.18 mm and then declines to 2.36 mm.

The potential alkali reactivity of aggregates was tested using the standard mortar-bar method (ASTM C1260). Table 6 displays the expansion measurements of different specimen types on various reading days. CM had the highest expansion rate of the specimens tested, although the increase was insignificant at less than 0.1mm. Specifically, CM showed an expansion rate of only 0.0080 after 28 days. When 5% MCGS and 5% CGS were used to replace sand, expansion rates of 0.0063 and 0.0069 were recorded, respectively. Interestingly, the Mixed-Colored Glass Sand samples showed less expansion than the Control Mix and the Clear Glass Sand samples, although the difference in expansion rates glasses was insignificant.

Figure 14 depicts the percentage expansion of various samples monitored across eight reading days in the study. The samples included CM, 10% and 15% MCGS, 5%MCGS, 5%CGS, 10% CGS, and 15% CGS. On day 2, CM showed an expansion of 0.037%, whereas on day 28, the expansion rate increased to 0.094 %. However, the 10% and 15% MCGS samples did not exhibit any expansion until day – 8 but recorded 0.032% and 0.021% expansion on day 28. Furthermore, when 5%MCGS, 5%CGS, 10% CGS, and 15% CGS were replaced with sand, the expansion rate for each sample was observed to be 0.074%, 0.081%, 0.042%, and 0.028%, respectively. These findings suggest that the percentage of MCGS and CGS used in the study reduced the ASR expansion as the replacement percentage increased.

Table 6. Rate of expansion of samples in different reading days

Mix	Reading Days (mm/day)							
	D – 4	D – 6	D – 8	D – 10	D – 12	D – 16	D – 21	D – 28
CM	0.0031	0.0031	0.0031	0.004	0.004	0.0072	0.0072	0.008
5 % MCGS	0.0012	0.0024	0.0024	0.0024	0.0036	0.0036	0.0048	0.0063
10 % MCGS	0	0	0.0014	0.0018	0.0022	0.0025	0.0025	0.003
15 % MCGS	0	0	0.0006	0.0006	0.0018	0.0018	0.0018	0.0018
5 % CGS	0	0.0015	0.0024	0.0036	0.004	0.0044	0.0051	0.0069
10 % CGS	0.0006	0.0006	0.0006	0.0011	0.003	0.003	0.003	0.0036
15 % CGS	0.0005	0.0005	0.0013	0.0013	0.0013	0.0028	0.0028	0.0028

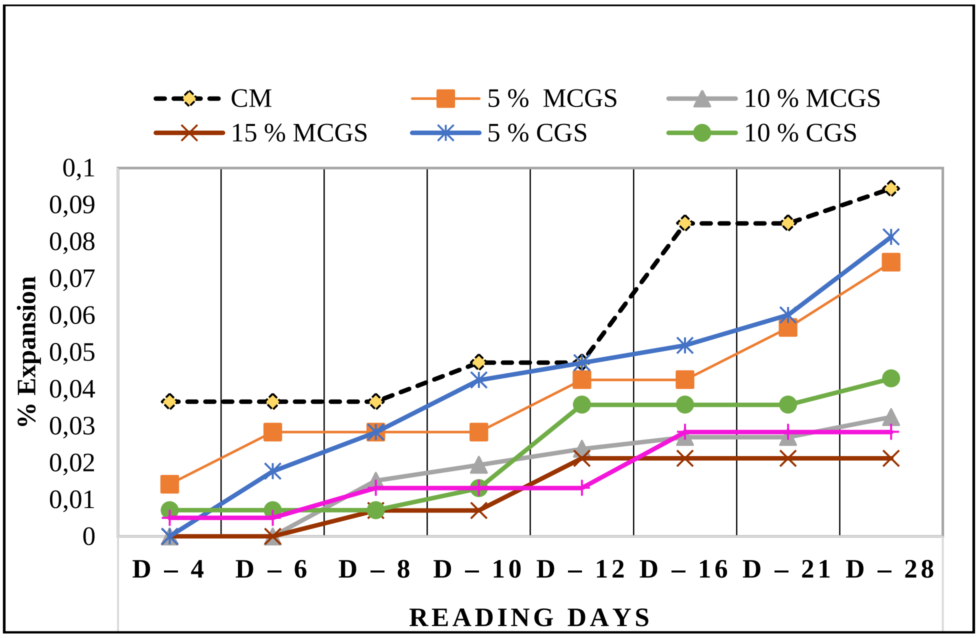

Figure 14. ASR expansion of mixes (%)

Evidence from the research work of Du and Tan (2014) and Ismail and AL-Hashmi (2009), indicates that concentrations enhance the expansion of clear glass sand in ASR. However, microcracks were observed among only clear glass sand crushed materials. In all quantities of replacements, no or minimal observable microcracks were noted in brown and green glass sand to ensure their safety. According to Du and Tan (2014), more glass sand helped to slow down the alkali-silica reaction (ASR). To produce a non-swelling ASR gel, soda-lime glass is infused with calcium ions by injection. The microstructure is improved by the formation of a more compact and impermeable interfacial transition zone by the presence of a secondary C-S-H gel. Color changes can occur when alkali-silica reactions (ASR) occur. Green glass exhibited enhanced resistivity when exposed to the alkali-silica reaction. Du and Tan (2013); Park and Lee (2004); Topcu and Canbaz (2004); Yuksel et al. (2013) have conducted multiple investigations that provide evidence of chromium oxide (Cr2O3) inducing a greenish hue in glass by the reduction of alkali-silica expansion. Multiple studies have shown that the repulsive force caused by the electrical double layer decreases as the ionic valence increases. Higher concentrations of Cr2O3 impede the growth rates of Gel 38 due to the presence of Cr3+. Du and Tan (2014) found that the Alkali-Silica Reaction (ASR) has a slower development rate in brown glass sand than green glass sand, as per their research. However, the green glass underwent substantial enlargement due to modifications implemented throughout production. This expansion impacts internal tension, leaching, and dissolving, as stated by Dhir et al. (2009). Kim et al. (2015) discovered the smallest expansion in flint glass sand. Du and Tan (2014)and Idir et al. (2010)found that the rate of alkali-silica reaction (ASR) growth over time is considerably greater in green glass compared to brown glass. In 2004, Park and Lee reported that the expansion of green glass is limited compared to brown-type ones containing Fe2O3. The research conducted by Yuksel et al. (2013) showed that greener glass has a lower expansion than flint glass sands. Topcu and Canbaz (2004)found that the highest risk is present when the combination of alkali and silica was made using white glass sand as the aggregate color. White glass sand exhibits a significantly greater expansion rate compared to colored glass sands due to its elevated silicate content. According to Du and Tan (2013)and Jani and Hogland (2014), white glass had the highest growth in alkali-silica reaction (ASR), while brown and green glass showed similar levels of progression. Figure 15 shows the linear relationship between the compressive strength and the ASR expansion of specimens. This relationship explains that the increase of ASR expansion will decrease the compressive strength and vice versa.

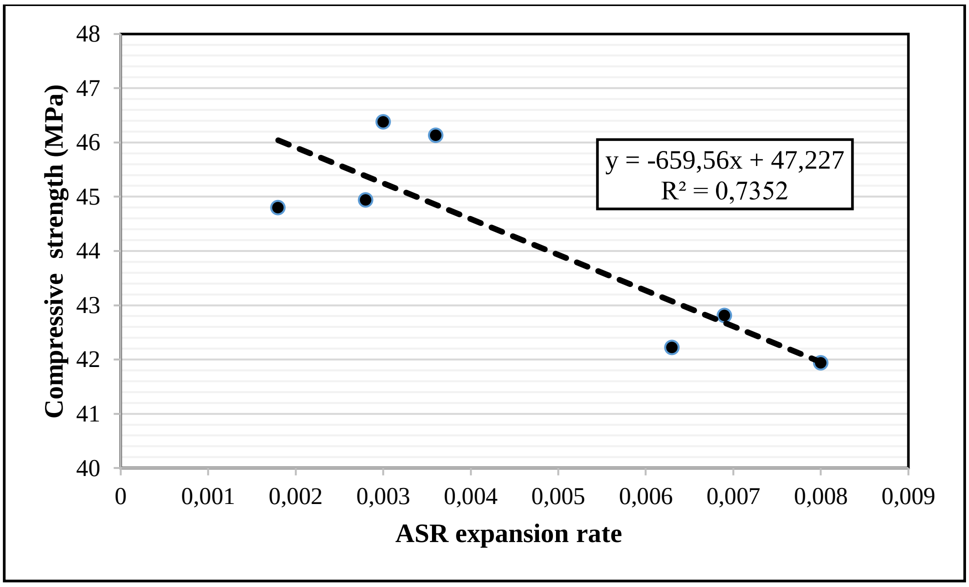

Figure 15. Relationship between Compressive strength and ASR expansion

Studies by Du and Tan (2014) and Idir et al. (2010) have shown that the alkali-silica reaction (ASR) rate is more pronounced in green glass than in brown glass over time. According to Park and Lee (2004), green glass experiences limited expansion compared to brown glass containing Fe2O3. Yuksel et al.(2013) discovered that greener glass has lower expansion rates than flint glass sands. Additionally, Topcu and Canbaz (2004) found that the risk is highest when alkali and silica combine using clear glass sand as the aggregate color due to their higher silicate content, which results in a significantly higher expansion rate than colored glass sands. Lastly, the insignificant expansion was due to the size of glass sand used (2mm – 0.75 microns) for the study; the larger the particle size of the glass, the higher the ASR expansion, and no cracks were seen on the samples during the testing days.

Environmental Sustainability

The growing trend of appreciating glass patronage for production brings a vital environmental risk to light. Although it is recyclable, glass still has to capture its recycling rate compared with the quantities produced year after year, and thus, most of the disposed glass is deposited into landfills. The latter pose multiple environmental problems, including air, soil, and water pollution. Waste glass takes hundreds of years to decompose and can cause harm to the environment and wildlife. Recently, a new type of sand called manufactured sand, or m-sand, has been introduced as an alternative. It is created by crushing rocks or quarry stones into small, angular pieces with a particle size typically smaller than 5 millimeters. M-sand is gaining popularity due to its high durability, compressive strength, and workability compared to natural river sand. Using waste glass as a substitute for river sand in construction can significantly reduce the amount of glass waste in landfills, ultimately protecting the environment. Table 6 shows the different percentages of waste glass sand replaced by sand.

Table 6. Materials used for mixes

Mixes	Sand (Kg)	Clear glass sand (Kg)	Mixed-colored sand (Kg)
CM	8.9	0	0
5 % MCGS	8.455	0	0.445
10 % MCGS	8.01	0	0.89
15 % MCGS	7.565	0	1.335
5 % CGS	8.455	0.445	0
10 % CGS	8.01	0.89	0
15 % CGS	7.565	1.335	0
Total	56.96	2.67	2.67

Figure 16 describes the percentage replacement of waste glass sand (CGS+WGS). Using 5%, WGS replaced 10% of the sand with clear or mixed-colored glass sand. When 10%WGS and 15%WGS were utilized, 20% and 30% of waste glass sand was replaced with sand, respectively. Incorporating waste glass into construction enhances the mechanical properties of concrete and promotes the conservation of natural resources and environmental sustainability.

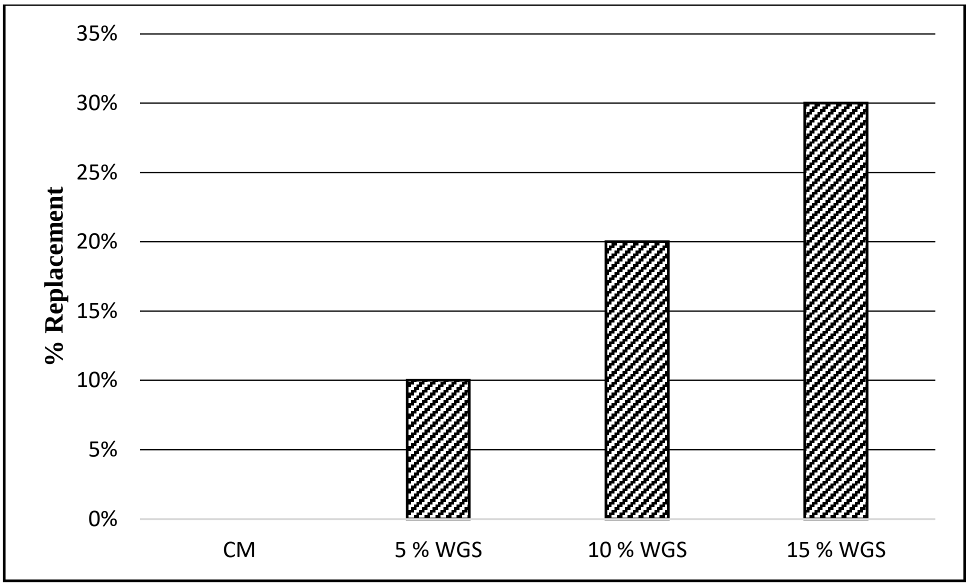

Figure 16. % replacement of WGS in cement mortar

Economical Assessment

The economic benefits of using waste glass are significant and cannot be ignored. Waste glass is easily accessible as waste material or in the earth's crust, making it a cost-effective replacement for natural sand. By using waste glass as a substitute for fine aggregate, the cost of natural sand can be significantly reduced. This study examined the economic advantages of replacing sand with waste glass and found that CM has the highest cost of 90.64 TL as shown in Figure 17. At replacement of 5%, 10% and 15% MCGS showed 1.07%, 1.96%, and 2.95% savings compared to the control mix, respectively. Moreover, Figure 17 shows that replacing 5%, 10% of natural sand with clear glass sand could bring about savings of 1.91%%, 3.63%, respectively. Replacing 15% CGS showed the highest savings of 5.45% compared to the control mix.These findings highlight the potential of waste glass as an affordable alternative to natural sand in construction and other industries.

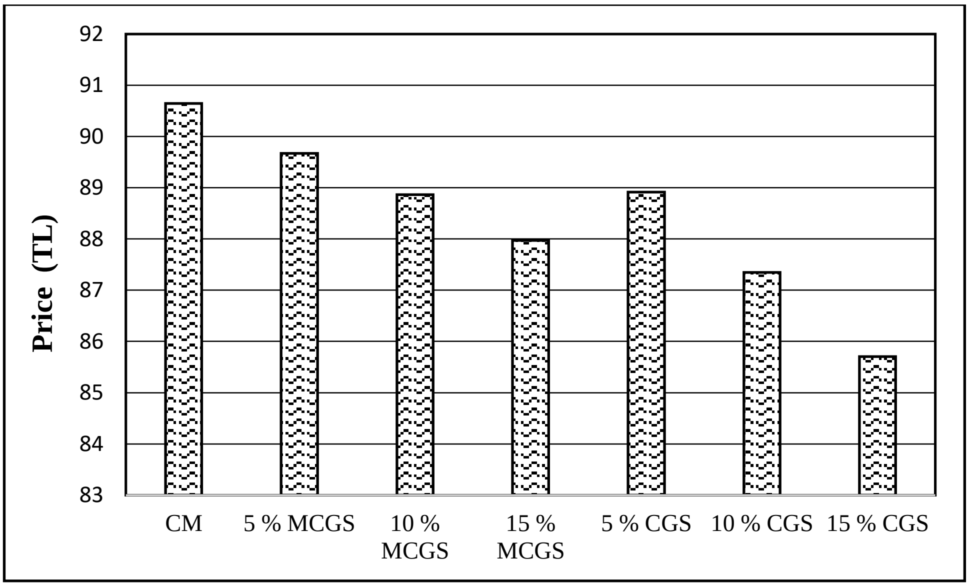

Figure 17. Cost of mixes (TL)

Conclusion

The results of this study indicate that the use of waste glass as a fine aggregate can not only enhance the properties of mortar but also contribute to a more sustainable environment.

- Increasing the recycling of glass from addition in construction keeps more waste away from landfills, and it also conserves natural resources.
- The study found that waste glass sand (WGS) can improve mortar's fresh and hardened properties. Based on the study, this replacement of a specific proportion of WGS leads to no significant impact on the workability of mortar. However, it led to a slight drop in workability. This is because glass sand does not absorb water like fly ash, which can affect the workability of mortar.
- Moreover, the study found an insignificant decrease in values of fresh and dry density less than 2%. However, the compressive strength was improved significantly while the sand was replaced by waste glass.
- Interestingly, the study also established that mortar possesses weak flexural strength. However, some improvement was noticed when clear glass sand (CGS) and mixed-colored glass sand (MCGS) were replaced in the mix.
- However, yet another benefit of using waste glass in construction is that as the percentage of waste glass in the mix increases, the water absorption will tend to decrease. This arises from the fact that waste glass is non-porous and, therefore, cannot allow water passage or even absorption into the same.
- The study on the compressive strength of the mortar also considered temperature. At 200℃, it had a remarkable increase in its compressive strength. The temperature increases the adhesive force between water cement and aggregates. However, a significant decrease in compressive strength occurs at temperatures d 400℃ and 600℃. This is because high temperature reduces the adhesive strength in the materials, whereas in the mortar, all the water evaporates from the specimens, resulting in a significant loss of strength.
- Finally, particle sizes of glass sand between 2.36mm – 0.75 microns were also analyzed to study expansion due to alkali-silica reaction (ASR), given the effect of future usage of this material for concrete production in mitigating this phenomenon. The ASR expansion was found innocuous, and no significant expansion was recorded during the study.
- Substitution of waste glass sand as a partial replacement for sand improved the environmental sustainability and can save money and natural resources.
- The fresh properties of mortar, and the flow table showed a minimal decrease and increase with different percentage replacements of glass sand. The fresh and dry density of samples reduced as the percentage of waste glass increased, but the reduction was minimal not more than 2%.
- The compressive strength of specimens improved as the percentage of glass was replaced with sand, while flexural strength showed both increase and decrease in strength when waste glass sand was used.
- The durability of the mortar was tested, 3 tests were done fire resistance, water absorption, and alkali-silica reaction. The waste glass sand specimens showed higher strength in fire resistance, while the compressive strength decreased when 400℃ and 600℃ temperatures were placed. There was no expansion caused by the alkali-silica reaction recorded through the study. However, it is worth mentioning that the control mix showed a higher expansion of 0.091% at 28 days, and the mixed-colored glass sand specimens showed the least expansion compared to clear glass sand and the control mix.
- In the study it was found that there is a strong relationship of 86% between compressive strength and ASR expansion which is inversely, the lower the ASR expansion rate the higher the compressive strength.
- Environmental sustainability was assessed, looking for the advantages of using waste glass for the environment and sustainability. The use of waste glass in construction increases the usage of recycled waste glass which will save a large amount of landfills in densely populated areas.
- The utilization of waste glass in construction saves a lot of money and natural resources.
- Finally, using waste glass as a partial replacement for sand in concrete is an eco-friendly solution that can significantly benefit the construction industry by reducing waste and carbon footprint. Overall, it is a solution worth considering, provided adequate testing and monitoring are conducted to ensure optimal performance.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgments or Notes

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