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PARTICLE SIZE DISTRIBUTION OF GGBS AND BLEEDING CHARACTERISTICS OF SLAG CEMENT MORTARS

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ABSTRACT

This paper reports an investigation into the influence of particle size distribution (PSD) of ground granulated blast furnace slag (GGBS) on the bleeding characteristics of slag cement mortars. Samples of slag powder with different PSDs (as represented by the parameters of the Rosin-Rammler distribution function, namely, position parameter, x_o, and slope, n, which describe the fineness and the size range of the PSD, respectively) were prepared using a method whereby a commercially available slag sample was first separated into different size fractions and later recombined in some pre-determined proportions. Bleeding rate and bleeding capacity of mortar mixes containing 0, 30, and 70% slag were investigated. The results showed that when varying the PSD of slag by altering n at constant x_0, no specific relationship between bleeding characteristics and psd could be established. However, the highest values of the bleeding rate and capacity were exhibited by the mixes in which the slag with the intermediate value of slope (i.e., having the medium range of PSD) was included. Furthermore, the results showed that for the slag samples with similar size range distribution (i.e., having a constant slope, n), the bleeding capacity increased with increases in x_o, except the 30% slag mixes, which were made to 0.35 w/c. © *1998 Elsevier Science Ltd*

Introduction

Blast furnace slag is a by-product of the manufacture of pig-iron, and in its liquid state rises to the top of the molten iron inside the blast furnace. Cooling the molten slag rapidly results in the formation of a granulated glassy material that possesses a latent hydraulic property. When the granules are ground to Portland cement fineness, it is called ground granulated blast furnace slag (GGBS). In blended cements, the alkalies released by the hydration of ordinary Portland cement (OPC) activate the GGBS.

The hydration of cements and the structural performance of mortar and concrete mixes are affected by many factors, including the particle size distributions (PSD) of the cementitious constituents of the mixes. Previous studies in this regard have concentrated on the mixes incorporating OPC alone, and there have been fewer investigations on the performance of mixes containing OPC partially replaced by GGBS.

According to Powers (1), bleeding of concrete is described as a special case of sedimentation whereby water tends to rise to the surface of a freshly placed concrete. The reason for this phenomenon is that the solid constituents of the mix are unable to hold all the mixing water when they settle downwards. Bleeding has both advantageous and disadvantageous effects on concrete. On the one hand, during the process of bleeding, some of the rising water may become trapped underneath the coarse aggregate and/or reinforcement. This may result in poor bond between concrete and the steel, thereby reducing the degree of protection of the steel to corrosion (2). Also, the upward movement of water may lead to a water/cement (w/c) gradient within the concrete with the surface zone having the highest value (3,4). On the other hand, when the rate of bleeding of the concrete is less than the rate of evaporation from the surface, there is the likelihood of plastic shrinkage cracking occurring (4,5).

The influence of the PSD of cementitious binder on bleeding characteristics of concrete has been studied for many years (6–8). Different methods have been employed by various investigators for varying the PSD of the cement. Therefore, making comparisons between the findings of various investigations is somewhat difficult. In this study, the PSDs of cementitious contents are represented by the parameters of the Rosin and Rammler (9) distribution function. Bleeding rate and capacity of mortar mixes containing a constant mix proportion of 1:3 (cement:sand) were investigated. The effects of the percentage of voids of the GGBS were also monitored, as this property may be affected by PSD (7).

Experimental Procedures

Materials

OPC and GGBS used in this work were obtained from the cement industry. The materials were kept in a cool dry place to avoid caking. Table 1 shows the chemical composition and other physical properties of both materials as supplied by the manufacturers. The washed sand used throughout the experimental programme came in five single-size ranges, namely A through to E as shown in Table 2. For each mix, the five different size ranges were combined so that the resulting combination conformed with the zone M grading of the British Standard BS 882 (10). Grading and other physical properties of the recombined sand are shown in Table 2.

Experimental Programme

The main experimental programme was designed using the method known as Completely Randomized Design (CRD). The use of this method ensures that the maximum amount of information (factors investigated) is obtained from a few tests (11). Completely randomized design is characterised by the experimental unit (an observation of a property under a given set of factors) being drawn as completely random as possible. An experiment is called complete factorial when more than one factor is involved in the experiment and all the levels of each factor is involved in levels of every other factor (12). A factor is an independent variable that could affect the measured value of a property, for example, the effect of the w/c factor on the bleeding rate of a given concrete mix. The various values associated with each factor are known as the levels of that factor, e.g., w/c values of 0.35 and 0.45. Three main factors were selected to be considered throughout this investigation: w/c, slag percentage, and PSD of the GGBS.

Apart from the PSD of the slag, chosen because it was within the primary objective of the

TABLE 1
Properties of OPC and GGBS.

(a) Chemical Analysis		
Oxides	OPC (%)	GGBS (%)
CaO	64.10	40.12
SiO_2	21.06	37.28
Al_2O_3	5.09	10.79
Fe_2O_3	3.01	0.43
MgO	2.58	8.83
MnO	—	0.68
TiO_2	—	0.58
K_2O	0.80	0.37
Na_2O	0.33	0.27
S (total)	—	1.04
S^{2-}	—	0.98
SO_3	2.92	0.15
Cl^-	0.03	—
C	—	0.12
Free CaO	1.20	0.06
L.O.I.	—	1.03
Ins. Res.	0.40	0.22
(b) Physical Properties		
Specific Surface Area (cm^2/g)	3880	4320
Relative Density	3.11	2.93

research programme, the other factors were selected because of their possible interaction with the PSD and/or because of their relative importance in mix designs. In order to derive maximum benefits from the results, the levels of each factor as shown in Table 3 were chosen such that they lay within the range expected in practice.

TABLE 2
Properties of the fine aggregates.

(a) Particle Size Distribution		
	Size Range	% Passing
A	>2.36 mm	100
B	1.18 mm–2.36 mm	85
C	600 μm–1.18 mm	65
D	300 μm–150 μm	35
E	<150 μm	15
(b) Physical Properties		
Relative Density		2.62
Water Absorption		0.13%

TABLE 3
Mix variables.

Variables		Level	Description		
Water/cement		2	0.35	0.45	—
Replacement Level		3	0%	30%	70%
PSD	n^*	3	0.70	0.93	1.20
	x_0^*	3	15.0	18.0	23.0

* parameters of the R-R distribution function; n = slope value and x_0 = position parameter.

The PSD of slag was represented by the parameters of Rosin-Rammler distribution function, namely, the slope value n and position parameter x_o. These parameters were considered separately, holding one constant while the other was varied. This meant that instead of considering a four-factorial analysis, two three-factorial analyses were considered, thus making it impossible to check the interaction between the two parameters. It was decided to separate the two because of time and cost constraints.

In any experimental design it is very important that the various experimental units are randomized. The randomization employed in this programme is time: i.e., the time when the various mixes were prepared. Numbers were initially assigned serially to all the mixes that were to be investigated, and then chosen at random. Randomization ensures that each experimental unit had an equal chance of being affected by any external factors or human errors.

Procedures

Separation of Commercial Slag. The separation process was carried out commercially by British Rema Limited, Sheffield by using the air elutriation technique, which is based on gravitational/sedimentation principle.

Recombining the Size Fractions. After calculating the weight proportions of each fraction, which conformed to a target combination of R-R parameters n and x_0, the fractions were weighed out and recombined in a ball mill. The mill, used without the balls, had a working capacity of 25 kg and each sample was recombined by subjecting the mill to 1000 revolutions.

Measurement of Particle Size Distribution. Radiation scattering technique is the principle on which the instrument used for determining the PSD of the samples is based. The technique is incorporated in the Malvern Instrument series 2600C.

Determination of Percentage Voids. Apart from determining the chemical composition of the cementitious materials, the packing density (as represented by the percentage of voids) of the OPC and all the slag samples were determined following the procedure specified by British Standard BS 812 Part 102 (13).

Mixing Procedure. All the mortar mixes were made using a 25-kg capacity Cretangle mixer. The cement (i.e., OPC and GGBS) and sand for each mix were first mixed in a dry state for about 30 s before water was added. The entire mixture was then mixed for another 90 s, after which the mortar was left in the mixer undisturbed for approximately 15 min. before doing any test on the mix.

Bleeding Characteristics. The method described by ASTM C232 (14) was employed for the determination of the bleeding rate and capacity of all the mixes. A modified version of the recommended apparatus was used. The apparatus, made from a plastic material instead of steel, consisted of a cylindrical container having an inside diameter of 254 mm and an inside height of 267 mm. Retained water on the surface of the mortar mixes was collected at intervals of 10 min. within the first 40 min., and 30-min. intervals thereafter until cessation of bleeding.

Results and Discussions

Results and Analyses

Properties of the Slag Size Fractions. The physical and chemical properties of the separated slag size fractions were investigated to establish any variations due to the separation. The results (15) of the chemical analysis of the seven size fractions showed that there exist no significant differences in the chemical composition, apart from the higher amount of Fe_2O_3 present in the coarsest fraction that is approximately twice the amount in each of the other fractions. The reason for this could be associated to the possibility of Fe_2O_3 being harder to grind, which therefore results in a greater proportion in the coarser size range on separation. This phenomenon has been observed (16,17) with OPC in which an increased amount of C_3A was found with increasing fineness of the cement because of the relative ease with which the compound can be ground.

The glass content of the fractions was determined according to BS:6699 (18) and the results (15) showed that the proportion of the pure glass increases as the slag sample becomes finer, suggesting that grinding the pure glass is easier than the glassy particles. Nevertheless, the results for the different size fractions conformed with the specifications of BS:6699. An examination of the morphological characteristics of the GGBS particles using a scanning electron micrograph revealed that, whatever the size range, all the particles appear to have similar angular shape and smooth texture suggesting that these properties of the particles will not have major influence on the properties of the mixes made from the different size fractions.

Reconstituted Slag Samples. Four slag samples (named A, B, C, and D), with the Rosin-Rammler (R-R) parameters shown in Table 4, were reconstituted. The target R-R parameters n and x_o were chosen so that one parameter could be varied while the other was kept constant. The constant values of n and x_o were determined by the parameters of the original slag sample, *N*. Previous observations by Sprung et al. (19) on the range of R-R parameters for industrial cements with the theoretical findings of Beke (20) on the behaviour of R-R distribution function formed the basis for the choice of the limits for these parameters. According to Sprung et al., for industrial cements the usual range of values for n and x_o were

TABLE 4
Rosin-Rammler parameters of the reconstituted slag samples.

Sample Id.	A		B		C		D		N	
Parameter	n	x_0	n	x_0	n	x_0	n	x_0	n	x_0
Target	0.70	18.50	0.93	15.00	1.20	18.50	0.93	21.00	—	—
Computed	0.76	16.70	0.93	14.90	1.16	19.50	0.95	20.40	—	—
Measured	0.88	18.65	1.09	15.00	1.34	18.10	1.05	21.50	0.93	18.50

0.7 to 1.2 and 15 to 30 μm respectively, and Beke reported that, in theory, values of n varied from 0.5 to 1.3.

Other physical properties, such as fineness and the packing density as related to the PSD of the GGBS samples, were also considered. The packing density was determined by measuring the percentage of voids in the dry GGBS powder and the results are shown in Tables 5 and 6. No distinct relationship could be established between percentage of voids and PSDs of the slag samples. This applies whether the position parameter of the slag powder was varied while the slope value was kept constant or vice-versa.

Analysis of Results. A computer software package for statistical applications was employed to carry out the analysis of the results shown in Table 7. To derive definite conclusions from the results of the analysis of variance (ANOVA), the computed averages for each factor at each level are compared using the Duncan's New Multiple Range (DNMR) Test (21). The test shows how significant the difference between two or more mean values is by comparing the difference between the mean values at each level within a factor with a critical range value. In this programme of study the comparisons were carried out at the 95% level of confidence. A detailed description of this analysis has been discussed elsewhere (15). All the mean values computed for the properties investigated at each level of the factors are shown in Tables 8 and 9. Mean values shaded in the Tables are those shown not to be significantly different according to the DNMR test.

The results presented in Tables 8 and 9 show that at either constant position parameter or constant slope, the effect of w/c on the bleeding characteristics is similar. Bleeding capacity and bleeding rate increased as the w/c was increased, similarly as the amount of slag in the mixes increased, irrespective of which Rosin-Rammler parameter was kept constant. Dun-

TABLE 5
Fineness and packing density of the GGBS samples
at constant $x_0 = 18.5$ μm.

Sample	Slope Value n	Fineness Blaine (cm^2/g)	Percentage Void (%)	Relative Density
OPC*	1.36	3880	35	3.11
A	0.70	4780	36	2.99
N	0.93	4320	34	2.93
C	1.20	4400	36	2.96

* $x_0 = 29.79$ μm.

TABLE 6
Fineness and packing density of the GGBS samples at constant $n = 0.93$.

Sample	Position Parameter x_0 (μm)	Fineness Blaine (cm^2/g)	Percentage Void (%)	Relative Density
OPC*	29.79	3880	35	3.11
B	15.00	4850	39	2.98
N	18.50	4320	34	2.93
D	23.00	3950	34	2.99

* $n = 1.36$.

can's test indicated that the mean values of the bleeding capacity are significantly different in the two cases of R-R parameters, irrespective of replacement level and w/c. Although the bleeding rate increased as the amount of slag increased, Duncan's test suggested that the differences between the mean values associated with each level of replacement were not significant.

Varying n at a constant x_o had an effect such that the mixes containing the slag with $n = 0.93$ had the highest mean values of both bleeding rate and capacity, whilst the lowest mean value was obtained with the slag with $n = 0.70$. Duncan's test showed that for n values of 0.93 and 1.20 the values of both the bleeding and capacity were not significantly different from each other, but both were significantly greater than those of the mixes containing GGBS with $n = 0.70$. The result of the analysis also showed that when keeping the slope constant

TABLE 7
Mixes and bleeding characteristics.

		at constant $x_0 = 18.5$ μm			at constant $n = 0.93$		
w/c	% slag	n	rate ($kg/m^2/h$)	capacity (%)	x_0 (μm)	rate ($kg/m^2/h$)	capacity (%)
0.35	0.0	0.70	0.17	0.66	15.0	0.17	0.66
		0.93	0.17	0.66	18.5	0.17	0.66
		1.20	0.17	0.66	23.0	0.17	0.66
	30.0	0.70	0.20	1.56	15.0	0.32	1.59
		0.93	0.31	3.12	18.5	0.32	3.12
		1.20	0.30	1.73	23.0	0.36	1.76
	70.0	0.70	0.29	2.70	15.0	0.36	2.13
		0.93	0.22	3.73	18.5	0.22	3.73
		1.20	0.31	3.28	23.0	0.29	4.16
0.45	0.0	0.70	1.27	5.80	15.0	1.27	5.80
		0.93	1.27	5.80	18.5	1.27	5.80
		1.20	1.27	0.17	0.66	1.27	0.17
	30.0	0.70	1.22	0.17	0.66	0.94	5.36
		0.93	1.54	0.17	0.66	1.54	7.54
		1.20	1.36	7.17	23.0	1.29	7.39
	70.0	0.70	1.53	7.26	15.0	1.15	6.58
		0.93	2.11	9.04	18.5	2.11	9.04
		1.20	1.37	8.76	23.0	1.68	9.42

TABLE 8
Mean values of bleeding characteristics at constant $x_0 = 18.50$ μm.

Variables	Rosin-Rammler parameter, slope, n			Percentage of slag (%)			Water/cement	
	0.7	0.93	1.2	0	30	70	0.35	0.45
Capacity (%)	3.67	4.98	4.57	3.23	4.2	5.79	2.01	6.81
Rate (kg/m^2/h)	77.89	93.61	79.63	71.96	82.24	96.92	23.72	143.7

the maximum mean values of the bleeding rate and capacity were obtained with the slag with $x_o = 18.50$ μm.

Similarly, the lowest mean values of the bleeding rate and capacity were associated with those mixes that contained the slag with $x_o = 15.00$ μm. The differences between bleeding rate over the entire range of the values of x_o considered were however small and were shown to be insignificant by the Duncan's test. Nevertheless, the test suggested that, in the case of bleeding capacity, the mean values were similar for those mixes made with the slag having $x_o = 18.50$ μm and $x_o = 23.0$ μm and that both were significantly greater than those of the mixes containing the slag with $x_o = 15.0$ μm.

Discussions

Effects of Water/Cement and Percentage of Slag

As stated previously, the analysis of variance and the Duncan's New Multiple Range test showed that the effect of increasing the w/c was to significantly increase both the bleeding rate and capacity for all the mixes regardless of the PSD and slag content. The influence of w/c and percentage of slag content on the mixes investigated was examined considering a typical slag, type A. Figure 1 shows the results of the bleeding characteristics of the mixes containing slag type A. Changing the w/c from 0.35 to 0.45 resulted in increases of 86, 83, and 71% in bleeding rate of the OPC, 30%, and 70% slag mixes respectively.

Previous investigators including Powers (1) and Steinour (22) offered explanations as to why increasing the w/c should bring about an increase in the bleeding rate and capacity of concrete mixes. At higher w/c ratios, the mean distances between the particles become larger, leading to a lower number of points of near-contact and weaker cohesive forces of attraction.

TABLE 9
Mean values of bleeding characteristics at constant slope value $n = 0.93$.

Variables	Rosin-Rammler parameter, position parameter, x_0 (μm)			Percentage of slag (%)			Water/cement	
	15	18.5	23	0	30	70	0.35	0.45
Capacity (%)	3.69	4.98	4.86	3.23	4.46	5.84	2.05	6.97
Rate (kg/m^2/h)	70.15	93.61	84.27	71.96	84.27	96.61	26.23	139.1

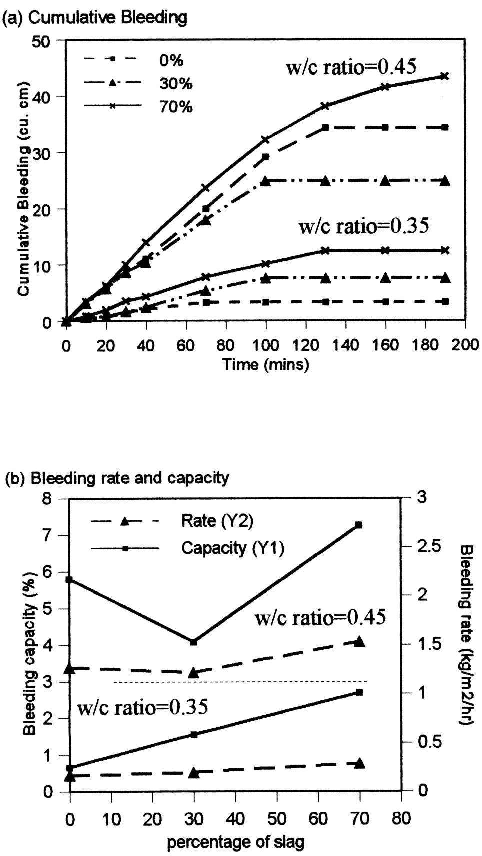

FIG. 1.
Bleeding characteristics of slag type A

These effects in turn create a situation whereby the settlement potential of the particles is increased, therefore resulting in increases in the rate and amount of bleeding.

In Figure 1b it can be seen that inclusion of slag in mortar mixes at both w/c ratios has the effect of increasing the rate and capacity, with the exception of 30% slag mix, which had the lowest bleeding capacity at 0.45 w/c. Results of ANOVA and Duncan's test presented in Tables 8 and 9 indicated that, irrespective of the influences of w/c and PSD of the slags, the mean values of both the bleeding rate and bleeding capacity increased significantly with increases in the levels of replacement. This trend is in agreement with that of previous investigators such as Hwang and Lin (23) and Ait-Aider (8). The fact that the inclusion of GGBS exacerbates the bleeding characteristics of mortar mixes can be explained, partially, by the dependency of the hydration of the slag on that of the OPC. The slag is activated in an alkaline environment, which in this case is provided as a result of early hydration of the OPC. Consequently, there is a reduction in the quantity of early hydration products, which help block the upward passage of water to the surface (17).

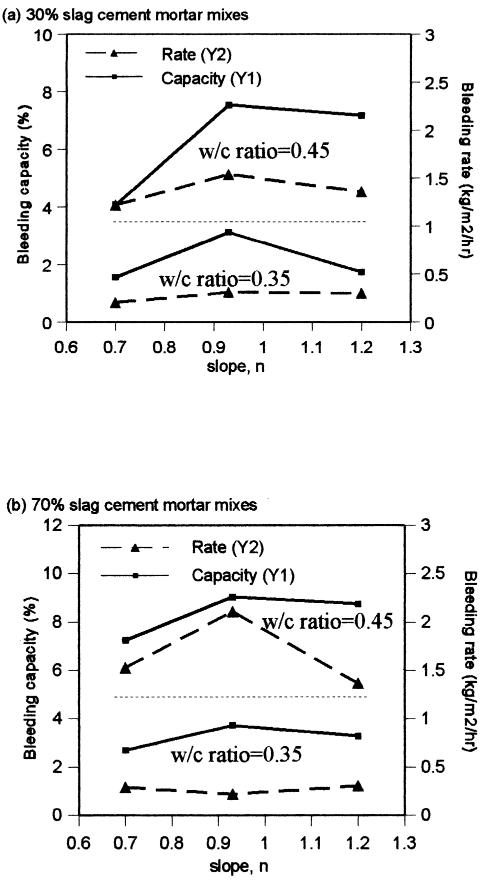

FIG. 2.
Effect of particle size distribtuion at constant position parameter.

Effect of Particle Size Distribution at a Constant Position Parameter

The relationship between the bleeding characteristics of the mortars and slope value, n (at constant x_o) of the GGBS are shown in Figure 2. With the exception of the 0.35 w/c mixes containing 70% slag (Fig. 2b), the trend is similar in all cases with maximum values for both bleed rate and capacity occurring in those samples made with the slags having a value of n = 0.93. According to the results of the statistical analysis presented in Table 8, the mortar mixes containing the slag powder with the n value of 0.70 had significantly different values of bleeding rate and capacity from those of other mortars.

Bleeding of cement paste, mortar, and concrete has been described as a special case of sedimentation whereby the mixing water tends to rise to the surface of a freshly placed mix (1). The reason for this phenomenon is that the solid constituents of the mix are unable to hold all the mixing water when they settle downwards. Similarly, studying the influence of the PSD of cement pastes, Sumner et al. (7), Sprung et al. (19), and Vivian (24) reported that cements with narrower particle size range required a greater amount of water for constant

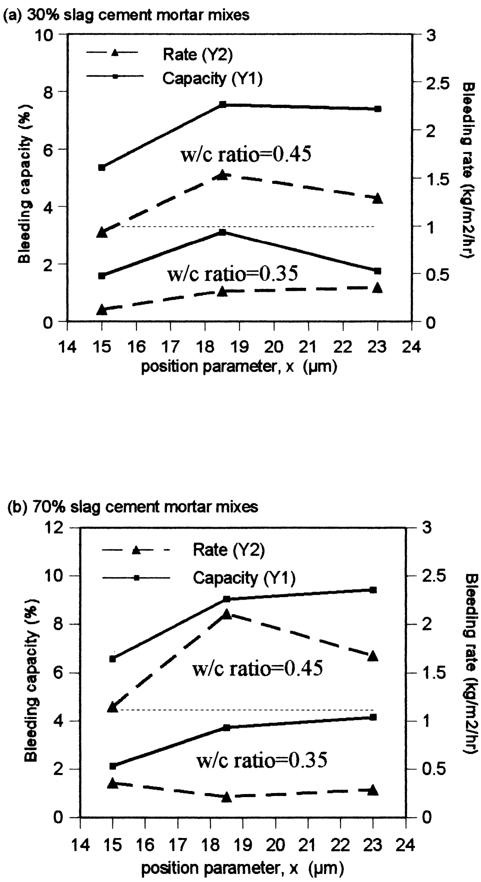

FIG. 3.
Effect of particle size distribution at constant slope.

workability. They attributed their findings to the fact that material with narrower range of particle sizes packed less well than those with a wide range and consequently have higher voidages. Also, investigations carried out by Ait-Aider (8) on the bleeding characteristics of cement paste at constant w/c, mortar, and concrete mixes incorporating GGBS showed that the mixes containing OPC with the narrower size grading exhibited the better bleeding characteristics (i.e., lower bleeding rates and capacities). Results similar to those reported by the investigators mentioned above were obtained in this work. The worst bleeding characteristics were shown by those mixes containing the slag with a slope value of $n = 0.93$ (Fig. 2a and b), which can be attributed to the fact that it contained the lowest percentage of voids (Table 5).

Effect of Particle Size Distribution at a Constant Value of Slope

Figure 3 shows the results of the bleeding chracteristics of the slag cement mixes as they are affected by varying the PSD of the GGBS at a constant slope value. Apart from the 30% slag mixes, which were made to 0.35 w/c as shown in Figure 3a, the bleeding capacity of all the mixes increased with increasing values of the postion parameter x_o of the slag, although the differences between those of $x_o = 18.50$ μm and $x_o = 23.00$ μm were very small (ranging from 0.15% to 0.43%). The trend for the bleeding rate is less obvious; in the two cases of 30 and 70% slag mixes at 0.45 w/c, the maximum bleeding rate occurred at $x_o = 18.50$ μm, while in the other two cases there was a very little change. The results obtained from the analysis of variance and Duncan's test indicated that the highest mean values of bleeding rate and capacity were associated with the mixes containing the GGBS with $x_o = 18.50$ μm. Furthermore, the statistical analysis indicated that the differences between the average values of all bleeding rates were insignificant (Tables 8 and 9).

The increases in the bleeding rate and capacity with increasing values of postion parameter could be explained by the fact that the GGBS powder became coarser and contained a lower percentage of voids, the higher the values of position parameter (Table 6). For the 70% slag mixes at 0.45 w/c, reducing the position parameter from 23 to 15 μm led to a 30% reduction in bleed rate and capacity. The observations in this programme of test are corroborated by the findings of another investigation on the effects of increasing the fineness of slag powder (25).

Conclusions

On the basis of equal w/c, the inclusion of slag tends to aggravate the bleeding propensities of the slag mixes; the values of the bleeding rate and capacity increased significantly with increases in the amount of slag included except for the 30% slag mortar mix, which had the lowest bleed capacity at 0.45 w/c.

When varying the PSDs of slag by altering the slope at constant position parameter, x_o, no specific relationship between bleeding characteristics and PSD could be observed. However, the highest values of the bleeding rate and capacity were exhibited by the mixes in which the slag with the intermediate value of slope (i.e., having the medium range of PSD) was included.

For the slag samples with similar size range distribution (i.e., having a constant slope, *n*), the bleeding capacity increased with increases in x_o, save the 30% slag mixes that were made to 0.35 w/c. The trend for bleeding rate is less evident. In the two cases of 30 and 70% slag mixes at 0.45 w/c, the worst bleeding rates were observed at $x_o = 18.5$ μm, there being a little change in the other two cases.

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