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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 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

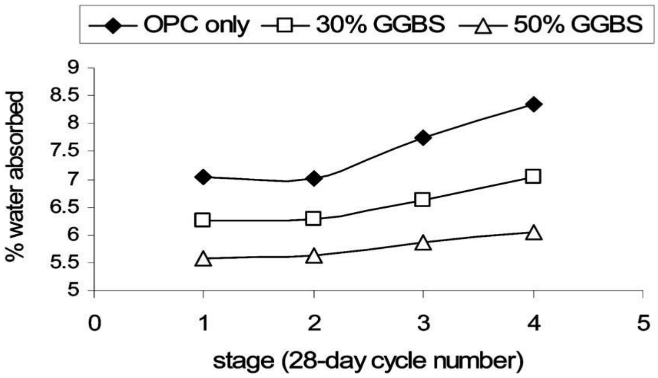

Fig. 2 Water absorption of PC and GGBS samples (Pavía and Condren 2008)

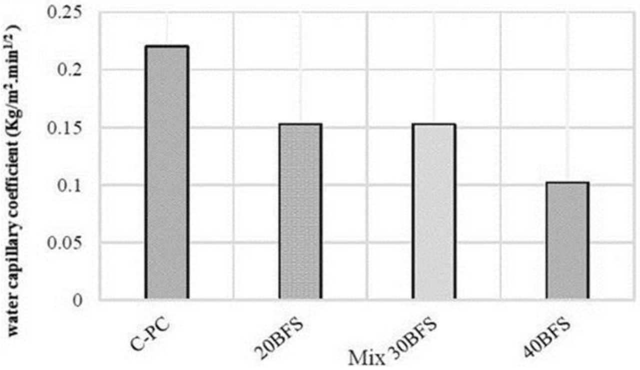

Fig. 3 Capillary water absorption coefficient of blast furnace slag by Walid *et al.* (2015)

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 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

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 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

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

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 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

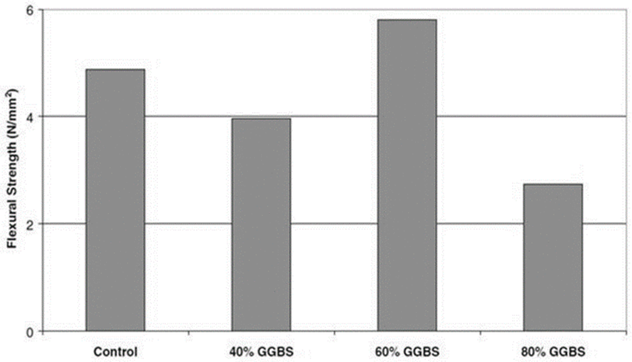

Fig. 7 Effect of different percentage of GGBS on flexural strength development of the geopolymer concrete (Khatib and Hibbert 2005)

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

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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