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Properties of concrete incorporating granulated blast furnace slag as fine aggregate

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Abstract. The present work investigates about the development of a novel construction material by utilizing Granulated Blast Furnace Slag (GBS), an industrial waste product, as substitution of natural fine aggregates. For this, experimental work has been carried out to determine the influence of GBS on the properties of concrete such as compressive strength (CS), modulus of elasticity, ultrasonic pulse velocity (UPV), chloride penetration, water absorption (WA) volume of voids (VV) and density. Concrete mixes of water/cement (w/c) ratios 0.45 and 0.5, and incorporating 20%, 40% and 60% of GBS as partial replacement of natural fine aggregate (sand) are designed for this study. The results of the experimental investigation depict that CS of concrete mixes increases with the increasing percentages of GBS. Moreover, the decrease in chloride penetration, WA and VV, and improvement in the modulus of elasticity, UPV, density of concrete is reported with the increasing percentage of GBS in concrete.

Acronyms: CS; compressive strength; GBS; granulated blast furnace slag; SEM; scanning electron microscope; WA; water absorption; VV; volume of voids; UPV; ultrasonic pulse velocity

Keywords: compressive strength; granulated blast furnace slag; volume of voids; water absorption; modulus of elasticity

1. Introduction

Aggregates are known to be a key constituent of concrete that consists approximately 75% of total volume the concrete matrix (Neville 1997). With vast enhancement in the use of concrete owing to the rapid growth in construction of various infrastructures, the demand for natural aggregates has been increased to many folds. In many parts of the world, the aggregates collected from natural resources are not enough to mitigate this huge demand for aggregates. Simultaneously, significant quantities of waste products have been generated across the globe, which creates various problems such as environmental pollution, lack of landfills for dumping those materials and enhanced cost of waste disposal. These waste products could be utilized in

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concrete mixes in developing sustainable concrete (Mukharjee and Barai 2015a, Ashish *et al.* 2016, Shu *et al.* 2016, Patra and Mukahrjee 2016). Therefore, utilization of aggregates retrieved from various alternate sources in concrete mixes are encouraged to fulfill the shortage of natural aggregates (Topcu and Boga 2010, Mukharjee and Barai 2015b, Ambily *et al.* 2015, Lee *et al.* 2016). In addition to above, several environmental problems such as sliding of river banks, loss of water retaining sand strata, lowering of river courses, lowering of the ground water table, loss of aquatic life and disturbance on the agriculture process are caused due to the increase in the extraction of natural sands from the river bed. Due to this non-availability of river sand, alternate materials such as bottom ash, fly ash, slag form various types of industries etc. are used to mitigate the requirement of construction industry (Kehagia 2009, Chithra *et al.* 2016, Kockal 2016, Ding *et al.* 2017, Dos Anjos *et al.* 2017).

The use of aggregates retrieved from steel slag as replacement of sand in concrete has a significant influence on properties of mortar and concrete mixes owing to the hydraulic activity of steel (Lin *et al.* 2003, Singh *et al.* 2015). The feasibility of use of GBS as fine aggregate in alkali activated slag was studied and found to be beneficial in resisting high temperature (Rashad *et al.* 2016). The static compressive strength and fatigue life of GBS incorporated mortar mixes were greater than that of control mix made with natural fine aggregate (Farooq *et al.* 2017). Incorporation of GBS as replacement of natural fine aggregate decreased the workability of concrete due to higher water absorbing capacity of GBS than the natural aggregates (Binici *et al.* 2008). However, the fresh concrete density was found to be similar to that of control mix made without GBS. The strength development ratio after 7 days for GBS incorporated mixes was similar to that of normal concrete (Binici *et al.* 2009). Moreover, around 30% increase in 28 days CS was detected for specimens containing steel slag as coarse and fine aggregate (Chunlin *et al.* 2011). In another study, Babu and Mahendran, (2014) found that strength of concrete improved up to 25% replacement of natural sand and after this level strength showed a declining trend. Binici *et al.* (2012) stated that 28 and 90 days compressive strength (CS) of concrete made with GBS was found to be higher than reference mix made without GBS. Furthermore, a significant reduction in permeability after 28 and 90 days and enhancement in sulphate resistance was detected with the incorporation of GBS in concrete mixes. The resistance to water and chloride penetration was detected when the natural sand was replaced with GBS in designing concrete (Binici *et al.* 2008). Investigation of the microstructure of concrete mixes with GBS was carried by analyzing scanning electron microscope and observed that increase in quantity of C-S-H gel in GBS incorporated mixes which could be attributed the fact that CaO present in GBS promoted the growth of C-S-H gel. Therefore, enhancement in strength parameters of concrete occurred with the replacement of natural sand by GBS. Yuskel *et al.* (2007) demonstrated that GBS having grain size more than 30 μm participated in hydration process similar to normal aggregate by carrying out a microstructural investigation using scanning electron microscope. The study also reported about enhancement in resistance to high temperature, abrasion, freezing, and thawing with the incorporation of 20% GBS as replacement of natural sand in concrete. In addition to above, the tensile behaviour of concrete improved with the incorporation of GBS in concrete (Zeghichi 2006, Patra and Mukharjee 2017). The application of fine aggregates retrieved from steel and copper slag for developing geo-polymer and self-compacting concrete mixes were reported in the literature (Valcuende *et al.* 2015, Singh and Siddique 2016, Mithun and Narasimhan 2016).

The aim of the present study is to carry out a systematic investigation for determining the influence of GBS as a partial replacement natural aggregate on mechanical and durability characteristics of concrete. The properties such as compressive strength after various curing days

Table 1 Properties of cement

Fineness (%)	Consistency (%)	Specific gravity	Initial Setting time (min)	Final setting time (min)	Soundness (mm)	Compressive strength (MPa)		
						3 days	7 days	28 days
99.98	31	3.09	132	328	9	34.8	44.9	54.1

Table 2 Composition of cement and GBS

Component type	CaO	SiO_2	MgO	Al_2O_3	S	FeO or Fe_2O_3	P_2O_5	MnO	Na_2O	KO	SO_3
GBS (%)	41.7	35.6	10.7	8.4	1.3	0.8	0.7	0.5	-	-	-
Cement (%)	65.67	16.57	1.31	11.74	-	0.34	-	-	0.44	2.11	1.47

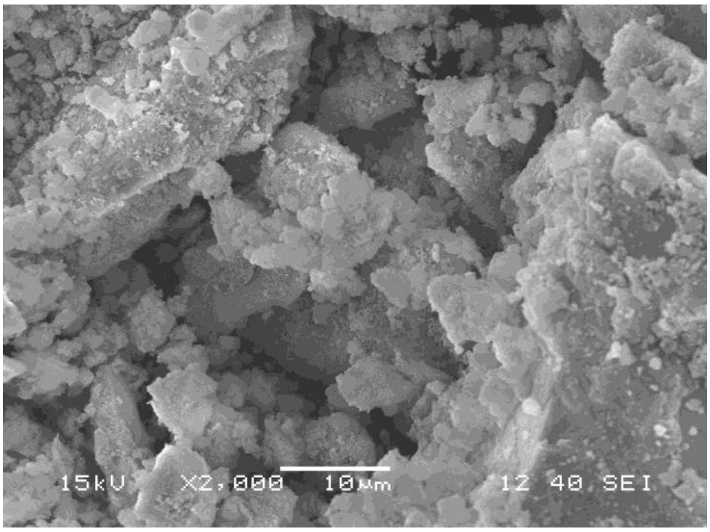


Fig. 1 SEM Micrograph of GBS

and with different sized specimens, modulus of elasticity, and UPV, chloride penetration, WA, density and VV of concrete containing 20%, 40%, and 60% GBS are determined and compared with control mix containing only natural sand as fine aggregate. In addition to above, empirical equations are developed for assessment of the relationship between compressive strength and various parameters and compared with relationships available in existing literature.

2. Experimental programme

2.1 Materials

Ordinary Portland Cement (OPC) of grade 43 confirming to Bureau of Indian Standards (IS 8112 1959) provided by Ultratech Co. Ltd. was utilized for making concrete mixes in the present experimental work. The preparation of concrete mixes have been finished within 30 days of procurement of cement. Standard procedures have been adopted to characterize the properties of

Table 3 Properties of aggregates and GBS

Material	Bulk density (kg/m^3)		Specific gravity (SD)	Water absorption (%)	Los Angeles Abrasion resistance (%)	Impact value (%)	Crushing value (%)
	Compact	Loose					
FA	1615	1462	2.63	0.4	-	-	-
CA	1622	1394	2.85	0.8	23.36	12.21	17.52
GBS	1250	1157	2.56	1.2	-	-	-

Table 4 Proportions of mixtures per cubic meter of concrete

Mix Designation	W/C ratio	Cement (kg)	CA (kg)	FA (kg)	% Replacement	GBS (kg)
WB1	0.45	438	1161	625	0	0
WB2	0.45	438	1161	500	20	106
WB3	0.45	438	1161	375	40	212
WB4	0.45	438	1161	250	60	318
WB5	0.5	394	1169	658	0	0
WB6	0.5	394	1169	526	20	112
WB7	0.5	394	1169	394	40	224
WB8	0.5	394	1169	264	60	336

cement and the results are illustrated in Table 1. The GBS used for the experimental work was brought from the steel plant located at Rourkela (A city of Eastern India). The chemical composition of GBS and cement is presented in Table 2.

Fig. 1 represents the Scanning Electron Microscope (SEM) analysis of GBS in bright field mode. SEM is one of the techniques in which the surface morphology of the materials is studied. From the figure, it can be observed that the surface of GBS is rough with angular particles.

For the experimental programme, the river sand available at nearby river bed which confirms to Zone-III as per the IS 383 (1970) was utilized for making concrete. Coarse aggregates manufactured from basalt rock of nominal size 20 mm were used. The GBS used in the present investigation was provided by the Rourkela steel plant. The standard test results for various properties of aggregates as well as GBS were presented in Table 3.

2.2 Concrete mixtures

Concrete mix design was carried out as per provision given in IS 10262 (2009). Concrete mix design was performed for two w/c ratios i.e., 0.45 and 0.5. Three different percentages of GBS 20%, 40% and 60% was replaced with natural fine aggregates. All the replacements were carried out by volume replacement of fine aggregate. Normal tap water confirming the drinking water standards was used for the test programme. Additional 10% of the material was used to mitigate the loss in the casting and placing of concrete. The detailed concrete mix was given in Table 4.

2.3 Specimen casting and curing

An electric operated manual laboratory mixer having capacity 0.06 m^3 was used for mixing of concrete. A standard mixing procedure outlined below was adopted for all mixes. Trial slump tests were conducted to obtain a better slump value. Workability of all the mixes was expressed in terms of slump. The consistency and uniformity were remained constant for each batch of concrete mix. After the completion of the mixing process, the fresh concrete was placed in the specified steel moulds in three layers with the tamping of 25 blows in each layer by the tamping rod until the achievement of sufficient compaction. Proper care had been taken to avoid over compaction followed by segregation of the concrete ingredients. Demoulding was done after 24 hours and the specimens were cured under water at 27ºC±2ºC and 90%±1% relative humidity for a specified period of curing. Concrete cubes 100 mm and 150 mm size cubes long with cylinders of size 150 mm diameter×300 mm were cast.

2.4 Testing of specimens

The CS of concrete was found out by using 2000 kN compression testing machine for the 150 mm and 100 mm size cubes and 150 × 300 mm size cylinders. The CS test for 100 mm cubes was carried out after 3, 7, and 28 days, whereas the CS of 150 mm cubes and cylinders was determined after 28 days in accordance to IS: 516 (1959). The ultrasonic pulse velocity test was carried out on 150 mm cubes after 28 days of water curing in accordance with BIS (IS: 1331(Part 1)-1992). The test was performed using TICO ULTRASONIC INSTRUMENT (UPV). The test for modulus of elasticity of concrete mixes was conducted on standard test specimens of 150 mm diameter×300 mm height cylinders in accordance with American Society for Testing and Materials (ASTM C 469-02). The chloride penetration test is carried out on 100 mm cube specimens. The specimens were cured in immersed water for 7 days after removing from the molds. Then, each of the specimens was sealed with epoxy base material on all four sides, except the faces in the casting direction. Then, the specimens are immersed in NaCl solution prepared equivalent to seawater concentration. The specimens are fractured after 28 days of immersion. The fractured surfaces were sprayed with 0.1N $AgNO_3$ solution. The white colour boundary resulting from the formation of silver chloride indicates the depth of chloride penetration (Otsuki *et al.* 1992). The tests for volume of voids, density and water absorption of hardened concrete were carried out as per ASTM (ASTM C642-06 (2006) on cubes of size 100 mm after 28 days of curing.

3. Results and discussion

3.1 Compressive strength

The CS results of 100 mm cubes at different GBS% and water/cement ratios are presented in Fig. 2. It is observed that at w/c ratio 0.45 the CS of control mix is 22.67, 28 and 38.67 MPa after 3, 7 and 28 days respectively. It is increased to 24.0, 30.3 and 41.2 MPa at 3, 7 and 28 days of curing which is 5.5%, 4.5% and 6.45% higher than the control concrete mix respectively at 20% incorporation level of GBS. It is further increased to 27.0, 33.0 and 43.3 MPa at 40% incorporation level after 3, 7 and 28 days of curing which are 19.1%, 17.85% and 12.05% higher than the control mix respectively. At 60% incorporation level the compressive strengths are 28.33, 35 and 46 MPa after 3, 7 and 28 days of curing which are 24.9%, 25% and 18.95% higher than the compressive strength of control mix respectively. A similar trend is observed in the case of w/c ratio 0.5. The control mix has CS of 20.33, 26.33 and 35 MPa after 3, 7 and 28 days of curing respectively;

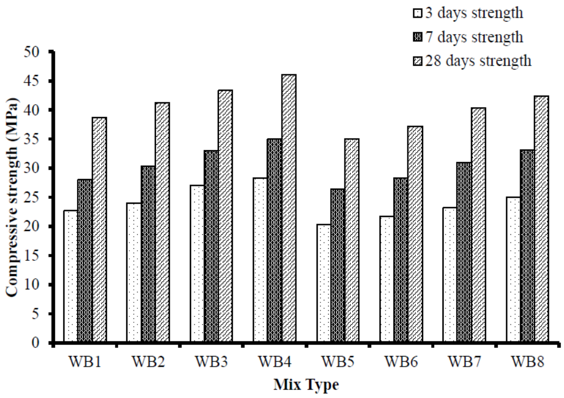


Fig. 2 Variation in compressive strength for 100 mm cubes

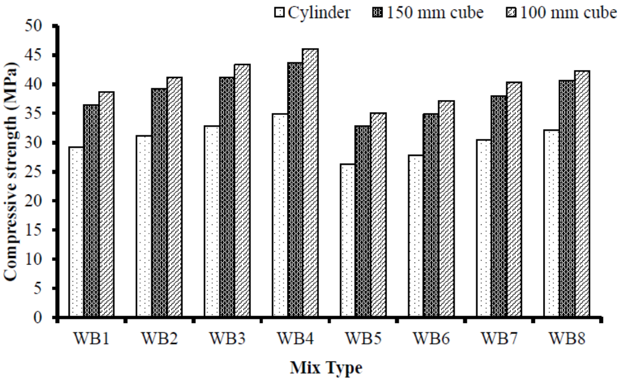


Fig. 3 Comparison of 28 days compressive strength of cubes and cylinder

Which is increased to 21.67, 28.33 and 37.17 MPa after 3, 7 and 28 days of curing which is 6.59%, 7.59% and 6.19% higher than the control mix at 20% replacement ratio. At 40% replacement level the CS are 13.95%, 17.73% and 15.22% higher than the control mix after 3, 7 and 28 days. At 60% replacement level the compressive strength is 25, 33.167 and 42.33 MPa after 3, 7 and 28 days of curing which are 22.97%, 25.58% and 20.94% higher than the control mix respectively. It is observed that with the increasing incorporation of GBS CS is increased with the increasing curing period. The CS is highest in the case of 60% replacement level for both the water/cement ratios. CS is higher in the case of w/c ratio 0.45 than 0.5. The rate of increase in compressive strength is higher in the case of early age. This improvement in CS could be attributed to the strengthening of microstructure with the formation of a secondary C-S-H gel. Binici *et al.* (2008) stated that CaO present in GBS prompted the formation of C-S-H gel, which could be visualized from the scanning electron microscopic images. Other investigations also reported about the presence of hydraulic activity in steel slag (Pal *et al.* 2003, Pang *et al.* 2015).

A comparison of CS of cubes and cylinder after a curing period of 28 days is presented in Fig. 3. The 28 days CS of concrete mixes at w/c ratio 0.45 of 100 mm cube and 150 mm cube are 38.67 and 36.42 MPa; whereas it is 29.136 MPa for cylinder for control mix. This indicates that in the case of 100 mm cubes the CS is highest and lowest in case of cylinders. For all the concrete mixes similar type of observations are found. This difference CS of cylinder and cubes is because of the

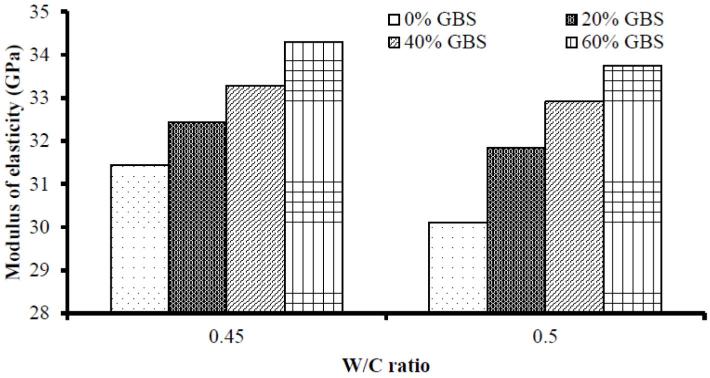


Fig. 4 Variation of elastic modulus of concrete mixes

Table 5 Formulations for prediction of E from f_c

Reference	Formulation
Ravindrarajah and Tam (1985)	$E = 7770 \times f_c^{0.33}$
Dillmann (1998)	$E = 634.43 \times f_c + 3057.6$
Dhir *et al.* (1999)	$E = 370 \times f_c + 13100$
Mellmann (1999)	$E = 378 \times f_c + 8242$
IS 456 (2000)	$E = 5000 \times \sqrt{f_c}$
NBR 6118 (2003)	$E = 5600 \times \sqrt{f_c}$
Hueste *et al.* (2004)	$E = 5230 \times \sqrt{f_c}$

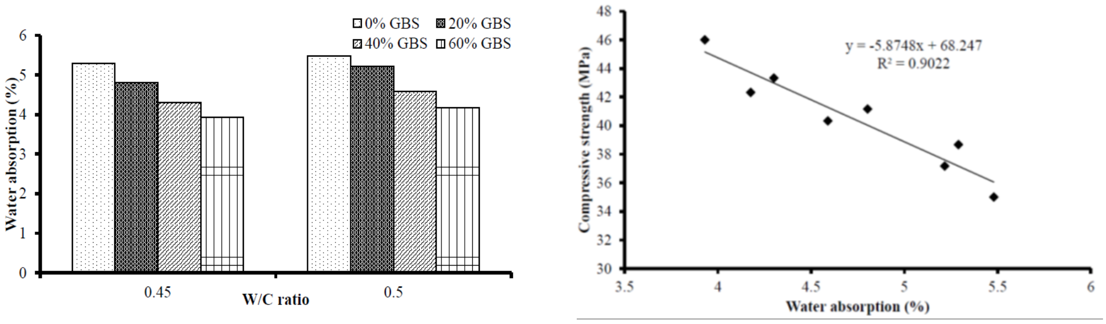
Table 6 Comparison of experimental E values with predicted values using various formulations

Mix designation	Ravindrarajah and Tam (1985)	Dillmann (1998)	Dhir *et al.* (1999)	Mellmann (1999)	IS 456 (2000)	NBR 6118 (2003)	Hueste *et al.* (2004)	Present study
WB1	25.44	26.15	26.57	22.008	30.17	27.03	25.25	31.48
WB2	26.06	27.89	27.58	23.04	31.28	28.02	26.18	32.44
WB3	26.47	29.11	28.29	23.76	32.04	28.71	26.82	33.28
WB4	27.00	30.71	29.23	24.72	33.01	29.58	27.62	34.29
WB5	24.59	23.88	25.24	20.65	28.64	25.66	23.97	30.11
WB6	25.07	25.14	25.98	21.40	29.50	26.43	24.68	31.83
WB7	25.80	27.16	27.16	22.60	30.82	27.61	25.79	32.91
WB8	26.37	28.81	28.12	23.59	31.86	28.54	26.66	33.75

size effect of specimens. This implies that decrease in aspect ratio increases compressive strength (Neville 1997).

3.2 Modulus of elasticity

The results obtained from the test for modulus of elasticity (E) of cylindrical specimens are



(a) (b)

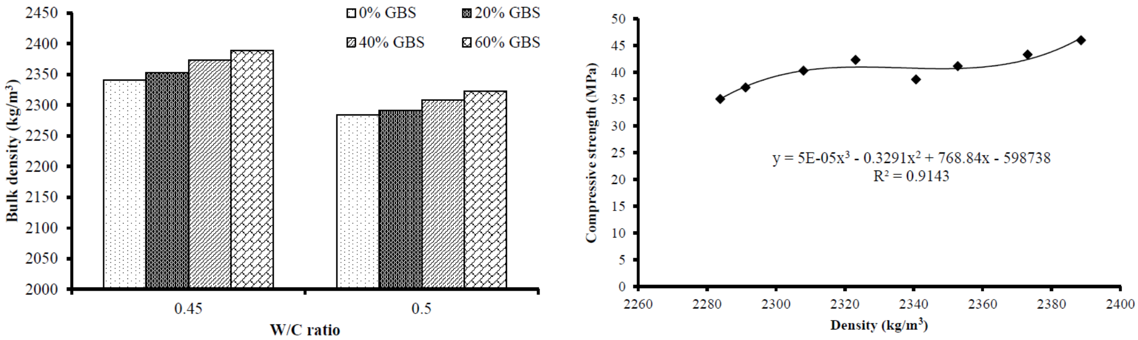
Fig. 5(a)Variation of water absorption of concrete mixes, (b) Relation between CS and water absorption

given in the following Fig. 4. For w/c ratio 0.45 and 0% GBS the value of E is 31.44 GPa, which increases to 32.44, 33.28 and 34.29 GPa for 20%, 40% and 60% GBS replacement, which is 3.17%, 5.85% and 9.06% higher than the control mix (0% GBS replacement) respectively. Similarly for w/c ratio 0.5 and 0% GBS the value of E is 30.11 GPa. For 20%, 40% and 60% GBS replacement the value of E is increased to 31.83, 32.91 and 33.75 GPa which is 5.71%, 9.29% and 12.08% higher than the control mix respectively. A comparative study of elastic modulus (E) values of present study and the elastic modulus values obtained from the existing formulations (Table 5) is presented in Table 6. The cylinder compressive strength (f_c) is adopted for computing elastic modulus using the formulation given by NBR 6118 (2003) and Hueste *et al.* (2004). For other formulations cube strengths of 150 mm cubes are used. It can be seen that elastic modulus values for present experimental study are higher than those values obtained from the formulation. The values obtained from the formulation given by Mellmann (1999) are the lowest among all. The comparative study indicates that relation between elastic modulus and compressive strength concrete prepared with GBS is similar to that of normal of concrete.

3.3 Water absorption

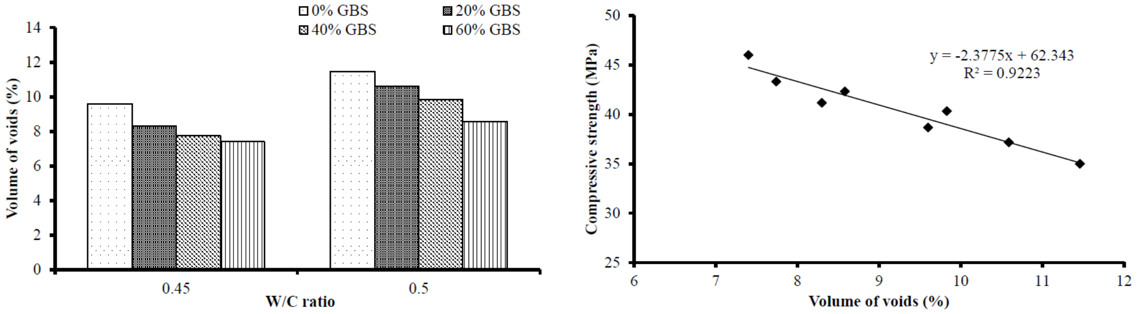
The variation of water absorption of different concrete mixes at different concrete mixes with different percentage of GBS is given in Fig. 5(a).

The water absorption for control mix at w/c ratios 0.45 and 0.5 are 5.29% and 5.48% respectively. It decreases to 4.803% and 5.216% with addition of 20% GBS at w/c ratios 0.45 and 0.5 respectively. It is further decreased to 4.3% and 4.59% with 40% addition of GBS at w/c ratios 0.45 and 0.5 respectively. At 60% replacement level the water absorption is observed to be lowest. For w/c ratios 0.45 and 0.5 it is 3.93% and 4.176% respectively. It is due to the presence of fewer voids in case of concrete mixes with the increasing percentage of GBS. The decrease in water absorption value is observed with increasing incorporation of GBS. This decrease in the WA caused increase in the CS of concrete. The relation between WA and CS is illustrated in Fig. 5(b). From the figure it can be detected that with an enhancement in WA resulted in a reduction of compressive strength. This relationship is expressed in linear equation. The determinant coefficient value (0.9022) indicates the existence of a strong correlation between compressive strength and water absorption. This indicates that concrete having less compressive strength contains more voids, and hence, absorbs more water, hence, concrete which has higher strength absorbs less water.



(a) (b)

Fig. 6(a) Variation of density of concrete mixes, (b) Relation between CS and density



(a) (b)

Fig. 7(a) Variation of volume of voids of concrete mixes, (b) Relation between CS and volume of voids

3.4 Density

The variation of density with different incorporation level of GBS is presented in Fig. 6(a). It can be seen that with the increasing incorporation of GBS density of concrete is enhanced. At w/c ratio 0.45 the control mix has density 2340.69 kg/m^3 which increased to 2352.79 kg/m^3 and 2373.063 kg/m^3 which is at 20% and 40% replacement ratio of GBS with natural fine aggregate respectively. This further increased to 2388.593 kg/m3 for 60% replacement level of GBS. Similarly, at w/c ratio 0.5, the control mix has a density of 2283.82 kg/m^3 which is increased to 2291.176 kg/m^3 at 20% replacement level. It is further increased to 2308.007 kg/m^3 and 2323.12 kg/m^3 at 40% and 60% replacement level respectively. The density of concrete improves with the increasing percentage of GBS in both the w/c ratios 0.45 and 0.5. The relation between density and CS of concrete containing different percentages of GBS is demonstrated in Fig. 6(b). It is found that with the increase in density improves the CS which indicates concrete with higher density can sustain higher loads. Therefore higher stress will be generated. The relationship between density and CS can be expressed in terms of a cubic equation and good correlation is observed due to the higher value of determination coefficients (0.9143).

3.5 Volume of voids

The volumes of void in concrete with varying percentage of GBS are presented in Fig. 7(a).

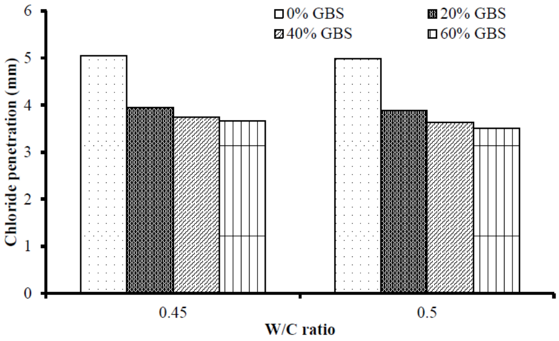
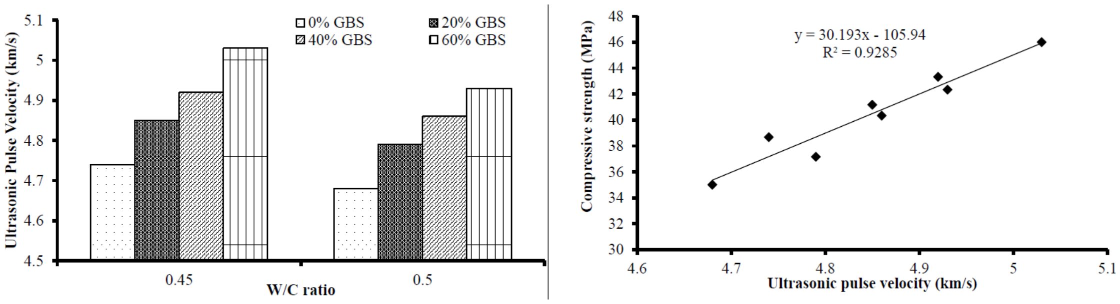


Fig. 8 Variation of chloride penetration of concrete mixes



(a) (b)

Fig. 9(a) Variation of UPV of concrete mixes, (b) Relation between CS and UPV

It is observed that increase in GBS has an adverse effect on the voids content of concrete specimen. At w/c ratios 0.45 and 0.5, the VV of the control mix are 9.6% and 11.46% which decreases to 8.3% and 10.59% due to 20% addition of GBS respectively. The volume of voids is 7.74% and 9.83% at 40% replacement level of GBS which decreases to 7.4% and 8.58% after addition of 60% GBS for w/c ratio 0.45 and0.5 respectively. It is observed that with the increase of GBS content the volume of voids decreases. The fibrous steel particles present in the GBS fills the voids in the concrete specimens. Moreover, the volume of voids is higher in the case of w/c ratio 0.5. Due to this decrease in voids content the water absorption decreases, which lead to enhancement in the density and strength of concrete. The relation between volume of voids and compressive strength is represented in Fig. 7(b). The best-fitted line between the volume of voids and 28 days compressive strength is a linear curve and it implies that with decreasing volume of voids compressive strength increases. A Strong correlation is observed between volume of voids and density due to the higher value of determination coefficient (0.9223).

3.6 Chloride penetration

The chloride penetration test results are expressed in the Fig. 8. The depth of chloride penetration for w/c ratio 0.45 and 0% GBS is 5.05 mm, which reduced to 3.95, 3.74, and 3.67 mm for 20%, 40% and 60% GBS which shows 21.78%, 25.94% and 27.32% lower value than the control mix respectively. Similarly for w/c ratio 0.5 and 0% GBS the chloride penetration depth is 4.98 mm which further reduced to 3.88, 3.63 and 3.51 mm for 20%, 40% and 60% GBS replacement which is 22.08%, 27.11% and 29.51% lower than the control mix respectively. It is the fact that due to the presence of fewer pores in the concrete and due to the fibrous property of GBS lower value of chloride penetration is observed in the high replacement of GBS.

3.7 Ultrasonic pulse velocity

The ultrasonic pulse velocity (UPV) test was carried out as per IS: 13311(Part 1)-1992. The result of the test is given in the Fig. 9(a). For w/c ratio 0.45 and 0% GBS the UPV value is 4.74 km/s, which is enhanced to 4.85, 4.92 and 5.03 km/s for 20%, 40% and 60% GBS which indicates 2.28%, 3.79% and 6.11% higher value than 0% GBS respectively.

Similarly for w/c ratio 0.5 and 0% GBS the UPV value is 4.68. For same w/c ratio and 20%, 40% and 60% GBS the values of UPV are 4.79, 4.86, and 4.93 km/s which shows enhancement of 2.35%, 3.84% and 5.07% than the concrete having 0% GBS respectively. The maximum value of UPV is obtained from 60% GBS and at w/c ratio 0.45. The fibrous particles present in GBS helps to fill the void which decreases the time of travel of wave through the specimen increasing the velocity. The relation between UPV and compressive strength is represented in Fig. 9(b). The best-fitted line between UPV and 28 days compressive strength is a linear curve and it implies that with increasing UPV values compressive strength increases. A Strong correlation is observed between volume of voids and density due to the higher value of determination coefficient (0.9285).

4. Conclusions

This research demonstrates an experimental investigation to develop a sustainable concrete by analyzing the influence of incorporation of GBS as partial replacement of river sand on the properties of concrete. The CS, modulus of elasticity, WA, VV, density, chloride penetration, UPV of concrete containing different percentages of GBS (20, 40 and 60) have been determined and compared with the reference mix designed with natural sand as fine aggregate. The conclusions drawn from the analysis of the results of the study are summarized as follows.

- The 28 days CS of concrete specimens is found to be increased with increasing percentage of GBS. This enhancement in CS could be due to enhancement in formation of C-S-H gel when GBS reacted with various hydration products. The result of compressive strength conducted on variously sized specimen shows that CS of 100 mm cube specimens is highest among cubes and cylinders which are attributed to the fact that the decrease in aspect ratio increases compressive strength from others. This indicates concrete mixes containing GBS is following a similar trend with natural aggregate concrete.
- The elastic modulus of concrete mixes improved with the replacement of natural sand with GBS which could be due to improvement in the interfacial behavior of concrete by incorporation of GBS in concrete. The increase in the number of secondary C-S-H gel is primarily responsible for this improvement.
- The chloride penetration depth of concrete exhibits significant reduction with increasing percentage of GBS in concrete, which shows the better resistance to chloride penetration as compared to reference mix made with natural sand. This could be attributed to the formation of more number of C-S-H gel in GBS incorporated mixes.
- The decrease in volume of voids and water absorption and an increase in density are observed for concrete containing different percentages of GBS. This is due to the fibrous particle structure

of GBS which helps to fill the voids present in the concrete specimen. This shows that addition of GBS improves the durability properties of concrete.

- The Strong correlation between compressive strength and durability parameters such as water absorption, volume of voids and density is detected for concrete mixes containing GBS. The compressive strength has an inverse relationship with water absorption and volume of voids, however, the density of concrete is directly related to strength.
- The improvement of the quality of concrete could be accessed from the results of non-destructive parameters of concrete. The enhancement of UPV values of concrete containing GBS is observed in this study. Furthermore, the relationship between CS and UPV found to be consistent with the literature.

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