Journal of Urban and Environmental Engineering, v.12, n.1, p.40-49

ISSN 1982-3932
doi: 10.4090/juee.2018.v12n1.040049

Journal of Urban and Environmental Engineering

www.journal-uee.org

SCOPE OF GRANULATED BLAST FURNACE SLAG AS FINE AGGREGATE IN CONCRETE FOR NORMAL AND FIRE EXPOSURE

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Received 7 November 2016; received in revised form 10 January 2018; accepted 17 January 2018

Abstract: Present work experimentally investigates the scope of utilizing granular blast furnace slag (GBFS) in concrete exposed to high temperature. Six series of concrete mixes of Grade M20 including control mix were prepared by replacing natural sand with GBFS in 10, 30, 50, 70 and 100% by weight. Sustainability of GBFS concrete for normal weather condition was ensured by preliminary investigation on mechanical strength for various GBFS concrete mixes at various ages. Later, fire durability of the concrete was evaluated by residual compressive strength, weight loss and surface observation of heat cured specimen through necked eye. Cube compressive strength improves by 2.15-6.31% while cylindrical compressive strength of concrete mix with 30% GBFS marginally improves at all ages. Split strength increases up to 2.9-8.07% up to 50% GBFS replacement while flexure strength increases by 0.81-7.0% at 30% with respect to all the age of curing at room temperature. Residual compressive strengths were 57.3, 55.89 and 54.46 % for 30, 50 and 70% GBFS concrete mixes at 600°C. Surface cracks in specimen were observed after 500°C which continued to grow with the increase in temperature. Furthermore, test results indicate the improvement in the properties of concrete with the incorporation of GBFS even though it exposes to high temperature.

Keywords: Sustainable concrete, Granulated blast-furnace slag, Sand Replacement, Mechanical strength, Elevated temperature, Weight loss, Cracks

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INTRODUCTION

The utilization of various types of industry wastes or by-products as alternative constituents in cement and concrete have been remains an emerging trend in the last decades for generating eco-friendly and environmentally green concrete (Dash et al., 2016, Siddique, 2014) . Metal industry such as steel, copper, aluminum etc. and thermal power plants play a key role in producing high volume slags and ashes which demands the huge disposal area before its further waste management. Many researchers have reported about the properties of fresh and hardened concrete, durability performance of concrete or mortar made by incorporating various types of blast furnace slag in different forms as binary or ternary constituents (Berndt, 2009). However, present study is based on the granular blast furnace slag available from Durgapur Steel Plant, SAIL (India).

Concrete containing various types of slag such as zink slag, lead slag, granular blast furnace slag(GBFS) etc. as fine aggregate in concrete decrease the workability, attributed to more angular shapes and its high water absorption capacity (Özkana, 2007; Mosavinezhad *et al*., 2012; Nataraja, 2013; Samanta *et al.,* 2014; Patra and Mukherjee 2017). Yuksel et al., (2006) reported that concrete made with granular blast furnace slag makes concrete porous and exhibits relatively low compressive strength. The ratio of GFBS and sand governs prime criteria for the effects on the strength and durability characteristics of concrete. Nataraja *et al.,* (2013) investigated the possibility of utilizing GBFS as sand substitute in cement mortar mix. They observed that flow ability of mortar decreases as the percentage of GBFS increases. Test results indicated that GBFS up to 75% could be used as an alternative to natural sand with marginal acceptance of results. Samanta *et al.,* (2014) concluded that GBFS sand can be used as an alternative fine aggregate to natural sand from strength point of view, but up to 50% replacement level and thereafter decreases considerably till 70% replacement level but maintaining the closer proximity of the strength with that of control concrete without GBFS. Patra and Mukherjee 2017 found that a workable concrete can be designed by incorporating 40% GBFS. Using fly ash (class F grade) as partial replacement of fine aggregate exhibited the pozzolanic advantage over the conventional concrete (Siddique, 2003).

Concrete is excellent to resist the effect of thermal exposure, even though it undergoes significant deterioration due to changes in physical and mechanical properties when it is subjected to high temperature because of the changes in the chemical composition of cement paste and in the physical properties of aggregates (Khoury *et al,*. 2002, Georgali *et al,*. 2002, and Demirel *et al*., 2010). Effect of high temperature on properties of concrete causes loss in physical and mechanical properties along with the formation of cracks and large pores (Xu *et al*., 2001, Janotka *et al.,* 2005). Fire resistance of concrete is affected by factors like the type of aggregate and composition of cement used, firing temperature and its duration, size of structural member, and moisture content of concrete (Phan *et al*., 2001 and Hüsem, 2006). All the materials exposed to high temperature during their formation and production stages are themselves a highly resistant to volume expansion and decomposition due to the elevated temperatures. The type of aggregates influence strongly the behaviour of concrete submitted to high temperature. The aggregates thermal expansion partly opposes to the drying of cement paste (Yüksel *et al*., 2011). Light weight aggregates such as pumice, foamed slag, and expanded clay products have high resistance to fire, and concrete made from them has low heat conductivity (Shoaib *et al.,* 2001).

Concrete made with lightweight aggregate concrete has a better thermal stability, lower thermal conductivity and lower thermal expansion coefficient than normal weight aggregate concrete as it is a product of high temperate sintering which results in more internal holes inside the aggregate (Mun, 2007). However, both light weight concrete and normal weight concrete behave in the same way at high temperature. No one can withstand temperature above 1000°C. But, rate of deterioration of strength is lower in normal weight concrete than light weight concrete (Emre Sancaka, 2008). The higher the moisture content, the higher the possibility and tendency of spalling for high performance concrete (Chan *et al.,* 2000). Khouri and Anderberg (2000) reported that concrete shows an increased susceptibility to spalling over normal-weight concretes. Furthermore, they concluded that concrete with low water to cement ratios (and thus having higher strengths and lower porosities) showed a greater susceptibility towards spalling, than concretes with a higher water cement ratio. These findings strongly support the use of light weight aggregate which has low unit weight and high absorption capacity. Sahani *et al.,* (2014) reviewed the role of blast furnace slag in various form utilized in concrete exposed to high temperature and found that fire performance of normal strength concrete containing OPC with 40% ground granulated blast furnace slag (GGBFS) is better than high strength concrete. In their next work based on GBFS concrete (Sahani *et. al* 2015) attempted to utilised granular blast furnace slag for development of concrete for fire exposed environment.

The moisture content has a significant bearing on the strength of concrete in the temperature range from 20 to 200°C. It is believed that water in concrete softens the cement gel, or attenuates the surface forces between gel particles, thus reducing the strength (Lankard, 1971). But at the same temperature range, a slight increase in concrete strength associated with a further increase in temperature is attributed to the general stiffening of the cement gel, or the increase in surface forces between gel particles, due to the removal of absorbed moisture. The temperature at which absorbed water is removed and the strength begins to increase depends on the porosity of the concrete (Cheng *et al*., 2004). When the temperature is above 110°C, the dehydration of chemically bound water from the calcium silicate hydrate (C–S–H) becomes significant (Khoury *et al*., 2002). Calcium hydroxide is one of the most important compounds in cement paste, dissociates at around 530°C resulting in the shrinkage of concrete (Georgali and Tsakiridis, 2005). The reduction in the compressive strength of concrete is significantly larger for specimens exposed to 600°C, and the decomposition of $Ca(OH)_2$ and calcium silicate gel, especially at 800°C, resulted in the total deterioration of concrete (Demirel and Kelestemur 2010).

Behaviour of fire exposed concrete usually assessed by observing colour change, crazing, cracking, and spalling. The colour change of heated concrete results principally from the gradual water removal and dehydration of the cement paste. Aggregates occupy 70% to 80% of the volume of concrete and thus heavily influence its behaviour at high temperature. By consequence, colour change of concrete will depend largely on the mineralogical composition of aggregate used for its manufacturing (Hager, 2014) .As temperature increases colour of concrete changes, at 300°C the concrete colour does not change noticeably. When temperatures are increased up to 400 to 600°C, the colour of concrete slightly changes to dust colour or brownish or yellowish grey. Beyond 600°C, concrete colour observed is straw yellow to pinkish yellow/pinkish red (Xiao and Falkner, 2006). It is generally agreed (Short *et al*., 2001, Colombo and Felicetti, 2007) that when heated to between 300°C and 600°C concrete containing siliceous aggregates will turn red; between 600°C and 900°C, whitish-grey; and between 900°C and 1000°C, a buff colour is present. (Arioz, 2007) reported that intensity of the yellow colour increased with increase in temperature and red colour appeared when the temperature increased to 800°C. Considering the real phenomena occurring during fire, heat curing has been classified into two types: slow heating (Bastami *et al*., 2011; Singha roy and Sai Krishna, 2012) and raid heating (Netinger *et al.,* 2011; Nouowe *et al.,* 2009) of structural concrete. Also, temperatures of 1000-1100°C in fire lasted for the duration of 1-2 hours have been observed more frequently (Gambhir, 2013). Many researchers have adopted different durations of heat curing and heating rate with aim to achieve same ultimate effect rate such as 6.7°C/min to achieve 800°C for 1h duration (Yüksel *et al.,* 2011); 10-20°C/min to achieve 600°C for 2h (Shoaib *et al.,* 2001).

Existing literature does not provide the detailed investigation of the mechanical properties concrete incorporating GBFS for normal construction work and for some industrial application where concrete structure might be exposed to high temperature. The findings of this investigation will help in predicting the behaviour of concrete made with GBFS fine aggregates intended for nuclear or similar applications concrete structures existing near the furnaces, air craft runways, nuclear reactor etc.

MATERIALS

Ordinary Portland cement (Grade 53) supplied by India cement was used for preparing concrete mixes. It's physical and chemical properties were conformed to Beuro of Indian standard (BIS) code (IS: 12269-1987). Crushed granite stone with maximum size of 20mm and 12.5mm well graded aggregate blended in the ratio of 60:40 were used as coarse aggregates. Grading of fine and coarse aggregates were carried out according to IS: 2386 (Part I)-1963 and the zone of sand was confirmed with IS 383: 1970.

Locally available river sand was used as fine aggregate in control mix concrete which was partially replaced with granulated blast furnace slag (GBFS), procured from Durgapur Steel plant, Durgapur, India. Grain size analyses of both the fine aggregates were performed as per IS: 2386(Part I)-1963 and found under zone II as per IS: 383-1970. According to IS: 2386(part III)-1963, specific gravity of natural sand and GBFS were determined as 2.62 and 2.32, respectively. As compared to natural sand, GBFS is a light weight fine aggregate having similar gradation but with high water absorption capacity. Presently, water absorption capacity of natural sand is 0.28 while GBFS has 4.06. Furthermore, commonly used natural sand is normally rounded and smooth texture while GBFS is rough textured, flaky and angular shaped particle. These characteristics play a major role in making concrete mix harsh (Nataraja, 2013 and Patra and Mukherjee, 2017). Chemical analysis of GBFS was performed at their manufacturing place in lab by using X-ray florescence analysis (XRF). It contains about 30.8% silica (SiO_2) 31.6% lime (CaO), 22.4% alumina (Al_2O_3), 0.44% iron oxide (Fe_2O_3), free from harmful ingredients. It has additional advantage of having high percentage of refractive additive alumina which further creating a scope for fire durability. More important regarding safety measures is that GBFS should be handled using safety gloves during casting work, it may punch the naked hand.

Table 1. Mix. proportion for per batch of concrete for grade M20 (0.48:1:1.71:3.08)

Mix ID	W/C	Cement	Sand	GBFS	Water	CA(kg)		Ch.Admix.	Slump (mm)
		(kg)	(kg)	(kg)	(Ltr)	20 mm (max.)	12.5 m (max.)	(ml.)	
M-0	0.48	20	34.2	0	9.6	36.96	24.64	0	47
M-10	0.48	20	30.78	3.42	9.6	36.96	24.64	0	35
M-30	0.48	20	23.94	10.26	9.6	36.96	24.64	90	42
M-50	0.48	20	17.1	17.1	9.6	36.96	24.64	120	40
M-70	0.48	20	10.26	23.94	9.6	36.96	24.64	120	35
M-100	0.48	20	0	34.2	9.6	36.96	24.64	174	28

RESEARCH METHODOLOGY

The scope of this work was to study the mechanical behaviour of concrete incorporating various percentages of granular blast furnace slag as partial replacement of natural sand (NS). Six series of concrete mixes for Grade M20 were prepared by partially replacing fine aggregate separately with GBFS. Replacement percentages were between 0, 10, 30, 50, 70 and 100% by weight of fine aggregate. Experimental work were carried out to study the mechanical behaviour such as compression, split tensile and flexure strength of concrete (M20 grade) at room temperature (27°C). Later, influence of elevated temperatures of the concrete containing non-ground granulated blast-furnace slag (GBFS) as fine aggregate, with aim to produce sustainable heat resistant concrete. All the concrete specimens were exposed to varying temperature from 100°C to 900°C at the interval of 100°C at the age of 90 days. Specimens were heated in electric furnace for 3h at target temperature, followed by furnace cooling and then natural cooling. Tests were conducted to determine loss in weight, compressive strength and thermal crack developed in the specimens. The method used in the present study is the unstressed residual strength test. These properties are very important for the safe design of concrete and in the repair of concrete structures.

MIXTURE PROPORTION

In the mix design, M20 grade of concrete was designed as per Indian Standard Specifications (IS: 10262-2009) to have 28-day target mean compressive strength 26.6 MPa. Design mix proportions for the control concrete) was 0.48:1:1.71:3.08 while other concrete mixes were prepared by replacing the natural sand (NS) with granular blast furnace slag (GBFS) by weight. In the present study, six different types of mixes via M-0, M-10, M-30, M-50, M-70 and M-100 were prepared by replacing the natural sand with granular blast furnace slag (GBFS) by 0, 10%, 30%, 50%, 70% and 100% of GBFS by weight of natural sand. In doing so, the water to cement ratio was kept the same in order to investigate the effects of replacing GBFS with natural sand when other parameters were unchanged. By adding 0.5% to 1 % of super plasticizer was used in the preparation of concrete mixes containing more than 30% GBFS to achieve the designed range of workability (25-50mm) for concrete mix. Conplast SP 430 complies with (IS: 9103:1979) was used as chemical admixtures to maintain the workability in the assumed slump range. The mixture, designation and quantities of the various materials for per batch of each designed concrete mixture are given in **Table 1**.

SPECIMEN PREPARATION AND TEST METHOD

Number and type of moulds were used for all type of tests as per Indian Standard Specification (IS: 516-1959). All the series of concrete specimens were demoulded after 24h and cured in tank at 27°C ± 2° C and 90% ± 1% relative humidity. Universal testing machine (300T) for performing mechanical load testing and Muffle furnace with capacity 1200°C for heat curing were used in entire experimental work. Concrete specimen. Concrete specimens such as 150 mm size cubes, 150 mm Φ x 300 mm sized cylinders, and 100 mmx 100 mmx 500 mm size prisms for normal case and 100 mm cubes for heat curing were prepared.

HEATING AND COOLING REGIME

Specimens were heated in muffle furnace (265 × 265 × 600 mm) up to target temperature 100, 200, 300, 400, 500, 600 700, 800 and 900°C for 3hours of heat curing period. The time-temperature curve of the furnace used is compared with the standard curve recommended in (IS: 3809-1979, ISO Fire 834) as mathematical expressions of temperature time curve for both the standards are same (**Fig. 1**). Furnace curve show that heating rate is slow, which is a limitation of the equipment available. However, the specimens were heat cured at the maximum temperature for 3 h to achieve a thermally steady state so that the effect on the ultimate results would be relatively small (Bastami et al., 2011); Singha Roy & Sai Krishna, 2012).

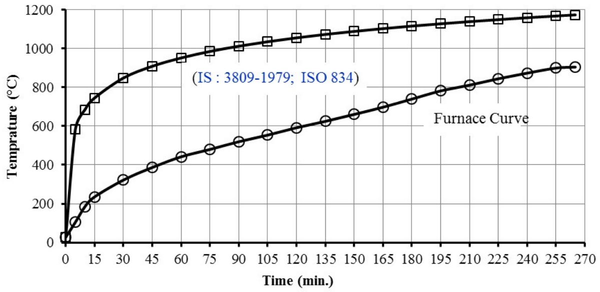

Fig. 1 Comparison of temperature curve of muffle furnace with BIS (IS: 3809-1979) and ISO 834.

RESULT AND DISCUSSION

Fresh concrete properties

Fresh properties of concrete were measured in terms of slump and the results are given in **Table 2**. **Figure 2** shows the slump of the mixes with and without adding chemical admixture. Design mix of the concrete was based on slump values ranging from 25-50mm. Slumps were adversely affected by increasing the percentage of GBFS. It was observed that as the percentages of GBFS were increased, water was soaked by the mix which makes the mix harsh. Harsh mix was observed for the concrete mix incorporating 50% of GBFS and higher replacement percentage. This may be attributed to high water absorption of GBFS and physical characteristics of particles.

Compressive Strength of Concrete

Compressive strength of concrete mixes including control mix were determined at various ages are shown in **Fig. 3**. Compressive strength of cube and cylinder for GBFS concrete mixes marginally improves the strength increases up to 30% and 50%, respectively. After that, a decrease in compressive strength was observed with the increase in GBFS. Chemical composition of GBFS is similar to cement and different compounds in GBFS (C_3S, C_2S, C_4AF, and C_2F) contribute to enhance the hydraulic activity of slag for strength development (Shi, 2004). Overall, compressive strength of all mixes continued to increase with the increase in age. It may be noted that the cube compressive strength of concrete mix with 30% GBFS increases up to 6.31% at 7days, 6.3% at 28days, 3.36% at 60days and 2.15% at 90days while cylindrical compressive strength of concrete mix with 30% GBFS marginally improves at all ages. Further increase in GBFS decreases strength. This increase in strength may be due to the replacement of fine aggregate with GBFS is attributed to the pozzolanic action of GBFS (Siddique, 2003). Beyond 50% replacement of NS with GBFS, considerable decrement of compressive strength has been observed for all ages. This may be because of insufficient water in the mix for compaction, too much of irregular shaped particle in GBFS, and it's glassy nature which might have developed the improper bond between cement paste and aggregate (Özkana,2007, Nataraja, 2013).

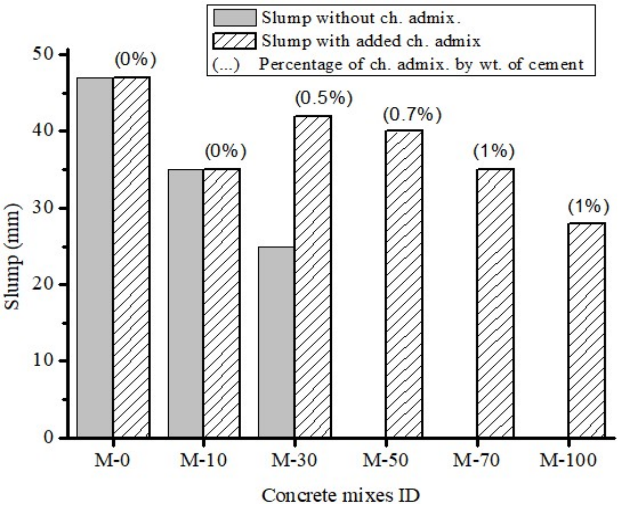

Fig. 2 Slump and doses of super-plasticizer for concrete mixes.

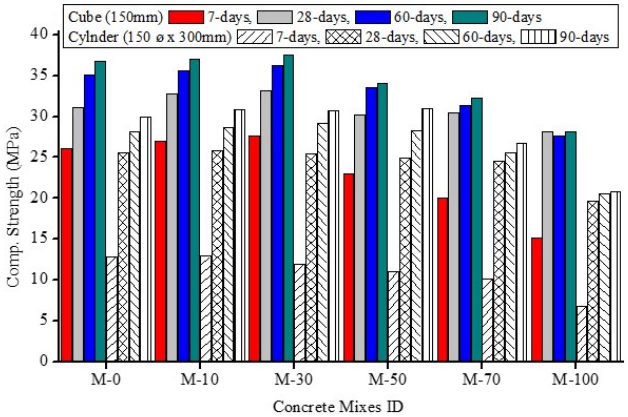

Fig. 3 Cube and cylindrical compressive strength of concrete mixes.

The ratios of the compressive strength of the cylinders (fc') in size 150 x300 mm to the cubes (fc) in size 150×150×150 mm are 0.82, 0.79, 0.767, 0.823,0.8 and 0.7 for the concrete mixes incorporating 0, 10, 30, 50, 70 and 100% GBFS. This ratio was 0.88 is for high performance lightweight foamed concrete (Hamad, 2017) while a factor of 0.8 is often recommended for normal strength concrete (Al-Sahawneh, 2013, Nevellie 2012). Concrete mixes with 50, 70% GBFS indicated close approximation towards the findings mentioned in literatures.

Split Tensile Strength and Flexure strength

The split tensile strength and flexural strength of the concrete mixes measured at the age of 28, 60, 90 days and their effect on strength are shown in **Figs. 4–5**. It can be seen that there is increase in split tensile strength by 2.9 to 5.84% at 28days, 4 to 7.67% and 3.73 to 8.07% at 90days with the increase in GBFS percentages up to 50%. However, further increase in GBFS decreases the strength. On the other hand, flexure strength improves the strength by 0.81 to 4.52% at 28days, 6.85 to 6.97% at 60days and 6.51 to 7.0% at 90days with the increase in GBFS percentages up to 30% whereas concrete mix with 50% GBFS exhibits little lower strength than control mix. Maximum value of split tensile strength and flexure strength are observed at 50% and 30% replacement level at the same water cement ratio. As said earlier the increase in strength can be attributed latent hydraulic activity or pozzolanic reactivity of slag and decrease in strength may be due to particle texture, shape and high water absorption capacity of GBFS which causes weak bond cement paste and aggregate from a number of empirical formulations existing in the literatures, national and international codes. It can be observed that the obtained test results have three distinct regions such as 0-10, 10-50 and 50-100% replacement level of GBFS. **Figures 6–7** represents the comparative study between 28-days test values and the values obtained. **Figure 6** shows that the value given by Lavanya and Jegan (2015) is higher than present study, whereas the lowest value is obtained from the formulation given by Kou and Poon (2008) whereas the test values of flexural strength values for concrete mixes are lower than those values obtained from the formulation given by ACI 318 (2011) but higher than the value of other formulations NZS-3101 and ACI:318 (2011). Moreover, the line plot shows that the relationship between split, flexural and compressive strength concrete containing GBFS is similar to that of conventional concrete.

Table 2. Empirical relationship for prediction of split tensile strength and flexure strength at 28 days

Split tensile strength (f_{spt})	
Carino & Lew (1982)	fspt = 0.272 fc’0.71
Gardner (1990)	fspt = 0.33 fc’0.667
Oluokun et al. (1991)	fspt = 0.294 fc’0.69
CEB (1993)	fspt = 1.56 ((fc’ -8)/10)2/3
GB 10010 (2002)	fspt = 0.19fc’0.75
NBR 6118 (2003)	fspt = 0.3 fc’0.667
Hueste et al., (2004)	fspt = 0.55 √ fc’
Xiao et al. (2005)	fspt = 0.55 fc’0.65
Arioglu et al. (2006)	fspt = 0.38 fc’0.63
Kou & Poon (2008)	fspt = 0.093 fc’0.8842
ACI:318 (2011)	fspt = 0.56 √ fc’
Vijaylakshmi et al. (2013)	fspt = 0.241 fc0.712
Flexure Strength	
CEB (1993)	$f_f = 0.81\sqrt{f_c}$
IS456:2000	$f_f = 0.7\sqrt{fc}$
ACI 318 (2011)	$f_f = 0.62\sqrt{fc'}$
NZS-3101	$f_f = 0.60\sqrt{fc'}$
DG/TJ-008 (2008)	$f_f = 0.75\sqrt{fc}$

where f_{spt} = Splitting tensile strength, f_r = flexure strength, f_c = cube compressive strength and f_c' = cylinder compressive strength.

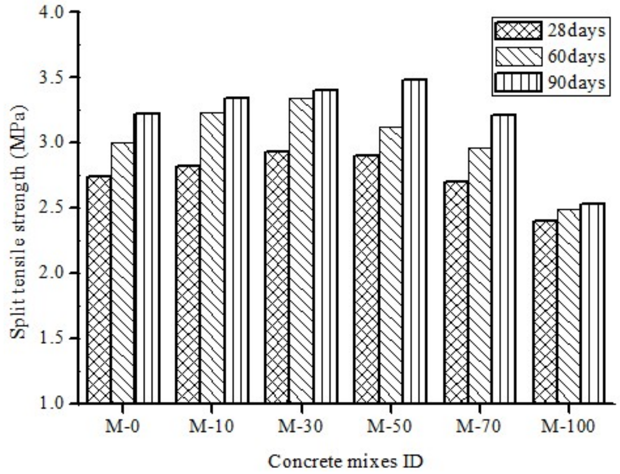

Fig. 4 Split tensile strength of concrete mixes.

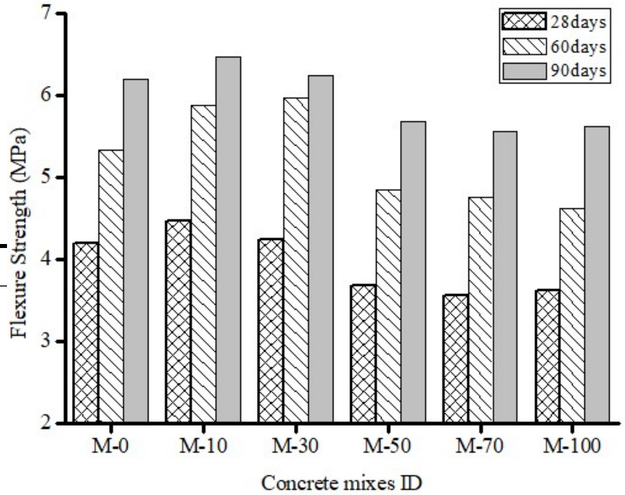

Fig. 5 Flexure strength of concrete mixes with various percentage of GBFS.

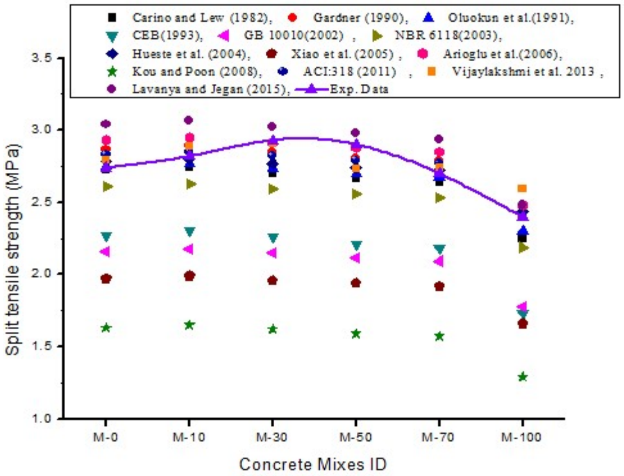

Fig. 6 Comparison of 28 days split tensile strength with various formulations.

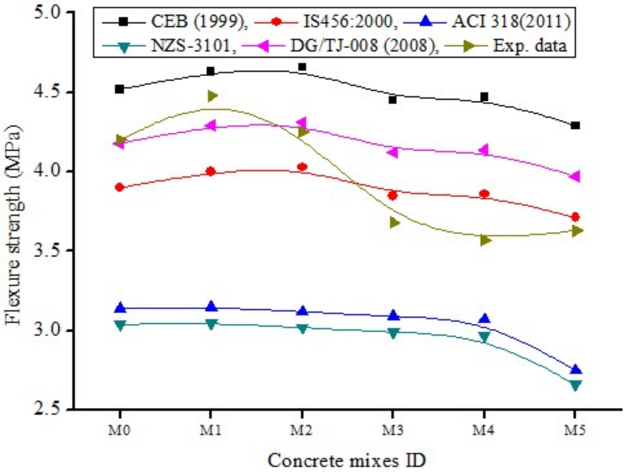

Fig. 7 Comparison of 28 days flexure strength with various formulations.

Effect of elevated temperature on compressive strength

Control mix concrete M-0, M-10, M-30, M-50, M-70 and M-100 have achieved compressive strength of 38.24, 40.3, 40.47, 36, 34.87, 32.39MPa respectively at the age of 90 days at room temperature. All the series of concrete cube specimens of 100mm have crossed the target mean strength of 26.6MPa. Compressive strength and the residual compressive strength ratio are shown in **Figs. 8–9**, respectively. As the replacement ratios increased, changes in the mentioned parameters were observed with respect to unheated specimens. Based on strength retention at a specific temperature, three temperature ranges have been classified as 27–300°C, 300–500°C and 500-800°C. The moisture content has a significant bearing on the strength of concrete in the lower temperature range from 27 to 300°C. With respect to literatures cited in the review, there is contradiction between the marginal increase or decrease in strength due to softening of cement gel or stiffening of cement paste (Lankard 1971, Cheng *et al.,* 2014). The loss or gain of compressive strength in this zone was varying from -18.68% (M-0) to 15.68 % (M-100) for all the mixes corresponding to initial compressive strength at room temperature. Peak values for M-0 to M-100 between 100-300°C were observed as 35.23, 38.22, 37.87, 34.90, 36.60 and 37.70 MPa respectively.

In the second temperature zone, the strength loss becomes gradual beyond 300°C with increase in temperature for all the mixes. Concrete mixes M-30, M-50, and M-70 retained the maximum percentage of residual strength, 61.16%, 65.39% and 57.59% respectively. But, steep fall in strength was observed in the case of concrete mix with 100 % GBFS. This may be attributed to simultaneous effect of exposed temperature and weak bond in mortar at higher replacement percentage. Therefore, the temperature range between 300 and 500°C may be regarded as critical to the strength loss of concrete. The residual compressive strength at temperature 500°C was varying from 49.46% (M-100) to 65.31 % (M-30) for all the mixes corresponding to initial compressive strength at room temperature.

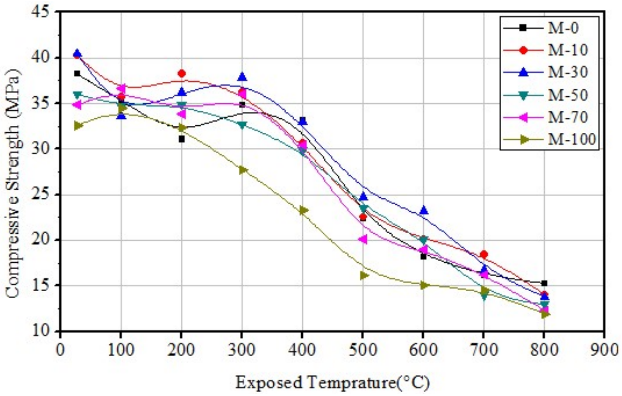

Fig. 8 Compressive Strength (MPa) at elevated temperatures.

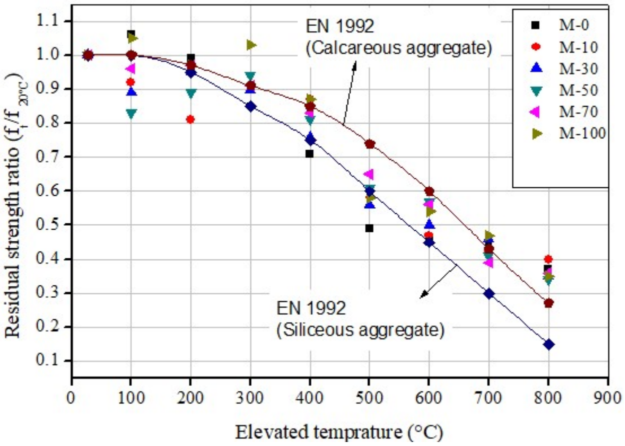

Fig. 9 Residual strength ratio with respect to elevated temperatures due to GBFS replacement.

In the third temperature zone, hair line cracks started to develop in the specimens at about 500°C in M-0, M-10, M-70 and M-100. At 600 °C, the concrete mixes, M-30, M-50 and M-50 were observed to retain percentage residual compressive strength of 57.3, 55.89 and 54.46% respectively. It is evident that after exposure to 800°C, the percentage residual compressive strength of all the concrete mixes was 39.94, 34.82, 33.93, 35.82, 35.23 and 36.53% respectively. There was noticeable strength retention in all the concrete mixes having GBFS even at 800°C and this range from about 33 to 37%. Effect of adding calcareous ingredients in concrete is more clearly observed at 600°C as shown in **Fig. 9**. As the percentage of replacement increases strength ratio tends to move towards EN 1992 (Calcareous curve). Control mix concrete consists of river bed sand which is mostly siliceous in nature having close approximation with EN 1992 (siliceous curve).

Percentage residual strength at maximum exposed temperature of 800°C is independent from replacement percentage of GBFS (Sancak et al., 2008**)**.

Effect of elevated temperature on weight Loss

Weight loss was measured in terms of loss in weight of sample prior to heating and after cooling, with respect to pre-heating weight, expressed in percentage. The weight losses (in percentage) of all the concrete mixes with increasing temperatures are shown in **Fig. 10.** It can be seen that loss in weight for all the series of concrete mixes were gradually increased from 0.61% to 7.7% with the increase in temperature 100 to 800°C. When temperature is raised from 100 to 350°C, the mass loss is little more owing to the release of both capillary water and gel water. All the specimens experienced the similar weight loss up to 110°C, which may attributed to easily evaporable water whereas steep gradient of curve up to 300°C confirms the material stiffening due to release of adsorbed water. From this temperature 300°C, behaviour of control mix concrete and GBFS concrete differ from each other. After 300°C, rate of increase in weight loss is decreasing. The losses in weight are not affected significantly for the replacement of 0, 10 and 30%. When replacement ratio is increased a gradual increase in loss in weight was observed. The final losses in weight were measured as 6.83 to 7.7% for all the concrete mixes. Test results revealed that the concretes containing higher GBFS amounts had generally higher weight losses.

Cracking Behaviour of GBFS Concrete

A thorough visual inspection was performed to evaluate the visible signs of cracking and spalling on the surface of the specimens after being subjected to high temperatures as shown in **Fig. 10**. Cracks or spalling were not observed in specimen up to 400°C. Hairline cracks began to appear extensively at 500°C and continued to widen as the temperature increased up to 800°C. Cracks developed in the specimen may be difference in thermal expansion coefficients of ingredients and transformation of chemical constituents of binding paste. At 500°C, hair cracks were observed for control mix M-0, M-70 & M-100, except M-30 and M-50 mixes. It was observed that cracks were more visible for all the mixes at temperature more than 600°C. Concrete mixes with 30% GBFS were more stable with respect to retention of strength, numbers and broadness of surface cracks.

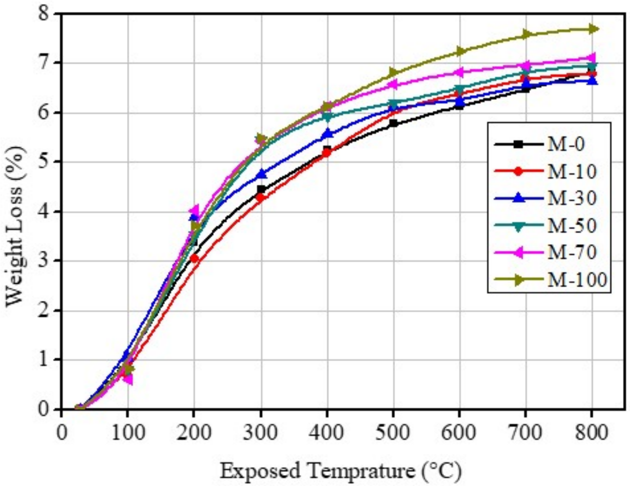

Fig. 10 Percentage weight loss of various concrete mixes (ID) at elevated temperature.

From the viewpoint of colour change, it was seen that no appreciable change in colour of the specimens up to 200°C. When the temperature were increased from 300°C to 600°C, concrete colour observed was straw brownish to yellowish grey. Beyond 600°C up to 800ºC, concrete colour observed was straw yellow to whitish. Scaling of heated specimen as white puffed material can easily observed along with wider cracks. With the further increase in temperature up to 900°C, relative strength was not sufficient even to sustain its integrity against gentle press while removing from furnace. During the heat curing, no explosive and bursting sounds for any kind of mixes were observed. This may be attributed to slow heating rate and slow cooling process in the furnace itself. Generally explosive spalling risk is higher for high strength concrete and high rate of temperature rise in furnace. Visual observations of the test specimens after exposure to the elevated temperatures reveal that no spalling or disintegration was noticed in any of the tested specimens upon heating that could be due to adopting a relatively high (water/cement) ratio which would generate more connected pores (Hosam et al., 2011, Bastami et al., 2011; Singha roy and Sai Krishna 2012).

CONCLUSION

Physical and mechanical properties of concrete containing GBFS as partial weight replacement fine aggregate were studied. Based on the properties of fresh concrete and hardened concrete at room temperature and residual compressive strength, residual strength ratio, percentage loss in weight and observation of colour and pattern of surface cracks after exposed to elevated temperature. Following conclusions can be drawn from this investigation:

- GBFS is lightweight material having glassy and angular shaped grains and possess high absorption characteristic which makes the concrete harsh after adding more 30% in place of natural sand. Hence, suitable dose of super plasticizer is needed to make workable concrete mix.
- The marginal improvement in compressive strength for cube and cylindrical specimen were observed up to 30% of replacement. Split tensile strength exhibited improvement up to 50% GBFS replacement while flexure strength up to 30%. With respect to percentage gain or marginal improvement mechanical strength, GBFS can be recommended to use up to 30% as a partial replacement of natural sand.
- Concrete mix having 100% GBFS retained strength up to 400°C and beyond this temperature considerable loss of strength was observed. 400°C was observed as critical temperature. On the other hand, mix with GBFS up to 50% exhibited improved result over control mix. Overall, mix with 30% and 50% GBFS performed better against fire between 400° to 600°C with respect to other mixes.
- The loss of weight on heating was more pronounced for concrete mixes with higher percentage of granular blast furnace slag (GBFS). Overall, loss in weight due to high temperature effect was independent from the replacement ratio of GBFS.
- Surface observation of concrete specimen through naked eye revealed that there was no appreciable change in colour of the specimens up to 200°C. Between 300°C to 600°C concrete colour observed was straw brownish to yellowish grey. Beyond 600°C up to 800ºC, concrete colour observed was straw yellow to whitish. Scaling of heated specimen as white puffed material can easily observed along with wider cracks. With the further increase in temperature up to 900°C, relative strength was not sufficient even to sustain its integrity against gentle press while removing from furnace
- Further investigation is needed to assure durability performance other than fire before the application in practice. Comparing to the performances of various concrete mixes before and after fire exposure, granular blast furnace slag may be recommended up to 30% even the concrete exposed to high temperature.

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