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RESEARCH ARTICLE

Sustainable Cement-Blast Furnace Slag Mortar

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ABSTRACT

New building materials that required and produced less energy are need of today's infrastructure development. The ability of such building materials to promote sustainable development always puts its demand in active mode. With huge consumption of naturally occurring materials in building construction, the problem related to environment degradation is now common for world. Along with this, world is also facing the problem of reuse, recover and scientifically approved disposal of non-biodegradable wastes. Blast furnace slag (BFS) is one of those steel industry wastes that are abundantly available and their disposal arises as prime challenge for industries. This research work makes an effort to reuse BFS in the form of fine aggregates by replacing it with river sand in cement mortar. A partial to full proportion of river sand was replaced with crushed BFS to form mortar specimens. As per the experimental investigations, a significant change in compressive strength was recorded. The 28th day compressive strength was found 200% more with full replacement of river sand to BFS as compare to reference sample. No significant changes in strength were examined against action of acid and salt. Rapid decrease in strength at elevated temperature was recorded. Results for rebound hammer and UPV were also showed identical concern between actual and predictive strength characteristics. Experimental results were also validated through regression models shows that the models are identically feasible and depicted good relationship between actual and predicted data.

Keywords: Mortar, blast furnace slag, river sand, cement, compressive strength

1. Introduction

Research studies concerning significant utilization and minimization of solid wastes are needed world-wide. In this context, the disposal of blast furnace slag (BFS) presents a major challenge for solid waste management authorities. BFS is a byproduct produced during the purification of crude steel in steel manufacturing plants [1, 14]. On average, approximately 500 kg of solid waste is generated for every tonne of structural steel produced by the steel industry [1, 2]. In India, per capita steel consumption was 65 kg as of 2017. With rapidly increasing demand, India has emerged as the world's second-largest steel producer, following China [1].

The reuse of blast furnace slag (BFS) in applications such as building construction [2, 3, 12, 13] and

sinter production [1] has been practiced for many years. However, only about 15–20% of BFS is currently utilized in such activities, while the majority of this non-biodegradable waste is disposed of through incineration and land filling [2, 15]. These disposal methods pose significant environmental risks, contributing to soil infertility and increased air pollution. Rather than relying on these unsustainable practices, BFS may transform as an important asset in construction activities [16].

Mortar is one of the oldest and most essential building materials, playing a crucial role in construction development. With the rapid growth of infrastructure in India, the demand for mortar has increased significantly in recent years. Mortar is a composite material made from cement and sand (or fine aggregates), mixed in various proportions to achieve the desired

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strength [1, 2]. It is primarily used for plastering and pointing in construction. Conventionally, river sand is been used as fine aggregate in mortar and its demand has risen in recent time due to rapid growing in infrastructure development which in turn has created the shortage of these natural resources. Hence the need has arisen to find a suitable alternate material to replace the natural resources [14].

The acute shortage of river sand and restrictions on sand mining has given rise to find an alternate material to this natural resource. Due to the fact that fine aggregates can significantly affect the properties of mortar, consequently, a thorough evaluation is necessary before using any waste material as fine aggregate in mortar [1]. According to the user guideline report from the National Slag Association, Virginia [4], the typical chemical composition of blast furnace slag (BFS) includes CaO (34–43%), SiO₂ (27–38%), Al₂O₃ (7–12%), MgO (7–15%), FeO and Fe₂O₃ (0.2–1.6%), MnO (0.15–0.76%), and sulfur (1.0–1.9%) [29]. This composition makes BFS rich in cementitious properties, enabling its potential use as a supplementary cementitious material in construction applications [3, 28, 29].

The present study aims to explore the reuse of blast furnace slag (BFS) in the crushed form as a replacement for fine aggregate in the development of cement mortar. River sand was partially replaced with varying percentages of BFS, and an experimental investigation was conducted to evaluate its mechanical properties.

2. Literature survey

(Natrajan et al., 2013) [7] Incorporated reuse of granulated blast furnace slag (GBFS) in cement mortar. The objective of this research work was to make 1:3 ratio cement mortar by replacing natural sand with GBFS considering 0%, 25%, 50%, 75% and 100% replacement. OPC 43 grade cement was used in definite percentage as binder with 0.4, 0.5 and 0.6 water-cement ratio. Mortar specimens were casted in 70.6 mm cube and tested for compression after identical curing period. The compressive strength at 3, 7 and 28 days curing was noted maximum for 0.4 water cement ratio and minimum for 0.6 water cement ratio. Authors concluded that GBFS can be reused in the form of river sand up to 75% replacement of percentage. At 100% reuse of GBFS in mortar, negligible decrease in compressive strength was reported as compared to conventional mortar.

(Human and Siddique 2013) [8] Investigated on properties of cement mortar having iron slag content. By considering 1:3 cement mortar mix proportion,

mortar specimens were casted containing percentage of iron slag as 0%, 10%, 20% and 40% that had been reused in the form of fine aggregate (sand). Various tests were performed after 7, 28 and 56 days curing of mortar specimens. Authors concluded that as compare to control mortar at (0% replacement), the compressive strength increases with increase of iron slag in the mortar. Maximum compressive strength was reported for mortar specimens with 40% iron slag. Along with compressive strength, split tensile strength was also observed in increasing order with the increase of percentage of iron slag in mortar.

(Sambhaji et al., 2016) [9] Reported the use of copper slag as fine aggregate in concrete. Partial to full replacement of natural fine aggregate with copper slag had been examined for M25 concrete. Different eleven concrete mixes were designated considering percentage of replacement form 0 to 100%. In each concrete mix, copper slag had been replaced in 10% definite amount of conventional fine aggregate. The prepared concrete specimens with size 150 mm cube were cured and examined for strength and durability standards. Authors concluded that the high performance concrete characteristics were reported at 50% replacement. The compressive strength for all other concrete mixes were noted better than the strength of control concrete which shows adequacy of copper slag to be used in the form of natural fine aggregate. To check durability of concrete, the prepared specimen were immersed into 10% sulphuric acid solution for 28 days and then tested for compression, no significant change in compressive strength had been observed which shows good durability features of concrete.

(Shi et al., 2008) [10] Researched on application of copper slag in cement and concrete production. Authors reported that many alternatives are available to manage copper slag but the best potential option is its reuse in cement and concrete production. Copper slag mainly contains oxides of iron and copper. Reuse of copper slag in cement results decrease in calcinations temperature which improve the grind ability process. Authors concluded that as more than 70% of concrete and mortar volume is occupied by naturally occurring aggregates, copper slag may reused in more amount in the form of fine and coarse aggregate for environmental point of view and also to achieve higher strength and durability characteristics.

(Shubbar et al., 2019) [11] Researched on mechanical and durability aspects of fly ash (MFA) and ground granulated blast furnace slag (GGBS) as replaced with cement in the cement mortar. Along with control mortar specimen of size 40mm X 40mm X 160mm, three ternary mixers were also prepared with identity T40 (total 40% replacement of cement as

20% MFA and 20% GGBS), T60 (total 60% replacement of cement as 30% MFA and 30% GGBS) and T80 (total 80% replacement of cement as 40% MFA and 40% GGBS). Prepared specimens were tested for compression and electrical resistivity after required curing period of 3, 7, 14 and 28 days. The 28th day compressive strength for T40, T60 and T80 mortar was reported 16%, 29% and 37% less than control mortar. Electrical resistivity was examined on cylindrical specimens having 100mm diameter and 200mm height. Ternary mortar specimens were found more electrical resistant than control mortar specimen. Author concluded that reuse of MFA and GGBS can reduce CO₂ emission with the reduction of construction cost. The above literature review indicates the potential feasibility of using blast furnace slag (BFS) as a substitute for natural fine aggregate in cement mortar. This approach can meet construction requirements while offering the added benefits of reduced environmental impact and lower overall costs.

3. Methodology

The experimental study began with the collection of raw materials, including blast furnace slag (BFS), river sand, and Portland pozzolana cement (PPC), selected for their suitability in mortar preparation. The physical and chemical properties of these materials were determined to ensure compliance with standard requirements. BFS-based mortar specimens were then prepared using several mix proportions, ranging from SM0 to SM100, to investigate the effect of BFS content. After casting, all specimens were properly cured as a pre-testing procedure to achieve adequate hydration and strength development.

The experimental investigation on the cured specimens included evaluation of durability through water absorption and dry density tests, assessment of mechanical performance via compressive strength using a Compression Testing Machine (CTM), and examination of surface hardness and internal quality using non-destructive testing methods such as Ultrasonic Pulse Velocity (UPV) and Rebound Hammer tests. Additionally, the specimens were subjected to acid and salt exposure to study chemical resistance, and the effect of elevated temperature was analyzed to evaluate thermal stability and overall durability of the BFS-based mortar.

4. Experimental design

The experimental design was divided into two phases. The first phase involved the collection of raw materials and the assessment of their physical and



Fig. 1. Raw BFS.

chemical properties. The second phase focused on evaluating the strength and durability characteristics of the mortar specimens.

4.1. Raw materials and their physical and chemical properties

4.1.1. Physical properties of portland pozzolana cement (PPC)

According to BIS 2250 [17], Portland Pozzolana Cement (PPC) is recommended for mortar preparation to minimize the risk of severe sulphate attack caused by exothermic reactions. Therefore, PPC cement was used as the binding agent in this research. More than 95% particles of cement were found to be less than 90 μ m. The physical properties were determined by referring BIS 4031-4 [18] and BIS 4031-5 [17]. Consistency, initial and final setting time of PPC cement was found to be 27%, 33 minutes and 550 minutes, whereas, the unit weight of cement was recorded 1310 kg/m³. Compressive strength of PPC cement was carried out as per the procedure described in BIS 8112 [18]. The 28th day compressive strength of PPC cement was recorded 36.58 MPa, which was higher than minimum strength of 33.0 MPa [2, 18].

4.1.2. Water

Tap water with a pH value of 7.1 was used for mixing and curing of the materials. The pH level was measured using a digital pH meter.

4.1.3. Physical properties of blast furnace slag (BFS)

Blast furnace slag (BFS), a waste material from the iron industry, was collected from the furnace workshop located near Gadbad Puliya, AB Road, Indore, M.P., India. (Fig. 1) shows the raw BFS used in this study. The physical properties of the raw materials were determined following the procedures outlined in BIS 2386-1 [21] and BIS 2386-3 [22]. The selected particle size range for the raw material was between 1.18 mm and 150 μ m. (Fig. 2) illustrates the crushed form of BFS. The coarser particles of raw



Fig. 2. Crushed BFS.

BFS were initially broken manually using a hammer and subsequently crushed in an aggregate abrasion machine. Sieve analysis of the crushed BFS was conducted according to BIS 383 [23]. (Fig. 3) presents the particle size distribution curves for both river sand and BFS, showing that their particle sizes are nearly similar. The specific gravity, water absorption, and silt content of BFS particles were measured as 3.2, 0.4%, and 1.0%, respectively, with a unit weight of 1800 kg/m³.

4.1.4. Physical properties of river sand

Narmada river sand was used in this study, with particle sizes ranging from 1.18 mm to 150 μ m. The properties of the sand were evaluated following the procedures specified in BIS 383 [23], BIS 2386-1 [21], and BIS 2386-3 [22]. The properties of river sand finally conform to BIS 2116 [24] to form mortar mix. The particle size distribution curve shown in (Fig. 3) confirms that the river sand meets the specifications as specified in BIS 2116 [24]. The specific gravity, water absorption, silt content, and fineness modulus of the river sand were measured as 2.6,

1.4%, 3.0%, and 2.8, respectively, with a unit weight of 1560 kg/m³.

Based on the observed physical properties, it can be concluded that BFS possesses suitable characteristics for reuse as a substitute for river sand in building materials.

4.1.5. X-Ray fluorescence (XRF) spectroscopy analysis of PPC cement, BFS and river sand

X-ray fluorescence analysis was performed at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore, Madhya Pradesh, India. Table 1 presents the chemical composition of the sand, cement, and BFS samples. The XRF results, illustrating the chemical properties of the raw materials, indicate that BFS contains significant amounts of strengthening, fluxing and stabilizing agents similar to those found in cement and sand, making it suitable for use in the production of BFS-based walling materials.

4.2. Testing procedure

4.2.1. Water absorption test and density determination of BFS based mortar

The water absorption test was conducted on BFS-based mortar specimens after 28 days of curing. The cured specimens were thoroughly wiped with a dry cloth and then oven-dried at 105°C for 24 hours to remove any remaining moisture. The weight of the oven-dried samples was carefully measured and recorded as (W1). After weighing, the samples were immersed in clean water for 24 hours. Following immersion, the specimens were weighed again and recorded as (W2). The water absorption was calculated using the formula mentioned below. (Fig. 4)

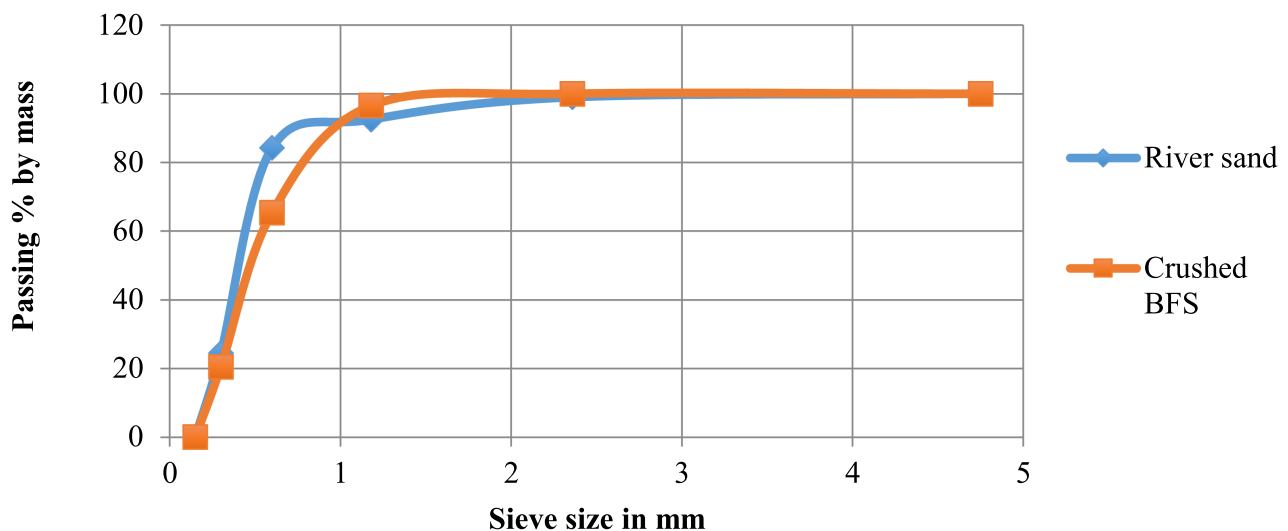


Fig. 3. Sieve analysis of river sand and crushed BFS.

Table 1. Chemical constituent present in BFS, Sand and Cement sample.

Chemical constituent and their oxides	Material with sample identity			Oxide proportion
	BFS (A)	Sand (B)	Cement (C)	
Silica (SiO ₂)	35-37%	78-80%	20-22%	Major
Alumina (Al ₂ O ₃)	10-12%	13-15%	4-5%	
Iron oxide (Fe ₂ O ₃)	0.75-1.25%	1-2%	3-4%	
Calcium oxide (CaO)	40-42%	≤1%	60-65%	
Titanium oxide (TiO ₂)	≤1%	≤1%	-	Minor
Potassium oxide (K ₂ O)	-	-	-	
Zinc oxide (ZnO)	≤1%	-	<1%	In (ppm)
Manganese (Mn)	<1%	-	-	

**Fig. 4.** Oven dried sample for water absorption test and density determination.

illustrates the oven-drying process and the oven-dried mortar samples.

$$\text{Water Absorption} = \frac{W_2 - W_1}{W_1} \times 100 \quad (1)$$

The dry density of BFS-based mortar was determined after 28 days of curing. The specimens were first oven-dried at 105°C for 24 hours to eliminate excess moisture. The oven-dried weight of the samples (W) and their corresponding volume (V) were then measured. Dry density was calculated using the formula provided below.

$$\text{Dry Density} = \frac{W}{V} \quad (2)$$

4.2.2. Compression test of BFS based mortar specimens

The compressive strength of BFS-based mortar specimens was determined using a digital compression testing machine (CTM) with a capacity of 2000 kN, following the procedure outlined in BIS 2250 [17]. The tests were conducted at two curing intervals i.e., at 28 and 56 days on 50.0 mm cement mortar cubes [17]. (Fig. 5) illustrates the compression testing of the specimens using the CTM.

**Fig. 5.** Compressive strength test of BFS based mortar.

4.2.3. Non destructive testing (NDT) of BFS based mortar specimens

To check overall quality parameters of BFS based mortar, non destructive testing involved ultrasonic pulse velocity meter (UPV) and rebound hammer were employed to provide predictive measurements of strength characteristics. The UPV test was conducted in accordance with BIS 13311-1 [25]. In this method, a pair of transducers is used to generate and receive ultrasonic pulses across a known path length (L) of the specimen. An electronic timing device measures the transit time (T) taken by the pulse to travel from one face of the specimen to the other. The pulse velocity is then calculated using the formula provided

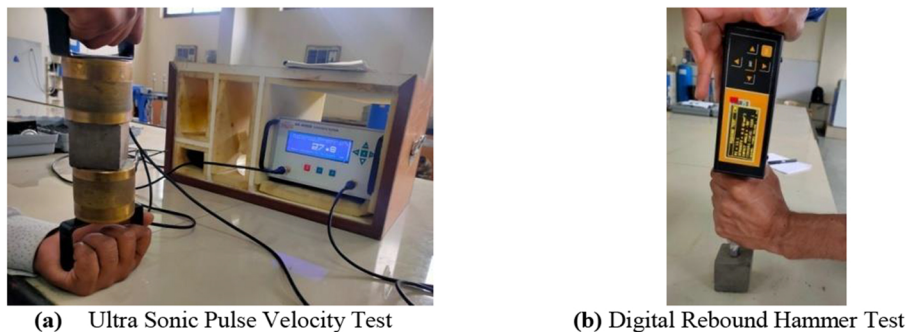


Fig. 6. NDT test on mortar specimen.

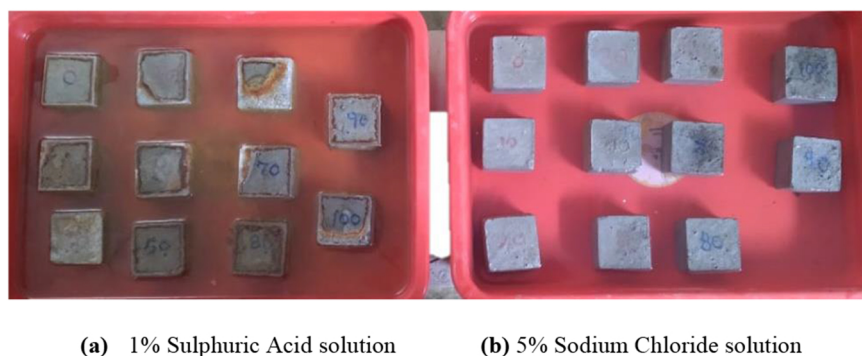


Fig. 7. Immersion of Mortar Moulds into acid and salt for 28 Days.

below. The experimental setup for the UPV test is illustrated in (Fig. 6).

$$V = \frac{\text{Path length of mortar specimen (L)}}{\text{Transit time (T)}} \quad (3)$$

The rebound hammer test is used to determine the rebound number by applying an impact to the surface of a specimen. In this study, a digital rebound hammer was employed, capable of accurately measuring rebound numbers on specimens with a lateral dimension of up to 50 mm. The test procedure was carried out in accordance with BIS 13311-2 [26]. Prior to testing, the surface of the mortar specimens was properly cleaned and dried. The plunger of the rebound hammer was then held perpendicular to the surface to deliver the impact and record the rebound value. (Fig. 6) illustrates the experimental procedure for the rebound hammer test.

4.2.4. Acid and salt attack test on BFS based mortar specimens

Acid and salt attack tests were conducted to evaluate the durability characteristics of BFS-based mortar. After 28 days of initial curing, the mortar specimens were immersed in a 1% sulfuric acid (H_2SO_4) solution with a pH of 2 for an additional 28 days. During this immersion period, the acid solution was regularly

monitored to maintain a consistent concentration. At the end of the exposure period, the specimens were tested for compressive strength and the results were compared with the 56-day strength values.

A similar procedure was followed for the salt attack test. After 28 days of curing, the specimens were cleaned and immersed in a 5% sodium chloride (NaCl) solution with a pH of 10 for 28 days. Upon completion of the immersion period, compressive strength tests were performed and compared with the 56-day strength. (Fig. 7) shows the immersion of BFS-based mortar specimens in both sulfuric acid and sodium chloride solutions.

4.2.5. Temperature variation test on BFS based mortar specimens

Post-fire structural integrity is a critical concern in the present scenario. Since mortar serves as the primary protective layer of a structure, improved fire resistance can help slow the degradation of the underlying structural components. To evaluate this aspect of durability, temperature variation tests were performed on BFS-based mortar specimens after 28 days of curing. The specimens were placed in a muffle furnace and exposed to temperatures of 200°C, 400°C, 600°C, 800°C, and 1000°C, each for duration of two hours. After heating, the samples were removed from

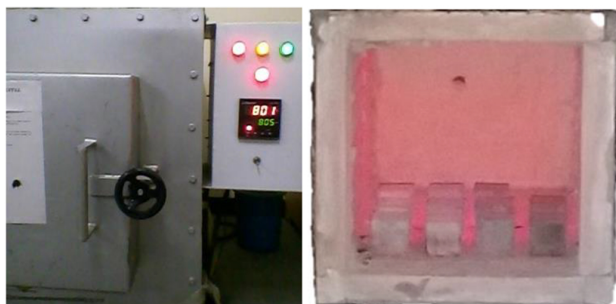


Fig. 8. Furnace process of BFS based mortar specimens.

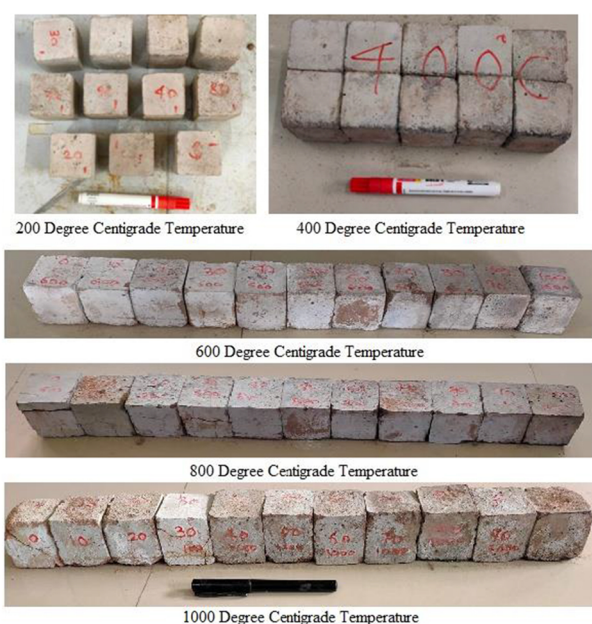


Fig. 9. Heated mortar specimens at various temperatures.

the furnace and allowed to cool at room temperature for 24 hours. Once cooled, the specimens were subjected to both destructive and non-destructive testing to evaluate their compressive strength. The furnace heating process is shown in (Fig. 8), while the appearance of the heated mortar samples is presented in (Fig. 9).

5. Mortar mixing conditions

Eleven different mixes were prepared containing partial to full replacement of river sand with crushed BFS. Around 300 specimens were casted and examined to observe strength and durability aspects of mortar mixes. As per specifications given in BIS 2250 [17], by considering environmental exposure conditions, mortar mix ratio of 1:6 was adopted to prepare BFS based mortar specimens. For nominal quality assurance, cement-sand reference sample of 1:6 ratio

Table 2. Mix proportions of different mortar mixes.

Mortar Mix	PPC cement (%)	River sand (%)	Crushed BFS (%)
SM-0	14.30%	85.70%	0.00%
SM-10		77.13%	8.57%
SM-20		68.56%	17.14%
SM-30		60.00%	25.70%
SM-40		51.40%	34.30%
SM-50		42.85%	42.85%
SM-60		34.30%	51.40%
SM-70		25.70%	60.00%
SM-80		17.14%	68.56%
SM-90		8.57%	77.13%
SM-100		0.00%	85.7%



Fig. 10. Curing of BFS based mortar specimens.

was also prepared as to set bench mark for BFS based mortar. Table 2 shows the proportions of different mortar mix containing a uniform percentage of PPC cement and 0 to 100% replacement of river sand to crushed BFS. The levels of BFS incorporated into the mortar mix are indicated in increments of 10%, labeled as SM-0, SM-10, SM-20, . . . , up to SM-100. SM-0 mortar mix shows composition of reference sample while SM-10 indicates 10% replacement of river sand with BFS. (Fig. 10) shows curing of finally prepared BFS based mortar specimens at room temperature conditions i.e., at 20–25°C.

6. Results and discussion

6.1. Water absorption and density of BFS based mortar

Table 3 is showing the results for water absorption and dry density of BFS based mortar specimens. Results indicating that, as percentage of BFS increases, water absorption percentage decreases. The maximum water absorption for SM0 specimen was found 30% more than that of SM100 specimen. Similarly, the average dry density of the mortar increased with higher BFS content. The SM0 specimen recorded a dry density of 1734 kg/m³, whereas the SM100 mix reached 2184 kg/m³. The reduction in water

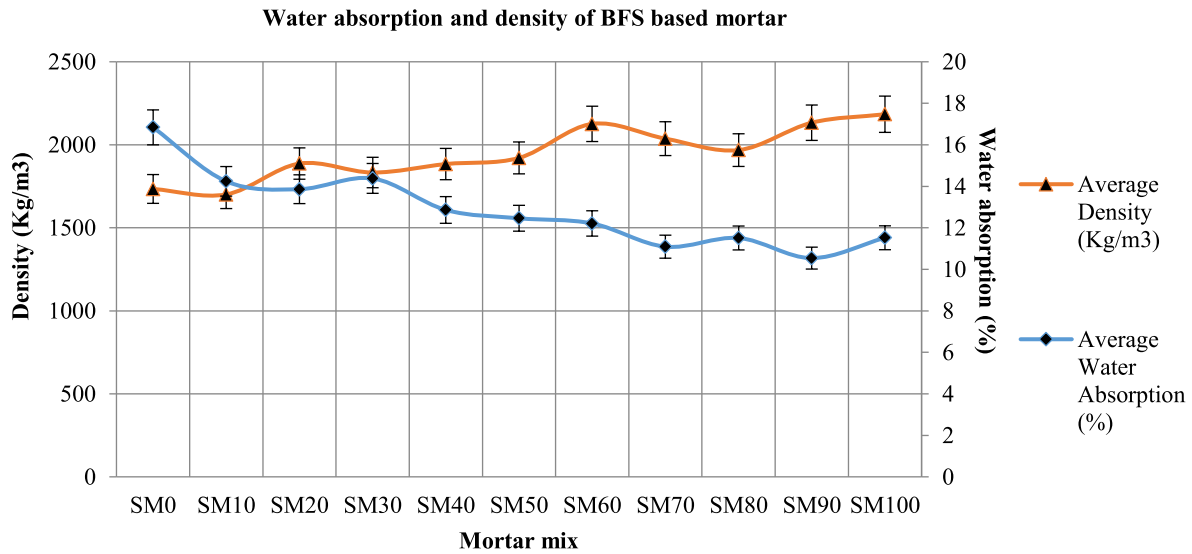


Fig. 11. Graphical representation of water absorption and dry density of BFS based mortar.

Table 3. Water absorption and dry density of BFS based mortar.

S.No.	Mortar Mix	Average water (%) absorption (%)	Average density (Kg/m ³)
1	SM0	16.84	1734
2	SM10	14.24	1701
3	SM20	13.86	1887
4	SM30	14.38	1833
5	SM40	12.86	1884
6	SM50	12.46	1921
7	SM60	12.21	2126
8	SM70	11.09	2037
9	SM80	11.51	1968
10	SM90	10.54	2133
11	SM100	11.52	2184

Table 4. 28th and 56th day compressive strength of BFS based mortar.

S.No.	Mortar Mix	Average 28 th day Compressive Strength MPa	Average 56 th days Compressive Strength MPa
1	SM0	4.02	4.52
2	SM10	3.36	4.70
3	SM20	4.24	5.42
4	SM30	4.80	5.24
5	SM40	4.40	5.40
6	SM50	4.76	6.66
7	SM60	6.46	7.61
8	SM70	7.32	8.18
9	SM80	7.36	8.06
10	SM90	8.10	8.31
11	SM100	8.54	10.20

absorption, combined with the increase in dry density, reflects the denser structure of BFS-based mortar, which contributes to improved strength characteristics. (Fig. 11) provides a graphical representation of these trends.

6.2. Compressive strength of BFS based mortar

Compressive strength is a key indicator of the mechanical performance of structural materials. According to BIS 2250 [17], the minimum 28th day compressive strength required for a 1:6 mortar mix used in building construction is 3 MPa. Based on this specification, Table 4 presents the average compressive strength results obtained from the experimental investigation of the prepared mortar specimens.

The results indicate that compressive strength increases progressively with higher levels of BFS replacement, ranging from 0% to 100% by volume of river sand. The SM100 specimen, with full re-

placement of river sand by BFS, achieved a 28th day compressive strength of 8.52 MPa representing a 200% increase compared to the SM0 specimen. Additionally, the 56th day compressive strength of SM100 was 225% higher than that of the SM0 specimen. (Fig. 12) illustrates the compressive strength development of BFS-based mortar specimens across different curing periods.

6.3. Statistical modeling for compressive strength

A statistical model was developed to establish the relationship between the actual and predicted compressive strength values. Two generalized statistical models were formulated during the analysis. The experimental results indicated that the 28th and 56th day compressive strength of BFS-based mortar was influenced by the percentage of BFS incorporated and the corresponding average density at each replacement

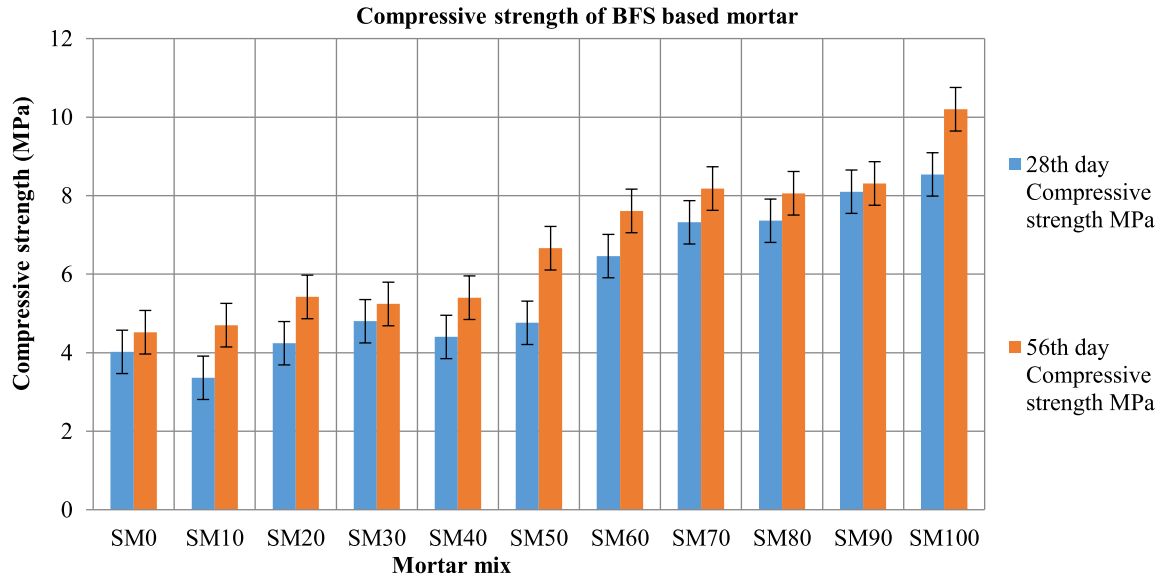


Fig. 12. Graphical representation for compressive strength of BFS based mortar.

level. Therefore, regression models were developed using these key variables. A total of 11 observations were included in each model. The regression equation for the 28th day compressive strength is presented below.

$$C28 = -0.817 + 0.043BFS (\%) + 0.0022 (A.D) \quad (4)$$

Here, (C28) representing predicted 28th day compressive strength, BFS (%) representing percentage of BFS used and (A.D) representing average density at definite percentage of BFS used. On the basis of coefficient of correlation and regression, best fitted model was obtained for 28th day compressive strength. The values for coefficient of determination (R^2) and root mean square error (RMSE) were recorded 91% and 0.498 respectively. R^2 with exact 100% value is the indication of perfect curve fit, with near to 100% for very good fit and negative value depicted very poor fit [14, 27]. RMSE with less than 0.50 is indication of good correlation between actual and predicted results. (Fig. 13) shows comparison between actual and predicted 28th day compressive strength.

The regression equation for 56th day compressive strength is shown below.

$$C56 = -1.19 + 0.040BFS (\%) + 0.0030 (A.D) \quad (5)$$

(C56) is the representation of 56th day predicted compressive strength. Coefficient of determination (R^2) and root mean square error (RMSE) for this model was calculated 94% and 0.427 shows that the regression model is most feasible and describe good statistical relationship between actual and predicted

Table 5. Non destructive testing results of BFS based mortar.

S.No.	Mortar Mix	Rebound Number	Transit time (μs)
1	SM0	15.90	32.20
2	SM10	14.35	27.45
3	SM20	17.10	26.70
4	SM30	14.05	27.50
5	SM40	15.70	25.05
6	SM50	16.75	23.55
7	SM60	19.15	22.75
8	SM70	18.80	22.75
9	SM80	17.60	22.0
10	SM90	18.30	21.0
11	SM100	18.45	20.05

data. (Fig. 14) shows comparison between 56th day actual and predicted compressive strength.

6.4. Non destructive testing (NDT) on BFS based mortar

Table 5 illustrated the results associated to non destructive testing of BFS based mortar specimens after 28 days curing. Results are showing that as percentage of BFS increasing from 0 to 100%, rebound number also increases. As per BIS 13311-2 [26], an increase in rebound number is indication of increase in compressive strength. Maximum rebound number for SM100 mortar specimen was found 14% more than the rebound number for SM0 specimen.

Transit time for mortar specimens was determined from UPV meter. As per BIS 13311-1 [25], higher the transit time, lower be the pulse velocity ultimately indicating lesser in predictive compressive strength. As the amount of BFS increases in mortar, the value of

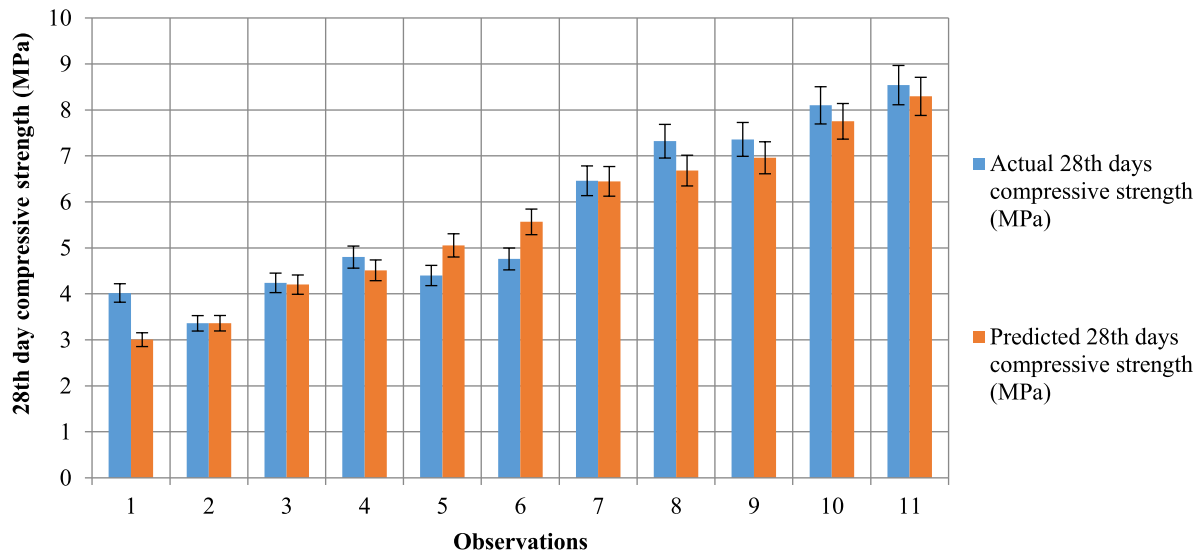


Fig. 13. 28th day actual and predicted compressive strength.

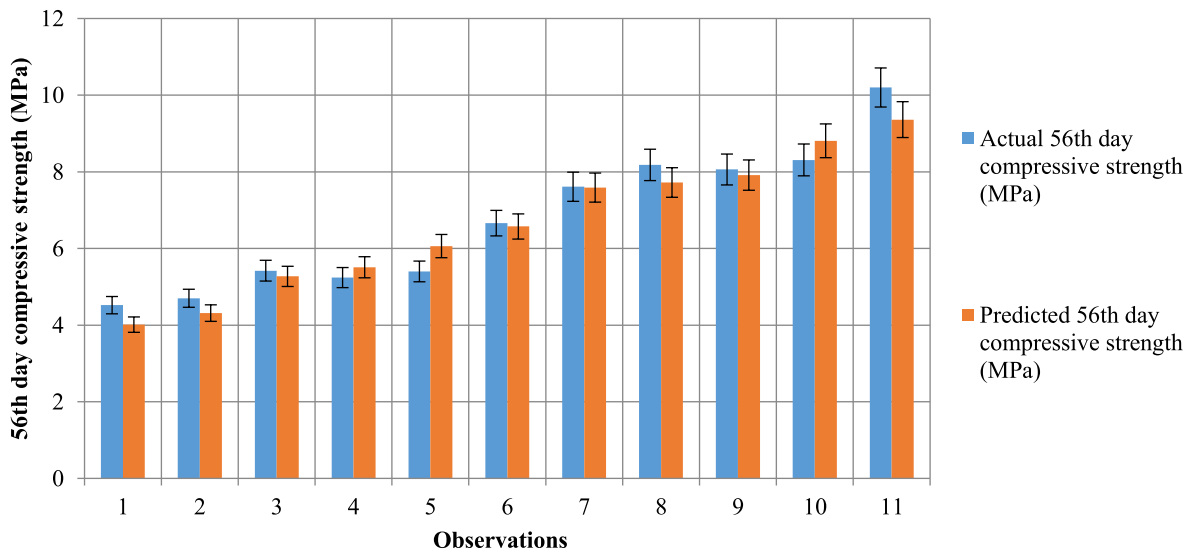


Fig. 14. 56th day actual and predicted compressive strength.

transit time reported in decreasing order. For SM 100 mortar specimen, the transit time was determined $20.5 \mu s$ found 32% less than the transit time of SM0 specimen. These results are indicating good strength characteristics along with variation in BFS percentage. (Fig. 15) is showing graphical representation of rebound number and transit time with percentage of increase in BFS.

6.5. Action of acid and salt

Table 6 presents the results of acid and salt exposure on BFS-based mortar specimens. Under acid immersion, the compressive strength of the mortar

Table 6. Action of acid and salt to BFS based mortar.

S.No.	Mortar Mix	Compressive strength after 28 days immersion into Acid	Compressive strength after 28 days immersion into Salt
1	SM0	3.88	4.02
2	SM10	4.66	3.92
3	SM20	4.49	5.56
4	SM30	4.39	5.32
5	SM40	4.90	5.04
6	SM50	5.51	6.84
7	SM60	6.66	7.38
8	SM70	7.31	7.76
9	SM80	7.38	7.44
10	SM90	7.06	8.48
11	SM100	8.37	10.02

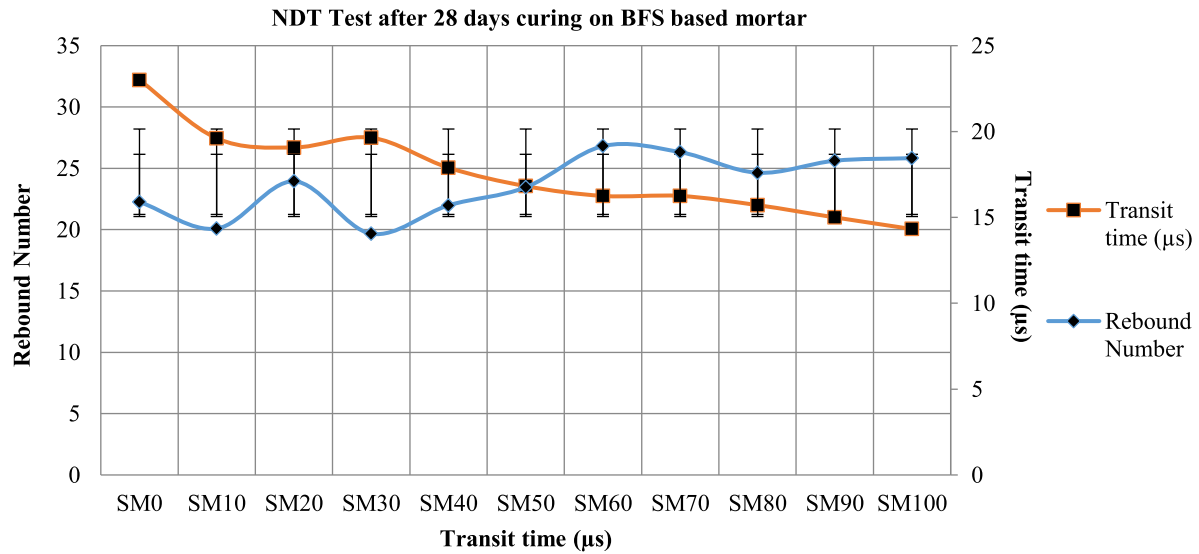


Fig. 15. Graphical representation of rebound number and transit time of BFS based mortar.

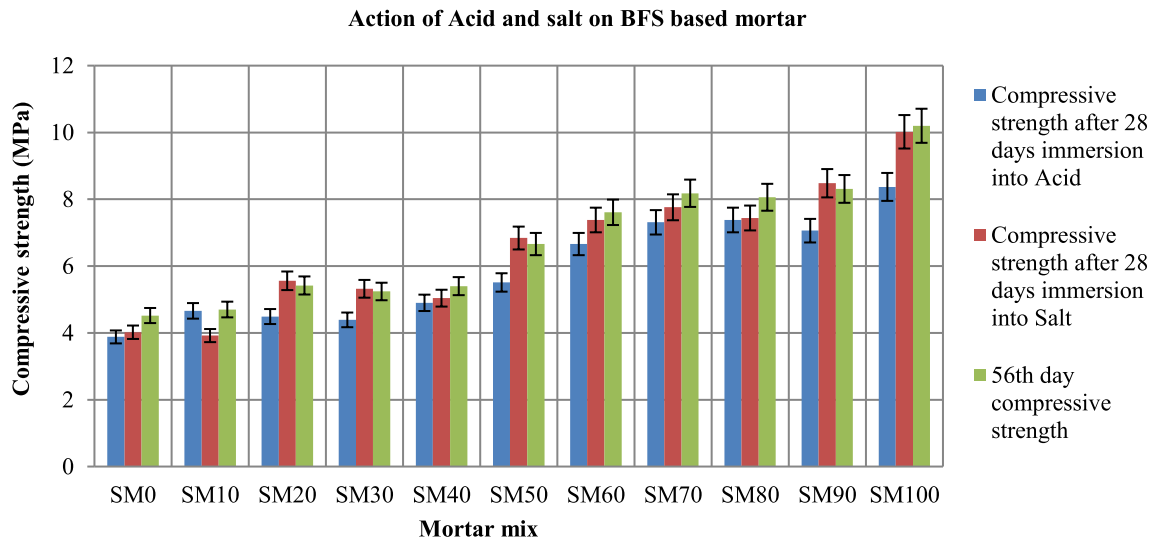


Fig. 16. Graphical representation for action of acid and salt on BFS based mortar.

increased progressively with higher BFS replacement levels. The SM100 specimen achieved the highest compressive strength of 8.37 MPa after 28 days of acid exposure. This value is more than double that of the reference sample (SM0), clearly indicating that increasing BFS content significantly enhances resistance to acidic attack.

Similarly, under salt immersion, compressive strength improved consistently as the BFS replacement level increased. The maximum strength was recorded for the SM100 specimen, reaching 10.02 MPa after 28 days of salt exposure. This also represents more than twice the strength of the reference sample, demonstrating the superior performance of higher BFS content in saline environments. (Fig. 16)

is showing graphical representation to compare compressive strengths at 56th day with salt immersion and acid immersion.

6.6. Temperature variation test on BFS based mortar

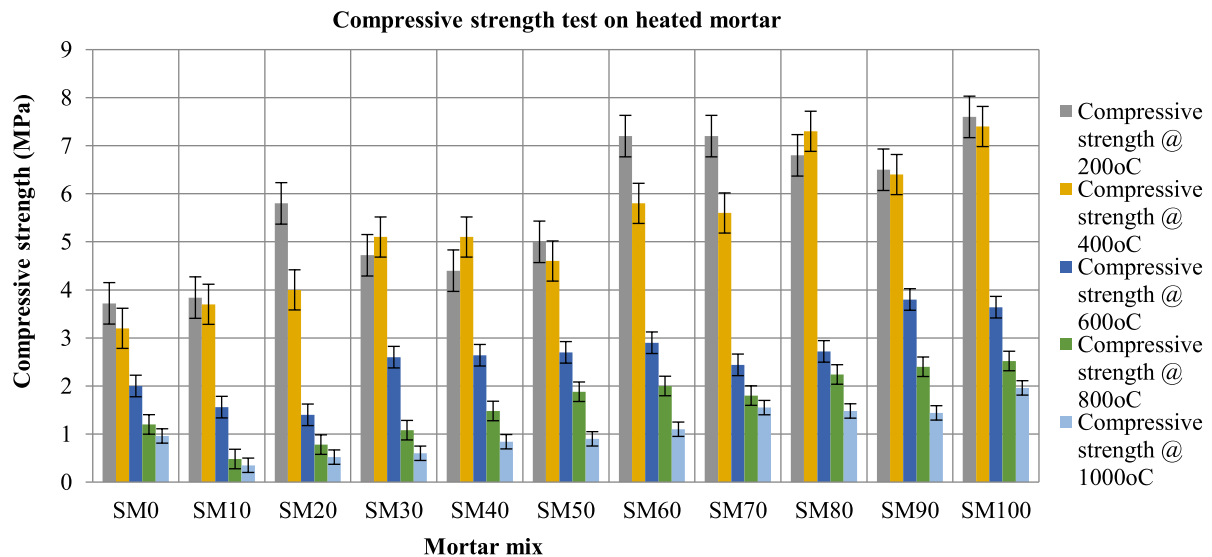
The results for furnace test on mortar are shown in Table 7. No considerable changes were noted for mortar heated at 200 and 400°C as compared to 28th day compressive strength. When mortar specimens reached 600°C, 800°C and 1000°C temperature, the average reduction of 55%, 71% and 81% in compressive strength with respect to 28th day compressive strength was observed. As per the results obtained from UPV test, transit time for 200 and

Table 7. Compressive strength of BFS based mortar after heated at different temperature.

S.No.	Mortar Mix	Compressive strength @ 200°C	Compressive strength @ 400°C	Compressive strength @ 600°C	Compressive strength @ 800°C	Compressive strength @ 1000°C
1	SM0	3.72	3.2	2.0	1.2	0.96
2	SM10	3.84	3.7	1.56	0.48	0.35
3	SM20	5.8	4.0	1.4	0.78	0.52
4	SM30	4.72	5.1	2.6	1.08	0.6
5	SM40	4.4	5.1	2.64	1.48	0.84
6	SM50	5.0	4.6	2.7	1.88	0.9
7	SM60	7.2	5.8	2.9	2.0	1.1
8	SM70	7.2	5.6	2.44	1.8	1.55
9	SM80	6.8	7.3	2.72	2.24	1.48
10	SM90	6.5	6.4	3.8	2.4	1.44
11	SM100	7.6	7.4	3.64	2.52	1.96

Table 8. UPV results of BFS based mortar after heated at different temperature.

S.No.	Mortar Mix	Transit time (μ s) @ 200°C	Transit time (μ s) @ 400°C	Transit time (μ s) @ 600°C	Transit time (μ s) @ 800°C	Transit time (μ s) @ 1000°C
1	SM0	39.5	43.5	78.3	107.2	116.3
2	SM10	39.4	50.1	95.5	122.7	152.0
3	SM20	28	48	101.1	111.1	120.0
4	SM30	33.9	47.8	76.5	110.0	133.0
5	SM40	32.4	42.6	74.5	75.4	85.0
6	SM50	30.2	42.2	77.5	74.5	87.8
7	SM60	28.5	43	70.0	76.3	77.0
8	SM70	29.3	33.6	67.0	65.6	77.0
9	SM80	27.2	33.7	51.4	72.6	75.5
10	SM90	29	31.3	37.3	39.6	48.9
11	SM100	26.7	29.9	34.5	38.4	49.5

**Fig. 17.** Compressive strength for heated mortar specimens.

400°C temperature mortar was noted nearly equal to 28th day transit time. For temperature ranged to 600°C, 800°C and 1000°C the transit time was found 281%, 329%, and 377% more than that of 28th day transit time. Higher values of transit time shows that the compressive strength at identified temperature goes reducing. Table 8 showing UPV results

for furnace mortar specimens. (Fig. 17) and (Fig. 18) are showing comparison of compressive strength and transit time for BFS based mortar processed at different temperature ranges. The figures indicate that the BFS-based mortar specimens exhibited significantly better strength and durability characteristics compared to the SM0 specimen.

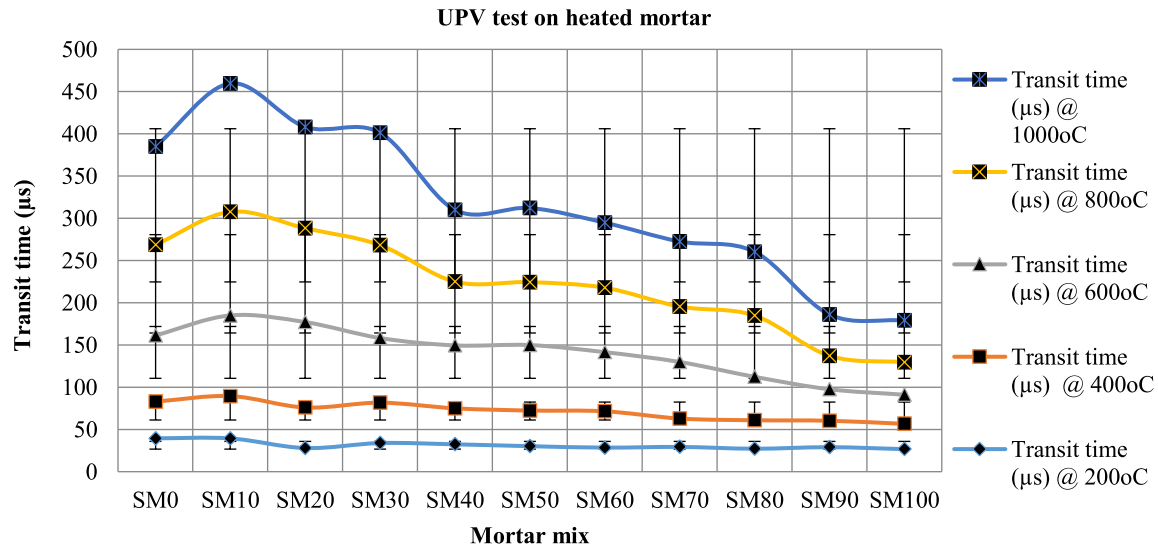


Fig. 18. UPV results for heated mortar specimens.

7. Conclusions

The outcomes of this study have great significance for providing the high strength as well as durable mortar by using BFS. All the tests have been done very carefully to get the strength and durability characteristics. On the basis of limited number mix ratios, test specimens, sand replacement and exposure periods the following conclusions can be drawn.

- Compressive strength increases with the increase of BFS percentage in BFS based mortar. Maximum compressive strength was recorded for SM100 specimen reported 200% more 28th day compressive strength and 225% more 56th day compressive strength than that of SM0 specimen. The strength of all other BFS based mortars was also examined better than SM0 specimen.
- Regression model for 28th and 56th day compressive strength with R^2 91% and 94% proves the importance of BFS into the mortar. The relationship between actual and predicted results was also found feasible as per lower reported values of RMSE.
- Higher value of rebound number is indication of higher impact resistance with higher compressive strength. As percentage of BFS increases in BFS based mortar specimens, impact resistivity feature also increases which shows improvement in overall strength characteristics. SM100 mortar specimen was examined with 14% more rebound number as compared to rebound number associated with SM0 specimen. All rest BFS based mortar specimens were also observed with better impact resistance as per as SM0 specimen.

- Less transit time is the indication of higher ultrasonic pulse velocity ultimately shows monolithic and denser nature of specimens. Transit time was found minimum for SM100 mortar specimen with 20.5 μ s, examined 32% less than transit time associated to SM0 specimen. Transit time for all other BFS based specimens were examined less than SM0 specimen shows that the composition of BFS based mortar specimens was denser than reference sample. An average reduction of 13% in compressive strength was examined for acid attack test as compared with 56th day compressive strength. Marginal reduction in compressive strength was observed that shows durable nature of mortar. For salt attack, there is no significant change in compressive strength was observed.
- No considerable changes were noted for mortar heated at 200 and 400°C as compared to 28th day compressive strength. When mortar specimens reached 600°C, 800°C and 1000°C temperature, the average reduction of 55%, 71% and 81% in compressive strength with respect to 28th day compressive strength was observed. As per the results obtained from UPV test, transit time for 200 and 400°C temperature mortar was noted nearly equal to 28th day transit time. For temperature ranged to 600°C, 800°C and 1000°C the transit time was found 281%, 329%, and 377% more than that of 28th day transit time. Higher values of transit time shows that the compressive strength at identified temperature goes reducing. But the overall strength and durability characteristics were found much better for BFS based mortar specimens as compared with SM0 specimen.

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Conflict of interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Data availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Author contribution

Richa Jain: Conception, Design, Write Up. **Harshit Jain:** Literature review, Supervision, Analysis. **Ashish Nim:** Conception, Correction, Interpretation.

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Dataset

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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