DEVELOPMENT OF HIGH STRENGTH SELF-COMPACTING CONCRETE WITH GROUND GRANULATED BLAST FURNACE SLAG – A NEW MIX DESIGN METHODOLOGY

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Abstract

Ground granulated blast furnace slag (GGBS), due to its pozzolanic nature, could be a great asset for the modern construction needs, because slag concretes can be of high performance, if appropriately designed. The use of GGBS as a cementitious material as well as fine filler is being increasingly advocated for the production of High Performance Concrete (HPC), Roller Compacted Concrete (RCC) and Self-Compacting Concrete (SCC), etc. However, for obtaining the required high performance in any of these concrete composites, slag should be properly proportioned so that the resulting concrete would satisfy both the strength and performance criteria requirements of the structure. The present paper is an effort towards presenting a new mix design methodology for the design of self-compacting GGBS concretes based on the efficiency concept. The methodology has already been successfully verified through a proper experimental investigation and the self-compacting slag concretes were evaluated for their self-compactability and strength characteristics. The results indicate that the proposed method is for proportioning mixes with maximum possible replacement of cement by GGBS for achieving self-compactability and strength.

Key words: slag, efficiency, self-compacting concrete, mix design

1. Introduction

Self-compacting concrete (SCC) is a special concrete that can settle into the heavily reinforced, deep and narrow sections by its own weight, and can consolidate itself without necessitating internal or external vibration, and at the same time maintaining its stability without leading to segregation and bleeding [1]. SCC demands a large amount of powder content compared to conventional vibrated concrete to produce a homogeneous and cohesive mix [2].

The common practice to obtain self-compactibility in SCC is to limit the coarse aggregate content and the maximum size and to use lower water–powder ratios together with new generation super plasticizers (SP) [3]. During the transportation and placement of SCC the increased flowability may cause segregation and bleeding which can be overcome by providing the necessary viscosity, which is usually supplied by increasing the fine aggregate content; by limiting the maximum aggregate size; by increasing the powder content; or by utilizing viscosity modifying admixtures (VMA) [4]. One of the disadvantages of SCC is its cost, associated with the use of chemical admixtures and use of high volumes of portland cement. One alternative to reduce the cost of SCC is the use of mineral additives such as limestone powder, natural pozzolans, fly ash and slag, which are finely divided materials added to concrete as separate ingredients either before or during mixing [5]. As these mineral additives replace part of the portland cement, the cost of SCC will be reduced especially if the mineral additive is an industrial by-product or waste. It is well established that the mineral additives, such as fly ash and slag, may increase the workability, durability and long-term properties of concrete [6, 7]. Therefore, use of these types of mineral additives in SCC will make it possible, not only to decrease the cost of SCC but also to increase its long-term performance. To assess the effectiveness of GGBS in SCC some of the parameters like chemical composition, hydraulic reactivity, and fineness have been carefully examined earlier [8]. It was seen that among these, the reactive glass content and fineness of GGBS alone will influence the cementitious/ pozzolanic efficiency or its reactivity in concrete composites significantly. Some of the earlier researchers tried to express this reactivity of GGBS in terms of slag activity index (SAI) or hydraulic index, considering its chemical composition. This paper presents a new mix design methodology for the design of self-compacting concrete with ground granulated blast furnace slag (GGBS) for percentage replacements varying between 20-80%.

2. Proposed method for proportioning GGBS in self-compacting concrete

This paper attempts to assess the cementitious efficiency of GGBS in self-compacting concrete at various replacement percentages through the efficiency concept proposed earlier for the design of normal slag concretes by using the efficiency factor “k” value [9]. The efficiency factor (k) is generally defined in terms of its strength relative to control concrete. The efficiency factor (*k*-value) is defined as the portion of the pozzolanic material such as fly ash, slag etc., that can be considered equivalent to Portland cement [10]. Therefore, a value of k = 1 indicates that, in terms of the compressive strength performance, the pozzolanic material is equivalent to cement. A value of k less than one indicates that the performance of the pozzolanic material is inferior to cement. The quantity of the pozzolanic material is multiplied by the *k* value to estimate the equivalent cement content, which can be added to the Portland cement content to determine the resulting water to effective cementitious materials content ratio (w/(c+k*g)), required cement content, etc. Since slag being a hydraulic material it has got the potential to be replaced in high volumes and the same has been attempted in the present investigation. High volumes up to 80% have been replaced in low strength SCCs and 40% in high strength SCCs. However, this would require specific adjustments to all the other ingredients like sand, coarse aggregate, superplasticizers and water, to arrive at an optimal mix proportion. The procedure of the proposed mix design method is summarized in the following steps:

Step 1: Fix the Total Cementitious or Powder Content for SCC

In the mix proportioning of conventional concretes, the water content is fixed based on the maximum size of the aggregate and/or aggregate grading. In the case of SCC, the quantity of total fines (powder) is of importance. In view of this fix the total cementitious materials (TCM) content (preferable to have this around 550kg/m^3). To understand the behaviour of SCCs one can choose this in the range of 500-600kg/m^3 [11].

Let the TCM = TP kg/m^3

Step 2: Fix the percentage of slag and calculate the efficiency of slag

Earlier Babu and Kumar [9] had proposed the efficiency concept methodology for the design of normal vibrated slag concretes.

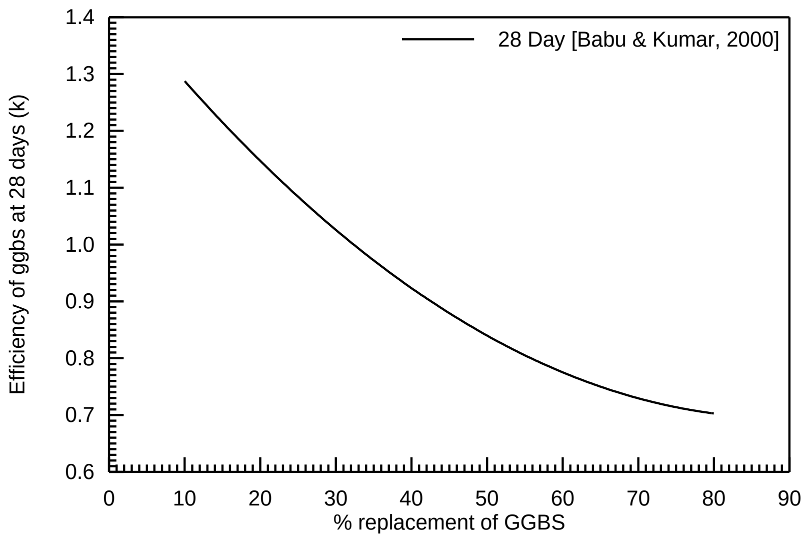

Figure 1. Variation of efficiency factor (k) with percentage replacement of GGBS

As per this methodology the slag content can be varied between 10-80% and the 28 day efficiency (k_{28}) for the said replacements varied from 1.29 to 0.70 as shown in Figure 1. The corresponding relationship for the overall efficiency (k_{28}) at 28 day for replacement levels varying from 10 - 80% proposed by Babu and Kumar [9] are

$$k_{28} = 0.000009468\, p^2 - 0.0168p + 1.44 \qquad (1)$$

Where 'p' is the percentage replacement of slag

The maximum compressive strength possible at the different percentage replacements, derived from the results of earlier investigators was also evaluated by Babu and Kumar [9] and shown in Figure 2.

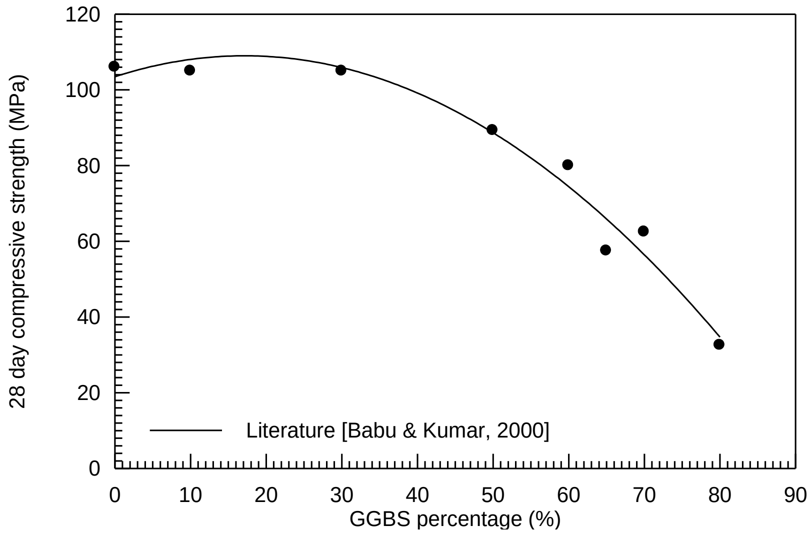

Figure 2. Maximum possible percentage replacement Vs compressive strength

It can be seen that, a maximum compressive strength of about 100MPa at 28 days is possible at 10% replacement level and a maximum of 30MPa at 80% replacement. The efficiency curve (Figure 1) and replacement percentages possible at particular strength (Figure 2) were used by Babu and Kumar [9] to propose a mix design methodology for the design of normal vibrated slag concretes. The same concept has been extended here for the design of self-compacting slag concretes. In this procedure the 28 day efficiency curve shown in Figure 1 is used for calculating the efficiency of slag for any replacements varying between 10-80%. The percentage replacement of slag is chosen as per the strength requirement using Figure 2. The efficiency of slag for this percentage is calculated using equation (1). However, recent experimental results have shown that it is possible to replace even higher percentages if one was to modulate the aggregate gradings and the filler proportions to minimize the water content needed. Let the slag percentage be p %.

Cement content (c_s) = TP (1-p) kg/m^3

Slag content (g) = TP (p) kg/m^3

The efficiency of slag at 28 days (k_{28}) for replacement levels varying between 10 - 80% is given in Figure 1. For a slag replacement of p% the efficiency is calculated using equation (1).

Step 3: Calculation of water content in SCC

Now the water to effective cementitious materials content ratio of self-compacting concrete with slag is calculated using w_s / (c_s + k_{28}*g), where 'w_s' is the water content of self-compacting slag concrete which needs to be determined. According to any of the recognized mix design methodologies, the water cement ratio of normal or conventional concretes (w_n/c_n) is chosen based on the compressive strength required. The water content (w) required from the workability consideration is also chosen from the same procedure. In the present investigation the modified ACI relationship was utilized as shown in Figure 3 [12].

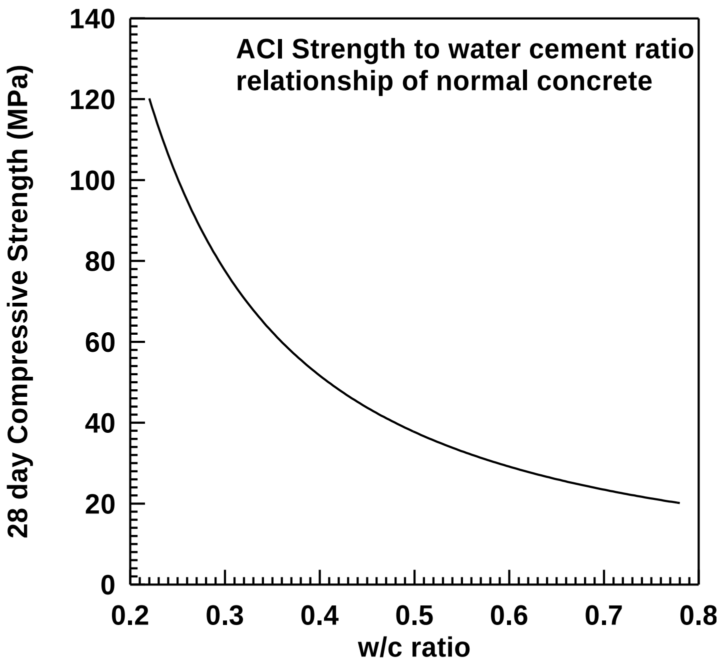

Figure 3. Strength to water-cement ratio relationship of conventional concrete

The water content (w_n) required from the workability consideration is also chosen from the same ACI procedure. From Figure 3 for a desired strength, the water cement ratio (w_n/c_n) is determined. This water cement ratio obtained for normal concrete shall be used to determine the water content of self-compacting concrete using the following relation

$$w_n/c_n = w_s / (c_s + k_{28}*g) \qquad (2)$$

Therefore, $w_s = (w_n/c_n)\ (c_s + k_{28}*g)$ kg/m^3

Step 4: Determination of coarse and fine aggregate contents

It is now possible to assess the total aggregate content according to the absolute volume method. The fine aggregate content in the total aggregate is generally recommended to be in the range of 48-55% [11]. Alternatively one can always follow the continuous grading curves, if required. However, in the present investigation a combined aggregate grading as recommended by the DIN 1045 standards was utilized.

Total volume = 1000 *litres*;

Assuming air content = 2 percent, Air = 20 *litres*

Net concrete volume= 980 *litres*

Let the cement content be c_s kg/m^3

Slag content be g kg/m^3

Water content be w_s kg/m^3

Volume of cement $(V_c) = c_s / G_c$ *litres*, where G_c is the specific gravity of cement

Volume of slag $(V_{slag}) = g/ G_s$ *litres*, where G_s is the specific gravity of slag

Volume of water $(V_w) = w_s / G_w$ *litres*, where G_w is the specific gravity of water

Volume of paste $(V_{paste}) = (c_s / G_c + g/ G_s + w_s / G_w)$ *litres*

Volume of Total Aggregate $(V_{agg}) = (980 – V_{paste})$ *litres*

In the combined aggregate grading for SCC let the percentage of fine aggregate in the total aggregate content be x% and that of the coarse aggregate (CA) content be y% (CA_1, mm = y_1%, CA_2, mm = y_2% and CA_3, mm = y_3%). This percentage of fine aggregate should be in correspondence with the proposed 48-55% range for fine aggregate in SCC according to EFNARC standards [11].

Volume of fine aggregate $(V_{fa}) = x\% \text{ x } V_{agg}$

Mass of fine aggregate = V_{fa} x G_s, where G_s is the specific gravity of sand.

Volume of coarse aggregate $(V_{ca}) = y\% \text{ x } V_{agg}$

Mass of CA_1 aggregate = y_1%x V_{agg} x G_{ca1}, where G_{ca1} is the specific gravity of CA_1

Mass of CA_2 aggregate = y_2%x V_{agg} x G_{ca2}, where G_{ca2} is the specific gravity of CA_2

Mass of CA_3 aggregate = y_3%x V_{agg} x G_{ca3}, where G_{ca3} is the specific gravity of CA_3

Step 5: Calculation of superplasticizer (SP) dosage

The chemical admixtures have the most profound impact on the behaviour of fresh SCC. Dosage of admixtures was adjusted in such a way in order to obtain initial slump – flow values greater than 550 mm, which is necessary for the production of a highly flowable SCC as per EFNARC guidelines [11]. Since for developing self-compacting concretes polycarboxylate ether (PCE) based admixtures are generally used and based on our experience gained in our laboratory it was found that the dosages levels should be between 0.9 to 1.5% of the total cementitious or powder content. Similarly, to attain stability or robustness to the mix viscosity modifying agents (VMAs) are also used; the dosage levels of VMAs should be between 0.1 to 0.3% of the total cementitious or powder content. If the dosage of SP used is equal to n% and that of VMA used is m% of the total cementitious content (TP), then the dosages can be obtained as follows:

Dosage of SP used W_{sp} = n% (TP) (3)

Dosage of VMA used W_{vma} = m% (TP) (4)

Step 6: Trial mixtures and fresh tests on SCC

Trials mixtures can be carried out using the proportions calculated as above. Fresh property tests such as slump flow, L-Box, V-Funnel tests should be carried out on SCC and they should comply with the specifications of EFNARC.

Step 7: Adjustment of mixture proportion

If the results of the fresh tests mentioned above fail to meet the performance required, adjustments should be made until all the properties of SCC satisfy the requirements according to EFNARC guidelines [11].

3. Verification of the mix methodology

Verification of the mix concept was carried out within the scope of a limited experimental program. Four different concretes of strengths 30, 60, 90 and 100 MPa have been designed with the mix design methodology explained above for slag replacements varying between 20 to 80%. The mix details are presented in Table 1. The applied Ordinary Portland cement (similar to ASTM Type I) and the slag meet the requirements mentioned in IS:12269 and ASTM C618 respectively. Crushed granite with nominal grain size of 20 mm and good quality well-graded river sand of maximum size 4.75 mm were used as coarse and fine aggregates, respectively. The different size fractions of coarse aggregates (20 mm downgraded, 12 mm down graded and 6 mm downgraded) were taken in order to get a dense concrete. The specific gravities of aggregates were determined experimentally. The coarse aggregates with 20, 12 and 6.0 mm fractions had specific gravities of 2.89, 2.87 and 2.88, whereas the fine aggregate had specific gravity of 2.65, respectively. The high range water reducer (HRWR) used in this study was a commercially available polycarboxylate ether (PCE). Commercially available viscosity modifying agent (VMA) was also used.

Table 1: Mix details of the concretes developed

Concrete Grade (MPa)	*Name*	*TP kg/m^3*	*Slag (%)*	*(k_{28})*	*Total Aggregate, kg/m^3*				*Water kg/m^3*	*SP (%)*	*VMA (%)*
					20mm	*12mm*	*6mm*	*Sand*			
30	*NC30*	*319*	*0*	*0*	*722*	*518*	*360*	*368*	*185*	*0*	*0*
	SCC30	*550*	*80*	*0.70*	*317*	*425*	*79*	*698*	*246*	*1.0*	*0.25*
60	*NC60*	*500*	*0*	*0*	*662*	*475*	*330*	*337*	*185*	*0*	*0*
	SCC60	*550*	*60*	*0.78*	*362*	*485*	*90*	*796*	*172*	*1.2*	*0.15*
90	*NC90*	*552*	*0*	*0*	*671*	*481*	*334*	*342*	*160*	*1*	*0*
	SCC90	*550*	*40*	*0.92*	*379*	*508*	*94*	*835*	*144*	*1.5*	*0.20*
100	*NC100*	*600*	*0*	*0*	*660*	*473*	*329*	*336*	*155*	*1.2*	*0*
	SCC100	*550*	*20*	*1.14*	*382*	*512*	*95*	*841*	*142*	*1.5*	*0.20*

TP– Total Powder Content, k = Efficiency of slag, SP – Super plasticizer, VMA – Viscosity Modifying Agent, NC – Normal or Conventional Concrete, SCC – Self-Compacting Concrete

A 120 kg batch has been prepared for each mixture. The mixing sequence consisted of homogenizing the sand, the coarse aggregate, slag and cement in a laboratory pan mixer. After incorporation of water, superplasticizer was finally introduced to the wet mixture. Initial mixing time is more critical for polycarboxylate based admixtures compared to naphthalene based admixtures due to their dispersing mechanism. In order to sustain the equilibrium viscosity, longer mixing times are required. The optimum mixing time and order should be determined by means of pre-tests for each type of plant and concrete composition. The results of pre-tests showed that a total mixing time of 5 min is enough to stabilize the slump flow and V-funnel flow values. Thirty percent of the batch was used for fresh concrete tests. The remaining part was used to prepare 100 mm cube specimens without any vibration in order to determine the strength properties.

The specimens were cured in water at 27^0 C right up to the testing day. For determining the self-compactibility properties, slump flow, V-flow time and L-box blocking ratio tests were performed. All fresh test measurements were duplicated and the average of measurements have been reported. In order to reduce the effect of workability loss on variability of test results, the fresh-state properties of mixtures were determined in a period of 30 min after mixing. Before testing, fresh SCC was remixed for 30 s. The order of testing was: (a) Slump flow test; (b) V-funnel test; (c) L-box test. The tests were performed in accordance with EFNARC standards [11]. The compressive strength was obtained on 100 mm cube specimens.

Generally demoulding was done between 12 to 24 hours of casting. There were no problems for concretes up to 60% replacement in demoulding after 12 to 24 hours. For GGBS replacement of 80%, problems like material sticking to the mould and loss in edges and corners were noticed, if demoulding was done between 12 to 24 hours period. These concretes were demoulded only after 3 days of initial moist. In general potable water was used for curing all the concretes at 27^{0} C until testing was carried out at 7, 28 and 90 days. Three specimens of each mixture were tested and the mean values were reported. All the concretes were put under moist environment immediately after initial set and before demoulding. All the GGBS concretes except 80% replacement were kept in water immediately after demoulding. For 80% replacement concretes immersion curing was adopted only after initial 3 days of moist curing. From the above observations, it can be inferred that while making the high volume self-compacting GGBS concretes, special care has to be taken in mixing, compaction and curing.

Results of the investigations on fresh concrete are reported in Table 2. The slump flow of the SCCs was in the range of 650 to 700 mm, and the V-funnel test flow times were in the range of 18-25secs. All self-compacting mixtures presented a slump flow between 650 and 700 mm, which is an indication of a good deformability and showed no signs of segregation. The different SCCs performed well in terms of stability.

Table 2: Fresh properties of the concretes investigated

S. No	*Concrete Grade (MPa)*	*Name*	*Slump (mm)*	*Slump flow (mm)*	*V – Funnel Flow Time (sec)*	*L- Box ratio For Gap of 40mm*
1	*30*	*NC30*	*80*	*--*	*--*	*--*
2		*SCC30*	*--*	*700*	*18*	*0.90*
3	*60*	*NC60*	*80*	*--*	*--*	*--*
4		*SCC60*	*--*	*670*	*20*	*0.85*
5	*90*	*NC90*	*75*	*--*	*--*	*--*
6		*SCC90*	*--*	*650*	*25*	*0.85*
7	*100*	*NC100*	*110*	*--*	*--*	*--*
8		*SCC100*	*--*	*650*	*25*	*0.82*

The slump flow seems to be more related to the percentage replacement of slag than to the dosage of superlasticizer or to the water –to-cementitious materials ratio. However, the dosage of the superplasticizer of the SCC that ranged from 1 to 1.5% of concrete seems to increase with a decrease in both the water-to-cementitious materials ratio and the percentage of slag used. For all SCC mixtures, the flow time increased with a decrease in the water content. Experimental measurements related with L-box ratio indicate the filling and passing ability of each mixture. L-box test is more sensitive to blocking. There is a risk of blocking of the mixture when the L-box blocking ratio is below 0.8 [13, 14]. The determined L-box ratios of the four SCC mixtures are presented in Table 2. From the results it can be seen that all the three SCC mixtures exhibited L-Box ratios of more than 0.80. From the fresh property results it can be concluded that all the SCCs developed have satisfied the norms that were required to qualify them as self-compacting concretes according to the EFNARC regulations [11].

The compressive strengths were evaluated at 7, 28 and 90 days for self-compacting GGBS as well as normal concretes. As already stated the normal concretes were designed for target strength of 30, 60, 90 and 100 MPa, based on the modified ACI water cement ratio to strength relation [12]. The results of concretes were presented in Table 3.

Table 3: Compressive strengths of the concretes investigated

S. No	*Concrete Grade (MPa)*	*Name*	*Compressive Strength(MPa)*		
			7 days	*28 days*	*90 days*
1	*30*	*NC30*	*33.4*	*44.2*	*45.6*
2		*SCC30*	*27.6*	*48.3*	*56.0*
3	*60*	*NC60*	*61.2*	*74.5*	*76.3*
4		*SCC60*	*58.2*	*73.5*	*82.6*
5	*90*	*NC90*	*75.7*	*91.3*	*94.4*
6		*SCC90*	*74.5*	*92.6*	*105.8*
7	*100*	*NC100*	*82.0*	*92.3*	*92.0*
8		*SCC100*	*84.3*	*94.6*	*105.5*

From the results it can be seen that the concrete of more than 90 MPa strengths at 28 days cannot be produced even with the use of high grade cement alone, inspite of the superplasticizer used to lower the water cement ratios. The designed target strengths were easily obtained for the concretes upto 90 MPa. Concretes of 30 and 60 MPa, strengths even higher than target strengths were obtained. Further it was observed that significant strength gain was observed even after 90 days in low strength concretes, but in high strength concretes the strength gain was marginal.

The self-compacting GGBS concretes were designed for an equivalent 28 day strengths (as that of normal concretes). The various strengths achieved by these concretes at the various replacements were presented in Table 3. The results of 30 MPa concrete show that, strength gain rate of self-compacting GGBS concretes at 80% replacement were almost similar to that of normal concretes. Also these concretes achieved their target strength at 28 days and showed higher strength than normal concrete at 90 days. Though at 7 days the SCC attained a low early strength compared to normal concrete, the strength gain rate was similar to that of normal concretes from 28 day onwards. In general, the strength gain rate of self-compacting GGBS concretes after 28 days were higher compared with the normal concretes. The results of the self-compacting GGBS 60 MPa concrete show even at 60% replacement, showed strength gain rate similar to normal concrete and attained target strength at 28 days and attained strengths much higher than normal concrete at 90 days.

The results of high strength normal and self-compacting GGBS concretes are presented in Table 3. It can be noticed from these results that the strength gain rate of self-compacting GGBS concrete is similar to that of normal concrete. As stated earlier, the normal concrete has attained the target strength at 28 days by adopting low water cement ratio along with the use of superplasticizer. The 90 MPa SCC with 40% GGBS addition has achieved slightly higher strength than the corresponding normal concrete at 28 days but achieved a strength of 105MPa at 90 days. The 20% replacement self-compacting GGBS concrete designed for 100 MPa showed strength gain rate similar to normal concrete, and did not attain the target strength at 28 days but reached the target strength at 90 days showing strength of 105 MPa. From the results of high strength (90 – 100 MPa) self-compacting GGBS concretes, it can be seen that, the strength gain rate after 28 days were low compared with that of low strength GGBS SCC.

It is evident from the experimental results that there is a maximum strength that can be achieved at a particular level of GGBS replacement. In general, it was seen that high-volume slag replacement is only possible in low strength SCC mixtures; high-strength concrete mixtures could be made only at the lower percentages of replacement. In order to understand these aspects clearly, the compressive strengths achieved at 28 and 90 days were plotted against the percentage of replacement (Figure 4).

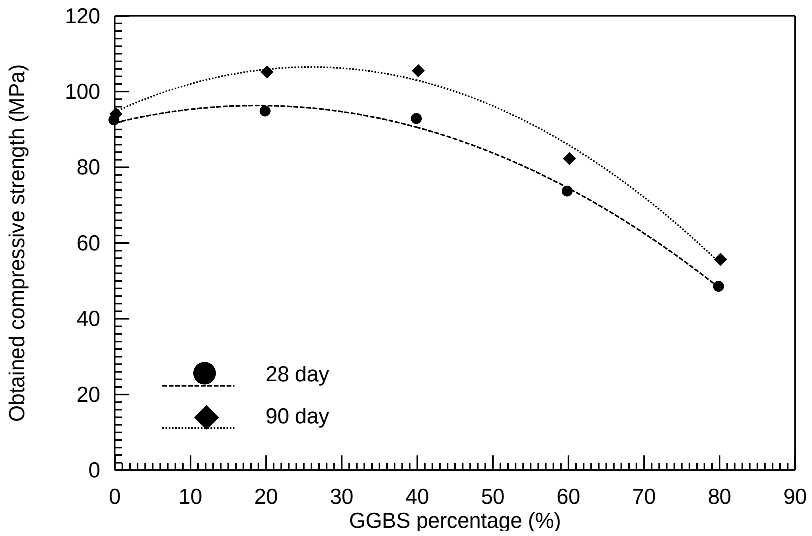

Figure 4. . Maximum possible percentage replacement Vs compressive strength obtained experimental

It can be distinctly seen that there is only a minor variation of strength at different possible percentages of replacement for any particular strength in these concrete types designed through the efficiency approach. This depicts the limitations on the maximum percentage of replacement possible for a particular strength. Finally, from this study, the level of replacement of slag for making the required strength of self-compacting slag concrete can easily be selected.

The overall results showed that the proposed mix design method gave good results and strengths of more than 90 MPa can be realized. All the self-compacting slag concretes have obtained their design strengths similar to normal concretes. From different ranges of strengths and percentage replacements it can be seen that high volume as well high strength self-compacting slag concretes can be made by using the proposed mix design methodology. High volume replacements of up to 80% for 30 MPa concrete was possible. High strength concretes of more than 90 MPa at 40% slag replacement was also possible. Hence, the proposed mix design method can be recommended for the design of high volume slag self-compacting concretes for an effective utilization.

4. Conclusions

A review of the earlier mix design methods in SCC show that there is no specific method for obtaining SCC based on the strength requirements like conventional vibrated concrete. In this paper a mix proportioning method was proposed for the design of SCC using GGBS based on efficiency concept proposed earlier for GGBS concretes. Using this method and earlier established efficiency values, self-compacting GGBS concretes of strength ranging from 30 to 100 MPa, at various replacement levels ranging from 0 to 80% were made. The experimental investigations on self-compacting GGBS concretes designed with the proposed mix design method, shows that concrete of very high strengths (more than 90 MPa) can be produced with reasonable confidence. The design method also presents a way for obtaining high volume replacements (up to 80% for 30 MPa).

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