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Utilization of Waste Glass for Enhancement of Chemical Properties of Concrete

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ABSTRACT

The world is facing a huge problem of waste generation; among these, solid waste in the form of glass has become a prime concern for the environment. The composition of the glass is silica-based, and its utilization in the preparation of concrete can be an efficient step in the direction of sustainable development by reducing the cement content. The formation of secondary calcium silicate hydrates (C-S-H) could take place due to the pozzolanic reaction of the fine ground glass with the cement. TGA techniques were used in this research to investigate the chemical properties of the waste glass, and later, these were compared with the properties of the cement. By keeping a constant w/b ratio for all the replacement levels from 0% to 35%, the evaluation of the workability and compressive strength were done. The evaluation showed that workability increased with an increase in the content of the waste glass. With 7 and 28 days cured samples, the strength and chemical investigation were conducted on the samples prepared with the same mix design. Constant Dose of superplasticizer used by weight of cement for mixes as 0.8%. Compared with the control sample, The level of replacement of waste glass to cement as 30% has depicted the augmentation in the compressive strength. Thus, the use of waste glass was found to be cost-effective and an environment-friendly solution for the sustainable development of concrete.

INTRODUCTION

In developed nations like the USA, EU, and China, the estimated average production of waste glass worldwide in the year 2005 was approximately 130 Mt (Gupta et al. 2020, Rashad et al. 2015). Open land dumping practice is mostly adopted for the disposal of waste glass and this leads to environmental and surrounding pollution along with negative economic impacts. Amenable and feasible management of the available resources with environment-friendly considerations is the sustainable practice of construction (Rashad 2014). Cement is the vital key ingredient for preparing concrete; the production of cement involves many processes which cause the emission of greenhouse gases. The substitution to cement with supplementary cementitious materials (SCMs) in concrete preparation may appear as an environment-friendly solution (Taha et al. 2009). Dissimilar to the above-discussed materials, waste glass is less likely to be used in studies as SCM besides being more feasible, due to its least commercial achievements (Matos & Sousa-Coutinho 2012, Gupta et al. 2021, 2020). Rashed et al. (2014) and Taha et al. (2009) utilized the waste glass in substitution of the natural aggregates. Besides the concern of the alkali-silica reaction, the long-duration enhancement has been depicted in various studies against chloride ingress. Sublimate ASR due to the chemical compound like alkalis and sulfates tend to produce more alkalis in the mix and this phenomenon creates peril to the concrete life span. Matos & Sousa-Coutinho (2012) and Rashed (2014) depicted that efflorescence created from lime can be minimized along with ASR suppression by employing the benign pozzolana function.

Recent research has represented the feasibility of waste glass in the production of brick and ceramics (Afshinania et al. 2016). Pozzolans, fineness, and pore solution along with the chemical composition of waste glass have efficacy on the properties of the concrete (Omran & Tagnit-Hamou 2016, Bisht et al. 2020, Nahi et al. 2020, Carsana et al. 2014). Shayan & Xu (2006) depicted in their study that waste glass particle sizes less than 300 lm show pozzolanic behavior, even at lesser cement content, the particle size lesser than 100 lm presents pozzolanic properties at 90 days of curing. Nassar and Soroushian in the year 2011 represented enhanced compressive strength by incorporating waste glass replacement as 15 to 20% to the main binder cement.

The United States disposed of waste glass to almost 9.3 million metric tons in the year of 1994 and almost eighty percent of it was only container glass (Tanwar et al. 2021). The substitution of aggregates with glass waste has been tried for a long duration, though it depicted the formation of cracks in the concrete (Ballester et al. 2007, Farinha et al. 2011, Idir et al. 2011). Whereas, finely ground waste glass has been used as a substitution for cement in a few studies only for concrete preparation (Choi et. al 2017). Few efforts have been made in recent duration for the preparation of Portland cement by incorporation of the waste glass, this waste is utilized by considering in form of raw siliceous material (Du & Tan 2017). The flash setting depicted by the cement due to the high alkali content, when waste glass is incorporated, the chemical compound found to be formed is $2CaSO_4{\cdot}K_2SO_4$ (Ling & Poon 2013). In concrete as well as in mortar the substitution of waste glass for cement is found to be the emphatic solution for the utilization of waste and minimizing the recycling efforts (Somani & Gaur 2020, Bisht & Ramana 2018). The chemical reaction between the pore solution of alkaline and the silica-containing forms of metastable which have their presence in various types of aggregates leads to the Alkali–silica reaction (ASR), and this reaction is found to have detrimental effects on the concrete (Matos & Sousa-Coutinho 2012). Decomposition of the silica due to the attack of alkali produces the ASR gel when the waste glass is substituted in place of the aggregates, and this phenomenon leads to the formation of cracks in concrete (Saccani & Bignozzi 2010). Perhaps, the glass powder in the form of fine grinding powder will prevent the expansion of the ASR when utilized as the supplementary cementitious material (Byars et al. 2019). This phenomenon can be understood by the fact that the particle size of glass has much impact on the expansion of the ASR, and it was depicted in the experimental studies (Gupta et al. 2020, Schwarz et al. 2008). Also, it has been reported that waste glass having a size of particle finer than 75 µm were tend to propagate the issue of ASR (Ling & Poon 2011). On other hand, particle sizes ranging from 1.18mm - 2.36 mm are more likely to rise the issue of ASR (Bisht et al. 2019). Furthermore, a particle size having size of less than 0.30 mm does not cause the ASR, but when the size of the particle of waste glass rises above 0.60 mm, it starts to present the issue of the ASR (Siad et al. 2018). How it be, the critical particle size of the waste glass can mitigate the ASR side effects is still a matter of technical argument (Gupta et al. 2021).

MATERIALS AND METHODS

Cement

The standards of IS 8112-2003 were followed for the sample preparation with the use of OPC 43 grade. Also, as per the standards of 10262:2009, the mix design was prepared by keeping the w/c ratio at 0.45 and the water incorporated in the preparation was having a pH of 6.5 (Fig. 1). However, to maintain the standard workability of the mixes, superplasticizers were used (SP-431) and the amount kept by cement weight was 0.8%.

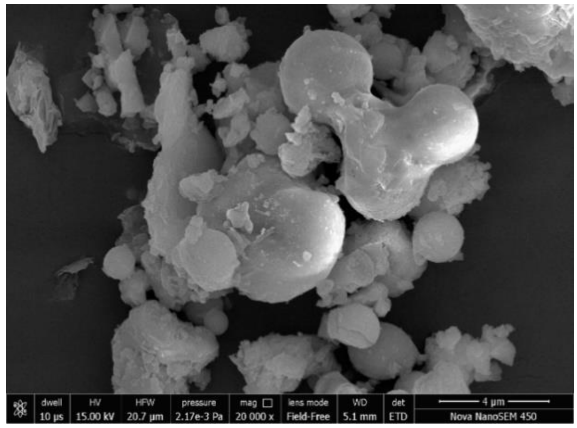

Fig. 1: Higher magnification image of cement particles.

Aggregates

i. **Coarse-** The specific gravity of the aggregates used was 2.66. The aggregates were ranging from 10-20 mm in this work.

ii. **Fine**- Banas River and Rajasthan sand were used in this work. The specific gravity of the aggregates used was 2.62. the percentage finer was observed as 99.4. The aggregates were ranging from 4.75 mm to 150 mm.

iii. The NaOH solution was prepared by utilizing Na_2O, which was procured from Jaipur. 1.0 $mol.L^{-1}$ chemical reagent was used in this work.

Beverage Glass (BG)

The size of the BG was identified before the addition of cement, and the size was lesser than 75 microns. The specific gravity was also tested for this and the value was found as

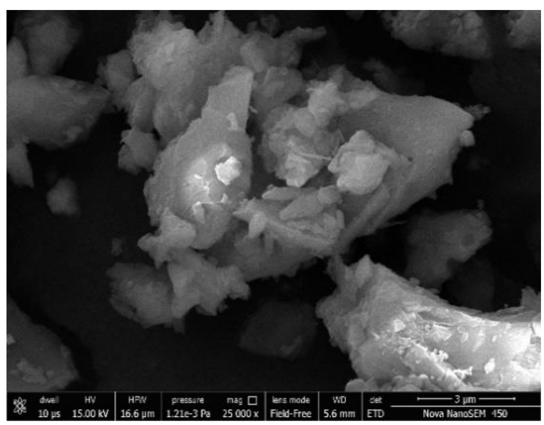

Fig. 2: Higher magnification of glass particles.

Table 1: Concrete preparing ingredients properties.

Material	Specific Gravity	Color	pH
Fine Aggregate	2.62	Light brown	-
Coarse Aggregate	2.66	Greyish white	-
Waste Glass (WG)	2.55	Dark grey	-
Water	-	Colorless	7-6.5

2.55 (Fig. 2 & Fig. 3). SEM image of glass shows its irregular shape and sharp edges which helps to provide better binding.

Mix Proportioning

For this experiment, M30 grade concrete with a fixed w/c ratio of 0.45 is used, in accordance with BIS 10262:2009. To achieve the desired workability, 0.8% by weight of cement is used as an additive. As shown in Table 2 below, PWG is substituted for cement at intervals of 5% from level 5 to level 40%.

Test Methods

ASR Expansion: The standards of the ASTM C1567 were followed for the conduction of the experiments on materials. The cement mortar bars were prepared for the testing and the dimension of the specimen was as 25 mm × 25 mm × 285 mm. After a day, the prepared and demolded sample was then cured for 24 h in the water bath by keeping a constant temperature of the water bath at 80°C. The water used in the water bath was distilled water. The DEMEC-type strain gauges were used for the measurements of the length variation of the sample. The initial length was recorded as L0. The sample marked with the initial points was then cured in the solution of NaOH. In the continuations the sample was cured in a curing tub at a fixed temperature of 80 °C, the curing tub contains the solution of the 1.0 mol/L NaOH. The afterward length measurements of the sample were denoted as Lt. and the time for the measurements was kept as 3, 7, 14, 28, and 35 days. By considering all these values of length variations the ASR expansion for the samples was determined by utilizing the following equation-1.

Table 2: Replacement percentage with cement.

Mix designation	Binder (kg.m^{-3})		
	Cement	% of WG	WG
M	385.00	0	0
BG1	365.75	5	19.25
BG2	346.50	10	38.5
BG3	327.25	15	57.75
BG4	308.00	20	77
BG5	288.75	25	96.25
BG6	269.50	30	115.50
BG7	250.25	35	134.75

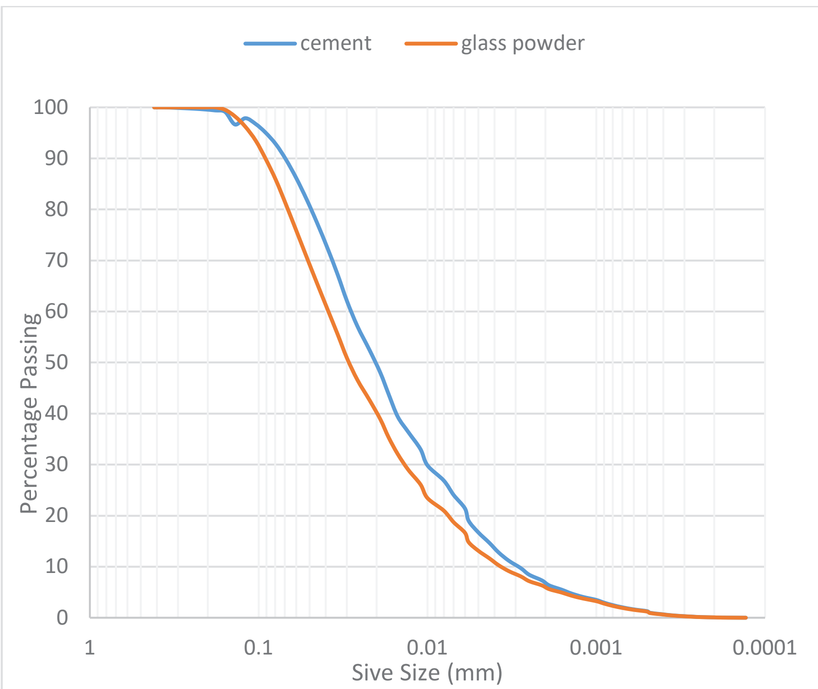

Fig. 3: Gradation curve of BG and OPC.

The average of three samples was considered for the final result.

$$P_t = \frac{L_t - L_o}{L_o} \times 100\ \%$$

Here:

L0: Initial length of the sample (mm).

Lt: Final length at a time interval of T days (mm).

Pt: ASR expansion of sample (%).

In measurements of L0 and Lt the copper head length was not considered.

Concrete Mix Proportion: As per the standards of IS 10262: 2009, the trial mix was prepared. The preparation is so done to achieve 100-125 of the slump value along with the 30 MPa target strength. The dose of the glass powder substitution to the cement varied ranging from 0% to 35%. Table 3 below represents the proportion of the mixes.

Table 3: Mix proportions for control mix.

Material	Weight [kg.m^{-3}]	Slump [mm]
Cement OPC	385	100
Coarse aggregate (20 mm)	645.81	
Coarse aggregate (10 mm)	424.05	
Fine aggregate	780.80	
Water	173	
Admixture	3.08	

RESULTS AND DISCUSSION

Chemical Composition of Beverage Waste Glass Powder and OPC

The EDX technique was used to investigate the composition of the chemical ingredients of the samples of glass powder. Table 4 represents the comparison of investigated findings with the other pozzolanic materials. The specimen of the waste glass depicts the standard content of the pozzolana, as per the IS 1727: 1967. The minimum required content of the (SiO_2+Al_2O_3+ Fe_2O_3) should be 70 %. The moisture content in BG samples was found lesser than the standard of acceptability and the respective values are 4%, 10%, and 3%. Also, the findings depict that the moisture content along with the LoI and SO_3 are nearly absent. Under the considerable limits of standards, the presence of NiO, CuO, BaO, PbO, Cr_2O_3, ZrO_2 TiO_2, and As_2O_3 was found in samples of the glass. Additionally, it has been noted that their presence is less than 0.5%. Thus, the beverage glass powder is expected to depict the pozzolanic nature in a cementitious system.

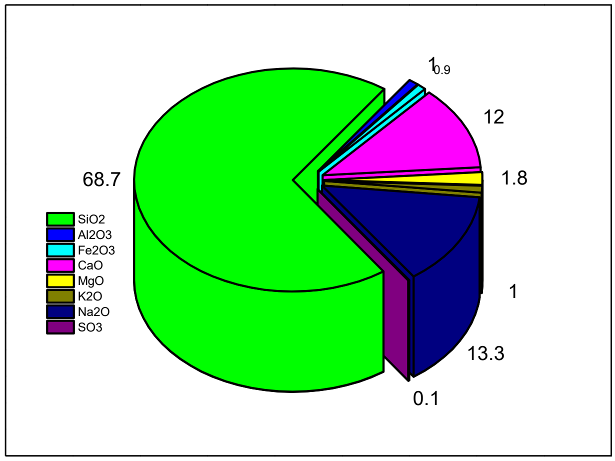

Fig. 4: Chemical composition of beverage glass.

Chemical Reaction to Enhance the C-S-H Gel

OPC: It achieves strength with the help of the chemical reaction of water with the cement since it is hydraulic cement (Fig. 5). The vital strength-gaining factor of OPC is calcium silicate hydrate (or C-S-H), and it is considered to be the primary hydration product. This whole phenomenon is named hydration. The main compounds of the cement are depicted in Table 5.

Table 4: Chemical composition depicted by EDX technique for waste glass samples, OPC, and other reference pozzolanas.

Compound	Bevrage glass	OPC	Waste glass (Nassar & Soroushian (2012)	Slag	Silica fume	Fly ash
SiO_2	68.7	22.8	68	35	90.9	59.2
Al_2O_3	1.0	5.9	7	12	1.1	25.6
Fe_2O_3	0.9	3.5	<1	1	1.5	2.9
CaO	12.0	63.0	11	40	0.7	1.1
MgO	1.8	1.5	<1	–	0.8	0.3
K_2O	1.0	1.0	<1	-	-	0.9
Na_2O	13.3	0.1	12	0.3	-	0.2
SO_3	0.1	2.0	–	9.0	0.4	0.3
LOI	-	1.5	–	1.0	3.0	1.4

Table 5: Cement compound.

Chemical Formula	Composition	Weight [%]
$CaSO_4.2H_2O$	Gypsum	5
$Ca_4Al_2Fe_2O_{10}$ or $4CaO.Al_2O_3.Fe_2O_3$	Tetra-calcium alumino-ferrite	10
$Ca_3Al_2O_6$ or $3CaO.Al_2O_3$	Tri-calcium aluminate	10
Ca_2SiO_4 or $2CaO.SiO_2$	Di-calcium silicate	25
Ca_3SiO_5 or $3CaO.SiO_2$	Tri-calcium silicate	50

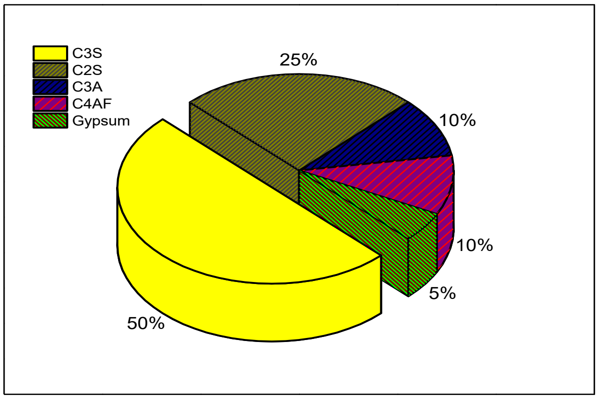

Fig. 5: Chemical compounds of cement.

The ettringite formation takes place during the complex hydration process. Some compound formed may depict shapes that looks like rod or needles and are in the form of amorphous solids. The complex reactions are presented below.

$$2\ Ca_3SiO_5 + 7\ H_2O \rightarrow 3\ CaO.2SiO_2.4H_2O + 3\ Ca(OH)_2 + 173.6\ kJ$$

$$2\ Ca_2SiO_4 + 5\ H_2O \rightarrow 3\ CaO.2SiO_2.4H_2O + Ca(OH)_2 + 58.6\ kJ$$

$$C_3A + 3\ CSH_2 + 26H \rightarrow C_6AS_3H_{32}\ , D\ H = 207\ cal/g$$

$$2C_3A + 3\ C_6AS_3H_{32} + 22H \rightarrow 3C_4ASH_{18}$$

$$C_3AF + 3\ CSH_2 + 3H \rightarrow C_6(A,F)S_3H_{32} + (A,F)H_3 + CH$$

$$C_4AF + C_6(A,F)S_3H_{32} + 2CH + 23H \rightarrow 3C_4(A,F)\ SH_{18} + (A,F)H_3$$

Rates of hydration: The dicalcium silicate has the least hydration rate compared to tetra calcium ferrite, also tricalcium silicate and tricalcium aluminate have more rate of hydration than both above respectively.

Air bubbles are trapped in the 5-6% voids that make up the cement paste after it has been created. Ettringite is also available in paste in amounts ranging from 15-20%. The amounts of CSH and calcium hydroxide in the paste are 50–60% and 20–25%, respectively.

The change in microstructure to enhance the strengthening process of the concrete can be achieved by reducing the w/c ratio, whereas the reaction for hydration can be compensated by the utilization of the superplasticizers. Hence this has been adopted on a large scale for concrete preparation (Jani & Hogland 2014). The reaction of hydration is a rapid process and to inhibit this process, the superplasticizers are used to provide more time for self-assembling along with the firm structure of the products borne during the process of cement hydration (Lu et al. 2017a). This phenomenon helps in the enhancement of mechanical strength (Lu et al. 2017b). The composition of the calcium silicate hydrate takes place during the hydration process, along with this, just after the CSH formation, the composition of the calcium hydroxide takes place. This is also termed Portlandite and is considered to be the product of the secondary reaction. While reacting with the CO_2, the portlandite changes to the compound named calcium carbonate. In the presence of adequate content of calcium hydroxide, this carbonation phenomenon provides the compact structure formation of the porous matrix.

Beverage glass: The degree of reaction during a time period is termed the pozzolanic activity of glass. This can also be identified as the Ca^{2+} or calcium hydroxide ($Ca(OH)_2$) - the rate of the reaction with the pozzolan along with the water. The main determining factors that influence the pozzolan's reaction rate are its active phase content, distinct surface area, and chemical composition. The factors that have an impact on the external control of pozzolanic reaction include reaction temperature, water content, mix proportioning, and hydration product expansion. Pozzolan reactions are frequently impacted by the mix design blend, w/b ratio, and pozzolan substitution ratio. When water is available, it is discovered that the pozzolan confines the calcium hydroxides. As a result, pozzolanic materials are evaluated by the chemical measurement of the reactivity of the pozzolans. By examining calcium hydroxide intake over time, an assessment can be made. When the w/b ratio is higher, the Titrimety method can be used to measure it, as well as the spectroscopic method. When the w/b ratio is lower, however, the X-ray powder diffraction method was traditionally used. In this study, selective dissolutions, X-ray powder diffraction, or scanning electron microscopy image analysis methods are used for the examination. In this study selective dissolutions, X-ray powder diffraction, or scanning electron microscopy image analysis methods are used for the investigation. It was also shown that ASR will be higher if the size increases beyond the limit to obtain the pozzolanic reactivity particle size indicated by the strength activity index in the limits of 45-75 m. The glass powder particles with a size range of 45 to 75 m were tested to address this issue.

$$SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\, wt.\%$$

$$Aluminate\ (Al(OH)_4^-)\ and\ calcium\ hydroxide\ (Ca(OH)_2)\ with\ Water\ H_2O$$

$$Al(OH)_4^- + Ca(OH)_2 \rightarrow C_4AH_{13}, C_3AH_6\ (Calcium\ Aluminate\ hydrates)$$

$$Portlandite\ (Ca(OH)_2)\ and\ Silicic\ acid\ (H_4SiO_4\ or\ Si(OH)_4)$$

$$\underset{(CH)}{Ca(OH)_2} + \underset{(SH)}{H_4SiO_4} \rightarrow \underset{(C-S-H)}{CaH_2SiO_4 . 2H_2O}$$

$$(Calcium\ Silicate\ Hydrate)$$

ASR Expansion

The cement mortar bars were prepared for testing and the dimension of the specimen was as 25 mm×25 mm×285 mm. The water used in the water bath for samples was distilled water. The comparison of control and BG mixes ASR expansion is shown in Fig. 6. According to Siad et al. (2018), the use of glass in mortar in place of sand is the primary cause of ASR expansion. All BG mortar bar mixtures demonstrated alkali-silica reaction expansion below the permitted limit specified by the code. The ASR expansion value was lower compared to the control mortar mix, according to BG. Similar to this, no ASR expansion was detected for glass particles smaller than 1 mm, according to the literature review. The size of the glass particle has a significant impact on the alkali-silica reaction. When compared to the control mix, which had an ASR expansion of 0.027% at 7 days and 0.068 at 28 days, it was shown that the GP mix reduced this expansion.

Compressive Strength

This test was performed to analyze the early age strength development along with the late ages for the mixes prepared with the utilization of ground glass. The control mix properties were compared with the mixes prepared with the ground glass up to 40 % replacement level. Fig. 7 shows the results of the compressive strength test for various mixes. All the samples have presented higher values of compressive strength than compared to the control sample, whereas the mix having substitution levels of 35 % and 40% are reported with a decrement in the strength than the control sample when tested at a duration of 28 days curing. The optimum results for the strength were obtained at a substitution of 30% tested for 28 days of curing. Also, the sample depicted the same trend when tested at a duration of 180 days. Whereas, a sample of mortar with a substitution level of 25% has shown the greatest strength out of all mixes. Statical insignificance was observed in the samples reported with increment in strength at 90 and 180 days of water curing when compared with the control sample. Since, the sample tested on 365 days depicted higher strength with a 25% substitution of the glass waste compared to the sample tested on 90 days of curing, which is higher by 8% compared with the control sample.

Flexural and Split Tensile Strength

The prism and cylinder samples were tested for the investigation of flexural and splitting strength (Fig. 8). The standards of the BIS 516: 1959 were followed for the flexural strength testing of the samples. The results of the investigation are 5.60, 5.75, 5.96, 6.20, 6.85, 6.95, 7.15, 6.10, and 5.15 $N.mm^{-2}$ for mixes from G0 to G8 respectively. The graphical representation in Fig.8 shows that the optimum results were achieved at a 30% powder glass substitution level with the cement. The standards of the BIS 5816:1999 were adopted for the investigation of the split tensile strength. The investigation shows that the same phenomena followed in the case of the split tensile test. The result of the investigation is as 4.40,4.62, 4.95, 5.25, 5.48, 5.90, 6.01, 5.05, and 4.96 N/mm^2 for mixes from G0 to G8 respectively.

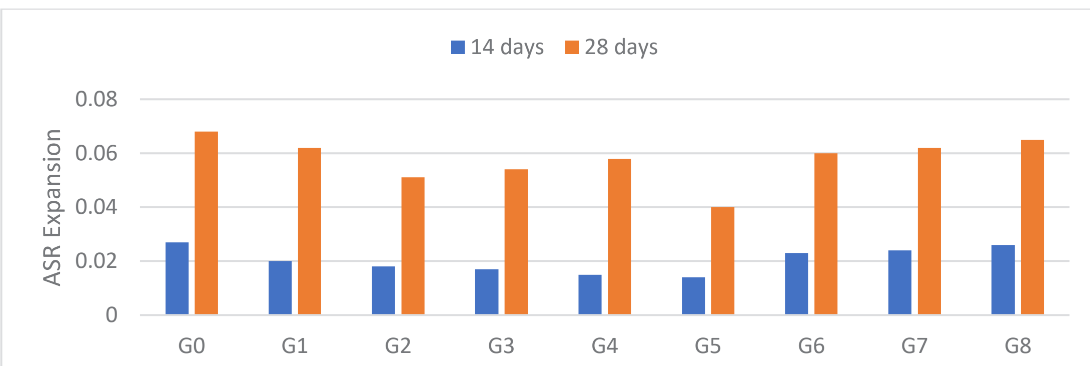

Fig. 6: ASR expansion for mixes.

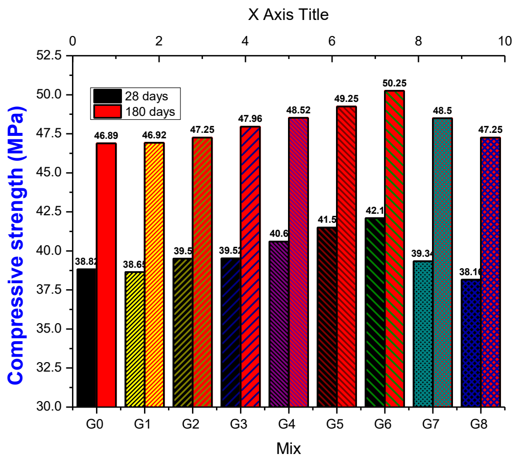

Fig. 7: Compressive strength for mixes.

Abrasion Resistance

The friction is applied on the faces of the concrete due to the skidding along with another exposure, then the wear and tear take place. IS 1237 (2012) recommendations were followed to determine the abrasion resistance. The abrasion resistance of the samples is shown in Fig. 9. The observation represents that up to the substitution level of 30% of BG, the resistance was found to be in increasing order, whereas, the substitution above this value decreases the abrasion resistance of the samples. This phenomenon provides the samples prepared with higher waste glass content with lower abrasion resistance. Despite the 20% replacement level the compression resistance goes on decreasing and this phenomenon alters the glass powder concrete volume.

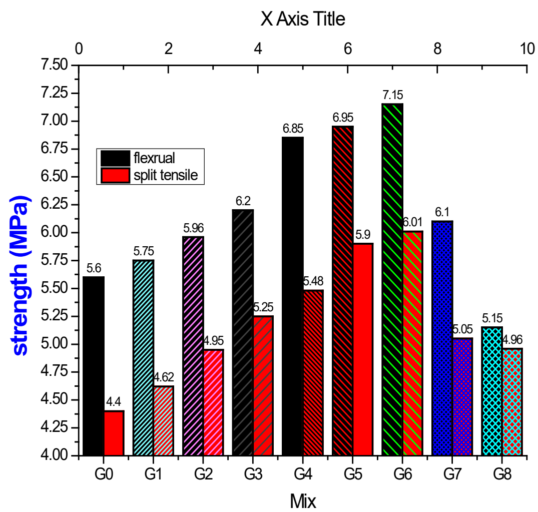

Fig. 8: Flexural and split tensile strength for a mix.

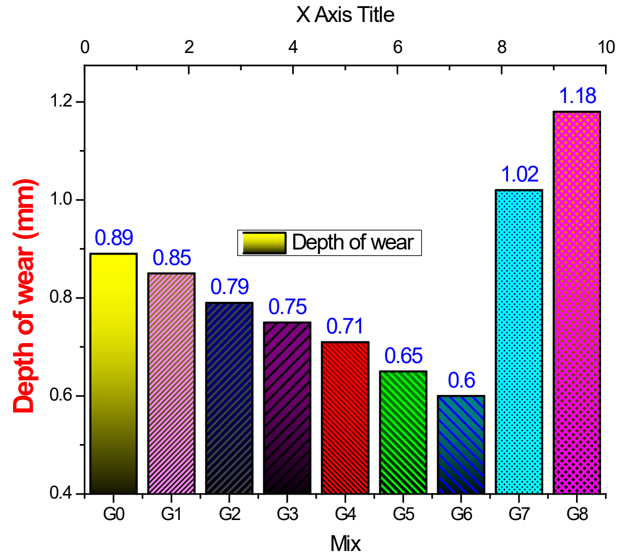

Fig. 9: Depth of wear (mm) for mixes.

Environmental and Economic Considerations

To obtain sustainable construction techniques, the utilization of waste products tends to be more practice in the construction industry. Almost 0.9 tons of CO_2 along with NO_X and SO_X in moderate amounts are released into the environment in the production of 1-ton cement (Khan et al. 2014). Theoretically, a 1-ton number of natural resources can be protected while performing recycling for the same amount of waste glass. The nature of the glass is considered to be non-biodegradable and the disposal practices adopted for this are mostly land-fill techniques, thus its incorporation in the construction industry will save a lot of useful land along with more benefits to the environment. Optimum quantity utilization of the waste glass enhances the concrete properties this also proves to be beneficial for the environment by reducing the waste load in the atmosphere (Patzias 1987). The experimental study depicted that 20% substitution to the cement of the waste glass proves to be beneficial for concrete mixes. At the study place, waste glass procurement was done for 3 rup.kg^{-1}, and after processing waste glass, the cost reached 3.5 rup.kg. Whereas, the cost of the cement bag is 450 rup. kg^{-1}., which contains a cement weight of 50 kg. So, a 7 to 14% price decrement can be achieved by utilization of 15 to 25% of the waste glass.

CONCLUSIONS

1. Beverage glass's physical, mechanical, and chemical characteristics fulfill the limits of Class F and Class C pozzolanic materials according to ASTM C 618.

2. ASR expansion shows that smaller particles of waste glass improve the resistance against alkali-silica reactions.
3. Compressive strength results indicated that waste glass increased up to 30% replacement with OPC increased the strength. The increment variation was 8.44% at 28 days and 7.14% at 180 days as compared to the control, but after that decrement in strength due to an increase in the finer voids in waste glass mixes.
4. Flexural strength and split strength show similar behavior as compressive due to its pozzolanic behavior. The variation in strength was achieved as 17.44% at 28 days for flexural and 7.57% at 28 days for spilled tensile but further increasing waste glass tensile strength was decreasing.
5. The economical consideration depicted that 25% substitution to the cement of the waste glass proves to be beneficial for concrete mixes. 7 to 14% price of concrete decreased by utilization of 15- 25% of waste glass.

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