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Influence of granulated blast furnace slag as fine aggregate on properties of cement mortar

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Abstract. The objective of present study is to investigate the effect of granulated blast furnace slag (GBS) as partial substitution of natural sand on behaviour of cement mortar. For this, the methods of factorial design with water cement (w/c) ratio and incorporation percentages of GBS as replacement of natural fine aggregate i.e., GBS(%) as factors are followed. The levels of factor w/c ratio are fixed at 0.4, 0.45, and 0.5 and the levels of factor GBS(%) are kept fixed as 0%, 20%, 40%, 60%, 80% and 100%. The compressive strength (CS) of mortar after 3, 7, 14, 28, 56 and 90 days, and water absorption (WA) are chosen as responses of the study. Analysis of variance (ANOVA) of experimental results has been carried out and those are illustrated by ANOVA tables, main effect and interaction plots. The results of study depict that the selected factors have substantial influence on the strength and WA of mortar. However, the interaction of factors has no substantial impact on CS and WA of mixes.

Keywords: ANOVA; granulated blast furnace slag; compressive strength; water absorption

1. Introduction

Utilisation of various industrial waste products as replacement of natural aggregates provides several sustainable benefits like preservation of sources of natural aggregates, reduction of landfills, conservation of energy and reduction in the rate of emission of greenhouse gases (Topçu and Boğa 2010, Mukharjee and Barai 2015a, Ambily *et al*. 2015, Lee *et al*. 2016). With vast increase in the use of concrete for construction work, several parts of world are facing acute shortage of natural aggregates. Furthermore, a number of 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. Therefore, researchers have been trying to utilise aggregates retrieved from various industrial waste products, construction demolition waste and agricultural waste for making concrete (Kehagia 2009, Chithra *et al*. 2016, Mukharjee and Barai 2015b, Kockal 2016, Ding *et al*. 2017, dos Anjos *et al*. 2017). The molten form of slag collected from blast furnace of iron and steel industry is of molten form, which is

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cooled quickly by using powerful water jets.

After the cooling process, the molten slag changes to granular, fine and glassy form which is known as granulated blast furnace slag (GBS). The use of powdered form of granulated blast furnace slag as partial replacement of cement for making concrete has been well established (Patra and Mukharjee 2014). The properties of mortar and concrete were significantly influenced by the use of aggregates produced from steel slag because of the hydraulic activity of steel slag (Lin *et al*. 2003, Singh *et al*. 2015). Moreover, around 30% increase in 28 days CS was detected for specimens with steel slag as coarse and fine aggregate (Chunlin *et al*. 2011). The GBS was utilized in alkali activated slag mortars as fine aggregate and found to have beneficial for improving its resistance to temperature (Rashad *et al*. 2016). Furthermore, enhancement in the fatigue life of mortar and static compressive strength (CS) was detected with the use of GBS in mortar (Farooq *et al*. 2017). Workability of concrete decreased substantially with the utilization of GBS as substitution of sand owing to its high water absorption (Binici *et al*. 2008, Patra and Mukharjee 2017a). However, the study depicted that incorporation of GBS had no substantial impact on the fresh density of concrete mixes. Strength development ratio calculated after days for GBS incorporated mixes was similar to normal concrete (Binici *et al*. 2009). Babu and Mahendran (2014) demonstrated that strength of concrete made with slag as fine aggregate improved up to 25% and further enhancement in the percentage of incorporation of GBS decreased the strength. Improvement in the 28 and 90 days CS, resistance to permeability and sulphate resistance of concrete was observed with the use of GBS in place of sand (Binici *et al*. 2012). Furthermore, the resistance to water and chloride penetration was enhanced with use of GBS as fine aggregate in designing concrete mixes (Binici *et al*. 2008). Scanning electron microscope was employed for analyzing the microstructure of concrete containing GBS as fine aggregate and it was observed that there was increase in number of C-S-H gel in GBS incorporated mixes, as 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. In another study, Yuskel *et al.* (2008) found that GBS having grain size more than 30 μm participated in hydration process similar to normal aggregate by performing analysis of microstructure by using scanning electron microscope. The study also reported about enhancement in resistance to high temperature, abrasion, freezing, and thawing with the use of 20% GBS in concrete. Furthermore, enhancement in the tensile behaviour of concrete was detected by use of GBS in concrete as fine aggregate (Zeghichi 2006). Durability of concrete also affected with the substitution of sand by GBS (Patra and Mukharjee 2017b) The utilization of fines made 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).

Design of experiments is very useful in determining the influence of factors and the responses when number factors are involved in a process. The determination of insignificant factors and elimination of these factors could be done by following procedures of design of experiments. Moreover, statistically planned experiments are employed for determining the best combination for achieving optimized properties of a mixture. Nehdi and Summer (2002) used 3^2 design for determining the effect of various waste products on characteristics of mortar. Sneff *et al*. (2012) adopted factorial design for evaluating the individual and interactive effect of nano-silica and nano- TiO_2 on long term properties of mortar. It was observed that the contribution of main effects and interaction between factors did not significant effect on CS; however, substantial influence on rheology of mortar was detected. Mukharjee and Barai (2014) utilized factorial design of experiments for accessing the influence w/c ratio and percentage of nano-silica on water absorption and strength of mortar. Several studies have been also conducted in area of application of procedures of design of experiments for accessing influence of different factors on the behavior of concrete. Lopez-Gayarre *et al*. (2009) studied the effect of quality and amount of the recycled aggregate on characteristics of concrete. ANOVA technique was used for analysis of experimental results and screening insignificant factors. Use of design experiments for analyzing the concrete behavior with consideration of various factors has been reported in literature (Correia *et al*. 2009, Alqadi *et al*. 2013, Mukahrjee and Barai 2014).

Determination of effect of various factors on the properties of mortar and concrete using design of experiment has been found in existing literature. Furthermore, several studies have been conducted in the area of use of from blast furnace slag as aggregates in developing sustainable mixes. The purpose of the current study is to determine the effect of the different factors on the properties of mortar using the procedures of factorial design. For this, the W/C ratio and GBS(%) are selected as factors and CS after different curing days and WA are chosen as responses. Two-way ANOVA has been performed on experiential results and the outcomes of this study are illustrated with the help of individual value, contour, main effects and interaction plots.

2. Material and methods

2.1 Materials

Commercially available OPC (Ordinary Portland Cement) grade - 43 confirming to BIS 8112 (1959) provided by Ultratech Co. Ltd. was used in the present experimental work, for designing mortar mixes. The experimental work completed within 30 days of procurement of cement to avoid the negative effect on cement because of storage. Table 1 illustrates the characterized properties of cement which are obtained by adopting standard procedures followed by Bureau of Indian Standards.

The GBS was brought from the steel plant located at Rourkela (A city of Eastern India) used for current study. Table 2 illustrates the chemical composition of cement and GBS. Scanning Electron Microscope (SEM) analysis which is performed for GBS in bright field mode and represented in Fig. 1(a). SEM is a unique technique 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.

Table 1 Properties of the cement

Fineness (%)	Standard Consistency (%)	Specific gravity	Setting time (min)		Soundness (mm)	Compressive strength (MPa)		
			Initial	Final		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

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	-	-	-
GBS	1250	1157	2.56	1.2	-	-	-

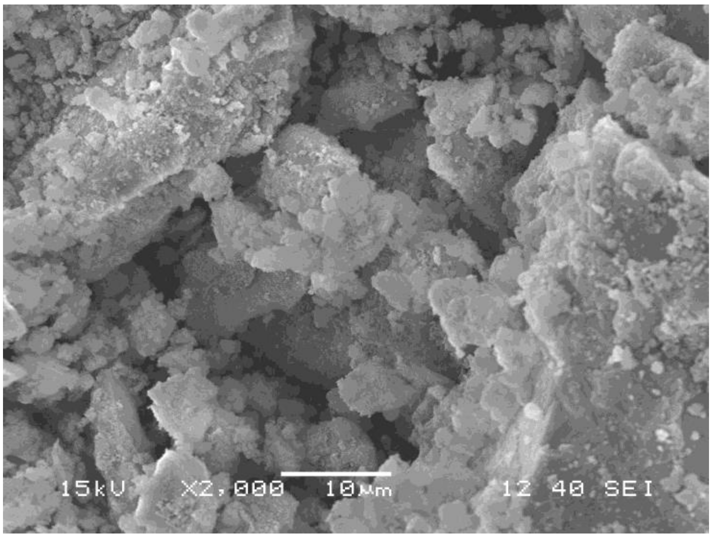


Fig. 1(a) Scanning electron microscope micrograph of GBS

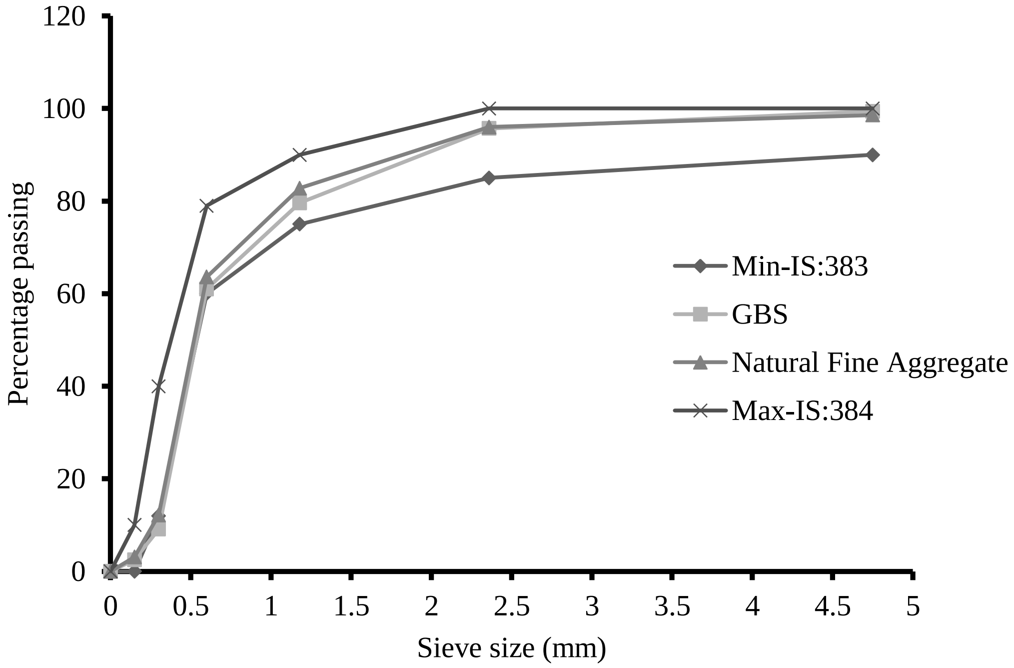


Fig. 1(b) Particle size distribution curve of natural fine aggregate and GBS

The gradation of sand for preparation of mortar specimens was kept in accordance to the BIS 4031 (part- 6) (1988). The gradation of GBS was kept similar to the sand as per aforementioned code while making replacements for natural sand. The standard test results for various properties of aggregates as well as GBS were presented in Table 3. In addition the particle size distribution curve of natural fine aggregate and GBS was represented in Fig. 1(b).

2.2 Specimen casting, curing and testing

A mechanical mixer having a working speed of 80 rpm was used for dry mixing of the solid ingredients which includes cement, fine aggregate and cement. The mortar mix proportion was taken as 1:3 for cement and fine aggregate ratio. GBS was replaced with natural sand with 20%, 40%, 60%, 80% and 100% replacement level and w/c ratio was varied as 0.4, 0.45 and 0.5. The mixer was operated for 4 min for each mix to ensure homogeneous mixing and water is added afterwards. Immediately after the mixing process was completed, the mortar mix was put into the moulds of size 70.6×70.6×70.6 mm conforming to BIS 10080 (1982) placed on the vibrating table and prodded for 20 times in about 8 seconds to ensure elimination of any entrapped air. The period of vibration was 2 minute at a speed of 12000±400 vibrations per minute. After keeping the mix for 24 hours, specimens were brought out from the moulds and cured under water at 27℃±2℃. A 2000 kN compression testing machine confirming to BIS 516 (1959) with a constant rate of loading 35 N/ mm^2/min was used to determine the CS of the mortar cubes after 3, 7, 14, 28, 56 and 90 days of curing period and WA test was performed after 28 days of curing period. For each curing period average test result of three mortar cube specimens were taken.

2.3 Factorial design of experiments

Design of experiments (DOE) has a substantial role in determining the influence of various factors on the responses and helps in screening of insignificant factors. When two or more factors are involved in a process then factorial experimental design is powerful technique for analyzing their effect on the process. Usually, experimental trials (or runs) are conducted for various combinations of levels of all factors for a full factorial design. Furthermore, the analysis of variance (ANOVA) is employed which is one of the major tools to analyze statistical data. The number of combinations are '$c\times d$', when the factor levels of two factors 'C' and 'D' are fixed at 'c' and 'd' respectively. If the experiment has 'n' replicates for each treatment then total numbers of observations are '$c\times d\times n$', which are determined in random order. The observations is represented by

$$y_{ijk}=\mu+\tau_i+\beta_j+(\tau\beta)_{ij}+\epsilon_{ijk,} \text{ where } i=1,2,3\ldots,a;\quad j=1,2,3\ldots,b;\quad k=1,2,3\ldots,n; \tag{1}$$

where μ is the overall mean effect, τ_i is the effect of the i^{th} level of factor C, β_j is the effect of the j^{th} level of factor C, $(\tau\beta)_{ij}$ is the effect of the interaction between C and D, and ϵ_{ijk} is a random error component having a normal distribution with mean zero and variance. The details of testing of hypothesis are being performed by ANOVA. The analysis of variance for the two-factor factorial design is given in following format (Table 4)

The total sum of squares is computed by

$$SS_T=\sum_{i=1}^{c}\sum_{j=1}^{d}\sum_{k=1}^{n}y_{ijk}^2-\frac{y_{\ldots}^2}{cdn} \tag{2}$$

Table 4 Details of terms associated with two-way ANOVA

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_0
C treatments	SS_C	c-1	$MS_C = SS_C/c-1$	$F_0 = MS_C/MS_E$
D treatments	SS_D	d-1	$MS_D = SS_D/d-1$	$F_0 = MS_D/MS_E$
Interaction	SS_{CD}	(c-1) (d-1)	$MS_{CD} = SS_{CD}/(c-1)(d-1)$	$F_0 = MS_{CD}/MS_E$
Error	SS_E	$cd(n$-1)	$MS_E = SS_E/cd(n-1)$	
Total	SS_T	cdn-1		

The sums of squares of the main and interaction effects are given as follows

$$SS_C = \frac{1}{dn}\sum_{i=1}^{c} y_{i..}^2 - \frac{y_{...}^2}{cdn} \quad (3)$$

$$SS_D = \frac{1}{cn}\sum_{j=1}^{d} y_{j..}^2 - \frac{y_{...}^2}{cdn} \quad (4)$$

$$SS_{Subtotals} = \frac{1}{n}\sum_{i=1}^{c}\sum_{j=1}^{d} y_{ij.}^2 - \frac{y_{...}^2}{cdn} \quad (5)$$

$$SS_{CD} = SS_{Subtotals} - SS_C - SS_D \quad (6)$$

$$SS_E = SST - SS_{substotal} \quad (7)$$

Main effect refers to the influence of the primary factors on the selected responses. The difference of response between the levels for one factor is not the same at all levels of the other factor which is due to the existence of interaction between the factors. The *p*-value of Fisher distribution is less than 0.05 in 95% confidence level for one factor or interaction of many factors is considered to be statistically significant. *F*-value is the distribution of one random variable defined as the ratio of two chi-square random variables each divided by their number of degrees of freedom. The p-value can be defined as the lowest level of significance which would lead to rejection of the null hypothesis, which is 5% in the present study. Degree of freedom (DF) can be defined as the number of independent comparisons that can be carried out between the elements of a sample.

3. Result and discussion

3.1 3 days CS

The individual value plot for the results of 3 days CS with varying w/c ratio and GBS(%) is illustrated in Fig. 2(a), which illustrates that 3 days CS reduces with increase in the level of GBS(%) for a fixed W/C ratio. This reduction in strength early days is because of slow pozzolanic action of GBS (Binici *et al*. 2008). Moreover, 3 days CS shows a decreasing tend with an enhancement in the factor w/c ratio, as the mortar matrix weakens with increase in the amount of water in the mix. It should be noted that individual standard deviation has been used for determining intervals in the individual value plot. Individual plots for 3days CS show closer values to particular combination of each factor. Fig. 2(b) represents the contour plots of 3 days CS

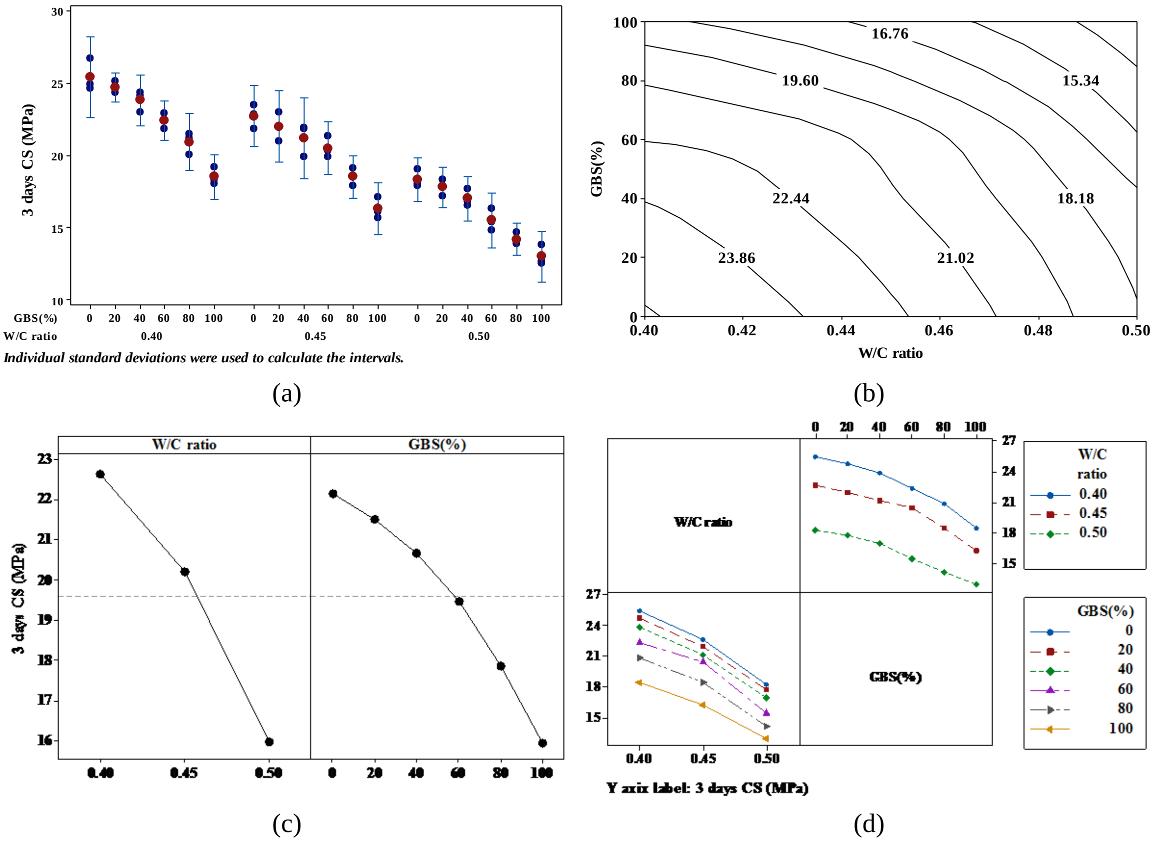


Fig. 2 (a) Individual value plot (b) Contour plot (c) Main effects plot (d) interaction plot of 3 days CS

with varying GBS(%) and w/c ratio. Contour lines are obtained at a fixed interval (1.42 MPa) and vary from 13.92 MPa to 25.28 MPa. The contour plot also indicated that reduction in contour values is detected with enhancement in the w/c ratio. Similar type of trend for an increase in the level of GBS(%).

Table 5 indicates the results of ANOVA of experimental data of 3 days CS, which shows that w/c ratio Higher *F*-values and *p*-value lower 0.05 shows that GBS(%) and W/C ratio are considerably influencing the CS strength after 3 days. The delay in the pozzolanic activity of GBS and weaker bonding with increasing W/C ratio are explanations for substantial impact of the selected factors W/C ratio and GBS(%) on the response. However, the ANOVA results indicate no significance impact of interaction of factors on 3 days CS as p-value higher than 0.05 is obtained. Fig. 2(c) represents the main effect plot for 3 days CS with variation of W/C ratio and GBS(%), which indicates that 3 days CS declines from 22.62 MPa to 15.97 MPa with the enhancement in W/C ratio (0.4 to 0.5). Furthermore, 3 days CS reduces from 22.13 MPa to 15.93 MPa with change in amount of GBS(0 to 100%). The interaction plot for 3 days CS is presented in Fig. 2(d), which depicts the non-existence of the interaction effect, as interaction lines are not crossing each other that signifies that for each W/C ratio, reduction in 3 days CS is observed with increase in level of other factor GBS(%). The lower strength GBS incorporated mortar could be attributed to the delay in hydration of cement as GBS contributes hydration process, which is lower in early days.

Table 5 Analysis of Variance for 3 days CS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
W/C ratio	2	407.903	203.952	367.48	0.000
GBS(%)	5	248.688	49.738	89.62	0.000
W/C ratio*GBS(%)	10	3.677	0.368	0.66	0.751
Error	36	19.980	0.555		
Total	53	680.248			

Table 6 Analysis of variance for 7 days CS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
W/C ratio	2	903.753	451.876	277.73	0.000
GBS(%)	5	616.156	123.231	75.74	0.000
W/C ratio*GBS(%)	10	5.496	0.550	0.34	0.964
Error	36	58.573	1.627		
Total	53	1583.979			

However, natural sand is inert and has no role in hydration process. During early days, the rate of hydration is lower for GBS incorporated mortar than natural ones.

3.2 7 days CS

Fig. 3 represents the individual value, contour, main effects and interaction plot of 7 days CS of mortar. The intervals of the individual plot are construction based upon the individual standard deviation each combination of factors. It can be seen from the figure that 7 days CS of mortar decreases with the enhancement in W/C ratio which leads to the lesser strength of mortar matrix with increase in the amount of water (Fig. 3(a)). However, 7 days CS improves with the increase in the GBS (%) from 0% to 60% and after 60% replacement level the strength starts decreasing. The contour plots of 7 days CS are plotted and presented in Fig. 3(b). The contour interval is fixed at 2 MPa and ranges from 22 MPa to 40 MPa. The plot indicates that CS after 7 days shows a decreasing trend with an enhancement in level of W/C ratio. However, contour lines for 7 days CS of mortar shows an increasing trend up 60% GBS and after that values of contour lines reduces. The main effects plot of 7 days CS Fig. 3(c). The 7 days CS reduces from 36.02 MPa to 26.15 MPa with the rise in level of the W/C ratio 0.4 to 0.45, which indicates that main 7 days CS shows a reducing trend for an enhancement in W/C ratio. However, the values of 7 days CS changes from 30. 73 MPa to 35.93 MPa with the change level of GBS from 0 to 60%, which indicates the beneficial effect of GBS on CS. The 7 days CS declines from 35.93 MPa to 26.22 MPa when the GBS(%) is increased from 60% to 100%. The effects of factors are found to have symbolic effect on the 7 days CS (p-value < 0.05) (Table 6). The interaction plot is represented in Fig. 3(d), which indicates that for each level of W/C ratio, the effect of the change in the level of GBS(%) is same.

In other way, the 7 days CS increases up to 60% and then starts reducing up to 100% for every W/C ratio. Similarly, for every level of GBS(%), 7 days CS reduces with change in W/C ratio from 0.4 to 0.45, which indicates no considerable impact of interaction of factors. The absence of interaction between could be seen from the ANOVA table as p-value is more than 0.05 (Table 5).

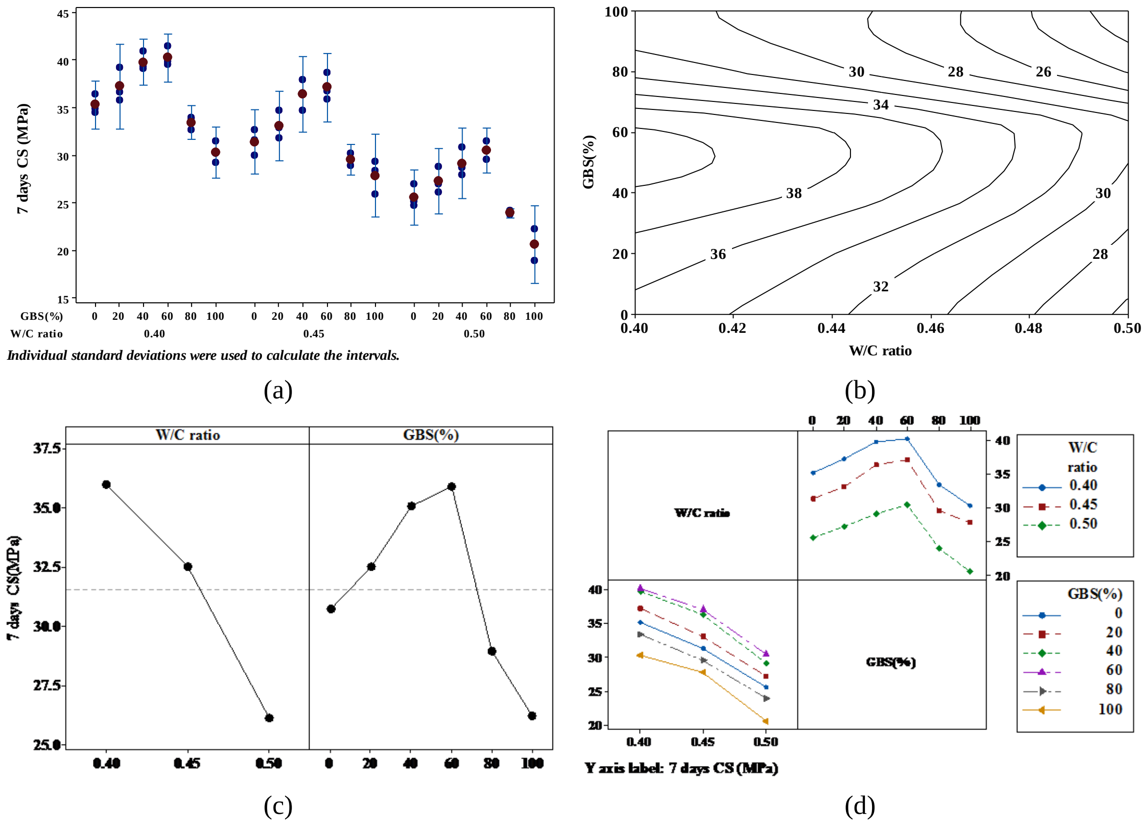


Fig. 3 (a) Individual value plot (b) Contour plot (c) Main effects plot (d) interaction plot of 7 days CS

3.3 14 days CS

The results of 14 days CS of mortar determined for varying amount of GBS and at different W/C ratio has been analysed and those are shown in Fig. 4. The individual plot for 14 days CS indicates that CS after 14 days reduces with augmentation in W/C ratio (Fig. 4(a)). However, 14 days CS increases with the increasing GBS(%) up to 60% and after this level strength reduces up to 100%. The 95% confidence interval is presented in individual plot based upon individual standard deviation. The contour plot of 14 days CS is represented in Fig. 4(b), which indicates reduced vales of contour lines with increase in W/C because of increase in amount of water in mortar mixes. However, enhancement in the contour values can be detected for increase in the level of GBS (%) up to 60% and beyond this level strength decreases. Fig. 4(c) represents the main effects plot for 14 days CS varying GBS (%) and W/C ratio. The CS reduces from 36.96 MPa to 30.55 MPa with enhancement in W/C ratio from 0.4 to 0.5. However, 14 days CS of mortar increases from 34.93 MPa to 40.22 MPa with an enhancement in the level of GBS (%) from 0% to 60%. Furthermore, 14 days CS of mortar reduces from 40.22 MPa 30.27 MPa with increase in the level of GBS (%) from 60% to 100%. The aforementioned analysis indicates that the main effects of W/C ratio and GBS (%) has considerable influence on the response which can be confirmed from the ANOVA results of 14 days CS (Table 7).

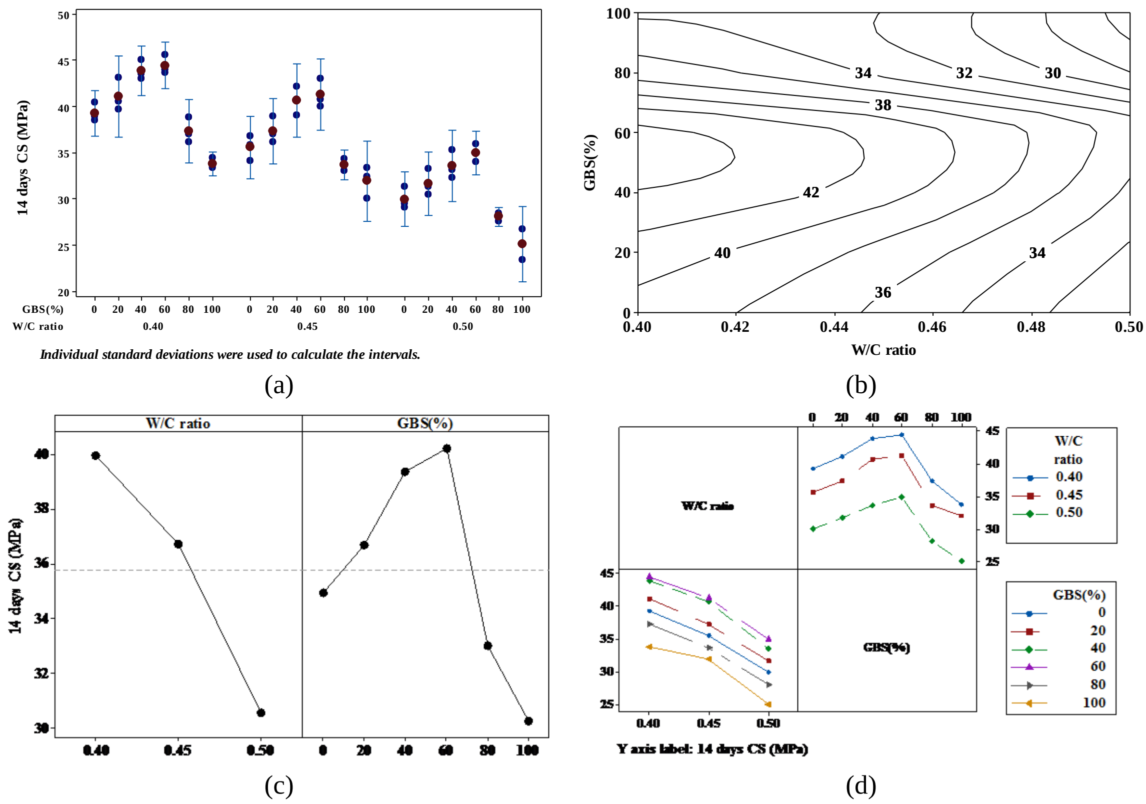


Fig. 4 (a) Individual value plot (b) Contour plot (c) Main effects plot (d) interaction plot of 14 days CS

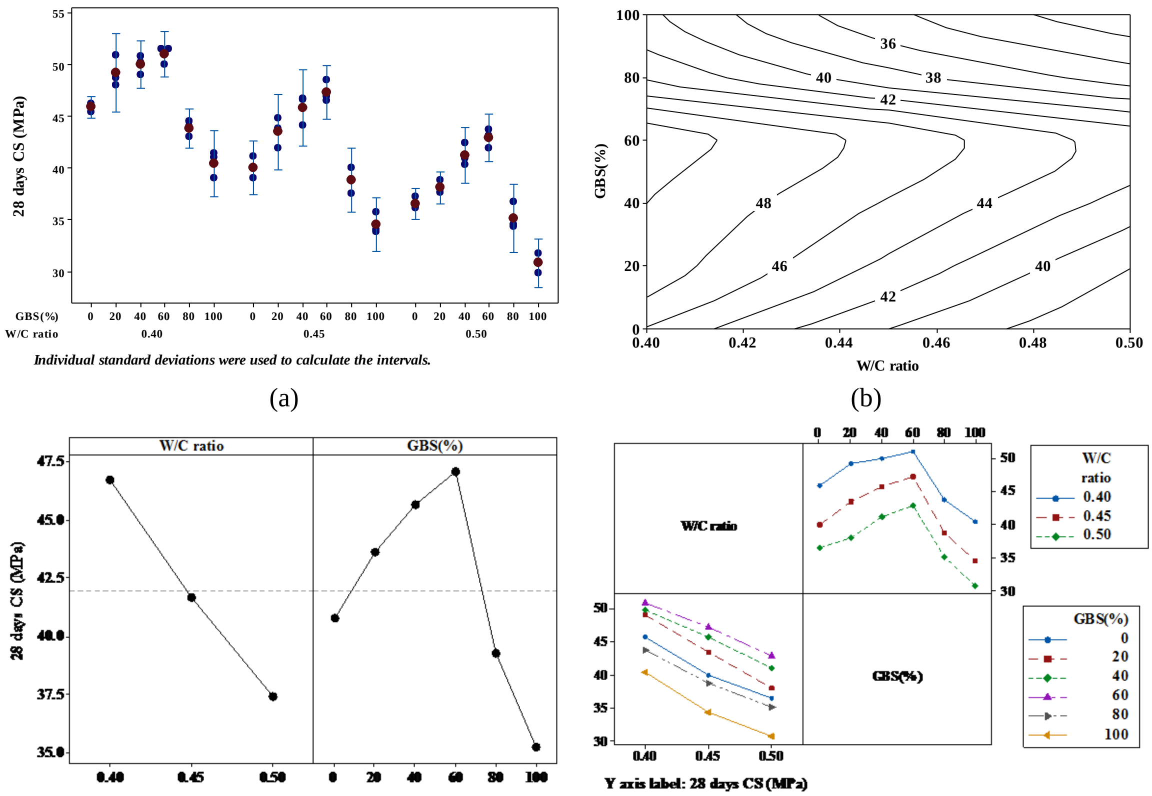
Table 7 Analysis of variance for 14 days CS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
W/C ratio	2	823.327	411.664	243.27	0.000
GBS(%)	5	650.519	130.104	76.88	0.000
W/C ratio*GBS(%)	10	6.169	0.617	0.36	0.954
Error	36	60.920	1.692		
Total	53	1540.935			

The *p*-values of the factors GBS (%) and W/C ratio are less than 0.05 confirms about the significance effect of these factors on 14 days CS of mortar mixes. The interaction plots of 14 days CS of mortar for various levels of factors is presented in Fig. 4(d), which indicates that interactions of factors have no significant influence on 14 days CS. For every level of W/C ratio the change in level of GBS (%) have similar effect on the response 14 days CS. Furthermore, for every level of GBS (%), enhancement in the level of W/C ratio, reduction in the 14 days CS has been detected. The ANOVA results also provide similar conclusion as p-value for interaction is more than 0.05.

3.4 28 days CS

The 28 days CS of mortar decreases with the change of W/C ratio from 0.4 to 0.45(Fig. 5(a));



(a) (b)

(c) (d)

Fig. 5 (a) Individual value plot (b) Contour plot (c) Main effects plot (d) interaction plot of 28 days CS

however, 28 days CS increases with an increase in GBS (%) from 0% to 60% and beyond this level it reduces significantly. In this plot, individual standard deviation is used for calculation of 95% of confidence interval. The contour plots for 28 days CS is furnished in Fig. 5(b), which indicates that contour values reduce with increasing the W/C ratio from 0.4 to 0.5, because of the weakening cement paste matrix.

However, the value of contour lines increases with increases in the level of GBS (%) from 0% to 60% and beyond this level 28 days CS of mortar reduces. Fig. 5(c) show the main effects plot of 28 days CS with the various levels of factors W/C ratio and GBS (%). The 28 days CS of mortar is 40.78 MPa at 0% GBS, which increases to 47.07 MPa for change in GBS(%) 0% to 60%. However, it reduces from 47.07 MPa to 35.25 MPa with the change in the GBS(%) from 60% to 100%. It is also obtained that 28 days CS of mortar changes from 46.72 MPa to 37.44 MPa with change in W/C ratio from 0.4 to 0.5. The analysis of main effect plot indicates that the main effects of the factors have substantial effect on the response, which can be seen from ANOVA Table (Table 8). The p-values are less than 0.05 for the main effects of factors. This indicates that 28 days CS is significantly affected by the factors. The interaction plot for 28 days CS of mortar shows that interaction of factors has no significant impact on the 28 days CS as non-intersecting lines are obtained from the interaction plots (Fig. 5(d)). This indicates that the impact of one factor on the response is unaffected by the change in the level of other factor. The behaviour of the factor

Table 8 Analysis of variance for 28 days CS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
W/C ratio	2	777.905	388.952	333.81	0.000
GBS(%)	5	864.719	172.944	148.43	0.000
W/C ratio*GBS(%)	10	12.640	1.264	1.08	0.399
Error	36	41.947	1.165		
Total	53	1697.210			

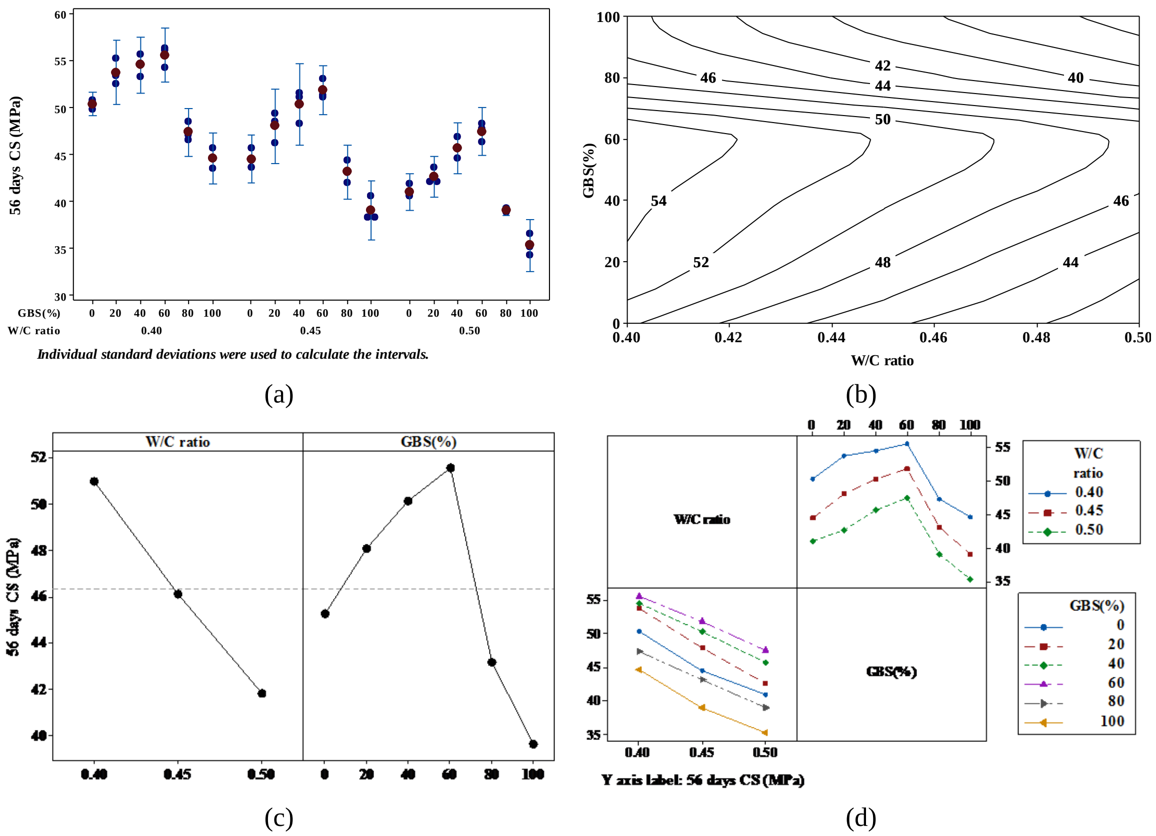


Fig. 6 (a) Individual value plot (b) Contour plot (c) Main effects plot (d) interaction plot of 56 days CS

GBS(%) is similar for all the levels of W/C ratio. i.e., CS of mortar increases upto the addition of GBS to 60% and reduces beyond 60% regardless of W/C ratio. Similarly, with the increase inW/C ratio from 0.45 to 0.5, CS decreases at each level of GBS(%). This causes due to the increment in the amount of voids. Furthermore, the results obtained from the ANOVA study illustrates that interactions of both factors have no considerable effect on the 28-days CS of mortar as p-value less than 0.05 is obtained.

3.5 56 days CS

Fig. 6(a) illustrates the individual value plot of the response 56 days CS, which depicts that 56

Table 9 Analysis of variance for 56 days CS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
W/C ratio	2	759.125	379.562	299.35	0.000
GBS(%)	5	910.896	182.179	143.68	0.000
W/C ratio*GBS(%)	10	12.311	1.231	0.97	0.485
Error	36	45.647	1.268		
Total	53	1727.979			

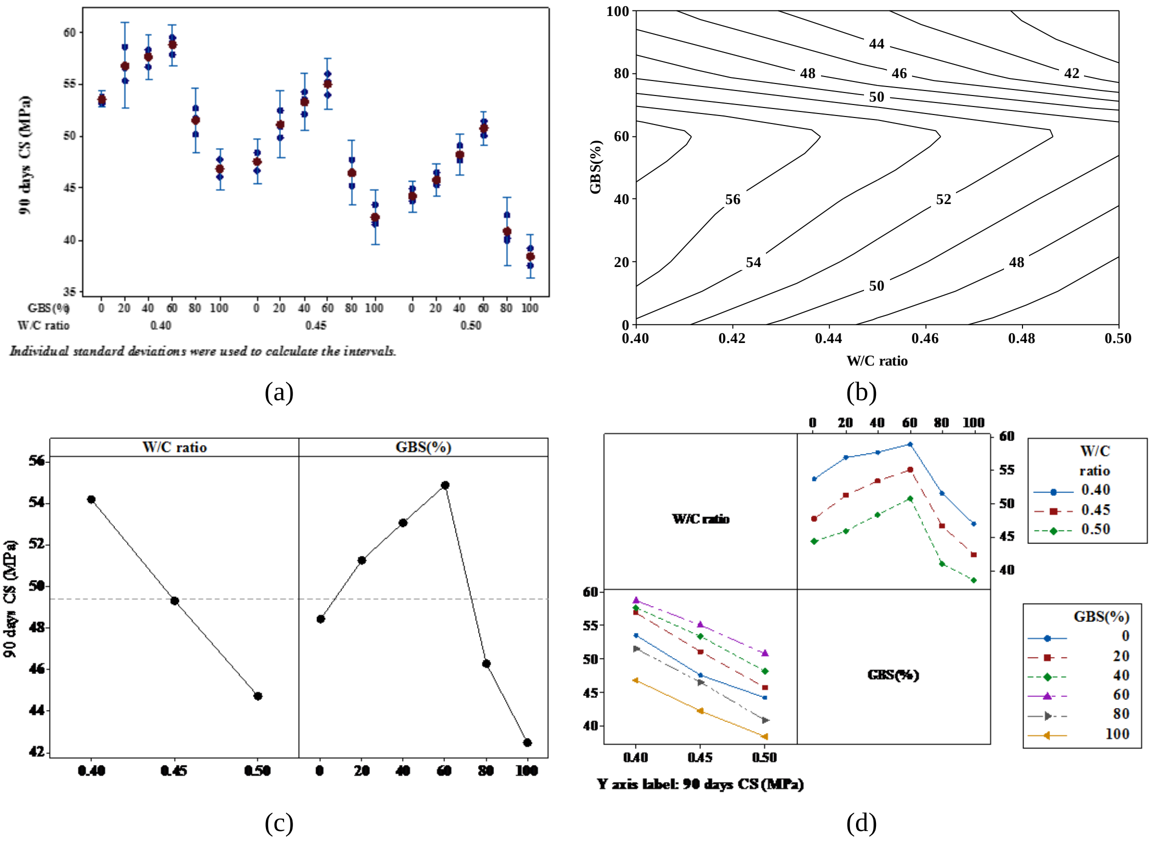


Fig. 7 (a) Individual value plot (b) Contour plot (c) Main effects plot (d) interaction plot of 90 days CS

days CS improves with the augmentation of GBS up to 60% and after this substitution level strength starts reducing. Furthermore, enhancement in the level of the other factor has negative impact on the CS after 56 days. Reduction in contour values of 56 days CS of mortar can be seen with the rise W/C ratio from 0.4 to 0.5 (Fig. 6(b)). However, improvement in the contour values are detected with the increase in the GBS(%) from 0 to 60% and beyond this level strength reduces. Theses contour lines are drawn at an interval of 2 MPa and are ranging from 36 MPa to 54 MPa. Fig. 6(c) represents the main effects of 56 days CS with consideration of varying levels of two selected factors. The 56 days CS changes from 45.28 MPa to 51.59 MPa with the rise in the GBS(%) from 0 to 60% and reduces from 51.59 MPa to 39.64 MPa for change in GBS(%) from

Table 10 Analysis of variance for 90 days CS

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
W/C ratio	2	811.60	405.80	401.56	0.000
GBS(%)	5	948.74	189.75	187.77	0.000
W/C ratio*GBS(%)	10	14.75	1.48	1.46	0.195
Error	36	36.38	1.01		
Total	53	1811.47			

60% to 100%. Increase in the level of W/C ratio from 0.4 to 0.5 reduces the 56 days CS from 51.01MPa to 41.83 MPa. From the aforementioned analysis, the selected factors are considerably affecting the response which can be confirmed from ANOVA table (Table 9).

The *p*-value for the factors is less than 0.05 which indicates about presence of significant influence of factors on the response. However, the interactions of factors have no substantial impact on the response (*p*-value >0.05). The interaction of factors have no significant influence as most of these lines are not intersecting i.e. for every level of GBS(%) , the effect of change of W/C ratio has similar effect on 56 days CS of mortar. Furthermore, for every level of W/C ratio, CS after 90 days increases up to 60% and beyond this mark strength decreases.

3.6 90 days CS

The individual values and contour plots of the response 90 days CS with varying W/C ratio and GBS (%) are presented in Fig. 7(a) and 7(b) respectively. The individual values for a specific combination factors are found to be close to each other. The individual standard deviation is used for calculating 95% confidence interval. The individual value plot indicates that CS of mortar after 90 days reduces with increasing W/C ratio from 0.4 to 0.5 and increases with enhancement of the level of factor GBS (%) from 0% to 60%. However, increase in the factor level from 60% to 100% shows an adverse effect on the 90 days CS mortar. The contour lines shows a decreasing trend with augmentation in W/C ratio and for fixed level of W/C ratio, the contour values increase up to 60% and beyond that values start reducing (Fig. 7(b)).

This indicates that beneficial effect of incorporation of GBS could be detected up 60%. The contour lines are drawn at an interval of 2 MPa and range from 40 MPa to 58 MPa. The main effects plot indicates about the substantial impact of the factors. The 90 days CS improves from 48.4 MPa to 54.88 MPa with an increase in the level of factor from 0% to 60% and CS reduces from 54.88 MPa 42.48 MPa for change in the level of GBS (%) from 60% to 100%. Furthermore, CS after 90 days declines from 54.20 MPa to 44.71 with the change in the W/C ratio from 0.4 to 0.5. The significant effect on factors could be detected from ANOVA table as p-value for the aforementioned factors less than 0.05 (Table 10).

3.7 28 days WA

The individual value plot of WA of mortar with varying W/C ratio and GBS(%) is illustrated in Fig. 8(a), which illustrates about the increase in WA with the enhancement in W/C ratio. This change is probably because of augmentation in quantity of voids in the mortar with rising W/C ratio. Conversely, the reduction in the WA has been detected with the increase in the GBS(%)

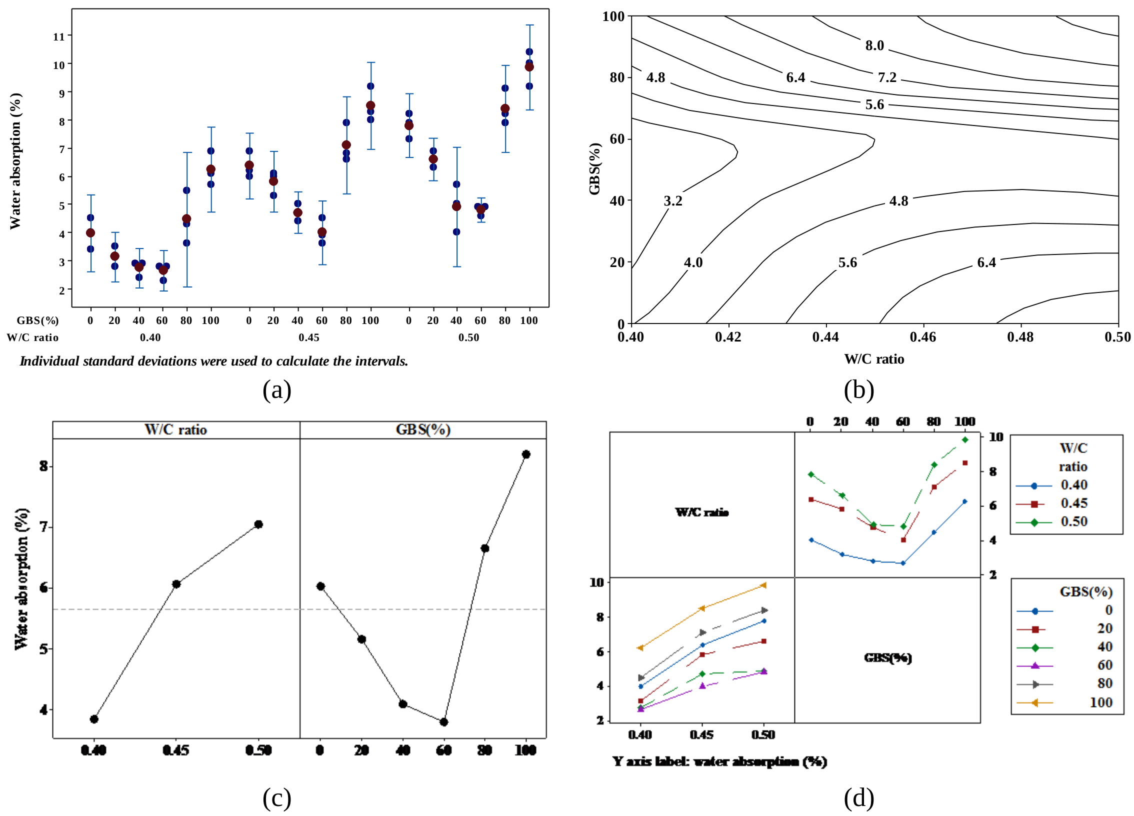


Fig. 8 (a) Individual value plot (b) Contour plot (c) Main effects plot (d) interaction plot of WA

from 0% to 60%, which is because of the reduction of amount voids present in the mortar. Further enhancement in the GBS(%) beyond 60% lead to the increase in WA of mortar mixes.

Fig. 8(b) presents the contour plot of WA of mortar specimens with varying W/C ratio and GBS(%). The contour lines are drawn at an interval of 0.8% and vary from 3.2% to 9.6%. The values of contour levels are increased with increase in W/C ratio. However, contour values decreases with increase in GBS(%) from 0% to 60% for particular level of W/C ratio and further increase in the GBS(%) increases the WA of mortar. The main effects plot of WA of mortar with is shown in Fig. 8(c), which illustrates that WA changes from 3.86% to 7.06% with the enhancement in W/C ratio from 0.4 to 0.5 with increase in the amount of voids in the mortar. However, WA of mortar reduces from 6.04% to 3.81% when the level of GBS(%) changes from 0% to 60% and further increase in GBS(%) from 60% to 100% the WA increases from 3.81% to 8.2%. The analysis of main effects plot of WA indicates that W/C ratio and GBS(%) are considerably influencing the WA, which can be confirmed from the ANOVA of test results of WA (Table 10). The *p*-value <0.05 and higher *F*-value confirms that these factors have substantial impact on WA of mortar. The increase in the amount of void with increasing WA ratio and densification of mortar with addition of GBS are main reasons for the substantial effect on the response. However, increasing the incorporation of GBS beyond 60% has negative impact on the mortar matrix. The interaction plot of WA is shown in Fig. 8(d), which shows that most of lines are not intersecting each other, which indicates about the insignificance of interaction effect. When

Table 11 Analysis of variance for WA

Source	Degrees of Freedom	Sum of Squares	Mean Square	F-value	P-value
W/C ratio	2	96.723	48.362	164.04	0.000
GBS(%)	5	122.762	24.552	83.28	0.000
W/C ratio*GBS(%)	10	5.661	0.566	1.92	0.074
Error	36	10.613	0.295		
Total	53	235.760			

two lines intersect each other or close to each other, interaction effects of the factors is substantial. Alternatively, the impact of a factor on the response is unaffected by the changing of level of other factor. This non-existence of interaction effect could be visualized from ANOVA table as the *p*-value for the interaction is more than 5% (Table 11).

4. Conclusions

The present study has been designed to access the impact of utilization of GBS as fine aggregates on the various properties of mortar. Factorial deign of experiment has been employed with W/C ratio and GBS (%) as factors. The levels of W/C ratio are 0.4, 0.45 and 0.5, and the levels of GBS(%) are 0%, 20%, 40%, 60%, 80% and 100%. Compressive strength after 3, 7, 14, 28, 56, and 90 days, and water absorption are selected as responses for this study. Two-way ANOVA has been conducted on the test results for determination of importance of the main and interaction effects. Furthermore, detailed description of the analysis is carried out by individual and contour plots, main effect and interaction plots. The inferences of this investigation are illustrated as follows:

- The individual and contour plots for CS after 3 days of curing illustrates that CS reduces with increase in the levels of the both factors (W/C) ratio and GBS (%). The wakening of cement paste with the enhancement in the (W/C) ratio and lower pozzolanic activity during early days are explanations for this type of behaviour of cement mortar. Moreover, W/C ratio and GBS (%) are considerably affecting strength after 3 days, which can be seen from ANOVA results and main effect plots. However, ANOVA results and interaction plot depicts that the interaction effect has no considerable influence on strength parameters.
- The 7,14, 28, 56 and 90 days CS is reduced with change in the W/C ratio from 0.4 to 0.5 and increased with the increase in the amount of GBS from 0% to 60% and beyond this level strength starts reducing. Factors like W/C ratio and GBS(%) have considerable impact on CS of concrete, which can be observed from the contour and main effect plots. However, analysis of ANOVA table and interaction plot indicates insignificant influence of interaction between factors.
- The WA of mortar mixes declines with augmentation in the GBS content up to 60% and after that it increases. This reduction in WA by the incorporation of GBS(%) is because of reduction in of voids. However, WA improves with enhancement in w/c ratio because of in the void quantity.

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