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Efficiency of GGBS in concrete

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Abstract

The utilisation of supplementary cementitious materials is well accepted because of the several improvements possible in the concrete composites and due to the overall economy. The present paper is an effort to quantify the 28-day cementitious efficiency of ground granulated blast furnace slag (GGBS) in concrete at the various replacement levels. It was observed that this overall strength efficiency of GGBS concretes can also be defined through a procedure adopted earlier for other cementitious materials like fly ash and silica fume. The overall strength efficiency was found to be a combination of general efficiency factor, depending on the age and a percentage efficiency factor, depending upon the percentage of replacement as was the case with a few other cementitious materials like fly ash and silica fume reported earlier. This evaluation makes it possible to design GGBS concretes for a desired strength at any given percentage of replacement.

Keywords: Concrete; Mixture proportioning; Granulated blast furnace slag; Compressive strength; Efficiency

1. Introduction

Blast furnace slag cements are in use for a reasonably long period due to the overall economy in their production as well as their improved performance characteristics in aggressive environments. Also, the use of pozzolans as additives to cement, and more recently to concrete, is well accepted in practice. Ground granulated blast furnace slag (GGBS) is one such pozzolanic material (termed by a few as a supplementary or complimentary cementitious material) which can be used as a cementitious ingredient in either cement or concrete composites. Research work to date suggests that these supplementary cementitious materials improve many of the performance characteristics of the concrete, such as strength, workability, permeability, durability and corrosion resistance. To assess the effectiveness of GGBS in cementitious composites, some of the parameters like chemical composition, hydraulic reactivity, and fineness have been carefully examined by many earlier. The details of the various chemical constituents and their effects have been summarised by the authors in an earlier paper [1]. 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.

2. Slag activity index

ASTM C989 defines SAI as the percentage ratio of the average compressive strength of slag cement (50–50%) mortar cubes to the average compressive strength of reference cement mortar cubes at a designated age [2]. Based on this slag was classified into three grades—Grade 80, Grade 100, and Grade 120, depending on the relative compressive strength. Hooton and Emery [3] observed that the properties of GGBS influencing its reactivity to be the glass content, chemical composition, mineralogical composition, fineness of grinding and type of activation provided. Researchers have suggested different compositional moduli to assess the reactivity of GGBS. However, Mantel [4] came to conclusion that hydraulic formulae for GGBS proposed in the literature do not adequately predict the strength performance of slag. He stated that there is no correlation between the chemical composition of a cement or that of a slag and the

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hydraulic activity of a blend made from that cement and slag. He also reported that the slag activity, tested as per ASTM, depends on the particle size distribution (fineness) of slag and the cement used and showed that this ranges from 62% to 115% at 28 days. He observed that cement with high alkali content has not effected the hydraulicity of the slag. In contrast, Hogan and Rose [5] have said that high alkali cement blends yield an appreciably greater SAI value than the low alkali cement blends. 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.

There have been a few attempts of this nature reported in literature. Swamy and Bouikni [6] reported that by a proper mix proportioning GGBS concretes can be produced with strengths comparable to those with ordinary Portland cement from the 3rd day onwards. He also suggested that the total cementitious material has to be increased by 10% for 50% replacement of GGBS and by 20% for 65% replacement to attain strengths comparable to normal concretes. For a general understanding of the reactivity of GGBS, the compressive strength results of Hwang and Lin [7] on GGBS mortars at different ages and at the various replacement levels have been replotted (Fig. 1). This shows that

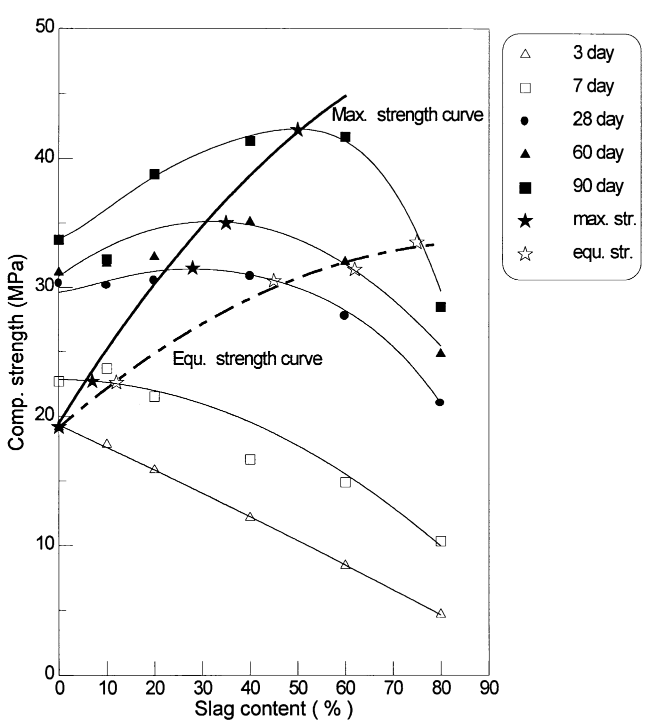

Fig. 1. Effect of slag content on strength development in cement mortars [7].

there is a maximum percentage for obtaining an equivalent strength (equivalent to the normal mortar at that age) and also, that there is a specific percentage of GGBS at which the maximum strength can be obtained at that age. From this, it can be said that the compressive strength of GGBS concretes depend both on percentage replacement level and on the age. This observation is similar to that seen in the case of fly ash and silica fume concretes studied earlier in this laboratory [8–10]. It is felt that the efficiency concept, proposed earlier for fly ash and silica fume, can also be used for understanding the behavior of GGBS in concrete.

3. Evaluation of efficiency

This paper attempts to assess the cementitious efficiency of GGBS in concrete at the various replacement percentages through the efficiency concept by establishing the variation of the strength to water-to-cementitious materials ratio relations of the GGBS concretes from the normal concretes at 28 days. In principle, this was done by using Δw concept, which attempts to bring the water-to-cementitious material ratio $[w/(c + g)]$ nearer to the water-to-cement ratio of the control concrete (w/c_o) by applying the cementitious efficiency factor k of GGBS at any particular strength. However, the first trails to bring the water-to-cementitious materials ratio to strength relations through a single efficiency value (general efficiency factor k_e), at all replacement percentages, did not lead to a good correlation. The remaining difference at this stage was corrected through the "percentage efficiency factor (k_p)." The "overall cementitious efficiency factor (k)" is the sum of the general efficiency factor k_e and the percentage efficiency factor k_p.

A detailed presentation of this method for evolution of efficiency of mineral admixtures in concrete was discussed in detail earlier [8–10]. Thus, in this method, the water-to-cement ratio (w/c_o) to strength relation of normal concrete will also be valid for the GGBS concretes, by considering the "water-to-effective cementitious materials ratio."

$$(w/c_o) = [w/(c + kg)] = [w/(c + k_e g + k_p g)]$$

where $k = k_e + k_p$.

For this evaluation of the efficiency, the data available from research efforts in the recent past [11–21] were collected and summarised in Table 1. It is to be noted that this was to ensure that the results of these investigations are representative of the cements and slags manufactured presently. It was made sure that these will form a fairly representative group governing all the major parameters that influence the behavior of GGBS in concrete and present the complete information required for such an evaluation. During the evaluation, it was seen that some of these mixes do not form a part of normal concretes, due to variations resulting from air entrainment, different curing conditions and high fineness of slag, etc. and these were not considered

Table 1
Details of the concretes evaluated

Slag no.	Percentage replacement	$w/(c+g)$ Range	Slump range (mm)	28-Day compressive strength range (MPa)	Average efficiency @ 28 days	Reference
1	0	0.23–0.83	40–170	19.7–106	–	[6,12,14–18,20,21]
2	10	0.26–0.38	150	58.5–105	1.29	[21]
3	30	0.26–0.55	100–150	49.1–105	1.02	[14,16,21]
4	50	0.30–0.80	35–190	21.2–89.3	0.84	[6,12,14–16,18]
5	60	0.26–0.50	150	43.5–80	0.78	[19,21]
6	65	0.46–0.75	100	23.0–57.5	0.75	[6,17]
7	70	0.41–0.61	45–65	32.5–62.5	0.73	[12,14,19]
8	80	0.5	–	29.5–32.5	0.70	[19]

for evaluation. Finally, out of the 175 mixes only about 70 concretes made with ordinary Portland cement confirming to ASTM type I cement (with fineness in the range of 283–391 m^2/kg) and cured under normal conditions were evaluated. The GGBS in these concretes confirm to the minimum characteristics specified by ASTM C989 [2] for use as mineral admixture in concrete (with fineness ranging from 350 to 465 m^2/kg, SiO_2 from 31.1% to 38.59% and CaO from 32.8% to 43.9%). The replacement percentages range from 10% to 80%. Natural river sand was used as fine aggregate and the maximum size of the coarse aggregate ranges from 10 to 20 mm. It is obvious that with replacement levels as high as 80%, some of these concretes had superplasticizers for improving the workability, because of the high fines content in these concretes. In view of this, only concretes up to a maximum superplasticizer percentage of 2% were considered for evaluation. Also, different researchers used specimens of different sizes and shapes and these have been corrected to their equivalent for a cube of 15-cm size through accepted guidelines [22]. In most cases, the change was the variation from cylinder to cube strength, and was corrected by using a single factor of 0.9 for concretes in the strength range of 55–70 MPa. The water-to-cementitious materials ratio [$w/(c+g)$] to compressive strength relations at different percentages of replacement were plotted for all the concretes at 28 days (Fig. 2). It can be seen from this that the 28-day compressive strengths of concretes containing GGBS up to 30% replacement were all slightly above that of normal concretes and at all the other percentages the relationships were below that of normal concretes. It was also observed that the variations due to the different percentages of slag replacement were smaller than the corresponding variations in the case of fly ash [9]. In order to bring the strength values at all replacement levels nearer to that of normal concrete, the water-to-cementitious material ratios were modified by applying the "general efficiency factor (k_e)," replacing the [$w/(c+g)$] with [$w/(c+k_e g)$]. After several trials with k_e values varying

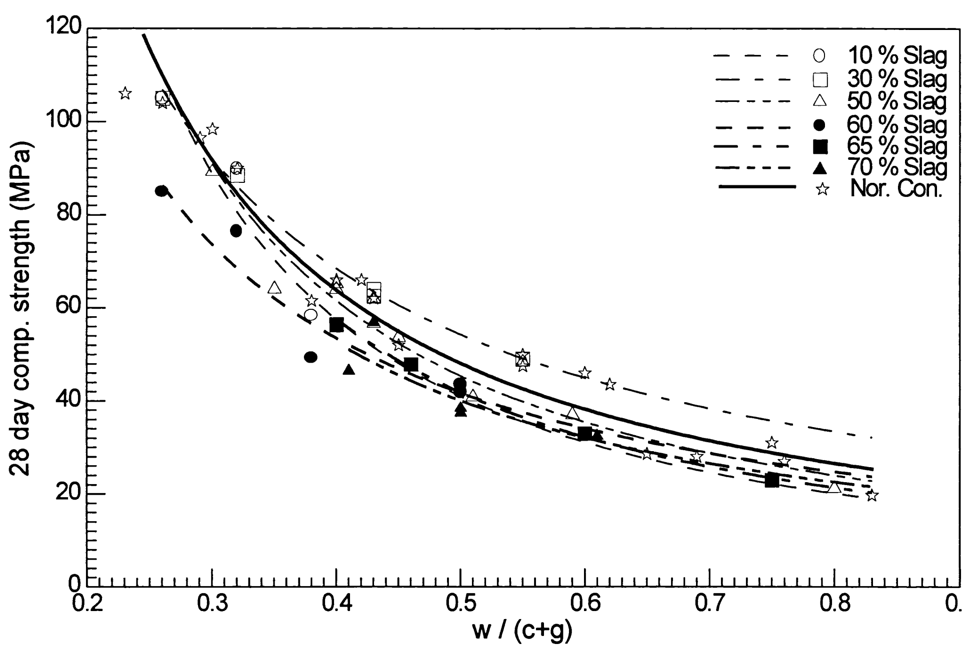

Fig. 2. Compressive strength variation with [$w/(c+g)$] at 28 days.

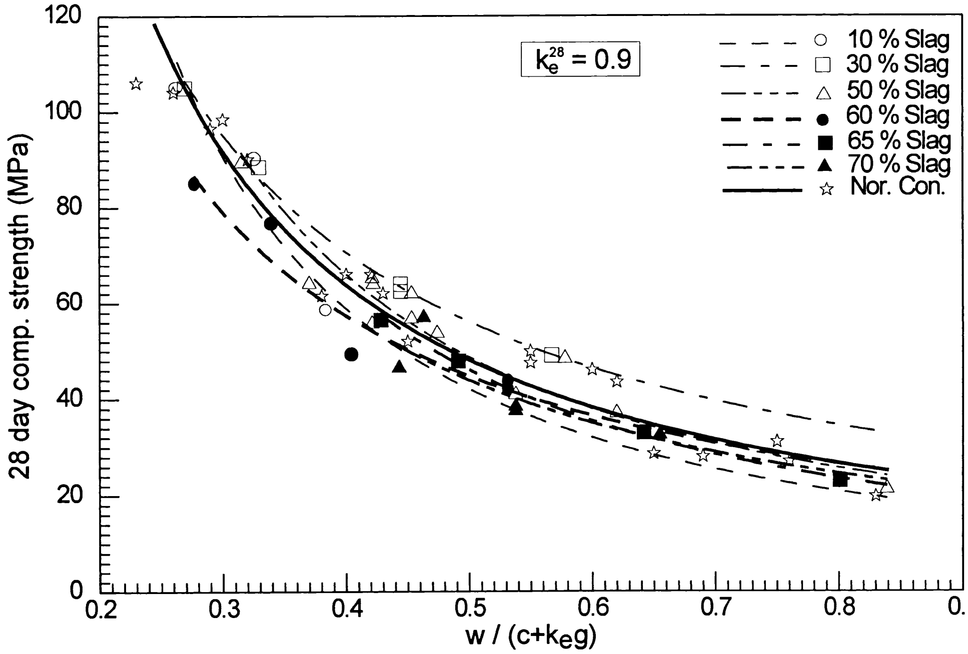

Fig. 3. Compressive strength variation with $[w/(c + k_e g)]$ at 28 days.

from 0.85 to 1.0, the appropriate k_e value was found to be 0.9 for the 28-day strength of these concretes. As already mentioned earlier, it was observed that this general efficiency factor k_e could not bring the $[w/(c + k_e g)]$ to strength relations very close to the water-to-cement ratio of normal concrete (w/c_o) at all percentage replacement levels (Fig. 3). At this stage, the effect of percentage replacement on efficiency, which can bring the GGBS concrete strength values closer to that of normal concrete was found by evaluating the remaining difference through a "percentage efficiency factor (k_p)." This value was observed to be varying between +0.39 and −0.20 for replacement levels between 10% and 80%. This results in an "overall efficiency factor (k)," the sum of the "general efficiency factor

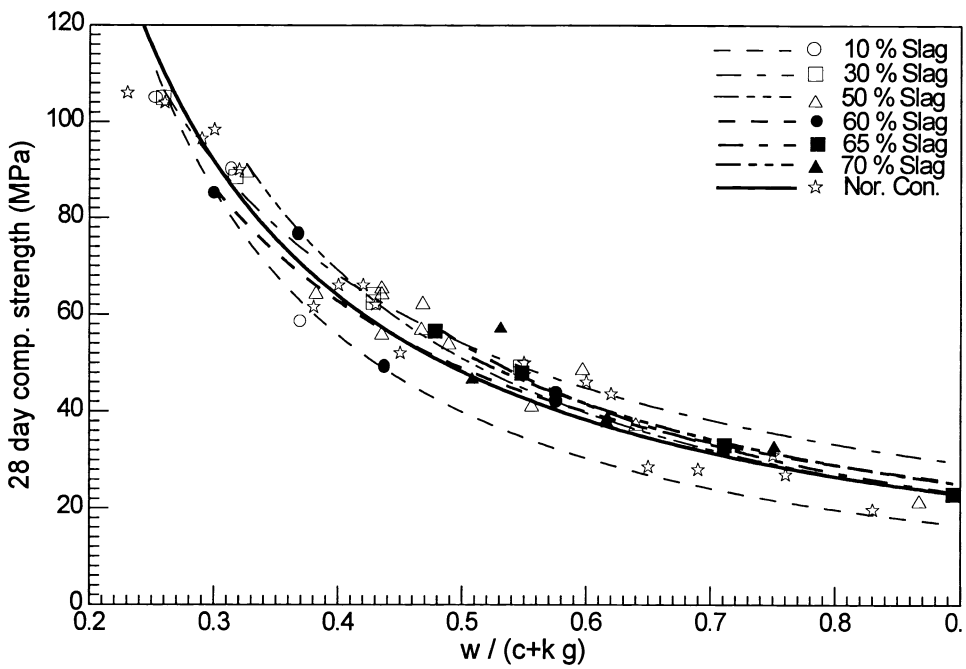

Fig. 4. Compressive strength variation with $[w/(c + kg)]$ at 28 days.

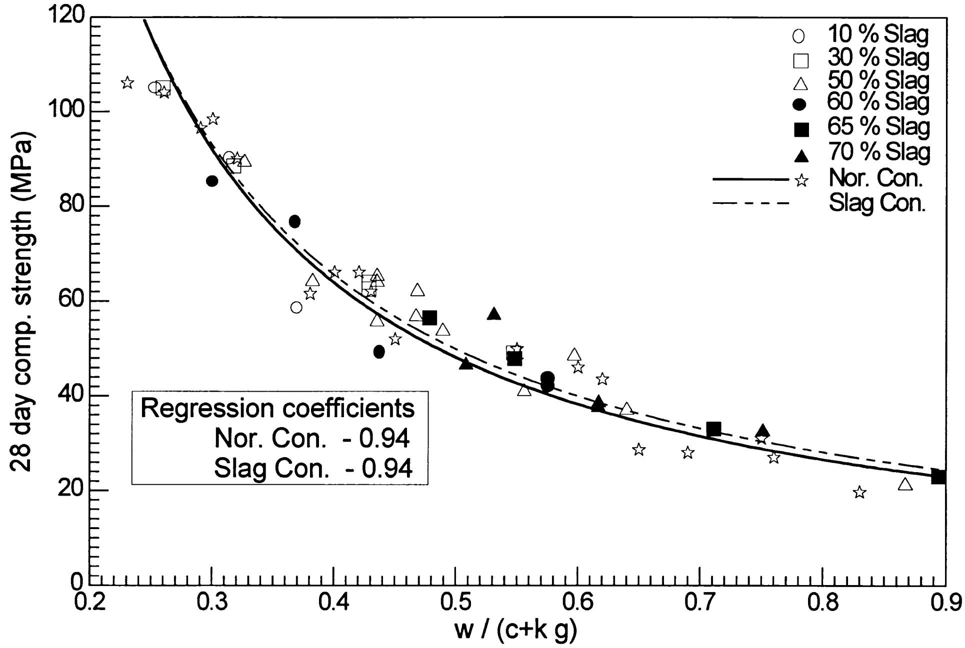

Fig. 5. Assessment of the reliability of the efficiencies evaluated.

(k_e)" and the "percentage efficiency factor (k_p)," varying between 1.29 and 0.70 for the percentage replacements varying from 10% to 80%. The typical variations of strengths with $[w/(c + k_e g + k_p g)]$ at 28 days were presented (Fig. 4). This shows that by adopting the two efficiency factors k_e and k_p, the strength of GGBS concretes at different percentages could be brought close to that of normal concrete. Fig. 5 shows best fit of the corrected water-to-cementitious materials ratio to strength relations of the GGBS concretes in comparison to that of the normal concretes. The regression coefficient for GGBS concretes as well as normal concretes was found to be 0.94 at 28 days. The above evaluation also showed that the slag concretes based on this overall efficiency factor (k), will need an increase of 8.6% for 50% replacement and 19.5% for 65% replacement in the total cementitious materials for achieving strength equivalent to that of normal concrete at 28 days. This agrees well with the observations of Swamy and Bouikni [6] reported earlier.

4. Conclusions

This study was primarily concerned with the evaluation of the efficiency of GGBS in concretes containing normal Portland cements from the results of the investigations reported in recent years. The replacement levels in the concrete studied varied from 10% to 80% and the strength efficiencies at the 28 days were calculated. The primary conclusions can be listed as follows.

(1) The earlier proposed method for evaluating the efficiency of pozzolans like fly ash and silica fume was also found to be appropriate for the evaluation of GGBS. This method recognises that the "overall strength efficiency factor (k)" of the pozzolan is a combination of the two factors—the "general efficiency factor (k_e)" and the "percentage efficiency factor (k_p)."

(2) The evaluations have shown that at 28 days, the "overall strength efficiency factor (k)" varied from 1.29 to 0.70 for percentage replacement levels varying from 10% to 80%.

(3) It was also seen that the "over all strength efficiency factor (k)" was an algebraic sum of a constant "general efficiency factor (k_e)," with a value of 0.9 at 28 days, and a "percentage efficiency factor (k_p)," varying from +0.39 to −0.20, for the cement replacement levels varying from 10% to 80% studied.

(4) Overall, the prediction of the strength of concretes varying from 20 to 100 MPa with GGBS levels varying from 10% to 80% by this method was found to result in a regression coefficient of 0.94, which was also the same for normal concretes.

(5) Finally, it was observed that for obtaining equal strength in concretes at 28 days, by adopting the efficiencies evaluated in the present investigation, it will be required to have an additional 8.5% and 19.5% increase in the total cementitious materials at 50% and 65% cement replacement levels, agreeing well with the values 10% and 20% additional material reported earlier.

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