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Technical Report

# Design of self-compacting concrete with ground granulated blast furnace slag

P. Dinakar [⇑], Kali Prasanna Sethy, Umesh C. Sahoo

School of Infrastructure, Indian Institute of Technology, Bhubaneswar 751 013, India

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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 can be capable of producing high quality SCC.

## 1. Introduction

The development of self-compacting concrete (SCC) also referred to as ''Self-Consolidating Concrete'' has recently been one of the most important developments in building industry [1]. 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 [2]. SCC demands a large amount of powder content compared to conventional vibrated concrete to produce a homogeneous and cohesive mix [3].

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) [4]. 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) [5]. 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 [6]. 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 [7,8]. 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 [9]. 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% and 80%.

## 2. Slag activity index (SAI)

According to ASTM C989-94a [10], slag activity index is the percentage ratio of average compressive strength of slag cement mortar (50–50%) cubes to average compressive strength of reference cement mortar cubes at a designated age. Based on this, slag is classified into three grades: Grade 80, Grade 100 and Grade 120. Many researchers expressed the reactivity of GGBS in terms of ''slag activity index (SAI)'' or ''Hydraulic Index''. The properties of

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[⇑] Corresponding author. Tel.: +91 674 2301563.

E-mail addresses: pdinakar@iitbbs.ac.in, pdinakar@rediffmail.com (P. Dinakar), kaliprasanna.sethy@iitbbs.ac.in (K.P. Sethy), ucsahoo@iitbbs.ac.in (U.C. Sahoo).

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GGBS, which influence its reactivity are glass content, chemical composition, mineralogical composition, fineness of grinding, and type of activation provided [11]. Various formulae have been proposed by many researchers to assess the reactivity of GGBS. Mantel [12] however, came to the conclusion that hydraulic formulae for GGBS proposed in literature do not adequately predict the strength performance of a slag and stated that there is no correlation between the chemical composition of a cement or that of a slag and hydraulic activity of a blend made from that cement and slag. He also reported that SAI depends on particle size distribution of slag and the cement used and suggested that SAI ranges from 62% to 115% at 28 days depending on fineness of the slag and the cement used. It was also observed by him that cement with high alkali content has not effected the hydraulicity of slag. In contrast Hogan and Rose [13] said that high alkali cement blends yields an appreciably greater SAI value than the low alkali cement blends. Meusel and Rose [14] reported that SAI of 130 for slags of blaine fineness 558 $m^2$/kg evaluated in accordance with ASTM C989-82 [10]. It is to be noted that all the above tests on SAI were conducted on mortar cubes only. Although it is well known that the behavior of mortar is different from that of concrete and, in particular, the reactivity of GGBS in mortar cannot directly be correlated to its performance in concrete, concrete mix proportioning based on the reactivity of slag is not looked into by many. The above discussion shows that there is a need to look at the possibility of proportioning mixes based on the reactivity of GGBS in concrete. The present effort is an attempt of this nature wherein with proper mix proportioning concrete composites such as SCC with GGBS can be produced with strengths comparable to those of normal vibrated concretes.

## 3. Review of earlier mix design methods

Most mix designs methods for SCC have empirical bases and differ considerably from those used in conventional concretes. The generalized method proposed by Okamura [15] and Ouchi et al. [16] considers the concrete to be composed of two phases: coarse aggregate and mortar. The volume of coarse aggregate is fixed at 50% of the solid volume of the concrete, and the fine aggregate volume is fixed at 40% of the volume of the mortar. The water/fines ratio and the superplasticizer dosage are determined from tests of fluidity on mortar. With these proportions, trails are performed on concrete to obtain the final mix composition. This methodology has been modified later by several researchers [17]. The procedure proposed by Petersson et al. [18], and known as the CBI method, consists of determining the minimum paste volume and aggregate proportions that guarantee the flow of concrete through the reinforcement, without any blocking. The determination of the fines, water and superplasticizer contents is based on tests with coaxial rheometer.

The method proposed by Sedran et al. [19] is based on the utilization of numerical model for determining a compact aggregate skeleton with minimum voids, taking into account the wall effect and viscosity of the concrete. The fines content is fixed by considering the strength required and the nature of the components. The superplasticizer dosage is chosen for the different combinations of fines using the Marsh cone test. The water and superplastizer dosages are finally adjusted to obtain the required fresh concrete behavior using a rheometer and the slump flow test.

The UPC method is based on simple tests that lead to an SCC mix in four steps [20,21]. In the first step, the saturation dosage of superplasticizer is determined, using the Marsh cone test, for the paste system having a water/cement ratio of 0.33–0.40; the optimization is started with an assumed value of w/c and this is reduced if the desired strength is not attained. Next, using the mini-slump test, the filler dosage is fixed so that a paste with the saturation superplasticizer dosage has good fluidity and moderate cohesion. In the third step, the aggregate skeleton proportions are fixed by choosing a combination that has the minimum voids in the dry, uncompacted state. With these relative aggregate proportions, concretes with various paste volumes are fabricated and tests in the fourth and final steps, using the paste composition fixed in the second step. The minimum paste volume that yields a self-compactable mix and satisfies the strength requisite is chosen. In spite of an understanding of the concepts and requirements of the mix design methodology, literature available today do not suggest any specific procedure for obtaining SCCs of a definite strength as in normal concretes.

## 4. 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 [22]. 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 [23]. 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 outlined in Fig. 1 and can be summarized in the following steps:

### 4.1. 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 (TCMs) content (preferable to have this around 550 $kg/m^3$). To understand the behavior of SCCs one can choose this in the range of 500–600 $kg/m^3$ [24].

Let the $TCM = TP\ kg/m^3$

### 4.2. Step 2: Fix the percentage of slag and calculate the efficiency of slag

Earlier Babu and Kumar [22] had proposed the efficiency concept methodology for the design of normal vibrated slag concretes. As per this methodology the slag content can be varied between 10% and 80% and the 28 day efficiency ($k_{28}$) for the said replacements varied from 1.29 to 0.70 as shown in Fig. 2. The corresponding relationship for the overall efficiency ($k_{28}$) at 28 day for replacement levels varying from 10–80% proposed by Babu and Kumar [22] are:

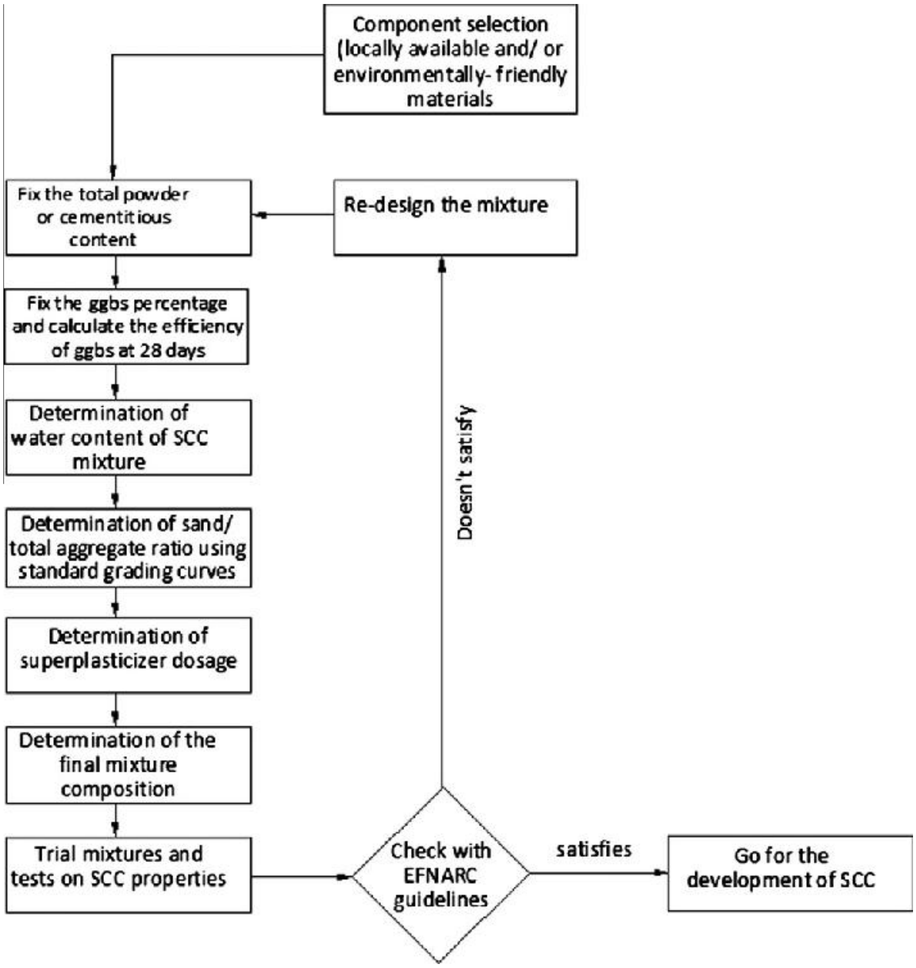

Fig. 1. Outline of the mix design methodology.

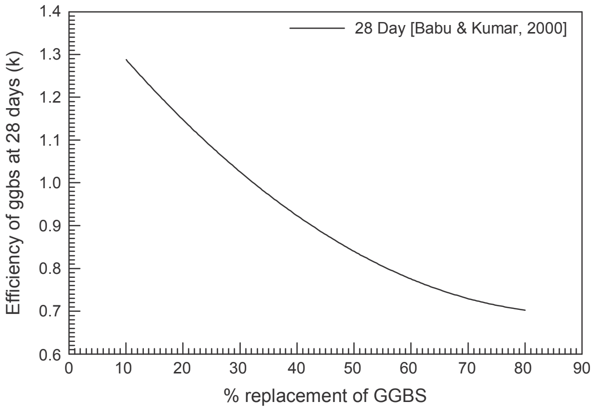

Fig. 2. Variation of efficiency factor (k) with percentage replacement of GGBS.

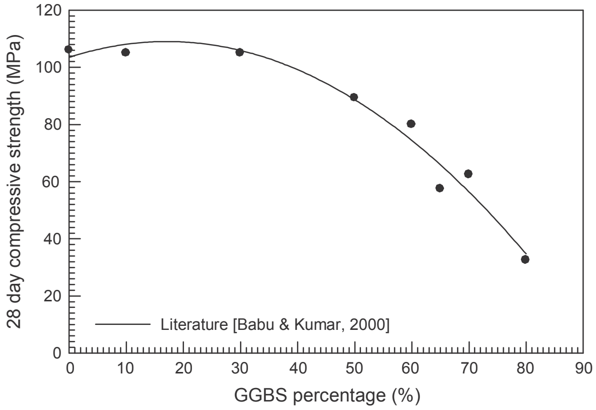

Fig. 3. Maximum possible percentage replacement vs. compressive strength.

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

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 [22] and shown in Fig. 2. It can be seen that, a maximum compressive strength of about 100 MPa at 28 days is possible at 10% replacement level and a maximum of 30 MPa at 80% replacement. The efficiency curve (Fig. 2) and replacement percentages possible at particular strength (Fig. 3) were used by Babu and Kumar [22] 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 Fig. 2 is used for calculating the efficiency of slag for any replacements varying between 10% and 80%. The percentage replacement of slag is chosen as per the strength requirement using Fig. 3. The efficiency of slag for this percentage is calculated using Eq. (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% and 80% is given in Fig. 2. For a slag replacement of p% the efficiency is calculated using Eq. (1).

### 4.3. 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 Fig. 4 [25]. The water content ($w_n$) required from the workability consideration is also chosen from the same ACI procedure. From Fig. 4 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:

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

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

### 4.4. 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% [24]. 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 [26] standards was utilized.

Total volume = 1000 l.
Assuming air content = 2%, Air = 20 l.
Net concrete volume = 980 l.
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 ($V_c$) = $c_s/G_c$ l, where $G_c$ is the specific gravity of cement.
Volume of slag ($V_{slag}$) = $g/G_s$ l, where $G_s$ is the specific gravity of slag.
Volume of water ($V_w$) = $w_s/G_w$ l, where $G_w$ is the specific gravity of water.
Volume of paste ($V_{paste}$) = ($c_s/G_c + g/G_s + w_s/G_w$) l.
Volume of Total Aggregate ($V_{agg}$) = (980 − $V_{paste}$) l.

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 [24].

Volume of fine aggregate ($V_{fa}$) = x% × $V_{agg}$.
Mass of fine aggregate = $V_{fa}$ × $G_s$, where $G_s$ is the specific gravity of sand.
Volume of coarse aggregate ($V_{ca}$) = y% × $V_{agg}$.
Mass of $CA_1$ aggregate = $y_1$%x $V_{agg}$ × $G_{ca1}$, where $G_{ca1}$ is the specific gravity of $CA_1$.
Mass of $CA_2$ aggregate = $y_2$%x $V_{agg}$ × $G_{ca2}$, where $G_{ca2}$ is the specific gravity of $CA_2$.
Mass of $CA_3$ aggregate = $y_3$%x $V_{agg}$ × $G_{ca3}$, where $G_{ca3}$ is the specific gravity of $CA_3$.

### 4.5. Step 5: calculation of superplasticizer (SP) dosage

The chemical admixtures have the most profound impact on the behavior 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 (Table 1) [24]. 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% and 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% and 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:

$$\text{Dosage of SP used } W_{sp} = n\%(TP) \quad (3)$$

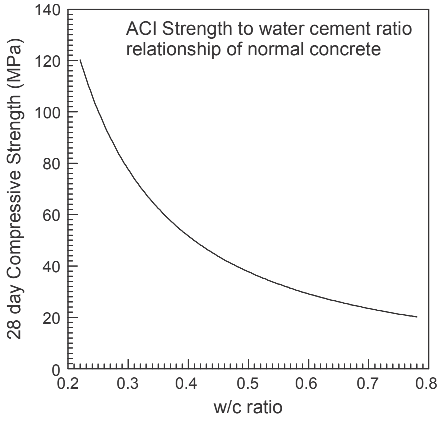

Fig. 4. Strength to water–cement ratio relationship of conventional concrete.

Table 1
Regulations for Self Compacting Concrete given by EFNARC (2005).

| Parameters | EFNARC guidelines |
|---|---|
| Volume of paste (l/m$^3$) | 300–380 |
| Powder content (kg/m$^3$) | 380–600 |
| Water content (kg/m$^3$) | 150–210 |
| Fine aggregate in total aggregate (%) | 48–55 |
| Size of coarse aggregate (mm) | ≤20 |
| Slump flow (SF) class (mm) | |
| SF1 | 550–650 |
| SF2 | 660–750 |
| SF3 | 760–850 |
| Viscosity class (V-funnel time in sec) | |
| VF1 | ≤8 |
| VF2 | 9–25 |
| Passing ability classes (L-box) | |
| PA1 | ≥0.8 with 2 rebars |
| PA2 | ≥0.8 with 3 rebars |

$$\text{Dosage of VMA used } W_{vma} = m\%(TP) \quad (4)$$

### 4.6. 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.

### 4.7. 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 given in Table 1.

## 5. Verification of the mix methodology – design example

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% and 80%. The mix details are presented in Table 2. The applied Ordinary Portland cement (similar to ASTM Type I [27]) and the slag meet the requirements mentioned in IS:12269 (53 grade) [28] and ASTM C618 [29], respectively. The chemical and physical characteristics of cement and slag are given in Table 3. 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 modifing agent (VMA) was also used. As an example, the design procedure is explained for a SCC with design strength of 90 MPa and a cement replacement level of 40%.

### 5.1. Step 1: fix the total cementitious or powder content for SCC

Let the TCM = 550 kg/m$^3$

Table 3
Characteristics of cement and GGBS.

| Chemical composition | Cement (%) | GGBS (%) |
|---|---|---|
| Silica ($SiO_2$) | 32.9 | 33.1 |
| Alumina ($Al_2O_3$) | 5.7 | 16.6 |
| Ferric oxide ($Fe_2O_3$) | 3.9 | 0.6 |
| Calcium oxide (CaO) | 62.5 | 34.8 |
| Magnesium oxide (MgO) | 1.2 | 8.0 |
| Sodium oxide ($Na_2O$) | 0.1 | 0.2 |
| Potassium oxide ($K_2O$) | 0.39 | 0.5 |
| Sulfuric anhydride ($SO_3$) | 2.4 | 0.4 |
| Loss on ignition (LOI) | 1.2 | 0.3 |
| Blaine (m$^2$/kg) | 370 | 430 |
| Specific gravity | 3.15 | 2.93 |

### 5.2. Step 2: determination of efficiency of slag and slag content

For concrete of compressive strength 90 MPa according to Fig. 2 the percentage replacement of slag should be around 20%, but in the present investigation higher percentage (40%) was chosen for designing 90 MPa SCC. Similarly for 30, 60 and 100 MPa SCCs percentages such as 80, 60 and 20 were chosen than the ones given in Fig. 2. With the present day high grade cements and high quality slag it is possible to realize higher percentages of slag. Refer to concrete mixtures given in Table 2.

Cement content ($c_s$) = 330 kg/m$^3$.
slag content (g) = 220 kg/m$^3$.

The efficiency of slag at 28 days ($k_{28}$) for replacement of 40% calculated using Eq. (2) is 0.92 ($k_{28}$ = 0.92).

### 5.3. Step 3: determination of water content of SCC

Now the water to effective cementitious materials content ratio of self compacting concrete with slag is given by $w_s/(c_s + k_{28}\ g)$, where '$w_s$' is the water content of self compacting slag concrete which is to be determined. From Fig. 4 for conventional 90 MPa concrete, the water cement ratio ($w_n/c_n$) is 0.27. This water cement ratio is used to determine the water content of self compacting concrete using Eq. (2):

$$0.27 = w_s/(330 + 0.92 \quad 220)$$

Therefore $w_s$ = 144 kg/m$^3$.

Table 2
Mix details of the concretes developed.

| S. no | Concrete grade (MPa) | Name | TCM (kg/m$^3$) | Slag (%) | Cement (kg/m$^3$) | ($k_{28}$) | Slag (g) (kg/m$^3$) | Total aggregate (kg/m$^3$) 20 (mm) | 12 (mm) | 6 (mm) | Sand | Water (kg/m$^3$) | w/(c + $k_{28}$ g) | SP (%) | VMA (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 30 | NC30 | 319 | 0 | 319 | 0 | 0 | 722 | 518 | 360 | 368 | 185 | 0.58 | 0 | 0 |
| 2 | | SCC30 | 550 | 80 | 110 | 0.70 | 440 | 317 | 425 | 79 | 698 | 246 | 0.58 | 1.0 | 0.25 |
| 3 | 60 | NC60 | 500 | 0 | 500 | 0 | 0 | 662 | 475 | 330 | 337 | 185 | 0.37 | 0 | 0 |
| 4 | | SCC60 | 550 | 60 | 220 | 0.78 | 330 | 362 | 485 | 90 | 796 | 172 | 0.37 | 1.2 | 0.15 |
| 5 | 90 | NC90 | 552 | 0 | 552 | 0 | 0 | 671 | 481 | 334 | 342 | 160 | 0.29 | 1 | 0 |
| 6 | | SCC90 | 550 | 40 | 330 | 0.92 | 220 | 379 | 508 | 94 | 835 | 144 | 0.29 | 1.5 | 0.20 |
| 7 | 100 | NC100 | 600 | 0 | 600 | 0 | 0 | 660 | 473 | 329 | 336 | 155 | 0.26 | 1.2 | 0 |
| 8 | | SCC100 | 550 | 20 | 440 | 1.14 | 110 | 382 | 512 | 95 | 841 | 142 | 0.26 | 1.5 | 0.20 |

TCM – total cementitious materials content (powder content).
k = efficiency of slag.
SP – super plasticizer.
VMA – viscosity modifying agent.
NC – normal or conventional concrete.
SCC – self compacting concrete.

### 5.4. Step 4: calculation 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% [24]. However, in the present investigation a combined aggregate grading as recommended by the DIN 1045 [26] standards was utilized. The aggregates were combined in such a way, so that it meets nearly the combined grading specification of DIN 'B' curve. The actual and the standard DIN 'B', combined aggregate curves are presented in Fig. 5. For normal vibrated concretes DIN 'A' curve was utilized and the combined aggregate grading adopted was presented in Fig. 6. The percentage fractions of aggregates used are also presented in the same figures.

Total volume = 1000 l.
Assuming air content = 2%, Air = (2/100) × 1000 = 20 l.
Net concrete volume = 980 l.
From above cement content ($c_s$) = 330 kg/m$^3$.
Slag (g) = 220 kg/m$^3$.
Water ($w_s$) = 144 kg/m$^3$.
Volume of cement ($V_c$) = 330/3.15 = 104.76 l, where specific gravity of cement = 3.15.
Volume of slag ($V_{slag}$) = 220/2.93 = 75.08 l, where specific gravity of slag = 2.93.
Volume of water ($V_w$) = 144/1 = 144 l, where specific gravity of water = 1.0.

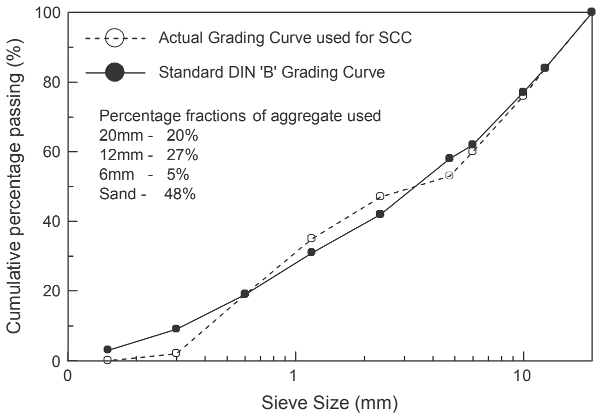

Fig. 5. Comparison between the actual and the standard combined aggregate grading used for SCC.

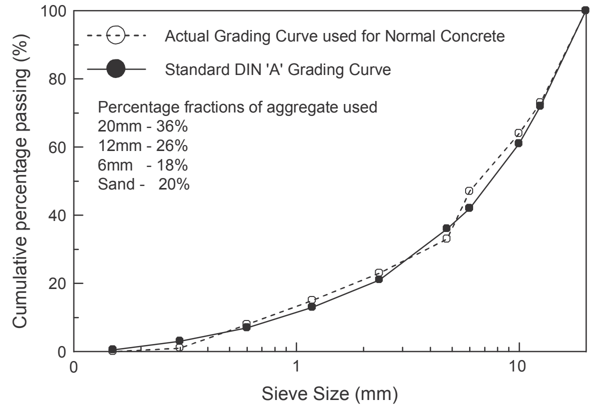

Fig. 6. Comparison between the actual and the standard combined aggregate grading used for normal concrete.

Volume of paste ($V_{paste}$) = 104.76 + 75.08 + 144 = 323.84 l.
Volume of total aggregate ($V_{agg}$) = 980 − 323.84 = 656.16 l.

In the combined aggregate grading for SCC it was observed that the percentage of fine aggregate in the total aggregate content is 48% and the coarse aggregate is 52% (20 mm = 20%, 12 mm = 27% and 6 mm = 5%). This percentage of fine aggregate is in correspondence with the proposed 48–55% range for fine aggregate in SCC.

Volume of fine aggregate ($V_{fa}$) = 0.48 × 656.16 = 314.95 l.
Mass of fine aggregate = 314.95 × 2.65 = 835 kg, where specific gravity of sand = 2.65.
Volume of coarse aggregate ($V_{ca}$) = 0.52 × 656.16 = 341.20 l.
Mass of 20 mm aggregate = 0.20 × 656.16 × 2.89 = 379 kg, where specific gravity of 20 mm = 2.89.
Mass of 12 mm aggregate = 0.27 × 656.16 × 2.87 = 508 kg, where specific gravity of 12 mm = 2.87.
Mass of 6 mm aggregate = 0.05 × 656.16 × 2.88 = 94 kg, where specific gravity of 6 mm = 2.88.
Total mass of concrete = coarse aggregate + water + sand + cement + slag = 379 + 508 + 94 + 144 + 835 + 330 + 220 = 2510 kg.

Summary of volume fractions:

| | | |
|---|---|---|
| $V_{ca}$ | =0.34 | |
| $V_{paste}$ | =0.32 | |
| $V_{fa}$ | =0.32 | $V_{ca} + V_{fa} = 0.66$ |
| Total | =0.98 | |

### 5.5. Step 5: calculation of superplasticizer (SP) dosage

According to previous engineering experience in our laboratory, it was found that the dosage of SP is 1.5% and that of VMA used is 0.2% of the total cementitious content for meeting the SCC regulations specified in Table 1.

$W_{sp} = 0.015 \times (330 + 220) = 8.25$ kg/m$^3$.
$W_{vma} = 0.002 \times (330 + 220) = 1.1$ kg/m$^3$.

### 5.6. Step 6: trial mixtures and fresh tests on SCC

Trails batches are made using the contents of materials determined as above. The methods and test results are discussed in Section 6.

## 6. Experimental program

A 120 kg batch has been prepared for all mixtures. 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 °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) spread flow test; (b) V-flow test; (c) L-box test. The tests were performed in accordance with EFNARC (2005) standards. The compressive strength was obtained on 100 mm cube specimens.

Generally demolding was done between 12 h and 24 h of casting. There were no problems for concretes up to 60% replacement in demolding after 12–24 h. For GGBS replacement of 80%, problems like material sticking to the mold and loss in edges and corners were noticed, if demolding was done between 12 h and 24 h period. These concretes were demolded only after 3 days of initial moist. In general potable water was used for curing all the concretes at 27 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 demolding. All the GGBS concretes except 80% replacement were kept in water immediately after demolding. 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 4. The slump flow of the SCCs was in the range of 650–700 mm, and the V-funnel test flow times were in the range of 18–25 s. 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. 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 [30,31]. The determined L-Box ratios of the four SCC mixtures are presented in Table 4. 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 (2005) regulations given in Table 1.

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 [25]. The results of concretes were presented in Table 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 up to 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.

Table 5
Compressive strengths of the concretes investigated.

| S. no | Concrete grade (MPa) | Name | Compressive strength (MPa) | | |
|---|---|---|---|---|---|
| | | | 7 Day | 28 Day | 90 Day |
| 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 |

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 5. 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 5. 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 105 MPa 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

Table 4
Fresh properties of the concretes investigated.

| S. no | Concrete grade (MPa) | Name | Slump (mm) | Slump flow (mm) | V – funnel flow time (s) | L- box ratio for gap of 40 (mm) |
|---|---|---|---|---|---|---|
| 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 |

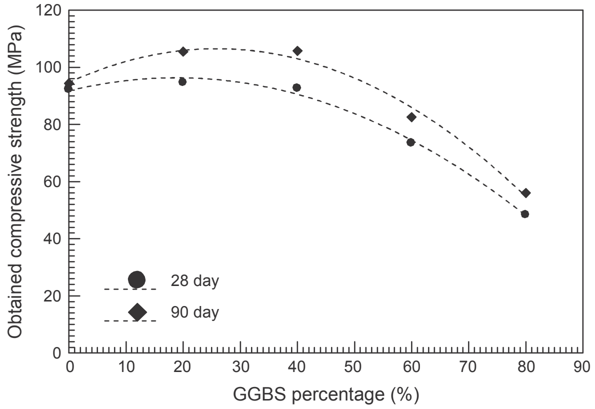

Fig. 7. Maximum possible percentage replacement vs. compressive strength obtained experimentally.

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 (Fig. 7). 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 as 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.

## 7. 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 the strength requirements and considering the efficiency of GGBS. The salient conclusions can be listed as follows:

(1) Using the proposed methodology and earlier established efficiency values for GGBS, self compacting GGBS concretes of strengths ranging from 30 to 100 MPa, at various replacement levels ranging from 20% to 80% can be developed.

(2) The proposed methodology consists of five steps, all of which are based on simple calculations. The total powder content is fixed in the first step, the percentage of slag is fixed based on the strength required and the efficiency (k) is determined for the same percentage with the equation proposed earlier in the second step. In the third step the water content required for developing the SCC is determined and in the fourth step the coarse and fine aggregates are determined using the appropriate combined aggregate grading curves of DIN standards. Finally the self-compactability of the fresh concrete is evaluated through the slump flow and V-Funnel tests for flowability, the L-Box test for the passing ability.

(3) The experimental investigations on self compacting GGBS concretes designed with the proposed mix design method, shows that the compressive strengths of the concretes obtained here surpass very high strengths of 90 MPa at 28 days and 100 MPa at 90 days. The design method also presents a way for obtaining high volume replacements up to 80% for 30 MPa.

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