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Original Article

Development of stress block parameters for steel fiber reinforced GGBS concrete

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Abstract

Stress block parameters play an important role in the design of structural elements. The objective of this study is to derive the complete stress-strain behavior for steel fiber reinforced ground granulated blast furnace slag (SFGGBS) concrete in which cement was partially replaced with optimum percentage of GGBS and steel fiber. Parameters such as compressive strength, modulus of elasticity, Poisson’s ratio and ductility of GGBS concrete were compared with ordinary Portland cement (OPC) concrete. GGBS concrete was found to have increased the ductility compared to OPC concrete. Steel fiber was added to GGBS concrete to study the ductility and cracking behavior, wherein the SFGGBS concrete was found to have an increased ductility than that of OPC concrete. Stress block parameters were developed for steel fiber reinforced GGBS concrete.

Keywords: compressive strength, ductility, GGBS, steel fiber, stress block parameter

1. Introduction

Concrete is the most widely used construction material round the globe. Cement is the main constituents in concrete. Cement binds the constituents of concrete together and enables the composite to attain strength. Although cement has many advantages and applications, it emits large quantity of greenhouse gases into the atmosphere. Since these green-house gases are the main reason for global warming, there is an urgent need to reduce the usage of cement (Naik, 2008). This challenge can be addressed by using industrial by-products such as fly ash, silica fume, rice husk ash, wood ash, ground granulated blast furnace (GGBS), and others, which have lower carbon emissions (Imbabi, Carrigan & Kenna, 2012; Karim, Zain, Jamil, Lai & Islam, 2011). GGBS is one of the by-products from steel manufacturing industry (Wainwright & Rey, 2000). Chemical composition of GGBS is almost similar to that of cement. Therefore, GGBS can be used as a partial replacement for cement while making concrete (Kumar, Bandopadhyay, Alex, Kumar & Mehrotra, 2008). Oner and Akyuz (2007) have conducted a series of experiments to evaluate the compressive strength of concrete by replacing cement with GGBS, where they have concluded that the optimum replacement of GGBS is 55-59% in terms of strength. Higgins (2007) conducted experimental investigation by replacing 50% of the OPC with GGBS. It has resulted in a 40% reduction in the carbon dioxide emissions and 40% reduction in energy associated with the concrete. Teng, Lim and Divsholi (2013) experimentally proved that ultrafine GGBS has more strength, workability and consistency than GGBS concrete (Karra, Raghunandan & Manjunath, 2016). Gao, Qian, Wang and Li (2004) conducted SEM and XRD analysis of GGBS concrete and found that GGBS reduces the size of $Ca(OH)_2$ crystals forming a dense microstructure. The above effect leads to strengthening of the concrete matrix when an optimum percentage of GGBS is used to replace cement (Tang, Millard & Beattie, 2015). Bijen (1995) experimentally investigated the durability of GGBS concrete and concluded that GGBS concrete has high resistance to chloride penetration, sulfate attack, and alkali silica reaction (Ahmed, Kayali & Anderson, 2008). Osborne (1999) studied the long term durability of concrete and his investigations established that slag concrete has several advantages over ordinary concrete like high strength at later stages, reduced permeability, low heat of hydration and better resistance to chemical attack. Vandewall (2000) incorporated steel fibers into normal

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concrete and concluded that steel fibers improve the cracking behavior and decrease crack width and crack spacing.

2. Experimental Program

The study was carried out by adding GGBS as a partial replacement for cement at various percentages such as 30, 35, 40, 45, and 50 by weight of cement. Steel fiber was added at 0.5, 0.75 and 1 % of total volume of concrete. The optimum percentage of GGBS and steel fiber for attaining maximum strength was estimated and stress strain curves were developed for the optimum mix proportion.

2.1 Materials

Cement used for the study was ordinary Portland cement with specific gravity of 3.05. The initial and final setting time was found to be 38 minutes and 450 minutes respectively. GGBS was obtained from Mangalore Steel Industries (Pvt. Limited), India. Specific gravity was found to be 2.98. Chemical composition of cement and GGBS is given in Table 1. River sand which satisfies the code requirements (IS 2386-3) were used as fine aggregate. It has fineness modulus of 2.75. Coarse aggregates of size 10mm were used. Water absorption for fine and coarse aggregates was obtained as 1.4% and 0.93% respectively. Crimped steel fibers having aspect ratio 60 were used for increasing the cracking resistance. Fibers having length of 30mm and diameter 0.5mm was used.

Table 1. Chemical composition (%) of cement and GGBS.

Chemical composition	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	LOI
Cement	61.53	20.36	4.31	5.98	1.36	6.46
GGBS	38.9	33.5	10.68	2.35	9.45	5.12

2.2. Setting time for GGBS concrete

Tests on initial and final setting time test were conducted as per IS: 4031(Part 5)-1988. The initial and final setting time of cement with varying replacement levels of GGBS is given in Table 2. Setting time was found to increase with increase in addition of GGBS in cement. This is because the slag will react slowly with water upon mixing (Siddique & Bennacer, 2012). Up to 40% replacement of cement with GGBS, the final setting time was found to be within the limit as per the standards for OPC.

Table 2. Initial and final setting time of GGBS concrete.

% of GGBS	Initial setting time (min)	Final setting time (hours)
0	38	7.5
30	50	9
35	70	9.5
40	95	10
45	108	12
50	125	13.5

2.3 Mix design and specimens

Mix design for getting a compressive strength of 25 N/mm^2 was carried out according to IS 10262-2009. Cubes and cylinders were cast by varying the percentage of GGBS and steel fiber. The details of different materials used for mix proportioning are given in Table 3. In the concrete mix, GGBS was added as partial replacement for cement at various percentages of 30, 35, 40, 45, and 50 by weight of cement. Steel fiber was added at 0.5, 0.75 and 1 % of total volume of concrete. Three specimens were prepared for each combination. Ingredients were mixed in a pan mixer and during mixing fibers were sprinkled by hand to avoid balling effect of fibers. Concrete was filled in each mould in three layers and compacted on a vibrating table. All the specimens were unmoulded within 24 hours and cured under water for 28 days.

Table 3. Mix proportioning of concrete.

Sl. No	Material	Quantity (kg/m^3)
1	Binder content	350
2	Water	175
3	Fine aggregate	618.24
4	Coarse aggregate	1196.48
5	Steel fiber	58.86

2.4 Properties of GGBS concrete

The mechanical behaviour of concrete with 30%, 35%, 40%, 45%and 50% GGBS as replacement to cement was investigated. Tests were conducted to determine workability and compressive strength. The cubes were cast and tested for compressive strength after 7 and 28 days of curing. Effects of steel fiber on GGBS concrete were investigated at 0.5, 0.75 and 1% of total volume of concrete. Effect of steel fiber on workability of concrete was also studied.

2.4.1 Workability of GGBS concrete

Slump test was conducted as per IS 1199:1959 to determine the workability of fresh concrete. The slump values of OPC and GGBS concrete are given in Table 4. It was observed that GGBS concrete showed higher workability than OPC concrete and the workability increased with the increase in the percentage of GGBS.

2.4.2 Compressive strength test for specimens

Compressive strength test was carried out on 150 x 150x 150 mm cubes cured for 28 days on a compression testing machine of capacity 3,000 kN. Strength of different mixes is summarized in Table 5. The 7-day strength of GGBS concrete was found to be lower than that of OPC concrete, because of the slow pozzolanic reaction of GGBS i.e. the calcium hydroxide formation takes longer time (Oner & Akyuz, 2007). At later stages, the compressive strength was more for GGBS concrete because of higher calcium silicate bond (C-S-H). The compressive strength was found to increase by 2.55%, 7%, 16.53%, 9.97% and 9.84% respec-

Table 4. Workability of GGBS concrete.

% of GGBS	Slump (mm)	% of increase
0	85	-
30	90	5.88
35	96	12.94
40	100	17.65
45	103	21.18
50	106	13.5

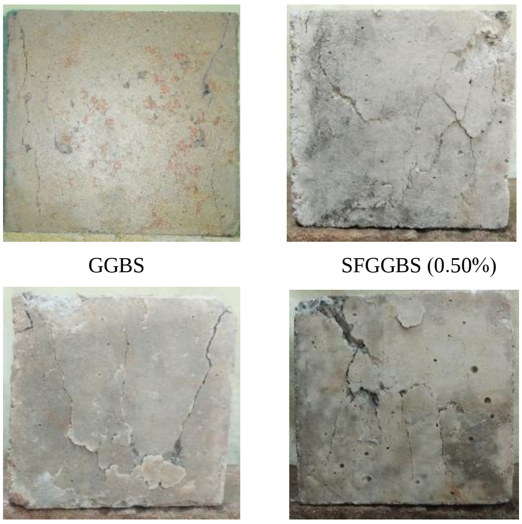
Table 5. Compressive strength of GGBS concrete at 7 and 28 days.

Mix no.	GGBS (%)	Steel fiber (%)	Compressive strength (N/mm^2)	
			7 day	28 day
1	0	0	20.12	31.34
		0.5	20.56	32.95
		0.75	21.02	33.35
		1	20.97	32.98
2	30	0	17.09	32.19
		0.5	17.15	33.08
		0.75	17.96	33.94
		1	17.88	33.86
3	35	0	16.98	33.59
		0.5	17.06	33.97
		0.75	17.25	34.41
		1	17.22	33.99
4	40	0	17.29	36.58
		0.5	17.53	36.86
		0.75	17.62	37.45
		1	17.61	37.33
5	45	0	16.26	34.52
		0.5	16.31	34.95
		0.75	16.44	35.02
		1	16.41	34.98
6	50	0	15.44	34.48
		0.5	15.63	34.76
		0.75	15.78	35.23
		1	15.68	34.97

tively for 30%, 35%, 40%, 45% and 50% replacement of cement with GGBS. The optimum percentage of GGBS and steel fiber obtained was 40 and 0.75 respectively in terms of strength. Figure 1 shows the failure pattern for GGBS concrete and SFGGBS concrete cubes. SFGGBS (0.5%), SFGGBS (0.75%) and SFGGBS (1%) represent the steel fiber reinforced GGBS concrete with steel fibers in 0.5, 0.75 and 1% of concrete volume respectively. The crack propagation and crack width was reduced in SFGGBS concrete than that of OPC concrete.

3. Stress-Strain Curve for GGBS and SFGGBS Concrete

The stress strain curves were developed for GGBS concrete (using optimum percentage of GGBS) and SFGGBS concrete (optimum percentage of steel fiber). Cylinders of size 150mm and 300 mm height were loaded uniaxially for developing stress–strain curves. Server controlled UTM with capacity 1,000 kN was used for testing the specimens. According to Mansur, Wee and Chin (1995) a correction



GGBS SFGGBS (0.50%)

SFGGBS (0.75%) SFGGBS (1.0%)

Figure 1. Failure patterns for GGBS and SFGGBS concrete.

factor should be applied to account for the machine flexibility and end zone effects. A correction factor (Equation 1) can be found by using a compressometer fixed directly to the test specimen and a pair of transducers placed between the machine platens. The modified stress-strain relation incurporating correction factor is given below (Figure 2).

$$\varepsilon_c = \varepsilon_{tp} - \left(\frac{1}{E_{tp}} - \frac{1}{E_{co}}\right)\sigma \qquad (1)$$

where ε_c = corrected strain at the stress σ, ε_{tp}= strain measured by transducer, E_{tp} and E_{co} are the initial tangent moduli from stress-strain curves measured by transducer and compressometer respectively.

The peak stress for OPC concrete, GGBS concrete and steel fiber reinforced GGBS concrete were obtained as 28.59 N/mm^2, 31.56 N/mm^2 and 33.35 N/mm^2 respectively. GGBS concrete was found to have peak stress 10.48% more than OPC concrete. Addition of steel fiber to GGBS concrete showed a further increase in peak stress. Peak strain for GGBS concrete and steel fiber reinforced GGBS concrete are 0.00275 and 0.003 respectively, which is 16.53% and 27.54% more compared to OPC concrete.

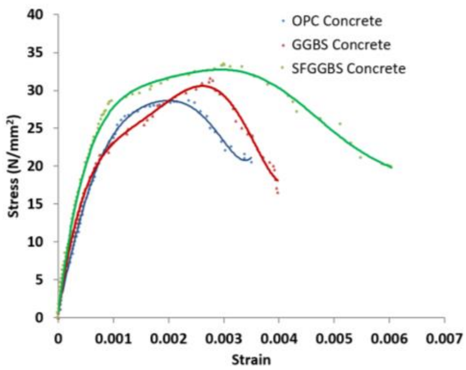


Figure 2. Stress-strain curves.

3.1 Ductility

According to Cui and Sheikh (2010), ductility ratio can be calculated from the following equation $\mu=\varepsilon_u/\varepsilon_1$ where ε_u is failure strain and ε_1 is maximum strain on the initial tangent line. In the concrete specimens tested, failure was found to occur due to crushing of concrete. Failure strain for OPC concrete, GGBS concrete and SFGGBS concrete obtained are 0.0035, 0.0039 and 0.006 respectively. Therefore the ductility ratio for GGBS concrete was 11.43% more than OPC concrete. The SFGGBS concrete have 2.14 times more ductility than normal concrete. Addition of steel fibers into concrete arrests the cracks after the first crack and steel fibers help the OPC to bear more strain and to resist the crack propagation.

3.2 Modulus of elasticity and Poisson's ratio

Modulus of elasticity and Poisons ratio were found using the procedure given in IS 516-1956. Modulus of elasticity for GGBS and SFGGBS concrete are given in Table 6. Modulus of elasticity and Poisson's ratio of GGBS concrete was 8.92 % and 5.95% higher than that of OPC concrete while for SFGGBS concrete, it was found to be 18.21% and 25.41% higher.

4. Stress Block Parameters

Developments of stress block parameters are necessary for the design of structural elements. Hognestad (1955), Desayi and Krishnan (1964) and Saenz (1964) have developed different models for the prediction of stress-strain behavior. Saenz (1964) discussed the drawbacks of the model proposed by Desayi (1964) and modified the model. Since the experimental results obtained were found similar to Saenz's model, it was used for fitting the stress-strain curve with analytical equations (Saranya, Nagarajan & Shashikala, 2019).

Following equation (Equation 2) proposed by Saenz was used for representing stress-strain relation.

$$f = \frac{A\varepsilon}{1+B\varepsilon^2} \tag{2}$$

where ε the strain in concrete and f is the corresponding stress, A and B are constants. The area between the curve and the strain axis was obtained from Equation 3 and 4.

$$\int_{\varepsilon}^{\varepsilon u} f\, d\varepsilon = \int_{\varepsilon}^{\varepsilon u} \frac{A\varepsilon}{1+B\varepsilon^2}\, d\varepsilon \tag{3}$$

$$= \frac{A}{2B} \ln \frac{1+B\varepsilon u^2}{1+B\varepsilon^2} \tag{4}$$

Non-dimensional form of Equation 4 is given by

$$\frac{f}{fu} = \frac{A\prime(\frac{\varepsilon}{\varepsilon_0})}{1+B\prime(\frac{\varepsilon}{\varepsilon_0})^2} \tag{5}$$

Constants A' and B' are obtained from boundary conditions, ε_0 and ε are the strain at maximum stress of f and failure stress f_u respectively.

Following equations were used for evaluating constants A and B,

$$A = A'\left(\frac{f_u}{\varepsilon_u}\right) \tag{6}$$

$$B = B'\left(\frac{1}{{\varepsilon_u}^2}\right) \tag{7}$$

Area under stress-strain (A) curve is given by,

$$A = \alpha' f_{cu}\, \varepsilon_{cu} \tag{8}$$

$$\alpha = \frac{A_b}{f_u\, \varepsilon_u} \tag{9}$$

$$C = \frac{bX_u}{\varepsilon u} A \tag{10}$$

$$T = \frac{\varepsilon_s - 0.002}{0.87} A_{st} E_s \tag{11}$$

Where ε_u =ultimate strain in concrete, A_{st} = area of cross section of steel, E_s = modulus of elasticity of steel, b = width of beam cross section. Different compressive and tensile stress values were obtained by varying parameters (b, ε_u, A_{st} and E_s were kept as constants). For each value of Xu varying from *0.1d* to *0.5d*, the ultimate strain value was varied from 0.002 to 0.01 with an increment of 0.001, until the compressive force became equal to the tensile force (Saranya, Nagarajan & Shashikala, 2019).

The ultimate strain ε_u obtained from Equation 10 is found to be identical with the experimental results. By using the above equations, stress block parameters were developed and are shown in Table 7. The stress block parameters such as α', β and X_u/d are shown in Figure 3. where $\alpha' = \frac{f_{cd}}{f_c}$; f_{cd}= Design compressive strength and f_c= Characteristic compressive strength of concrete. $\beta = \frac{X}{X_u}$; X=distance of resultant compressive force from top fiber and X_u is the neutral axis depth.

Table 6. Modulus of elasticity and Poisson's ratio of concrete.

MIX	Modulus of elasticity (N/mm^2)	Poisson ratio
OPC Concrete	2.69×10^4	0.185
GGBS Concrete	2.93×10^4	0.196
SFGGBS Concrete	3.18×10^4	0.232

Table 7. Stress block parameters.

Concrete	Stress block parameters		
	α	β	X_u/d
OPC Concrete	0.45	0.352	0.422
GGBS Concrete	0.47	0.38	0.427
SFGGBS Concrete	0.53	0.43	0.435

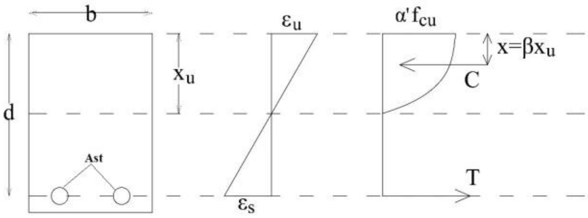


Figure 3. Stress block parameters.

5. Conclusions

Following conclusions were derived from the study: (a) The setting time of concrete was found to increase with increase in percentage of GGBS. This results in lower early age strength of concrete. But at later stages, the GGBS concrete has higher strength compared to OPC concrete. (b) Addition of GGBS was found to increase the workability of concrete but the addition of steel fiber was found to have negative impact on workability. (c) The optimum percentage of replacement of cement with GGBS obtained was 40% of the weight of cement and that of steel fiber was 0.75% of total volume of concrete in terms of strength. (d) The GGBS concrete was found to have 11.43% higher ductility than OPC concrete. The steel fibers increased the ductility of GGBS concrete by 2.14 times than that of OPC concrete. Moreover, addition of steel fiber increased the first crack load and hence resisted the propagation of cracks. (e) The modulus of elasticity of GGBS and SFGGBS concrete was increased by 8.76% and 18.32% respectively when compared to OPC concrete; and (f) The failure strain for GGBS concrete and SFGGBS concrete was 16.53% and 27.54% more than that of OPC concrete.

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References

Ahmed, M. S., Kayali, O., & Anderson, W. (2008). Chloride penetration in binary and ternary blended cement concretes as measured by two different rapid methods. *Cement and Concrete Composites, 30*(7), 576-582.

Bijen, J. (1996). Benefits of slag and fly ash. *Construction and Building Materials, 10*(5), 309-314.

Cui, C., Sheikh, S. A. (2010). Cui, C., & Sheikh, S. A. (2010). Experimental study of normal-and high-strength concrete confined with fiber-reinforced polymers. *Journal of Composites for Construction, 14*(5), 553-561.

Desayi, P., & Krishnan, S. (1964, March). Equation for the stress-strain curve of concrete. *Journal Proceedings, 61*(3), 345-350.

Gao, J. M., Qian, C. X., Liu, H. F., Wang, B., & Li, L. (2005). ITZ microstructure of concrete containing GGBS. *Cement and Concrete Research, 35*(7), 1299-1304.

Higgins, D. (2007). Briefing: GGBS and sustainability. *Construction Materials, 160*(3), 99-101.

Hognestad, E., Hanson, N. W., & McHenry, D. (1955, December). Concrete stress distribution in ultimate strength design. *Journal Proceedings, 52*(12), 455-480.

Imbabi, M. S., Carrigan, C., & McKenna, S. (2012). Trends and developments in green cement and concrete technology. *International Journal of Sustainable Built Environment, 1*(2), 194-216.

Bureau of Indian Standards. (1959). *Indian standard, methods of test for strength of concrete* (IS: 516). New Delhi, India: Author.

Bureau of Indian Standards. (1963). *Indian standard, methods of test for aggregate for concrete, part 3, specific gravity, density, voids, absorption and bulking* (IS: 2386). New Delhi, India: Author.

Bureau of Indian Standards. (1988). *Indian standard, methods of physical tests for hydraulic cement, part 6, determination of compressive strength of hydraulic cement other than masonry cement* (IS: 4031). New Delhi, India: Author.

Bureau of Indian Standards. (2009). *Indian standard, concrete mix proportioning - guidelines* (IS: 10262). New Delhi, India: Author.

Karim, M. R., Zain, M. F., Jamil, M., Lai, F. C., & Islam, M. N. (2011). Use of wastes in construction industries as an energy saving approach. *Energy Procedia, 12*, 915-919.

Karra, R. C., Raghunandan, M. E., & Manjunath, B. (2016). Partial replacement of fine aggregates with laterite in GGBS-blended-concrete. *Advances in Concrete Construction, 4*(3), 221-230.

Kumar, S., Kumar, R., Bandopadhyay, A., Alex, T. C., Kumar, B. R., Das, S. K., & Mehrotra, S. P. (2008). Mechanical activation of granulated blast furnace slag and its effect on the properties and structure of portland slag cement. *Cement and Concrete Composites, 30*(8), 679-685.

Mansur, M. A., Wee, T. H., & Chin, M. S. (1995). Derivation of the complete stress–strain curves for concrete in compression. *Magazine of Concrete Research, 47* (173), 285-290.

Naik, T. R. (2008). Sustainability of concrete construction. *Practice Periodical on Structural Design and Construction, 13*(2), 98-103.

Oner, A., & Akyuz, S. (2007). An experimental study on optimum usage of GGBS for the compressive strength of concrete. *Cement and Concrete Composites, 29*(6), 505-514.

Osborne, G. J. (1999). Durability of Portland blast-furnace slag cement concrete. *Cement and Concrete Composites*, *21*(1), 11-21.

Saenz, L.P. (1964) Discussion of paper "Equation for stress-strain curve of concrete" by Desai, P. and Krishnan, S. *Journal of American Concrete Institute*, *61*(9), 1229-1235.

Saranya, P., Nagarajan, P., & Shashikala, A. P. (2019). Performance evaluation of geopolymer concrete beams under monotonic loading. *Structures*, *20*, 560-569.

Siddique, R., & Bennacer, R. (2012). Use of iron and steel industry by-product (GGBS) in cement paste and mortar. *Resources, Conservation and Recycling*, *69*, 29-34.

Tang, K., Millard, S., & Beattie, G. (2015). Technical and economical feasibility of using GGBS in long-span concrete structures. *Advance Concrete Construction*, *3*(1), 1-14.

Teng, S., Lim, T. Y. D., & Divsholi, B. S. (2013). Durability and mechanical properties of high strength concrete incorporating ultra fine ground granulated blast-furnace slag. *Construction and Building Materials*, *40*, 875-881.

Vandewalle, L. (2000). Cracking behaviour of concrete beams reinforced with a combination of ordinary reinforcement and steel fibers. *Materials and Structures*, *33*(3), 164-170.

Wainwright, P. J., & Rey, N. (2000). The influence of ground granulated blastfurnace slag (GGBS) additions and time delay on the bleeding of concrete. *Cement and Concrete Composites*, *22*(4), 253-257.