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The Influence of Slag Fineness on the Workability of Cementitious Pastes

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ABSTRACT: In South Africa, the fineness of Ground Granulated Blastfurnace Slag (GGBS) has remained the same for nearly 40 years. In 1999, producers of GGBS were considering the use of relatively finer ground GGBS, with a view to improving the strength performance of concrete. The concomitant increase in compressive strength of concrete with an increase in GGBS fineness was confirmed in an extensive investigation carried out by Slagment (Pty) Ltd (Slagment, 1999). However, the effect of relative fineness of South African GGBS on the workability of concrete mixes had not been assessed.
This paper discusses the results of an investigation that was aimed at quantifying the influence of finer ground GGBS on the workability of concrete, based on the work of Page (2001). Traditionally, GGBS was ground to a fineness of 3 600 cm^2/g, (GGBS 3600), and it was proposed to increase its fineness to 5 000 cm^2/g (GGBS 5000). The experimental programme included four binder types, namely CEM I 42,5 alone, or in a combination with either GGBS (3 600) or GGBS (5 000) or fly ash (FA). To eliminate the effects of aggregates on workability, only binder pastes were tested.
The results revealed that, as expected, the binder containing the fly ash was the most workable. In general, the finer slag, GGBS (5 000), exhibited a higher viscosity and hence lower workability than GGBS (3 600), due to its relatively higher surface area.

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In South Africa the fineness of Ground Granulated Blastfurnace Slag (GGBS) has remained the same for nearly forty years. In 1999, producers of GGBS were considering the use of relatively finer ground GGBS with a view to improving the strength performance of concrete.

The concomitant increase in compressive strength of concrete with an increase in GGBS fineness was confirmed in an extensive investigation carried out by Slagment (Pty) Ltd (Slagment, 1999). However, the effect of relative fineness of South African GGBS on the workability of concrete mixes had not been assessed.

This paper discusses the results of an investigation that was aimed at quantifying the influence of finer ground GGBS on the workability of concrete, based on the work of Page (2001). Traditionally, GGBS was ground to a fineness of 3 600 cm²/g, GGBS (3600), and it was proposed to increase its fineness to 5000 cm²/g, GGBS (5 000).

The experimental programme included four binder types, namely, CEM I 42,5 alone or in combination with either GGBS (3 600) or GGBS (5 000) or Fly Ash (FA). To eliminate the effects of aggregates on workability, only binder pastes were tested.

The results revealed that, as expected, the binder containing the Fly Ash was the most workable.

In general, the finer slag, GGBS (5 000), exhibited a higher viscosity and hence lower workability than the GGBS (3 600), due to its relatively higher surface area.

INTRODUCTION

The results of an investigation, in 1999, conducted by Slagment (Pty) Ltd, showed the strength of concrete to improve with the use of relatively finer ground Ground Granulated Blastfurnace Slag (GGBS) (Slagment, 1999). However, the effect of GGBS fineness on the workability of concrete was not determined.

The fineness of cementitious material is normally indicated by the surface area of the material, which is generally determined by the Blaine method. Traditionally, GGBS was ground to 3 600 cm²/g (Blaine) and the proposed finer material investigated was ground to a fineness of 5 000 cm²/g.

There is another school of thought that advocates that a more accurate assessment of the fineness can be determined from a particle size analysis. The characteristic parameters generally adopted for this distribution are a position parameter 'X' and the slope (n-value) of the distribution function according to the Rosin, Rammler, Sperling and Bennett (RRSB) distribution (Blunk et. al., 1989). A high value of n (slope of the distribution curve) indicates a narrow particle size distribution which will result in a higher water requirement. Lower n-values should result in a reduced water demand.

Patzelt (1993) stated that the water requirement for GGBS even when finely ground should be the same in comparable systems. Hence, the water requirement can be altered by altering the particle size distribution of the material.

Fujiwara and Dozono (1997) carried out a study on the effect of Blaine and n-value on viscosity and on the yield stress. Fifty one types of powder were tested with Blaine values ranging between 3 500 and 7 500 cm²/g and n-values ranging from 0,7 to 1,1. The results of their tests showed the following:

- the n-value has a definite effect on the yield stress. As the n-value decreases the yield stress decreases. When the n-value is below 0,8 the yield stress increases as the n-value decreases
- when the Blaine is less than 4000 cm²/g, the n-value has a strong influence on the viscosity (viscosity decreases as the n-value reduces). When the Blaine is greater than 4000 cm²/g the influence of the Blaine, rather than the n-value, is greater (as the Blaine increases the viscosity increases).

The purpose of the investigation reported here (based on the work of Page, 2001) was to determine the influence of GGBS fineness on the workability of cementitious pastes. This research was based on the premise that there is a direct correlation between the workabilities of concrete and the included paste. The effect of both Blaine and n-value on workability was considered.

The experimental programme included four binder types, namely, CEM I 42,5 alone and in combination with either GGBS (3 600) or GGBS (5 000) or Fly Ash (FA). Fly ash (FA) was included in the binders tested in order to provide another reference. To eliminate the effects of aggregates on workability, only binder pastes were tested. Commonly used blending proportion ratios were adopted.

The Standard Consistency, Flow Table, Viscosity over Time (Single Speed) and Rheology of Mortar (Variable Speed Viscometer) tests were carried out on all the mixes.

EXPERIMENTAL DETAILS

Materials

Portland Cement - CEM I 42,5

For the purposes of this project, cement from only one supplier (PPC) was considered. The cement was a CEM I 42,5, which complied with SANS EN 197-1 (2000). The cement had a specific surface area of 3 468 cm^2/g and a mean particle diameter of 30,13 μm.

Ground Granulated Blastfurnace Slag - GGBS

The Ground Granulated Blastfurnace Slag was taken from the same source for the two samples tested. The GGBS (5 000) was ground finer than the GGBS (3 600) by being subjected to a longer period in the mill. Both Samples of GGBS complied with SANS 1491-1 (2005).

The GGBS (3600) was the traditional slag used in the South African market. This material was ground to a Blaine of 3 600 cm^2/g, had a specific surface area of 4 630 cm^2/g and a mean particle diameter of 19,76 μm.

The GGBS (5 000) was the finer ground slag proposed for the market. This material was ground to a Blaine of 5 000 cm^2/g, had a specific surface area of 5 613 cm^2/g and a mean particle diameter of 13,39 μm. This material was produced as a once-off run and hence is not currently available.

Fly ash

The FA conformed to SANS 1491-2 (2005) and was obtained from a local supplier. The FA was classified by a 12,5 % residue on a 45 μm sieve.

Particle Size analysis

The results of particle size analyses that were carried out on the CEM I 42,5 and on the GGBS samples are shown in Figure 1:

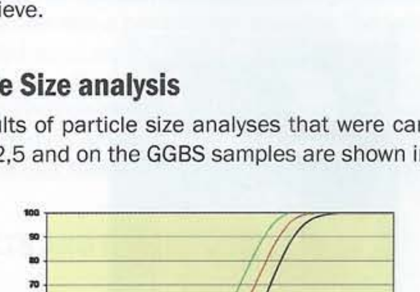

Fig. 1 - Particle size analyses

In summary, the GGBS (5 000) had 100 % of the particles smaller than 60 μm and in the case of the GGBS (3 600) the equivalent figure was 100 μm. The three curves show the three binders getting progressively coarser with the Portland cement being the coarsest.

The surface area of the material increased by 16% from the CEM I 42,5 mix to a 50/50 CEM I/ GGBS (3 600) blend and a further 12% in the case of 50/50 CEM I/ GGBS (5 000) blend. Table 1 shows n-values for the cementitious materials included in this investigation (excluding the FA).

Table 1: N-values of CEM I and GGBS

Cementitious Material	n-value
CEM I 42,5	1,14
GGBS (3600)	1,22
GGBS (5000)	1,36

Chemical analysis

The results of a chemical analysis of the CEM I 42,5, GGBS (3 600) and GGBS (5 000) are shown in Table 2. This analysis was carried out by the X-ray Fluorescence (XRF) technique by PPC (Pty) Ltd.

Table 2: Chemical analysis

Chemical	Cementitious Material		
	CEM I 42,5	GGBS (3600)	GGBS (5000)
SiO_2	22,6	35,6	34,80
Al_2O_3	4,00	15,00	14,20
Fe_2O_3	2,32	1,00	0,97
Mn_2O_3	0,33	1,21	1,16
TiO_2	0,27	1,23	0,56
CaO	66,30	33,50	37,00
MgO	2,70	10,60	8,50
P_2O_5	0,03	0,00	0,01
SO_3	1,92	1,77	1,66
K_2O	0,38	0,80	0,84
Na_2O	0,00	0,23	0,12
LOI	0,00	0,00	0,00
Total	100,90	100,90	99,80

Referring to Table 2, the CaO content of the GGBS (5 000) is higher than the GGBS (3 600). This difference, which may have a significant affect on strength, is probably attributed to a difference in the chemical composition of slag from different blastfurnaces.

Laboratory procedures

Paste mix proportions

The four binder types shown in Table 3 were used for the test programme. The proportioning was done on a mass basis.

Table 3: Paste mix proportions

Binder	CEM I 42,5 (%)	GGBS (3600) (%)	GGBS (5000) (%)	FA (%)
PC	100			
PC/SL	50	50		
PC/SL	50		50	
PC/FA	70			30

Fig. 3 - Flow table

Paste preparation

The cementitious pastes were weighted as indicated below. The pastes were made up using a Hobart mixer with a standard mixing time of two minutes at the lowest speed (to prevent air entrainment/ entrapment in the mix). The water was first placed into the mixer followed by the binder. After 45 seconds of mixing, the mixer was stopped for 10 seconds to scrape-off the material deposited on the sides of the bowl.

Tests

The binder pastes which are listed in Table 3, were subjected to the following tests.

Standard consistency tests

The tests were carried out in accordance with SANS EN 196-3 (2005). The materials were weighed out with 500 g of binder and the relevant amount of water required to obtain the specified workability. The Vicat apparatus with the plunger (50 mm long and 10 mm in diameter), which is shown in Figure 2, was used for this test.

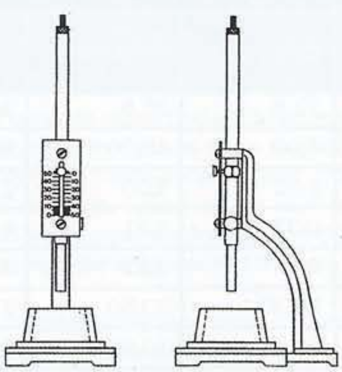

Fig. 2 - Vicat apparatus

This test entails allowing the plunger to vertically penetrate a 40 mm deep paste (in a 75 mm average diameter mould) under its own weight. The standard consistency is defined as the consistency at which a penetration of 33 to 35 mm is achieved.

The results are expressed in terms of the moisture content, expressed as a percentage of the mass of the binder, at which the standard consistency was obtained and the actual penetration recorded. The penetration result is recorded as the distance between the plunger face and the bottom of the mould. Therefore, for example, a penetration of 35 mm into the paste would be recorded as a result of 5 mm (40 mm minus 35 mm).

Flow table tests

Three tests were carried out on each binder type in accordance with SABS Method 1153 (1989).

Figure 3 shows a flow table with the accompanying mould. The mould is 50 mm high and its diameters at the top and bottom are 70 mm and 100 mm, respectively.

The total binder used for each test was 770 g. After filling, tamping and lifting the mould, in accordance with the test method, the table is raised and dropped (through a height of 12,7 mm), 25 times within a 15 second period.

The average diameter of the spread is determined from measurements of the diameter taken at four approximately equally spaced intervals. The flow of the mortar is defined as the increase in diameter expressed as a percentage of the original diameter of the bottom of the specimen (100 mm). The test is repeated at various water contents until a flow of 100 to 110 % is obtained.

The results are expressed in terms of the water content that produced the 100 to 110 % flow, and the average diameter of the flow.

Viscosity with time tests

In the absence of a test specification, the tests were conducted as follows.

Three samples of each binder type were tested at each of three different water/binder (w/b) ratios (0,4;0,5; and 0,6). These w/b ratios are the usual ratios used, as mentioned by Ish-Shalan and Greenberg (1960). Before the pastes were tested in the viscometer, the temperature was recorded. An initial viscosity reading was taken and then readings were recorded at 1, 2, 3, 4, 5, 10, 15 and 20 minutes. The test was stopped and the temperature was re-recorded.

The viscosity was measured using a VT-04 Portable Viscotester, manufactured by the Rion Co. Ltd, shown in Figure 4. This instrument determines the viscosity of the paste by rotating a rotor in the sample which causes viscous resistance.

Fig. 4 - Viscometer

The results from this test are expressed in deci Pascal seconds (d Pa s). One d Pa s is a tenth of a Pascal second (Pa s) which is identical to a kilogram per metre second (kg/m s). At 20 ° C, water and olive oil have approximate dynamic viscosity values of 0,01 and 0,84 d Pa s, respectively. The viscosity of cementitious pastes generally varies from 1 to in excess of 50 d Pa s.

Rheology - Variable speed viscometer

Figure 5 shows the variable speed viscometer. The test method used was that of Banfill (1990).

Fig. 5 - Variable speed viscometer (Visco-Corder)

The material was tested in a cup which was rotated at various speeds, whilst a stationary paddle, which was located inside the cup, measured the torque created by the rotating sample. The torque was relayed, through a spring, to a pen which recorded the measurement on a chart that moved at a constant rate.

The results were presented in the form of a flow curve where torque versus speed was plotted. The y intercept and slope of a flow curve represented the yield value and plastic viscosity of the material, respectively.

In the case of this investigation, the mix preparation differed from the general procedure described above. The mixes were weighed and prepared according to DIN 1164 (1998). This entailed placing water into the mixing bowl before adding the binder. The cementitious paste was mixed for 30 seconds before the graded sand (as specified by the test procedure) was added, after stopping the mixer. The mixer continued at 140 rev/min to complete one minute. The mixer was stopped and the speed adjusted to 285 revs/min, mixing took place for a further minute. The total mixing time was two minutes. The standard sand used, which had the particles greater than 1 mm removed by sieving, was expected to have very little influence on the workability. The Visco-Corder cup was then filled to the indicated position and the testing started within one minute after completion of mixing. The total approximate duration of each test was about two and half minutes. The total period for each test varied because the speed adjustment was manual, making it difficult to keep the interval period from one speed to the next exact. However, preliminary trials conducted to determine the influence of varied duration at the specified speed indicated that these varied durations had little effect on the results achieved.

RESULTS AND DISCUSSION

Standard consistency tests

The results of the Standard Consistency Tests are shown in Table 4.

Table 4: Standard consistency test results

Binder	Water Required	Penetration
PC	135,02	5
PC/SL	137,08	5,6
PC/SL	137,04	5
PC/FA	128,01	7

Referring to Table 4, it is evident that both the slag blends (PC/SL) required approximately 1,5 % more water than the PC mix to achieve the same workability. In the case of the PC/FA blend, the water content was reduced by 5,2 % relative to the PC.

Flow Table Tests

The first trial was done to determine the water required to achieve a flow of 100 to 110 % (diameter of 200 to 210 mm). Then two more mixes were made using the same amount of water and the flow was measured. Table 5 shows the average flow of three samples of each of the mixes with the same amount of water.

Table 5: Flow table test results

Binder Type	Water that produced 100 to 110% Flow (g)	Measured Flow (mm)
PC	245	202,8
PC/SL	239	200,8
PC/SL (F)	240	198,1
PC/FA	231	204,9

With reference to Table 5, there is a reduction in water for the slag mixes compared to the PC mix. However, it must be noted that the average flow for the slag mixes was less than that for the PC mixes.

The water reduction and flow of the binder types containing slag or Fly Ash relative to the PC is shown in Table 6.

Table 6: Water reduction and flow differences relative to PC

Binder Type	Water Reduction Relative to PC (%)	Flow Difference Relative to PC (%)	Water Reduction/ Flow Difference
PC/SL	2,4	-0,98	-2,45
PC/SL (F)	2,0	-2,32	-0,86
PC/FA	5,7	+1,04	4,80

As expected, the Fly Ash mixes yielded the highest water reduction/ flow ratio (4,80). This means that this mix provided the most flow with the least amount of water.

Comparing the two slag blends, it is evident that the blend with the finer ground slag, PC/SL (F) yielded a lower workability.

Viscosity with time tests

The results of the viscosity with time tests, for the three w/b ratios (0,4; 0,5 and 0,6) are shown in Figures 6 to 8. The results shown in each figure are based on the average of three tests carried out on each binder type. Details of the test data are included in the work of Page (2001).

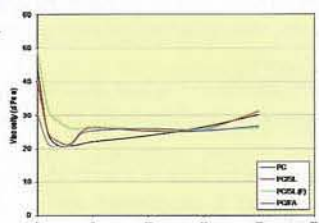

Fig. 6 - Viscosity with time for a w/b ratio of 0,4

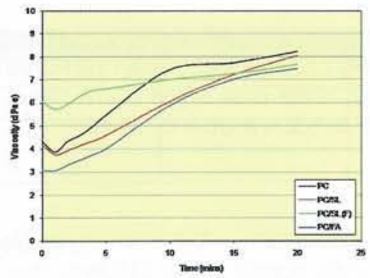

Fig. 7 - Viscosity with time for a w/b ratio of 0,5

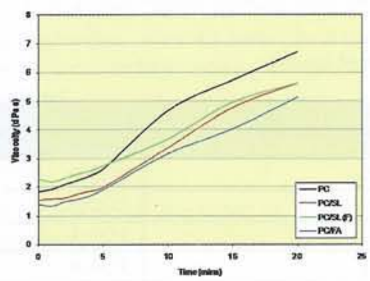

Fig. 8 - Viscosity with time for a w/b ratio of 0,6

With reference to Figures 6 to 8, as expected, for each of the blends, viscosity decreased with increasing w/b ratio. Furthermore, for each w/b ratio, the viscosity during the initial test period (up to 3 to 8 minutes) decreased due to gypsum going into the solution in the order PC/SL (F), PC, PC/SL and PC/FA. The PC/SL (F) was the most viscous of the binders during the abovementioned early period probably due to its relatively high surface area.

In the case of the w/b ratios of 0,5 and 0,6 (Figures 7 and 8), the viscosity of the PC binder mix increased and exceeded that of the other binders, after the early period. This was probably due to the fact that this mix contained more Portland cement than the other mixes and hence, in the presence of sufficient water, hydration occurred and resulted in a relative increase in viscosity.

The rate of increase in viscosity was of a similar magnitude in the case of all the w/b ratios. Table 7 below shows the average rate of increase of all the binders, from 5 to 20 min, for each of the w/b ratios.

Table 7: Rate of increase in viscosity

Water Binder Ratio	Rate of Increase (d Pa s/min)
0,4	0,23
0,5	0,18
0,6	0,23

The only consistent trend common to all three w/b ratios was that the FA blend had a lower viscosity (better workability) than all the other mixes.

The lack of prominent trends in the test results may be attributed to the following inaccuracies associated with the coaxial viscometer (Banfill,1973).

- Slippage - slippage on the surface of a smooth cylinder. Although the instrument used had a roughened surface there was no evidence to prove that slippage did not occur with a roughened surface.
- Sedimentation - the w/b ratio should be kept below 0,4 with this type of equipment to ensure a maximum 10 % error. Only one set of mixes had this value.
- Plug flow - at no time was it monitored and confirmed that total shear flow was present in the sample being tested.

Rheology - variable speed viscometer

The results shown below in Table 8 are average results from three sets of tests. The detailed data are included in the work of Page (2001).

The flow curves for the binders are shown in Figure 9.

Table 8: Summary of results for variable speed viscometer

Rev/ min	Average Torque (g cm)			
	PC	PC/SL	PC/SL (F)	PC/FA
250	393,3	383,3	431,7	245,0
200	350,0	346,7	386,7	211,7
150	311,7	301,7	343,3	185,0
100	271,7	260,0	298,3	156,7
50	225,0	215,0	248,3	128,3

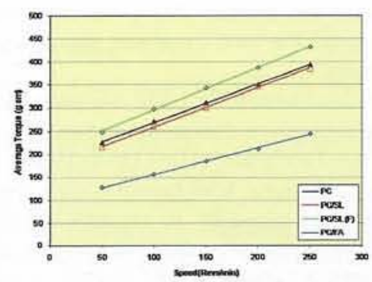

Fig. 9 - Flow curves for the binders

The equation below (Bingham model) shows the relationship between shear stress (τ) and shear rate (γ), and indicates that two parameters are required to characterize a material, namely yield value (τ_o) and plastic viscosity (μ).

$$\tau = \tau_o + \mu\,\gamma$$

For the purposes of this investigation, a large emphasis was placed on the yield stress, which indicates the mobilizing force required for the movement of the material. According to Neville (1995), this value is a good indicator of the workability of concrete.

The viscosity and yield stress values pertaining to the flow curves in Figure 9 are shown in Table 9.

Table 9: Viscosity and yield stress values

Binder Type	Viscosity (μ)	Yield Stress (γ)
PC	0,83	185,8
PC/SL	0,85	174,3
PC/SL (F)	0,91	205,2
PC/FA	0,58	98,8

With reference to Table 1 (containing the n-values) and Table 9 (containing the yield stresses) the following observations were made from this investigation.

- No relationship was found to exist between the n-value and the yield stress of a material. This is in disagreement with Fujiwara and Donozo (1997) who found that, for n-values of 0,8 and greater, a positive correlation existed between the n-value and the yield stress of a material. However, as the particle shape of a material has an effect on the yield stress, the n-values and yield stresses of PC pastes should not have been compared with those of the blended pastes. Therefore, when the n-values and yield stresses of the two PC/SL pastes were compared, the trend established by Fujiwara and Donozo (1997) was confirmed.
- The n-value had a strong influence on the viscosity (viscosity decreased as the n-value decreased. This trend was in agreement with the work of Fujiwara and Donozo (1997).

SUMMARY OF RESULTS

The results from the different tests are summarised in Table 10 below. For each test the results of the PC were considered as the reference for this relative comparison of results obtained by the other blends. Therefore, a relative decrease in percentage indicates a relative increase in workability.

Table 10: Summary of relative workability results

Binder	Variable Speed Viscometer (Yield stress)	Variable Speed Viscometer (Viscosity)	Coaxial Cylinder Viscometer (Viscosity @ 3 mins)	Flow Table Variation in water requirement	Standard Consistency Variation in water requirement
PC	100%	100%	100%	100%	100%
PC/SL	94%	102%	103%	98%	101%
PC/SL (F)	110%	110%	126%	98%	101%
PC/FA	53%	70%	100%	94%	95%

As expected, the mix incorporating the FA had the lowest yield stress and viscosity and hence the best workability.

With regards to the two mixes containing GGBS, the results of the yield stress correlated well indicating a decrease in workability when the finer ground GGBS was used. Furthermore, the viscosity (μ) also increased when moving to the finer material. This means that once the material is mobilized more energy is required to maintain the flow.

CONCLUSIONS

The standard common workability tests such as the slump test and the flow table test measure one parameter whereas the variable speed viscometer can solve for the yield stress and the viscosity of the material.

The variable speed viscometer was the most sensitive test in determining the difference between the various blends.

The results of the yield stress correlated well indicating a decrease in workability when the finer ground GGBS is used.

From these results it can be inferred that the finer ground GGBS will reduce the workability of concrete. For the purposes of concrete mix design there will be an increase in water requirement for an equivalent slump when moving to a finer ground GGBS.

Based on the above it is recommended that further workability tests be carried out on various finenesses of GGBS (between 3 600 - 5 000 cm2/g) with different n-values. It is also recommended that more than one source of CEM I 42,5 be included in any further research. The workabilities and corresponding strengths achieved should be compared in order to optimize the effect of finesses on the workability and strength.

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