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Research Article

Effect of discarded smooth and rough glass waste on mechanical properties of cement concrete

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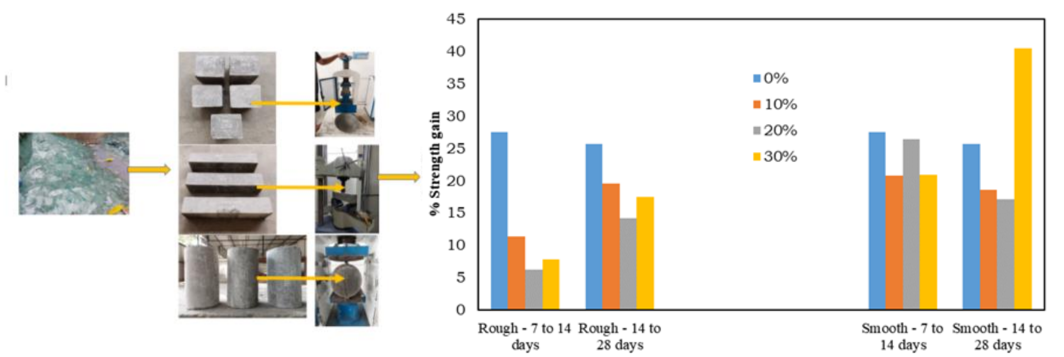
Graphical Abstract:



Abstract: The depletion of natural material leads to an alternative material in its place in concrete. If the alternative material is a recycled material, it serves the purpose of reuse and reduces its impact on the environment. One such material is glass waste. In this study, two varied textures of transparent waste glass of size 12.5 mm are used as an alternative material for coarse aggregate with 10, 20, and 30% of replacement. The mechanical properties such as compressive strength, flexural strength and split tensile strength are studied along with water absorption and unit weight characteristics. It is observed that the compressive strength showed a maximum value at 10% replacement for both textured glasses, beyond that it reduces irrespective of curing period. A similar trend is observed in flexural strength also. The split tensile strength increases with percentage replacement due to the contribution of waste glass in interface transmission zone. The water absorption falls well within 3% for all the combinations indicating its good behaviour. The unit weight decreases making it suitable for making lighter material. When comparing cost, there is a reduction in cost by 3 to 7 %; however, it is minimum it addresses the environmental aspects.

Highlights:

- To understand the recyclability of glass waste as a partial replacement for coarse aggregate or as an auxiliary construction material.
- To study the basic mechanical properties of the concrete without and with GW in 10, 20 and 30% as partial replacement material.
- Compressive strength increases from 33.17 to 38.07 and 34.68 MPa for rough and smooth textured GW.
- Flexural strength shows a peak value at 10% of GW of 2.4 and 1.65 for rough and smooth texture.
- Split tensile strength increases with increase in percentage of GW both rough and smooth, indicating its contribution in interface transition zone.

Keywords: Waste glass, mechanical property, water absorption, unit weight, cost- comparison.

List of abbreviations:

GW	glass waste
Mw	wet mass
Md	dry mass
ASR	alkali – silica –reaction gel
GGBS	ground granulated blast furnace slag
f_c	compressive strength of concrete
f_r	tensile strength of the concrete
b	width of the specimen
d	depth of failure point
l	supported length
P	maximum load

1. Introduction

The waste generated is broadly classified into two main categories: i). industrial wastes and ii). household wastes. The household waste consists of organic fraction, fine – earth, plastics, paper, glass and metal. Over 200 million tons of glass waste are generated around the world, out of which 21% is recycled. To produce 1 ton of glass, 300 kg of cullet and 700 kg of sand is used, as the main elements of glass are sand, soda ash and limestone. Considering the fact, glass can be recycled 100% and hence tones of natural resource could be saved. The reuse of the glass waste is very minimum in the developing countries compared to developed countries and the same is understand in better from Figure 1(Manikandan P and Vasugi V, 2021).

As the recycling is not done fully, it occupies the landfill and reduces the space and making the creating a non- safe environment. Silica being a major component in the composition of glass (62.98 to 73.5%) (J. xin Lu et al., 2017), (Vijayakumar et al., 2008), it has the potential to act as pozzolanic material in concrete. Bearing the statics in mind, researchers started using glass in the construction industry as partial replacement of cement and aggregates.

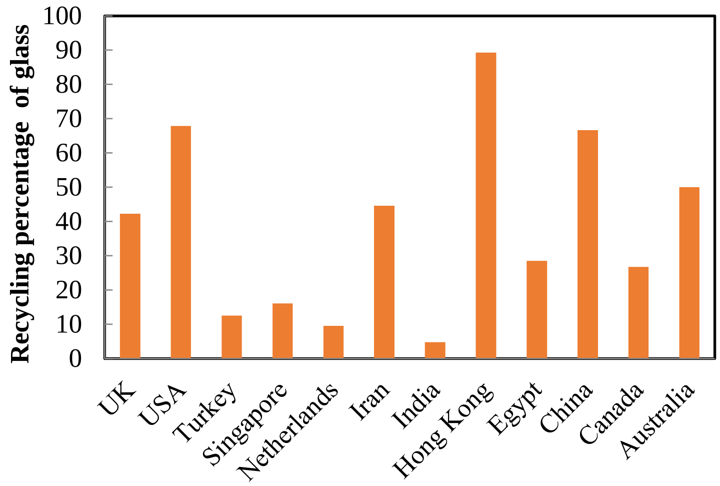


Figure 1. Countries wise waste glass recycling.

It involved the process from collection of waste glass (GW), sorting (by color, surface and type), upon sorting glass is crushed into tiny particles (cullet), removing the contamination from the glass and using the processed glass into a material. One major factor to be considered while processing is '*sorting – by – color'*, as it reduces the quality. The presence of GW in cement behaves the same as the ordinary alkali cement (Xie and Xi, 2002; Almeshal et al., 2022). As the principal composition of glass is Silica, it is used in partial replacement of cement (Islam et al., 2017; Saribiyik and Gurbuz, 2021). With 20% of cement replaced with glass provides better compressive strength and also it reduces the cost of cement production by 14%; which plays a good environmentally safe material. It is used as a good pozzolanic material because of its high surface area and produces Alkali – Silica –Reaction (ASR) gel. From the figure 2, it is potential evident, that the glass has potential function in cement-based material because of ample SiO_2 which is a main reactive component in pozzolanic reaction and its fine grade.

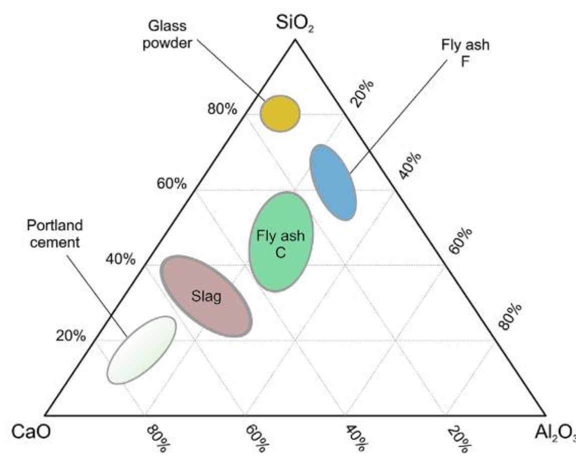


Figure 2. Ternary diagram of Portland cement.

The addition of glass in cement mix leads to form liquid phase of glass that decrease the C_3S content and increases $NCSA_3$, which leads to flash setting and reduce the compressive strength. The bottle glass undergoes both ASR and pozzolanic reaction and exterior surface of glass undergo pozzolanic action (Maraghechi et al., 2014) (Figure 3). The usage of large size glass particles reduces the compressive strength because of its nature of micro – cracking, showing poor mechanical properties (Tan and Du, 2013; Aslam Fahid et al., 2023). If the replacement increases beyond 20%, $CaCO_3$ increases and cause dilution effect (Harrison et al., 2020; Saha et al., 2020) and also increases the occurrence of air voids (Drzymala et al., 2020). This can be minimized by increasing the fluidity of the mix or by vibro pressing or less liquid mix (Drzymala et al., 2020), even if the GW is from electrical glass waste.

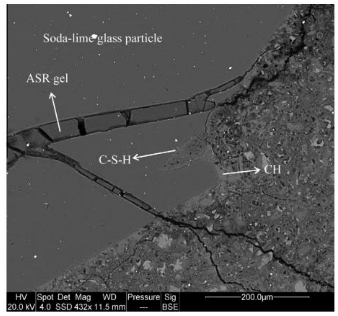


Figure 3. Alkali silica reaction.

To improve the strength, the GW should have a particle size lesser than 20 µm when used as replacement for cement (Khmiri et al., 2013) and it showed the same pattern in long-term curing. From the experiments study by Tittarelli et al., the glass is non-reactive in water at 80 degree Celsius (Tittarelli et al., 2018) and the study by Lu and Poon (J. X. Lu and Poon, 2018) proves the resistance and ion penetration improves with addition of glass. Even 20% of Portland cement with zeolite reduces the expansion caused by ASR (Khalooee et al., 2021). The by-product from industrial such as fly-ash and GGBS has potential role in mitigating ASR expansion (Du and Tan, 2013).The addition of fly-ash with supplementary cementations material reduces the chemical composition and reduces the alkali and calcium content formed (Guo et al., 2018). The modulus of the mortar is 3% more than the base mix when 20% GW is added to the mortar which is due to increase in modulus of elasticity (Małek et al., 2020). Apart the strength characteristics, the presence of GW reduces the crack width with 81% reduction in plastic shrinkage cracks for 30% replacement and 96% reduction for 100% replacement (Gorospe et al., 2019). The addition of glass aggregates reduces the thermal conductivity; this even shows minimal variation with time (Gorospe et al., 2019).

Studies of using glass in paver blocks by replacing the natural aggregate to reduce the drying shrinkage and water absorption properties; this also improves the photocatalytic performance (Poon and Lam, 2008). The replacement of glass mixture with asphalt cement meets the minimum strength (Foster, 1970). The block made with 50% replacement of GW shows good quality of strength when the aggregate to cement ration for 3 (Poon and Lam, 2008). As the transparent glass has no plane of atoms, the stress developed leads to form crack as there is no zone to release the developed stress; hence it can be used as a good binder material (Gerges et al., 2018). Considering the fact of using GW in porous medium as secondary raw material, GW mixed concrete can be used as lightweight structures (Petrella et al., 2007).

The function of GW is tremendous in partial replacement of cement and fine aggregate in a concrete mix. Considering its advantage in concrete mix, an experimental study is proposed to understand its function as coarse aggregate. As most of the study focuses on various colored glass; tests are proposed to conduct with GW as partial replacement for coarse aggregate by varying the surface texture (i.e., smooth and rough side) of transparent glass. The mechanical properties (i.e., compressive strength, flexural strength and split tensile strength) are studied experiment in addition to water absorption and unit weight characteristics. The cost of one cubic meter of M 30 grade concrete is calculated without and with GW in this study.

2. Experimental methods

2.1. *Material properties*

The specific gravity of M- Sand is found using the pycnometer is 2.72; where the value of coarse aggregate is around 2.8. The particle distribution curve for the M-sand and coarse aggregate is shown in Figure 4; the curve shows that the gradation is poorly graded showing uniform particle size.

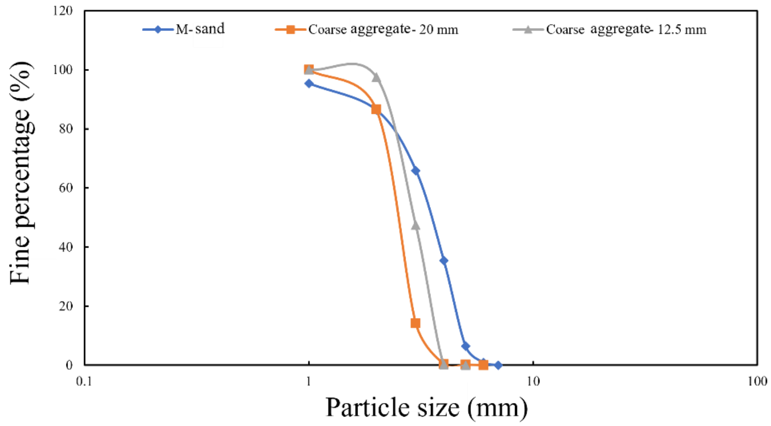


Figure 4. Particle size distribution.

2.2. Glass

The glass is obtained from local glass recycling units with two different varieties i) both sides smooth and ii) rough (Figure 5). The glasses are broken into pieces and pieces with 12.5 mm size is used as partial replacement.

a. From local collecting unit b. smooth glass c. rough glass

Figure 5. Glass collection unit and glass types.

2.3. Mix proportions

The mix ratio has 1 part of cement (Ordinary Portland cement), 1.5 part of fine aggregate and 2.3 part of coarse aggregate for M 30 grade concrete. For better binding coarse aggregate is divided into two sizes say 20 mm and 12.5 mm and used in the mix design. The materials are initially mixed in dry condition with a trowel for a minute and water is added at a proportion of p/4 + 3%; where p is the percentage of water required to produce a paste of standard consistency. The 12.5 mm aggregate is replaced by both types of GW in various proportions say 10, 20 and 30% by weight.

The maximum time utilized for mixing is not less than 3 minutes and not more than 4 minutes. Once the concrete is prepared, it is poured into mold and tapped to remove the entrained air. After 24 hours, the mold is removed and immediately submerged in the curing tank.

2.4. Test methodology

The effect of glass as partial replacement of coarse aggregate was studied by adding 10, 20 and 30% of smooth and rough GW and it is compared with the control specimen with 0% GW. Compressive strength is found for 7, 14 and 28 days of curing. As the compressive strength of the concrete decreases with partial replacement of coarse aggregate (Carsana et al., 2014; Terro, 2006) with GW which is due to the specific surface and the roughness. Hence two different types of surface-glass (smooth and roughness), with coarse aggregate size of 12.5 mm is used. The cube of 150 x 150 mm is subjected to a loading of 350 kg/ cm^2 per minute for three samples, the average value is considered as the compressive strength (Figure 6). The flexural strength, failure strength at bending is found for the specimens after 28 days of curing with size of 500 x 100 x 100 mm in a universal testing machine. The other important property of the concrete is the split tensile strength; the specimen of 150 mm diameter and 30 mm long is used in the tests after 28 days of curing. This can also be estimated from the compressive strength as the tensile strength is 10% of the compressive strength. IS 516 and 5816 are used to conduct the tests (IS 516, 1959; IS 5816-1999, 1999).

Apart from these tests, water absorption test is also conducted to understand the capacity of the specimen to absorb the water by capillarity (Standard NBN B 15-215, 2018; Sivapriya S.V et al., 2018). The concrete specimen of 100 mm diameter and 50 mm is casted and immersed in water for the next 24 hours (Mw) (Figure 7). After 24 hours, the specimen is taken out of the waterbed and dried in an oven at a temperature of 105 ± 5^0 for the next 24 hours (Md). The water absorption is the ratio of weight of water (Mw-Md) to Md. To understand the use of GW as light weight material, the density of the concrete is also found by checking its unit weight after 28 days of curing.

a. Compressive test   b. Flexural test   c. Split tensile test

Figure 6. Casted and tested sample.

a. At Mw b. At Md

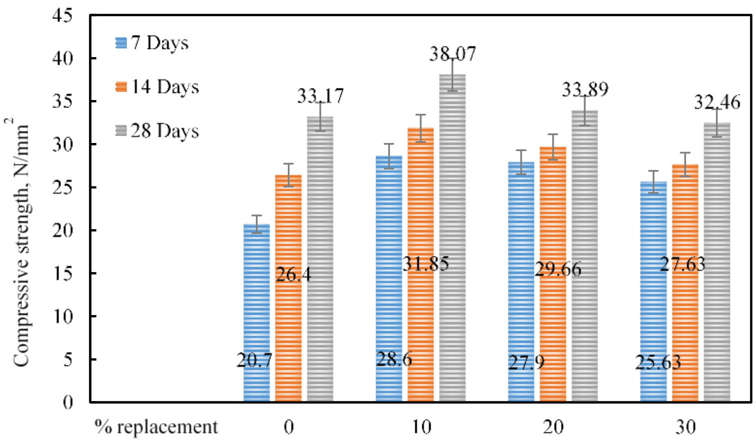
Figure 7. Test specimen for water absorption.

3. Results and discussion

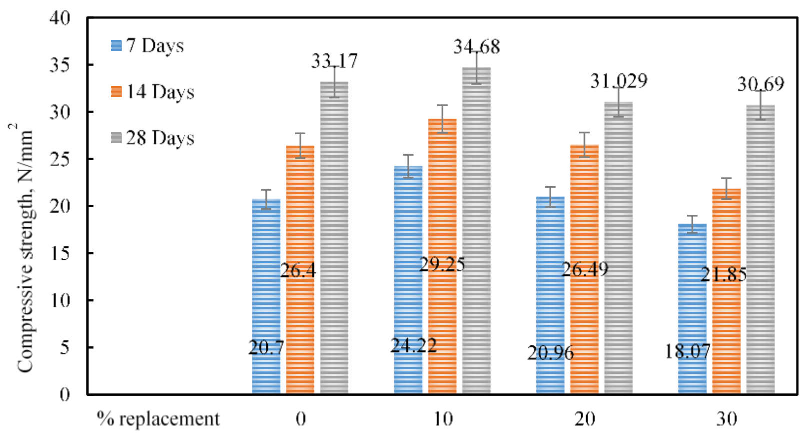
3.1. Compressive strength

The compressive strength (f_c) of the concrete is found at 7, 14 and 28 days of curing. The reference value for comparison is done without any addition of aggregate and cured for the same set of periods. With 10 % addition of aggregate at 7 days, the strength increases to 28.6 from 20.7 MPa, which shows an increase in strength of 38.16% for rough glass. Whereas for 10% waste smooth glass, the strength increases to 24.22 MPa; which shows an increase in strength of 17.01%. There is an increase in strength by 44.56% while comparing the rough and smooth GW. The increase in strength is due to the pozzolanic action between the material and the GW. With further percentage of replacement of GW in the concrete reduces the strength, but it is higher than the controlled sample (zero replacement). For 20 and 30% replacement of rough GW in concrete, the strength increases to 27.9 and 25.63 MPa. But when smooth GW is added in the concrete beyond 20%, the strength decreases when compared to the controlled specimen by 12.71%.

Under 14 days of curing for 10, 20 and 30% replacement the strength increases to 31.85, 29.66 and 27.63 MPa from 26.4 MPa for rough GW and for smooth GW it had increased to 29.25 and 26.49 MPa for 10 and 20% replacement, but the strength decreases to 21.85 MPa from 26.4 MPa for 30% replacement. The compressive strength of a concrete is determined after 28 days of curing the specimen. For rough GW, the strength increases to 38.07, 33.89 and 32.46 MPa from 33.17 MPa for 10, 20 and 30% replacement. With smooth GW as replacement, the strength increases to 34.68, 31.029 and 30.69 MPa from 33.17 MPa. The smooth GW replacement shows an increase in strength at 10% replacement, but beyond 10% of replacement there is reduction in strength. Further addition indicates the increase in silica/ alumina ratio which affects the compressive strength of the concrete(Tho-In et al., 2016). The increase in strength in rough GW to is due to friction development and reduces at higher percentage, it is due to development of dilution effect because ASR reduces the compressive strength. The quantum of hydrated calcium's part in developing cementitious bond is higher at lower percentage of GW in both smooth and rough GW (Figure 8).



(a) Rough GW.



(b) Smooth GW.

Figure 8. Compressive strength of concrete with GW replacement.

As the curing period increases the strength increases. For zero additives, the increase in strength for 14 days of curing shows a great increase in strength for controlled specimen which is about 27.54 %. But when the inclusion of GW increases, the percentage increase in strength reduces to 11.36, 6.31 and 7.81% for 10, 20 and 30% of replacement of rough GW. But the percentage increase in strength is quite high for smooth GW; it has increased to 20.77, 26.38 and 20.92% for 10, 20 and 30% of replacement (Figure 9). As the curing period increases to 28 days, the rate of increase in strength reaches 60.24, 33.11, 21.47 and 26.65% for 0, 10,20 and 30% replacement with 7 days curing for rough GW and for smooth GW, the increase is about 60.24, 43.19,48.04 and 69.84% for the same percentage of replacement for 28 days curing. The gain in strength at initial curing period is less compared to higher curing period considered in this study as the pozzolanic reaction progress slowly, this is similar to the study made by Ahmad et al. (2022). From the results it is seen the influence of GW both rough and smooth beyond 20% replacement is not significant (Ahmad et al., 2021).

This indicates the occurrence of void due to replacement of coarser particles in a concrete aggregate and also because of the abundant unreactive silica in ASR.

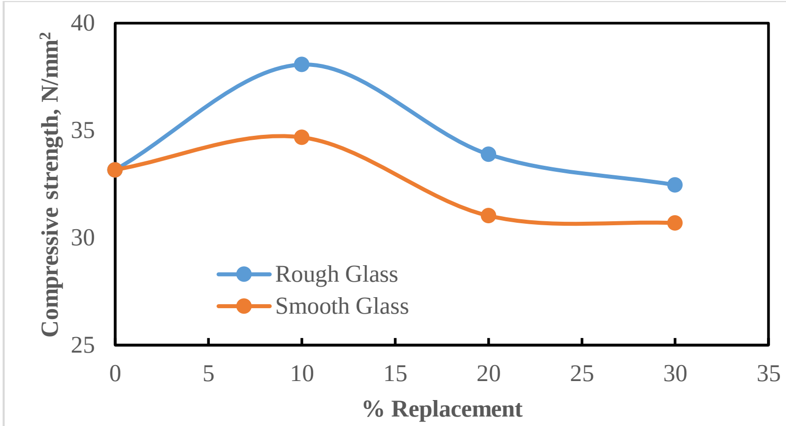


Figure 9. Compressive Strength behaviour with GW as partial replacement.

3.2. Flexural strength

From the flexural test (f_r), the tensile strength of the concrete specimen of a dimension 500 x 100 x 100 mm beam molds at a single point load is found indirectly using IS 4031 – part VIII (methods of physical tests for hydraulic cement - determination of transverse and compresive strength of plastic mortar using prism, 1988) after 28 days of curing. The flexural strength is calculated using the equation 1.

$$Flexural\ strength\ (fr) = \frac{Pl}{bd^2} \quad (1)$$

where, b – width of the specimen (m), d – depth of failure point (m), l – supported length (m) and P – maximum load (kN). 'P' is the load noted when the failure of the specimen occurs.

For controlled specimen, the flexural strength is found as 3.42. With addition of GW, the flexural strength increases. With addition of 10% with rough GW, shows a peak increase compared to controlled specimen. Beyond 10% there is a decrease in flexural strength and almost reaches/ attain the similar value with further addition of rough GW. Due to presence of air voids, with further addition of GW the failure type is brittle. The strength increases by 2.4 times compared to controlled specimen for 10% rough replacement. With further increase in rough GW, the flexural strength is more than the controlled specimen but it reduces beyond 10%. For 20 and 30% replacement, the strength increases by 1.72 and 1.62 times the controlled specimen, it is almost becoming flat beyond 20% of replacement. Similarly for smooth GW, the strength increases about 1.65, 1.61 and 1.51 times the controlled specimen (Figure 10).

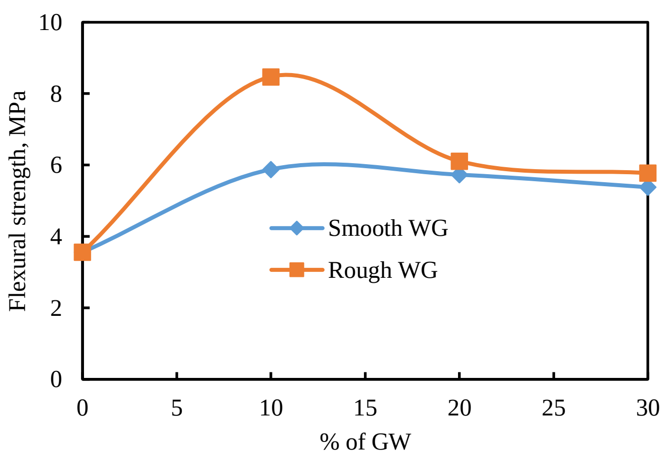


Figure 10. Tensile strength.

Flexural strength is related to compressive strength by the various countries code given in the table 1. From the compressive strength of the modified concrete with GW, the flexural strength is calculated by substituting in the formula given in various code.

Table 1. Comparison of compressive and flexural strength.

Code	f_r, MPa
IS 456 -2000,(Bureau of Indian Standard(BIS), 2000)	$0.7\sqrt{f_c}$
ACI, USA, (Building code requirements for structural concrete and commentary, 2019)	$0.62\sqrt{f_c}$
BS – 8110, Britain (BS 8110-1:1997, 1997)	$0.6\sqrt{f_c}$
EC – 02, Europe (EC-02, 2011)	$0.201f_c$

The maximum strength is observed from experimental results for rough GW, the nearest value is observed in the Euro codes and it shows the highest value. For smooth GW, Eurocode shows the maximum value. The Indian standard, American and British code shows similar trend for both rough and smooth GW (Figure 11).

3.3. Split tensile test

The tensile strength of the concrete is found by mixing varied percentage of GW in a cylindrical sample. The tensile strength of controlled specimen is 3.06 MPa, with addition of 10% GW the tensile increases to 3.23 and 3.44 MPa for smooth and rough GW; this shows an increase in tensile strength by 5.69 and 12.53%. With further addition of GW there is a tensile strength increases to 3.23 and 3.48 MPa for smooth and rough 20% GW. The rate of increase in tensile is by 5.99 and 15.95% compared to the controlled specimen for 30% GW for smooth and rough showing the strength value as 3.23 and 3.54 MPa respectively (Figure 12 a).

Here the smooth GW showed an average increase in tensile strength by 5.8 % but the strength increases to a 15.9% for rough GW compared to controlled specimen. The maximum tensile strength is observed at 30% rough GW. The concrete as a weak tensile member is because of the "interface transition zone". The smooth GW did not contribute to develop a bond in the interfacial zone whereas the rough is able to bear the tensile stress for the applied load. In general, the tensile strength is 10 to 12 % compressive strength. The increase in tensile strength of rough GW increases linearly with increase in percentage of replacement, but the increase trend for smooth GW looks flatten. However, the glass itself is a brittle material, if it has a rough surface the composite is able to bear large tensile strength; however, the crack is similar to that of the controlled specimen (Figure 12b).

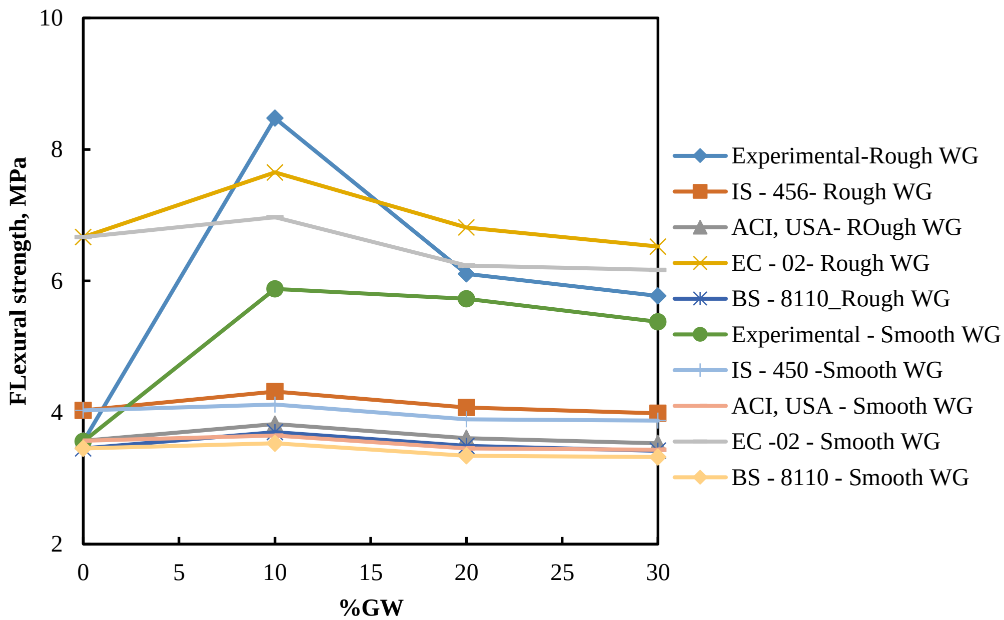
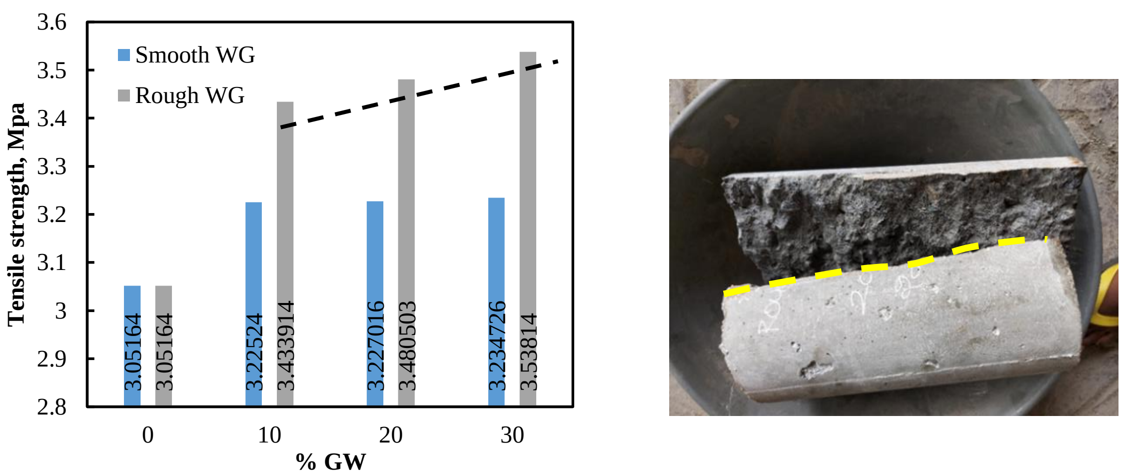


Figure 11. Comparison of flexural strength with various codes.

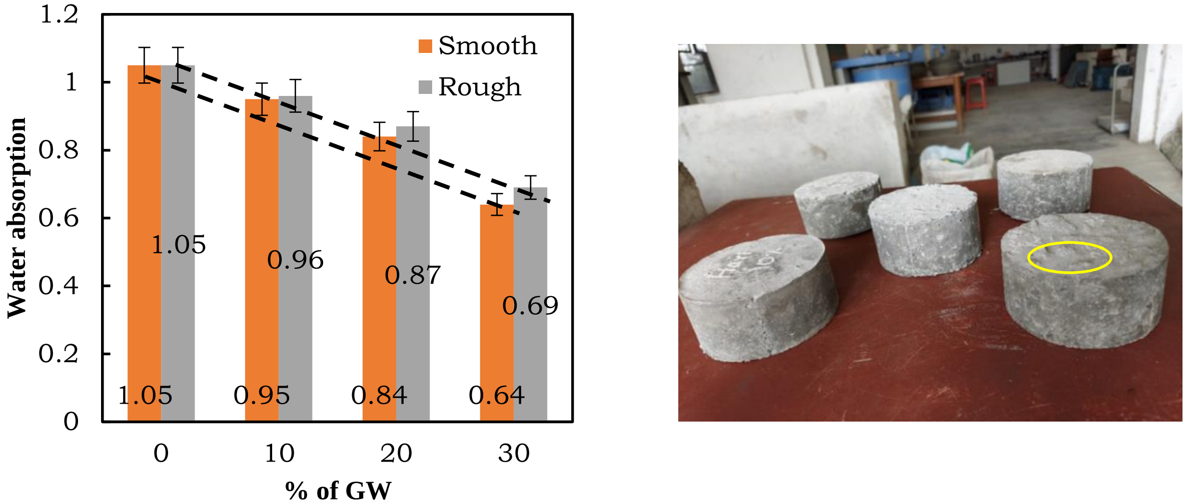


(a) Relation between GW and tensile strength (b) Failure pattern

Figure 12. Tensile strength.

3.4. Water absorption and bulk density

The water absorption value is found after 24 hours of immersing the sample in the distilled water between the temperature 22 and 32 ºC for a period of 24 hours. The water absorption reduces with increase in the percentage of both smooth and rough GW. Without the addition of GW, the value is 1.05 which then decreases in further addition of GW. The reduction in for both the nature of GW is similar as we can see the trend in Figure 13. As the water absorption value for all the combinations is less than 3%, it indicates the absorption characteristics is good (Mardani-Aghabaglou et al., 2015). The maximum reduction is observed at 30% with 30.05 and 34.29 % for smooth and rough GW respectively. The reduction trend for both rough and smooth is a similar trend. The decrease in absorption indicates the presence of water available for hydration, where surface pores are blocked by the glass aggregates. As the ability of water absorption is less, it can inferred that the possibility of sulphate attack is reduced (Zhang and Zong, 2014). As there is no specific relation between the strength and absorption, it is not further compared with strength.



(a) Water absorption relation with GW (b) Sample

Figure 13. Water absorption behaviour.

The influence of GW in its unit weight is also found to check its feasibility to act as a lightweight concrete material. The addition of GW decreases the unit weight of the concrete decreases. Comparing the rough and smooth GW behaviour, smooth GW shows a significant decrease in unit weight (Figure 14). The unit weight of controlled specimen shows a value of 2.48 g/cc; this further decreases to 2.46, 2.44 and 2.41 g/cm^3 for 10, 20 and 30 % rough GW with a minimal percentage increase. As the texture of GW changes to smooth, there is better reduction in unit weight to 2.45, 2.42 and 2.39 g/cm^3. If the GW is considered for making light-weight concrete, smooth glass can be used with greater percentage of replacement because of the low specific gravity of the GW(Małek et al., 2020). Figure 13 also indicates that the reduction in unit weight is more in smooth GW than rough GW.

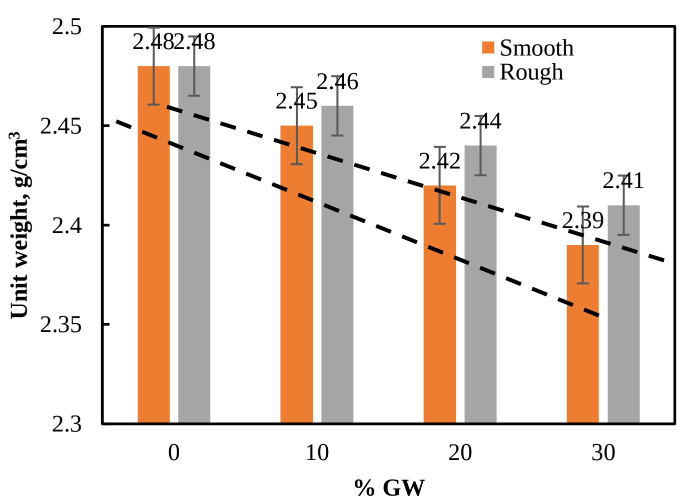


Figure 14. Unit weight relation.

3.5. Strength gain

The gain in strength is considered in two phases: i) the strength gain at initial (7days) is compared with strength gain after 14 days called as *'initial strength gain'* and ii) strength gain in the next 7 days i.e from 14 to 28 days *'later strength gain'* is further compared with first seven days of curing. The strength attained at 28 days of curing is considered as the compressive strength. The initial strength gain without addition of rough textured GW is high showed a high value of 27.53%. With increase in % rough GW, the strength increase in initial stage is less compared to that later strength gain. The strength gain decreases at 10 and 20% replacement, where it starts increasing by 30% rough GW as a replacement material.

In smooth GW, the percentage of strength gain in the initial gain period is high compared to that later gain period of strength. The smooth GW shows an increase in strength gain in 'later' stage compared to that of the 'initial stage for higher percentage of replacement. Especially at 30% smooth GW, the increase in strength gain at initial stage is 20.92% and for later stage it is 4046% which is almost double (Figure 15). It becomes evident the strength gain in the later stage for rough GW increases irrespective of replacement percentage of GW.; but 10% of rough GW shows a better strength gain. In case of smooth GW, the strength gain is high in the initial stage and shows a reduced gain percentage in later stage; where the scenario is different for higher GW percentage.

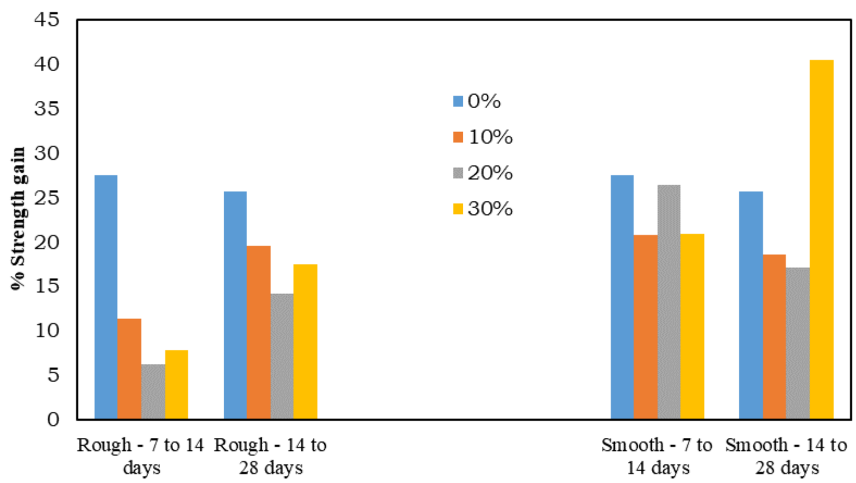


Figure 15. Strength gain.

3.6. Cost comparative study

The concept of sustainable material as an alternative is an emerging topic because of depletion of natural ore. When the cost of the alternative material shows a significant reduction in total cost of material in construction process, the utilization of that material is widely accepted especially in the developing co for 1 cubic meter of concrete (M30). The required quantity of each material is given in Table 2. It is further converted in US Dollar for overall understanding, considering I US Dollar = 78.05 INR.

Table 2. Cost comparison.

Commodity				Required quantity, kg				Cost in Indian Rs				Cost in US Dollar			
Cement				420				3612				46.28			
M-Sand				685				906				11.61			
Aggregate															
20 mm				702				813				10.42			
12.5 mm															
Replacing 12.5 mm aggregate, %															
0	10	20	30	468	421	375	328	1548	1393	1238	1083	19.83	17.85	15.86	13.88
Total								6879	6724	6569	6414	88.14	86.15	84.16	82.19

Without any addition of GW, the cost of 1 cubic meter of M30 grade concrete comes around Rs.6879 ($88.14); this further reduces into Rs. 6724 ($86.15), Rs. 6569 ($84.16) and Rs. 6414 ($82.19) for 10, 20 and 30% for GW replacement. However, the reduction in cost ranges around 2 to 7 %, the usage of GW as an alternative material in concrete also reduces its contribution to environmental pollution because 0.57 tons of CO_2 is emitted while producing one ton of glass (Ling et al., 2013; Amin et al., 2023) and also it reduces the usage of natural aggregate which is in depletion phase.

4. Conclusion

The main agenda of this work is to understand the recyclability of glass waste as a partial replacement for coarse aggregate or as an auxiliary construction material. The study includes the basic mechanical properties of the concrete without and with GW in 10, 20 and 30% as partial replacement material. The following conclusions were arrived from the study:

1. The compressive strength of concrete increases with addition of GW till 10%; the value increases from 33.17 to 38.07 and 34.68 MPa for rough and smooth textured GW respectively at 28 days of curing. At lower percentage of GW, the hydrated calcium present in the GW is more; it further reduces due to the dilution effect making it unsuitable for higher percentage of GW as partial replacement as aggregate.
2. The flexural strength shows a peak value at 10% of GW of 2.4 and 1.65 for rough and smooth texture. However, beyond 10%, both the glass types show reduction in their flexural strength and also indicate its less interaction beyond 10% of GW.
3. The split tensile strength increases with increase in percentage of GW both rough and smooth, indicating its contribution in interface transition zone. The water absorption and unit weight reduce with increase in GW. As smooth GW shows better performance in unit weight, it can be considered in making filler blocks.

However, the reduction in cost of the material is around 2 to 7%, the reuse of GW reduces the pollution caused by the material and also indicates the minimal utilization of space in landfill. The study shows the usage of glass particles as an alternative to coarse aggregate and the results show a promising value of 10% partial replacement. This not only acts as a replacement material but also reduces the production of CO2 emitted during the new production of glass.

Hence future study can focus much on using GW as a partial replacement of coarse and as well as fine aggregates with long term – curing and acid – attack can also be included. An extensive mineralogical study helps in understanding the ASR gel formation and other reactions can also be included.

Author contributions:

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