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Fresh and hardened properties of concrete incorporating ground granulated blast furnace slag–A review

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Abstract. Several types of industrial byproducts are generated. With increased environmental awareness and its potential hazardous effects, the utilization of industrial byproducts in concrete has become an attractive alternative to their disposal. One such by-product is ground granulated blast furnace slag (GGBS), which is a byproduct of the smelting process carried out in the iron and steel industry. The GGBS is very effective in the design and development of high-strength and high-performance concrete. This paper reviews the effect of GGBS on the workability, porosity, compressive strength, splitting tensile strength, and flexural strength of concrete.

Keywords: compressive strength; flexural strength; split tensile strength; porosity; workability

1. Introduction

Concrete has a wide range of usage in the area of construction. Compared to other building materials, concrete is a widely used construction material, because it can take any shape made up by formwork. It is a basic construction material that requires attention and diligence at every stage, from production to implementation. It is economical and durable, requires less energy in production, and can be produced anywhere. In our environment, airports, buildings, bridges, roads, dams, power plants, ports, water tanks, retaining walls and etc. are made with concrete.

Concrete based on industrial by-product materials such as slag can play a vital role in the context of sustainability and environmental issues. Steel slag is an industrial waste from either the conversion of iron to steel in a basic oxygen furnace or from melting scrap to make steel in an electric arc furnace. It makes up a portion of approximately 15% of steel output. Most steel slag consists primarily of CaO, MgO, SiO_2, and FeO. Additionally, steel slag has cementitious properties and has the potential to be recycled and utilized in cement-based materials. Approximately 5% of global CO_2 emissions originate from the manufacturing of Ordinary Portland cement (OPC). On the other hand, industrial by-product materials such as slag have been shown to release up to 80% less greenhouse gas emissions. Therefore, a full replacement of OPC

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Table 1 Variation of slump value for various sources of GGBS (Wainwright and Rey 2000)

Percentage replacement	Source	Slump (mm)
OPC (0%)		15
55%	1	30
	2	20
	3	25
	4	45
85%	1	30
	2	40
	3	25
	4	20

Table 2 Workability of concrete from Rourkela sample

Percentage replaced	Height of subsidence (mm)	
	M20	M25
30%	45	55
40%	60	70
45%	73	82
50%	85	103

with ground granulated blast-furnace slag (GGBFS) would significantly reduce the CO_2 emission of concrete production. Presently, GGBFS has been widely used in cement based material production around the world for vitreous structures and exhibits cementitious properties. The concrete containing GGBFS usually has retarded setting times and lower early-age strength but shows higher later strength, and better durability compared with Portland cement concrete.

The inclusion of GGBS has been recognized to have an influence on properties of concrete. In comparison to OPC, the production of GGBS requires less energy and it produces fewer greenhouse gasses. Thus concrete with GGBS is a more environmentally friendly concrete as compared to concrete without GGBS. Several studies comprising of the use of GGBS in cement concrete and mortar has been carried out. The influence of incorporation of GGBS on fresh and hardened properties of concrete is represented in following sections.

2. Workability

The use of GGBS as partial and full replacement of cement in cement mortar and concrete has significant influence on fresh concrete properties such as workability. Wainwright and Rey (2000) observed the influence on slump of concrete due to the addition of GGBS. GGBS from four different sources (source-1 to source-4) with different percentage of chemical composition of GGBS and Portland cement from one source were used. The w/b ratio was taken as 0.56, with fine aggregate of 750 kg/m^3 and coarse aggregate of 1080 kg/m^3, and water of 168 kg/m^3. Slag replacement levels were 55% and 85% by weight of cement. Mixture proportions and slump results are given in the following Table 1.

Table 3 Workability of concrete from Bhilai sample

Percentage replaced	Height of subsidence (mm)	
	M20	M25
30%	48	50
40%	65	65
45%	75	80
50%	90	105

Table 4 Variation of slump value (Payam *et al.* 2013)

Percentage replacement by GGBFS	Slump (mm)
0%	55
30%	75
50%	50
70%	35

Veena *et al.* (2012) performed workability test on M20 and M25 concrete with slag from Bhilai and Rourkela plant with water/cement ratio of 0.5. The percentage mix of GGBS was 30%, 40%, 45%, 50%. The results were given in the following Tables 2 and 3. It was observed that the workability of concrete enhanced with the increasing percentage of GGBS. This improvement could be attributed to the addition of fine particles of GGBS.

Choi *et al.* (2013) reported that the concrete mixture with GGBS and porcelain substitution mostly satisfied the target slump value i.e., 180±20 mm. When the GGBS was 90%, the quantity of super plasticizer was increased to satisfy the target slump value of 180±20 mm, as workability was reduced due to increase in viscosity.

Wang and Lin (2013) reported that the slump decreased from 0 min to 90 min were 260-250 mm, 270-260 mm and 260-240 mm, respectively in the specimens with 0%, 15% and 30%, slag replacement. The maximum slump loss was obtained approximately 20 mm when the amount of furnace slag replacement was 30%. With fixed water consumption, the mortar thickens, its consistency increased as the addition of cementitious material increased. Among the three furnace slag addition ratios and the control group, the addition of 15% furnace slag met the design requirements.

Payam *et al.* (2013) reported that the slump values of Oil Palm Shell (OPS) concrete with different percentages of GGBFS (Table 4). It can be seen that with increasing the percentage replacement from 0% to 30% the slump of the concrete was improved. Beyond this replacement level, the slump value reduced significantly. As GGBFS can increase the viscosity of the concrete mixture and it resisted the floating of lightweight aggregates and prevented significant bleeding occurring in the concrete. They also observed that by increasing the amount of GGBFS, the viscosity of the OPS concrete increased. The viscosity was very significant in the mixture with 70% GGBFS. It was concluded that the optimum level of substitution of GGBFS for achieving maximum workability for lightweight aggregate concrete, was in the range of 20-30%.

Kuo *et al.* (2014) reported that when the water/cement was 0.28 and no superplasticizers were used, the low water consumption resulted in an electrostatic attraction between the charge on the surface of the GGBS particles and the adjacent particles, which caused the GGBS particles to hold

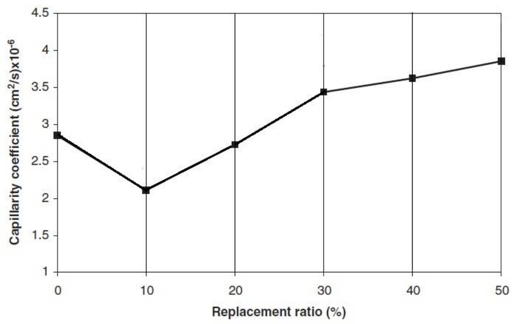

Fig. 1 Capillarity test results (Isa *et al.* 2007)

moisture, resulting in the poor dispersion. It was also observed that GGBS did not react with the water completely, and hence the high water absorption of the desulfurization slag (DS) aggregate resulted in poor workability. There was an increase in concrete flow-ability with the increase in the amount of mixing water, and the slump value increased with the addition of water/cement and GGBS (i.e., a decrease in DS addition). The water repellency was strong in the case of GGBS as the surface of GGBS was unlikely to absorb moisture which led to increasing the amount of free water between the mixtures. The slump value also increased due to increase in lubrication between material particles in the fresh concrete. For a given amount of superplasticizer, the water consumption was a key factor in determining sample behavior.

Deb *et al.* (2014) observed that mixture with 20% GGBS showed a slump value of 195 mm whereas a slump value of 250 mm was observed for a mixture containing 10% GGBS. It was also observed that the mixture with Sodium Silicate/ Sodium Hydrate ratio of 1.5 showed a slump value of 180 mm whereas mixture with Sodium Silicate/ Sodium Hydrate ratio of 2.5 showed a slump value of 195 mm. They reported that the workability of the geopolymer concrete mixtures showed decreasing trends with increasing the slag content and decreasing the Sodium Silicate/ Sodium Hydrate ratio. Lowest slump value was observed in mixture with 20% slag content among all the geopolymer concrete mixtures because it had a higher percentage of slag (20%) and a lower Sodium Silicate/ Sodium Hydrate ratio (1.5) as compared to the other mixtures.

Pradip and Prabir (2014) reported that the influence of slump of concrete and flow of mortar by the inclusion of GGBFS in the binder. Mixtures with 0%, 10%, 20% and 30% GGBS were mixed with the same quantity of activator solution and the control geopolymer mixture with 0% GGBS showed the highest slump and flow values. Generally, the slump and flow values decreased with the increase of slag content in the mixture. However, the effect was more significant at higher levels of slag content.

3. Porosity

The porosity of mortar mixes is significantly influenced by the use of finer supplementary cementitious materials. Isa *et al*. (2007) reported that when the replacement ratio increased, the structure of concrete was getting more porous which could attribute to increase in capillarity. However, the result for the 10% replacement does not obey this trend. The reason of lower capillarity coefficients of mixture containing 10% replacement ratio, compared to other mixture

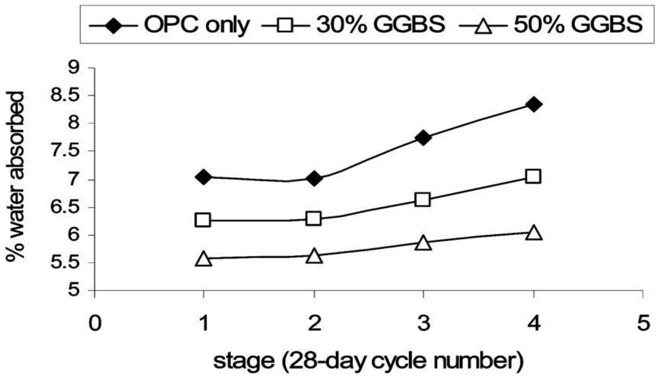

Fig. 2 Water absorption of PC and GGBS samples (Pavía and Condren 2008)

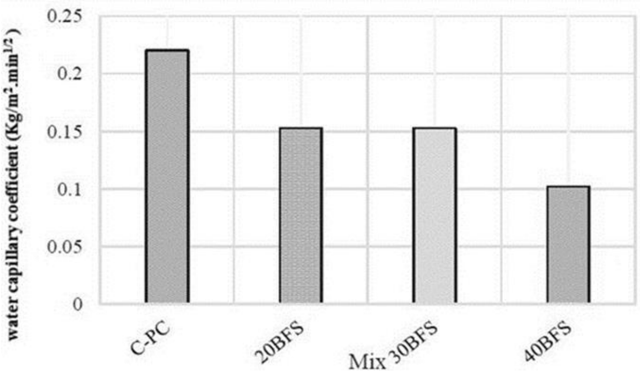

Fig. 3 Capillary water absorption coefficient of blast furnace slag by Walid *et al.* (2015)

containing different replacement ratios, can be consisted in the pozzolanic reaction. GGBFS had reacted with free lime (CaO) during hydration and occurred additional to bermorite gels to the silicate gels of cement. Thus, capillary pores of 10% by-product replaced mixture are filled. Therefore, capillarity of these specimens is lower than the other groups due to the decrement of capillary pores. Higher capillarity of other specimens containing 20%, 30%, 40% and 50% replacement ratios has consisted because of a porous structure composed by the usage of GGBFS.

Pavia and Condren (2008) observed that plain concrete (PC) mortars initially absorbed more water than the GGBS samples. Moreover, a progressive increase in water absorption over the course of the experiment was observed in this study. The water absorption results of this investigations are presented in Fig. 2. It was observed that the amount of water absorbed by the GGBS samples was lower than that absorbed by the PC samples and that the higher the GGBS content, the lower the amount of water absorbed.

Elahi *et al.* (2010) observed the water absorption results of concrete containing 50% and 70% GGBS at after 44 and 91 days. The water absorption values of control concrete were found to be 100 $m^3 \times 10^{-7}/\sqrt{(min)}$ after 44 and 91 days respectively. The mix with 50% GGBS showed a lower value of water absorption (77.1 $m^3 \times 10^{-7}/\sqrt{(min)}$) at 44 days compared to that at 91 days (96.9 $m^3 \times 10^{-7}/\sqrt{(min)}$). They observed an increase in water absorption by increasing the content of GGBS of 70% (120.1 $m^3 \times 10^{-7}/\sqrt{(min)}$) at 44 days but considerably reduced the water absorption (103.8 $m^3 \times 10^{-7}/\sqrt{(min)}$) at 91 days.

Table 5 Effect of blast furnace slag on the compressive strength of concrete at various ages (Li and Yao 2001)

Replacement percentage level	Compressive strength (Mpa)		
	3 days	7 days	28 days
0%	63.8	71.2	81.1
30% GGBS	69.3	83.2	100.4
30% GGBS+10% SF	69.3	87.0	104.0

Walid *et al.* (2015) observed the highest capillary water absorption of 3.32 kg/m^2 at the control concrete mixture. Fig. 3 represented the evolution of capillary water absorption coefficient of concretes containing different amounts of blast furnace slag.

It can be seen that use of blast furnace slag (BFS) was remarkably effective in decreasing the capillary water absorption in concrete mixtures; particularly with the incorporation of 40% of blast furnace slag decreased the capillary water absorption as compared to the concrete mixture without blast furnace slag. It was also observed that this binder combination had an influence in capillary absorption coefficient. There was an improvement in capillary water absorption coefficient by use of a 40% BFS as a cement replacement in the comparison to the control concrete. This improvement of the capillary water absorption due to the more pore structure refined, the distribution and dimension of the capillary porosity which is mainly due to the formation of the secondary C-S-H gel issued from the pozzolanic reaction of blast furnace slag.

4. Compressive strength

When GGBS is added to concrete, it results in a significant change in the compressive strength of the mix. The outcomes of the studies comprising of the use of varying percentage of GGBS is presented as follows;

Jau1 and Tsay (1998) observed the compressive strengths of the slag concrete specimens immersed in seawater for a period of one year. They reported that with an increase in the slag substitution ratio the compressive strength decreased. The control specimens were made of Portland cement without slag and stored in the atmosphere. It was seen that the compressive strengths of the slag concrete specimens immersed in seawater are always smaller than those of the control specimens. This concludes that the compressive strength reduced due to seawater attack, and the older the concrete was the larger the reduction. The best slag substitution rate was 20%. Also, the lower the water/cement ratio was, the smaller the strength reduction was.

Li and Yao (2001) reported that concrete with 30% GGBS and 30% GGBS addition to 10% silica fume (SF) acquired much higher compressive strength as compare to concrete without GGBS at each testing age (Table 5). At the age of 3 days, the compressive strengths of concrete with 0% GGBS, 30% GGBS, and 30% GGBS addition to 10% silica fume were 63.8, 69.3 and 69.3 Mpa, respectively. At 28 days of age, the compressive strengths of Concrete with 30% GGBS, and 30% GGBS addition to 10% silica fume increased greatly to 100.4 and 104.0 Mpa, respectively, compared with 81.1 Mpa of Concrete with 0% GGBS. This tendency reflected the strengthening effect of ultrafine GGBS and SF on mechanical properties of concrete.

Maria and Surendra (2003) reported the development of compressive strength for the cement

Table 6 Effect of blast furnace slag on the compressive strength of concrete at various ages (Higgins 2003)

Percentage replacement	Compressive strength (N/mm^2)					
	3 days	7 days	28 days	1 year	2 year	6 year
Portland cement (0%)	34	41	53	66	68	69
60%	17	31	48	65	69	73
70%	13	28	49	63	66	71

kiln dust (CKD)-slag blends up to 56 days. When compared to Portland cement concrete, use of Grade 100 slag typically resulted in lower compressive strengths at early ages, but equal or higher at later ages. At the age of 7 days, the compressive strength of the cement-slag blend was lower than that of the OPC concrete. However, both the 28- and 56-day compressive strength was the highest of all blends, indicating a high degree of pozzolanic reaction. The compressive strength of all four CKD-slag blends increased with curing time indicating slag activation by the CKD and the formation, precipitation, and accumulation of calcium silicate hydrates as products of hydration. The strength of all CKD-slag blends was always lower compared to OPC and OPC-slag mixes, at all ages. The slag blend activated with CKD (P) had the lowest early and late strength of all the mixtures, ranging from 12.1 Mpa at 7 days to 17.2 Mpa at 56 days.

Higgins (2003) studied the compressive strength of the cubes stored in water and in the sulfate solutions. The strengths in the sulfate solutions are expressed as a percentage of the strength of equivalent concretes stored in water for the same age. The sulfate solutions are about five times stronger than concrete is likely to be exposed to in a natural environment. In sodium sulfate solution, the plain concrete only had almost completely disintegrated by 6 years, while the GGBS concretes were generally showing only minor strength-loss. The observed values were given in the following Table 6.

Kyong and Eun (2005) reported that all the concrete mixture specimens made with or without ground granulate blast furnace slag (GGBS) showed strengths in excess of 350 kg/cm^2 after 14 days. The performances of the GGBS-containing mixtures (25%, 40%, and 50%) were found to be similar to that of the mixture with 0% GGBS at 28 days but were superior to that of the 0% GGBS mixture at 56 days. At the early age of 7 days, all the GGBS mixtures, up to 55% cement replacement, attained lower compressive strengths than the 0% GGBS mixture. These results suggested that latent hydraulicity reactions by GGBS slowed down the development of compressive strength with an increase in GGBS content at the early age. However, at later times, 28, 56, and 91 days, the compressive strengths of the GGBS concrete mixtures were similar or slightly stronger than that of GGBS-free concrete i.e., 0% GGBS mixture.

An *et al.* (2005) reported that at the age of 91 days, the compressive strengths of specimens were 42.4, 45.3 and 48.6MPa for 0% GGBS, 40% GGBS and 60% GGBS, respectively. Compressive strength development depended upon the GGBS replacement percentage and concrete age. The glassy compounds in GGBS reacted slowly with water and it took the time to obtain hydroxyl ions from the hydration product of Portland cement to breakdown the glassy slag parcels at an early age. However, GGBS concrete had higher compressive strength than ordinary Portland cement concrete (OPC), after GGBS hydration and the pozzolanic reaction is almost accomplished. The study demonstrated that higher GGBS replacement percentage had higher ultimate strength. Khatib and Hibbert (2005) reported the compressive strength development for concretes containing 0%, 40%, 60% and 80% GGBS. There was a systematic decrease in

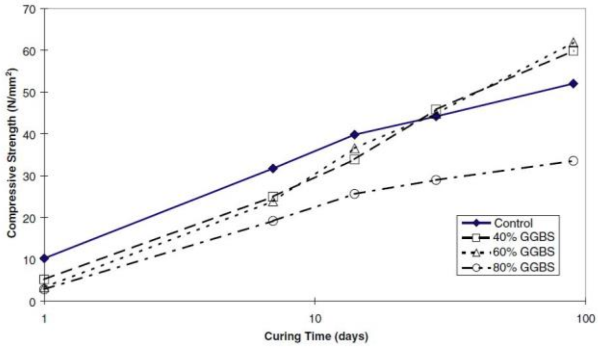

Fig. 4 Effect of GGBS on compressive strength development (Khatib and Hibbert 2005)

Table 7 Effect of blast furnace slag on the compressive strength of concrete at various ages (Pavía and Condren 2008)

Percentage replacement	Average loss in compressive strength (N/mm^2)	% loss in compressive strength
0%	7.05	46.74
30%	5.79	32.74
50%	4.11	21.82

compressive strength as the GGBS content increased during the early stages of hydration. Beyond 28 days and up to at least 90 days, the presence of GGBS was highly beneficial at 40 and 60% replacement with a strength exceeding that of the control.

Cengiz and Cahit (2007) reported the compressive strength of control and GGBS concrete at 28 days and 3 months for dry and wet curing conditions separately. It was observed that wet cured compressive strength of GGBS is higher than that of control NPC concrete for 20% and 40% replacement ratios at 28 days and three months. The compressive strength of GGBS was found to be equivalent to that of control NPC concrete for 60% replacement ratio. However, the compressive strength of GGBS was found to be satisfactory when compared to control NPC concrete for 80% replacement ratio. It was also observed that, for dry curing conditions, the compressive strength of GGBFS concrete was found to be equivalent to that of control NPC concrete for 20%and 40%replacement ratio at 28 days and three months. The compressive strength of GGBS was found to be satisfactory when compared to control NPC concrete for 60% replacement ratio. However, concrete containing 80% GGBS developed lower strength than that of control NPC concrete.

Hanifi *et al.* (2008) reported the compressive strength results of concretes versus curing time in seawater. There is a relatively high loss of compressive strength in reference (R) specimens compared to those of the others. The total compressive strength reductions of reference, specimen with slag (CS), specimen with ground blast furnace pumice (CP) and mixture of GGBS and GBP (CSP), concrete specimens after 3 years exposure to seawater are about 41%, 4%, 20%, and 9%, respectively. It can be observed that CSP concrete specimens present an excellent behavior in both short and long-term compressive strength variation under seawater attack.

Pavia and Condren (2008) reported that at the end of the silage immersion experiment, mortar mixes containing GGBS performed better, showing a greater strength than those including 100% PC (Table 7). The initial compressive strength of the samples prior to effluent exposure was 13.83;

19.76, and 24.79 N/mm^2 for the OPC, 30% GGBS and 50% GGBS samples, respectively. This could be probably due to the cement produced by GGBS. This cement had a greater proportion of strength-enhancing compounds and less lime, which contributed little to concrete strength, than those produced in the hydration of PC. The percentage loss in strength of the 100% PC samples was 46.74% which was nearly twice as much as that of the 50% GGBS samples which is 21.82%.

Seyed and Seyed (2011) reported that with 30% replacement of GGBS there was an increase in the compressive strength at 14, 28, 56 days. The compressive strength increase of concrete was from 18 to 28 Mpa, 18 to 30 Mpa and 18 to 31 Mpa at the ages of 14, 28 and 56 days, respectively.

Ilker and Ahmet (2010) reported that the highest compressive strength results were obtained with the usage of 25% GGBFS for both curing conditions i.e., uncontrolled relative humidity and temperatures media(C1) and standard water curing, (C2). In the C1(after 28 days), C2(after 28 days), C1(after 90 days) and C2(after 90 days) curing conditions, compressive strengths of 25% GGBFS series increased at the ratios of 17.41%, 39.37%, 29.23% and 47.83%, respectively. Likewise, the compressive strengths of 50% GGBFS series exposed to these curing conditions increased at the ratios 3.14%, 22.74%, 2.64% and 20.15% compared to control series, respectively. As seen from the results, when GGBFS replaces cement at the ratio of 50%, the compressive strength increment in series exposed to C2(after 90 days) curing was as 20.15% and the increment in series exposed C1(after 90 days) curing is 2.64%. Hence compressive strength increased with an increase in curing ages for both of curing methods. If the series exposed to C2 curing are compared to each other, the compressive strengths of the series, containing GGBFS at the ratios of 0%, 25% and 50%, increased in the ratios of 5.22%, 11.60% and 3.00%, respectively, with the increase in curing ages from 28 days to 90 days. The hydration reactions took place in a better way with the increase in curing ages and the compressive strengths increase by occurring new C-S-H gel. Hence it was observed that increasing curing time and exposing the concrete to water curing instead of air curing increased the compressive strengths of the specimens.

Lubeck *et al.* (2012) reported that the compressive strength of all concrete specimens increased with the period of curing and decreased as the water/cement ratio increased. As the percentage of blast-furnace slag in the mixture increased, the compressive strength decreased an observation valid for white and grey Portland cement. However, mixtures with 50% and 65% blast furnace slag and with a Blaine fineness of 420 m^2/kg yielded values greater than those of the reference mixture at 7 days. It was reported that increase in strength due to the presence of slag for the mixtures with white portland cement. At 7 days, the 50% slag to white portland cement (WPC) and slag to white portland cement mixtures presented compressive resistance values between 53% and 70% and between 43% and 76%, respectively, of the values observed at 91 days. The mixtures with 100% WPC showed higher resistance values that those with 100% grey Portland cement up to an age of 28 days. The strength of the white Portland cement mixtures increased more quickly than that of the grey Portland cement mixtures. At 7 days, the strength of the white portland cement mixtures was between 63% and 85%, while the strength of the grey Portland cement mixtures was between 54% and 72% of the strength observed at 91 days. At 1 and 28 days, the strength of the WPC was greater than that of the mixture made with grey cement, even though the latter presented a higher Blaine fineness.

Bagheri *et al*. (2012) reported that the compressive strength of concretes containing silica fume are higher than control concrete at all ages and with increasing dosage of silica fume the gain in strength becomes higher. The reduction in compressive strength caused due to low reactivity slag at 15% cement replacement level. For mixes containing higher amounts of slag especially for the mix incorporating 50% slag, the strength reduction is considerable at all ages. The addition of

Table 8 Compressive strength at different percentage replacement of fine aggregate (Binici *et al*. 2012)

% replacement	28 day	180 day
5	49.2	60.9
10	52.7	63.2
15	56.1	66.9

Table 9 Effect of blast furnace slag on the compressive strength of concrete at various ages (Atul *et al.* 2012)

GGBS (%)		0%	5%	10%	15%	20%	25%	30%
Compressive strength (MPa)	7 days	21.03	20.74	20.44	19.85	18.07	16.88	15.40
	14 days	23.70	22.81	22.66	22.36	19.55	18.51	16.74
	28 days	26.9	25.0	24.59	24.29	20.88	20.74	18.81

various dosages of silica fume to the mix containing 15% slag improves its rate of strength gain and the drop in its 28-day strength compared to the control mix is compensated for and at later ages shows improvements over control. Compressive strengths are still lower than the control mix for ternary mixes containing 30% slag and various dosages of silica fume, but with the progress of pozzolanic reactions at 90 and 180 days the difference in strength becomes smaller. For ternary mixes containing 50% slag and various dosages of silica fume, compressive strengths are still much lower than the control mix at all ages. In ternary mixtures containing silica fume and slag, it seemed that silica fume has two different effects on the development of properties. Silica fume due to its high specific surface and its micro-filler effect results in strength enhancement from 7 days onwards. The pozzolanic reaction of silica fume and consumption of $Ca(OH)_2$ and also the incorporation of ionic species such as Na^+ and K^+ in reaction products of silica fume led to a reduction in pore solution alkalinity. Slag hydration reactions, however, depend on the alkalinity of pore solution and reduction in alkalinity will have an adverse effect on slag contribution to strength. For ternary mixes containing higher slag contents; i.e., 30% and 50%, it appeared that the micro-filler and pozzolanic action of silica fume have not been able to compensate for reduced slag activity caused by lower alkalinity, and despite the use of 7.5% of silica fume the strengths are lower than the control mix.

Nourredine *et al*. (2012) reported that replacement of hydrated lime by GGBS as a binder results in a significant reduction in compressive strength. The strength of sample reduced to 21% by 40% replacement of GGBS and 77% with full replacement by GGBS. Also, GGBS was slightly reactive mixture in the absence of lime, as it plays an important role in the. It was also observed that the variation in GGBS specific surface did not impact on compressive strength. There was a slight change in compressive strength when specific surface changes from 2,500 to 3,500 cm^2/g. There was not noticeable change at higher specific surface change i.e., from 3,500 to 4,500 cm^2/g. It was also observed that temperature had a contribution on activation of GGBS resulting in increasing in strength. In the case of autoclave condition the kinetics of the chemical reaction between lime and GGBS increases. There was an increase in mechanical strength of 21% when vapor pressure ranges from 1.0 to1.5 Mpa inside the autoclave condition and only 12% increase when it changes from 1.5 to 1.8 Mpa, corresponding to temperature change from 176° to 190℃ and from 190^o to 204^oC, respectively.

Rafat and Deepinder (2012) reported that the compressive strength of concrete mixtures decreased with the increase in GGBFS content at normal temperature (27^oC). At room temperature

Table 10 Compressive strength of M20 concrete from Bhilai sample

Percentage replacement	Compressive strength (MPa)		
	3 days	7 days	28 days
0%	8.14	13.33	20.21
30%	5.33	8.44	19.66
40%	7.11	9.33	20.92
45%	7.91	10.22	17.44
50%	7.55	11.11	15.56

Table 11 Compressive strength of M20 concrete from Rourkela sample

Percentage replacement	Compressive strength (MPa)		
	3 days	7 days	28 days
0%	8.14	13.33	20.21
30%	5.12	8.42	19.67
40%	7	9.35	21.20
45%	7.72	10.01	17.88
50%	7.32	11.21	15.56

Table 12 Compressive strength of M25 concrete from Bhilai sample

Percentage replacement	Compressive strength (MPa)		
	3 days	7 days	28 days
0%	9.87	16.25	25
30%	8.33	11.52	22.21
40%	10.72	12.67	25.02
45%	11.11	13.01	26.77
50%	10.98	12.98	24.01

Table 13 Compressive strength of M25 concrete from Rourkela sample

Percentage replacement	Compressive strength (MPa)		
	3 days	7 days	28 days
0%	9.87	16.25	25
30%	8.89	11.55	22.33
40%	11.55	19.11	23.22
45%	13.33	16.89	28.44
50%	12	15.11	26.67

(27^{o}C), 28-day compressive strength of concrete containing 20%, 40% and 60% GGBFS was respectively 16.8%, 23.9% and 28.5% lower than the control mixture (34.8 Mpa).

Binici *et al.* (2012) reported that the maximum 28-day compressive strength values were obtained from slag specimens. The compressive strength values of these specimens were between 49-56 MPa, and the compressive strength of this group of specimens was about 20% greater than that of the reference specimen (Table 8). However, the compressive strength of specimens with pumice was about 13% lower than that of the reference specimen. On the other hand, the compressive strength of specimens with pumice and blast furnace slag was equal to the compressive strength of the reference specimen. The maximum 180-day compressive strength values were obtained from slag specimens. The compressive strength values of these specimens were between 60-66 MPa, and the compressive strength of this group of specimens was about 18% greater than that of the reference specimen. However, the compressive strength of specimens with pumice was about 13% lower than that of the reference specimen. On the other hand, the compressive strength of specimens with pumice and blast furnace slag was almost equal to the compressive strength of the reference specimen.

Atul *et al.* (2012) conducted compressive strength test to evaluate the strength development of Cement concrete mix, containing a various percentage of blast furnace slag powder at the age of 7, 14, 28 days respectively. Cubes of standard size (150 mm×150 mm×150 mm) were made. The result was given in Table 9. It was observed that 7 days, 14 days and 28 days compressive strength on 30% replacement of cement reduces about 30% that is from 21.03 N/mm^2 to 15.40N/mm^2, 23.70 N/mm^2 to 16.74 N/mm^2 and 26.9 N/mm^2 to 18.81 N/mm^2 respectively. It was observed that as the percent of GGBS increase, the strength tends to decrease.

Bernal *et al.* (2012) reported that concretes based on GGBS alone showed an increase in compressive strength when formulated with higher SiO_2/Al_2O_3 ratios. This effect was more notable in samples formulated with SiO_2/Al_2O_3 ratios of 4.0 and 4.4, which showed twice strength as that of the specimens formulated with SiO_2/Al_2O_3 3.6 at 7-day. The GGBS-only concretes achieved the highest compressive strengths with a SiO_2/Al_2O_3 ratio of 4.4, reporting the strength of 40 Mpa at 7 days, and then a further increase of 83% in strength from this time to 180 days.

Veena *et al.* (2012) performed compressive strength test on M20 and M25 concrete with slag from Bhilai and Rourkela plant at 3, 7, 28 days curing with water/cement ratio of 0.5. The percentage mix of GGBS was 0%, 30%, 40%, 45%, 50%. The results were given in the following Tables 10-13.

Ahmed *et al.* (2012) reported that the development of compressive strength of concrete mixtures with and without GGBFS for different W/B ratios. In concrete with W/B ratio is 0.65, a reduction of compressive strength with the increase of GGBFS content at the age of 28 days was observed. This reduction was more pronounced for a concrete mixture containing 50% of GGBFS as cement replacement. At 90 days wet curing, compressive strength for concrete mixtures incorporating 15% and 30% of GGBFS were found to be comparable to that of OPC concrete. The reduction of W/B ratio from 0.65 to 0.42 showed a beneficial effect on the compressive strength of concrete mixtures containing GGBFS. Despite a low compressive strength at an early age (7 days) of GGBFS concrete, a good activation of GGBFS for substitution rate below 30% seems to occur after 28 days moist curing. At 28 days of age, a comparable compressive strength to that of concrete reference with 0% GGBFS was obtained for concrete mixtures with 15% GGBFS and 30% GGBFS. However, a noticeable reduction in strength (13%) is observed for concrete mixtures with 50% GGBFS compared to the concrete mixture without GGBFS. At 90 days, the compressive strength of GGBFS concrete with 0.42 W/B ratios was similar to that of OPC concrete, independently of the rate of GGBFS.

Hiraskar and Chetan (2013) observed the compressive strength of the concrete design mix by casting and testing of cubes (size 150 mm×150 mm×150 mm) after the curing period of 3 days, 7 days, 14 days, 28 days & 60 days. They reported a decreasing trend in strength.

Payam *et al.* (2013) reported the 28-day compressive strength of Oil Palm Shell (OPS) concrete without GGBFS (mix M) was 42.5 Mpa, which shows that the reference mixture is a high strength lightweight concrete. The effects of inclusion of GGBFS on the compressive strength of the OPS concrete specimens up to 56 days were observed. They reported that at all ages, the compressive strength of OPS concrete containing GGBFS is lower than the compressive strength of OPS concrete without it. Also for OPS concrete with GGBFS, the strength decreases as the percentage replacement increases for all ages. In comparison to concrete mix without GGBFS the reduction in compressive strength of concrete mix with 30% GGBFS, 50% GGBFS and 70% GGBFS at 1 day was 28%, 46% and 61%; at 3 days it was 21%, 34%, and 45%; at 7 days it was 21%, 31% and 39%; at 28 days it was 8%, 15% and 23%; and at 56 days it was 9%, 13%, and 24%, respectively. They observed that rate of strength gain was more pronounced for mixes with higher amounts of GGBFS. This is due to the filler effect of GGBFS. This is because the GGBFS hydrates more slowly than Portland cement.

Teng *et al.* (2013) reported that the specimens with ultra-fine ground granulated blast furnace slag (UFGGBS) generally achieved higher compressive strength as compared to the specimens from their control mixes regardless of curing duration. The strength was reported to be more when the water/cement ratio was less as compared to UFGGBS. They observed that the effectiveness of UFGGBS is greater when the w/c ratio was lower. Also, the effect of UFGGBS was mainly in the compressive strength development at the early age of concrete.

Xu *et al.* (2014) reported that the geopolymer samples with GGBS grades 80, 100 and 120 revealed the 1-day compressive strength of 3.5, 5.3 and 16.0 Mpa, respectively. The 1-day compressive strength of sample with GGBS grade 120 was 4.6 times higher than that of GGBS grade 80. They also reported that there was a decrease in the difference among compressive strength after curing of 14 days. Samples with GGBS grade 80, GGBS grade 100 and GGBS grade 120 showed compressive strengths of 38.8, 37.7 and 35.7 Mpa, respectively at 28 days curing, which showed the high reactivity of high-grade GGBS.

Bagheri and Nazari (2014) observed the positive effect of lower percentage of GGBS on the compressive strength. This might be as a result of the ratio between the cementitious pastes to the GBFS wt%. The possibility of reaction between the aggregate and cementitious paste was decreased with the increase of GBFS wt%. Therefore, weak interfaces accelerated the crack propagation at lower forces. Also due to the increased aggregate would result in the smaller amount of paste. Hence a comprehensive geopolymerisation process is decreased due to complete formation of alumino silicate compound. Specimen with 30 wt% GGBS showed the compressive strength of 69.3±5.3 Mpa while specimen with 55 wt% GGBS showed the compressive strength of 21.0±1.0 Mpa.

Kuo *et al.* (2014) reported that the strength increased with the addition of furnace slag, and the desulfurization slag (DS) provided high alkalinity as the catalyst for furnace slag hydration, which provided an adequate amount of OH^- ions for hydration and increasing the early strength. The strength development was rapid before the age of 7 days and was affected by water/cement after 28 days. At a constant water/cement, the strength became stable after 28 days, and the long-term strength was relatively constant. Because the $Ca(OH)_2$ in the DS failed to effectively provide strength, as the pozzolanic reaction derived from GGBS was the main source of strength. The pozzolanic reaction was generated continuously for a long period, and the addition was advantageous to the development of long-term strength. The compressive strength value was in the range of 1.83-13.21 Mpa, which corresponds to a low-strength concrete. Because the concrete strength increased with the amount of SP for the same water/cement, it was clear that the addition of SP contributed to strength development. DS is a porous material that, compared to natural

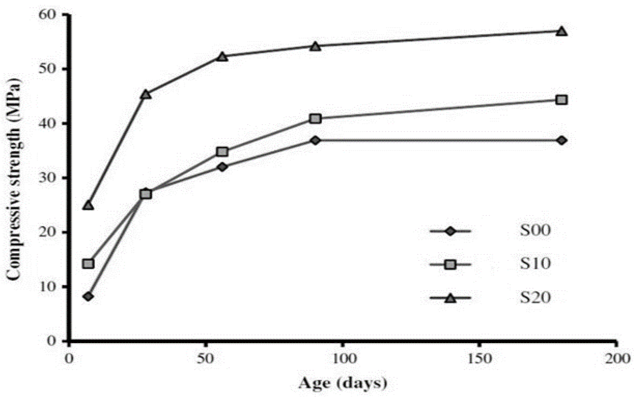

Fig. 5 Compressive strength variation of geopolymer concrete with different slag (Deb *et al.* 2014)

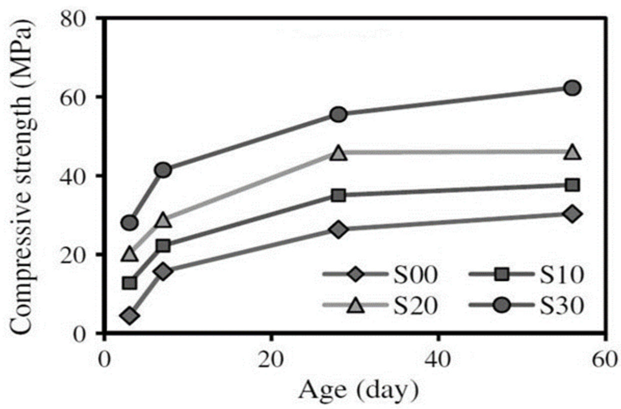

Fig. 6 Effect of different percentage of GGBS on compressive strength development of the geopolymer concrete (Pradip and Prabir 2014)

aggregates, appeared to be more fragile. The fragility and high alkalinity (pH=11.3) of the DS aggregate affected the development of strength, and the concrete strength could be enhanced only by increasing the amount of furnace slag binder.

Deb *et al.* (2014) reported that there was a decrease in strength development of the geopolymer concrete mixtures after 28 days and which continued to increase at slower rates until 180 days (Fig. 5). It was observed that there was an increase in compressive strength with the increase of GGBS content in the mixtures. Geopolymer concrete mixture containing 20% slag achieved 17% higher compressive strength than a mixture containing 10% slag at the age of 28-days. The effect of GGBS at 20% replacement level on the increase of compressive strength appeared to be more pronounced when the Sodium Silicate/Sodium Hydrate ratio was reduced from 2.5 to 1.5. With 20% GGBS in the binder, the mixture with Sodium Silicate/Sodium Hydrate ratio of 1.5 achieved 15% higher 28-day compressive strength than the mixture with Sodium Silicate/Sodium Hydrate ratio of 2.5. The addition of more was reported to Increase in compressive strength was reported by addition of more calcined source materials which improved the microstructure of geopolymer matrix. Hence the increase of compressive strength in the geopolymer concrete specimens by the

Table 14 Effect of blast furnace slag on the compressive strength of concrete at various ages (Walid *et al.* 2015)

Specimen	Compressive strength		
	7 day	28 day	90 day
C-PC	26.56	35.42	49.35
20 BFS	25.17	37.11	51.09
30 BFS	24.38	36.57	50.19
40 BFS	20.55	34.31	47.515

inclusion of GGBS was attributed to the formation of more compact microstructure of the binder. The compressive strength of geopolymer concrete increased from the early age of 7 days to 180 days. Mixtures having 10% and 20% slag respectively, showed higher strengths than the geopolymer concrete without slag at 28 days. The increase in strength was due to the increase of calcium bearing compound in the dissoluted binder which formed a reaction product from both slag and fly ash. It was observed that the strength increase was more significant for 20% slag than for 10% slag in the binder. The highest strength increase at all ages up to 180 days was observed for 20% slag and Sodium Silicate/Sodium Hydrate ratio of 1.5.

Pradip and Prabir (2014) observed the compressive strength developments of Geopolymer concrete (Fig. 6). Geopolymer mixture having 0% GGBS when cured at ambient condition (20-23^{o}C), reacted slowly to develop strength. When GGBS was incorporated in the mixture with unaltered alkaline activator the strength increased significantly from the early age of 3 days. At 28 days, concrete mixtures having 10%, 20% and 30% GGBS of total binder achieved 33%, 74%, and 110% higher strength as compared to the strength of control geopolymer mixture (0% slag) respectively. In other words, the 28-day compressive strength increased about 10 Mpa for every 10% increment of the slag content. Similar compressive strength development was observed over the age up to 56 days.

Moruf *et al.* (2014) reported that the effect of GBFS content on the compressive strength of alkali-activated GGBS with combination of ultrafine palm oil fuel ash (AAGU) binder. The strength can be observed to increase with time. The 3-day compressive strength of 20.11 Mpa was obtained in AAGU with 0% GGBS and this increased by 51%, 28.7%, 76.47%, 80% and 31.92% when 5%, 10%, 20%, 25% and 30% of GBFS were added respectively. At 28 days 51.56% of strength was gained in AAGU 0% slag. The maximum strength at 28 days of 44.57 Mpa was obtained in AAGU with 20% slag. The 28 days strength in AAGU0.2 system was about 22% of strength at the 3 days strength. In other words, almost 80% of the strength could be achieved in 3 days due to the addition of 20% of GGBS in the AAGU paste. This indicated that the addition of GGBS in AAGU 0% slag enhanced early strength development.

Walid *et al.* (2015) reported that decrease in compressive strength with increased slag content at an early age was observed. The reduction was more for mortar mixture containing 30% and 40% of blast furnace slag as cement replacement. However, at 28 and 90 days, the compressive strength of concrete containing 20% blast furnace slag was higher (≈5%) than that of control concrete. In addition, the concrete containing 30% blast furnace slag exhibited an equivalent or a greater final strength than that of control concrete. For example, when the concrete made with 30% BFS as a cement replacement, the compressive strength loss at 7 days was 8%. However, the strength at 28 days increased by 3% compared to the control concrete. The results obtained in this study show

Table 15 Effect of blast furnace slag on the split tensile strength of concrete at various ages (Li and Yao 2001)

Replacement percentage level	Split tensile strength (MPa)		
	3 days	7 days	28 days
0%	3.80	4.54	5.54
30% GGBS	4.06	5.03	5.91
30% GGBS+10% SF	5.20	5.44	6.14

that the use of blast furnace slag decreased the strength of concretes at early ages compared to the control concrete. This decrease observed at the beginning, due to the relatively slower rate of pozzolanic hydration process. But at later ages, blast furnace slag, which is latently hydraulic, undergoes hydration reactions in the presence of water with calcium hydroxide $Ca(OH)_2$. This secondary pozzolanic reaction yields a denser microstructure because the $Ca(OH)_2$ was consumed and C-S-H paste is formed and thus leads to enhance the later strength.

5. Splitting tensile strength

Li and Yao (2001) reported that concrete with 30% GGBS and 30% GGBS addition to 10% silica fume (SF) acquired much higher split tensile strength than concrete without GGBS at each testing age. At the age of 3 days, the split tensile strengths of concrete with 0% GGBS, 30% GGBS, and 30% GGBS addition to 10% silica fume were 3.80, 4.54 and 5.54 Mpa, respectively. At 28 days of age, the split tensile strengths of Concrete with 30% GGBS, and 30% GGBS addition to 10% silica fume increased greatly to 5.91 and 6.14 Mpa, respectively, compared with 5.54 Mpa of Concrete with 0% GGBS. This tendency reflects the strengthening effect of ultrafine GGBS and SF on mechanical properties of concrete. The results were given in the following Table 15.

Topcu and Boga (2010) reported that splitting tensile strength of 25% GGBS content series, exposed to standard water curing (C2) during 28 and 90 days, increased at the ratios 5.52% and 11.63% compared to control series, respectively. Splitting-tensile strengths of 50% GGBS series decreased at the ratios of 3.31% and 12.70% for 28 and 90 days respectively. Splitting tensile strengths of 25% and 50% GGBS series exposed to uncontrolled relative humidity and temperatures media (C1) curing during 28 days decreased at the ratios 21.32% and 34.21% compared to control series, respectively. Splitting-tensile strengths of these GGBS series exposed to C1 curing during 90 days decrease at the ratios 17.07 and 19.51 compared to control series, respectively. The increase in splitting-tensile strengths was seen by exposing to C2 curing while splitting-tensile strengths were decreased with the addition of GGBS exposed to C1 curing. It was also observed that splitting tensile strengths increased with the increase in curing ages for both of curing methods.

Rafat and Deepinder (2012) reported that 28-day splitting tensile strength of concrete at room temperature (27^{o}C) decreased with increases in GGBFS content. The splitting tensile strength of concrete containing 20%, 40% and 60% GGBFS was respectively 17.4%, 8.2%, and 15.6% lower than the control (3.2 Mpa) at room temperature.

Hiraskar and Chetan (2013) observed the split tensile strength of the concrete design mix by

Table 16 Effect of blast furnace slag on the split tensile strength of concrete at various ages (Hiraskar and Chetan 2013)

% Replacement of GGBS	Split tensile strength (Mpa)		
	7 days	28 days	60 days
0	3.65	4.18	4.59
50	3.31	3.93	4.20
75	2.62	3.14	3.73
100	2.69	3.25	3.65

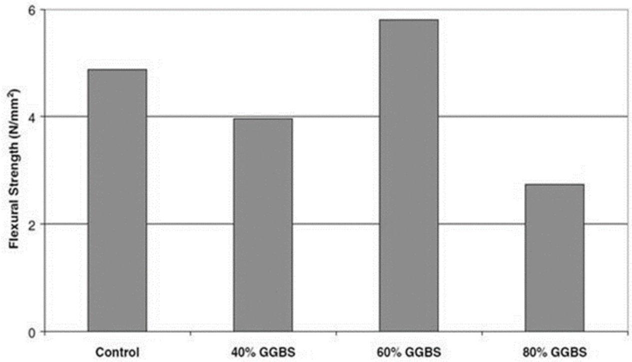

Fig. 7 Effect of different percentage of GGBS on flexural strength development of the geopolymer concrete (Khatib and Hibbert 2005)

casting and testing of 100 mm diameter and 200 mm depth size Cylinders after curing period of 7 days, 28 days and 60 days. They reported a decreasing trend in strength. The result was given in the following Table 15.

Deb *et al.* (2014) observed the tensile strengths of geopolymer concrete at 7, 28 and 90 days. It was reported that tensile strength increased with the increase of age for all the mixtures. The results showed that the tensile strength of concrete increased with the increase of slag content and decrease of Sodium Silicate/Sodium Hydrate ratio in the mixtures. Geopolymer concrete mixture with 20% GGBS and Sodium Silicate/Sodium Hydrate ratio of 1.5 gained 55% higher 2 tensile strength at 28-days than a mixture with 10% GGBS and Sodium Silicate/Sodium Hydrate ratio of 2.5 at 28-days. The rate of tensile strength development of geopolymer concrete was affected by the amount of extra water in the mixtures. It was also reported that the tensile strength of the mixtures with reduced alkaline activator (35%) was less than those of the mixtures with higher alkaline activator strength to compressive strength varied from 0.07 to 0.13. This correlation tends to be similar to that shown by conventional water cured OPC concrete.

6. Flexural strength

Ujhelyi and Ibrahim (1991) observed the flexural strength of concrete containing various percentages of GBFS and ground rhyolite tuff as partial replacement of cement at different hot weather condition. The cement content in control mix was 350 kg/m^3. The water/cement ratio was

Table 17 Effect of blast furnace slag on the split tensile strength of concrete at various ages (Hiraskar and Chetan (2013))

Percentage replacement of BFS	Flexural strength (MPa)		
	7 days	28 days	60 days
0	3.73	6.25	7.00
50	2.93	5.80	6.50
75	3.45	5.00	5.25

kept at 0.531. Two mixes were made; the first were stored in laboratory room and the second in a special room. They concluded that concretes with slag as a partial replacement of cement (up to 40%) had higher flexural strengths than that of concretes made with Portland cement alone. Flexural strength of concretes made with slag was higher comparing to Portland cement concrete cured in high temperature.

Khatib and Hibbert (2005) observed the effect of GGBS on the flexural strength of concrete. Portland cement (PC) was partially replaced with 0-80% GGBS. Mixes with partially replaced with 40%, 60% and 80% GGBS of cement was prepared. The following figure showed flexural strength values of mixes containing 0%, 40%, 60%, and 80% GGBS at 90 days curing. There was a noticeable increase in the flexural strength of concrete containing 60% GGBS than the control mix. But a decrease at 40% and marked decrease at 80% replacement level were observed.

Bernal *et al.* (2012) observed that concretes with GGBS content showed improved toughness (related to the area underneath the load–deflection curve) when formulated with increased SiO_2/Al_2O_3 ratios. Concretes with 10% replacement of GGBS by Metakaolin showed only slight differences in maximum load at different SiO_2/Al_2O_3 ratios. Increasing the content of Metakaolin in the binder to 20% showed a reduction in the maximum load and toughness at the higher SiO_2/Al_2O_3 ratios (4.0 and 4.4), but concretes with an SiO_2/Al_2O_3 ratio of 3.6 do not exhibit variations in the maximum load when compared with specimens prepared with similar formulation conditions but lower contents of Metakaolin. Based on the flexural testing curves, the flexural strength has been calculated via the modulus of rupture (MOR). Concretes based solely on GGBF show an increase in MOR with higher SiO_2/Al_2O_3 ratios; after 28 days of curing, the MOR is 73% higher at a SiO_2/Al_2O_3 ratio of 4.4 compared to concretes formulated with a SiO_2/Al_2O_3 ratio of 3.6. These results are consistent with the reduced toughness and compressive strength observed in these samples. With longer curing durations, a similar trend in the MOR at higher SiO_2/Al_2O_3 ratio is identified; however, differences between formulation conditions in the MOR are less reported.

Teng *et al.* (2013) reported that the development of flexural strength followed the same trend as that of the compressive strength. Concrete mix with 30% ultra-fine ground granulated blast furnace slag (UFGGBS) replacement showed increased results than the control mixes. They observed that UFGGBS has a greater effect on the flexural strength of the concrete with lower w/c ratio.

Hiraskar and Chetan (2013) observed the flexural strength of the concrete design mix by casting and testing of beams (size 100×100×500 mm^3) after the curing period of 7 days, 28 days and 60 days. They reported a decreasing trend in strength. The result is shown in Table 17.

7. Conclusions

Several studied has been carried out related to the use of GGBS as partial and full replacement of cement for the preparation of cement mortar and concrete. The outcomes of the previous studies have been analyzed and the major findings are stated as follows:

• The addition of GGBS increases the slump value of concrete (up to 50% replacement). Whereas addition of other additives such as oil palm shell the slump value is increased (up to 30% replacement) and then it decreased with further addition of GGBS. This may be due to the fineness of the GGBS.

• The flexural strength is increased with increasing amount of GGBS up to 40% replacement ratio, after which it decreased. But in some cases decreased in the flexural strength was observed by the authors with the increase in the GGBS content.

• Increase in the splitting tensile strength is also observed by some authors regardless decrease in the strength is also observed. Moreover the later age splitting tensile strength is increased in each case.

• The increased in compressive strength value is observed up to 40-50% replacement ratio after which decrease in the compressive strength is observed by some authors. This is due to the high reactivity of the slag.

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