Concrete Beton, Volume 94, pp 4-10, July 1999

Influence of GGBS Fineness on the Pore Structure of OPC/GGBS Mortar

Author: F T Olorunsogo

Lecturer, Concrete Structures and Materials, University of Durban-Westville, South Africa

ABSTRACT:

An investigation into the effects of ground granulated blastfurnace slag (ggbs) fineness has been carried out considering ggbs samples with fineness ranging from 4320 to 7500 cm^2/g (Blaine). Mortar mixes were prepared using cement/sand and water/cement ratios of 3 and 0.45 respectively. In all mixes Ordinary Portland Cement was replaced with 70% ggbs by mass. The pore structure of the mixes was studied at 3, 7 and 28 days by examining intrinsic oxygen permeability, total porosity and pore size distribution.

The results show that at all ages considered, the hardened mortar became less permeable and less porous as the ggbs fineness increased: the relationship between intrinsic oxygen permeability and ggbs fineness became almost curvilinear at the age of 3 days whilst at later ages of 7 and 28 days it is almost linear. Furthermore, the results show that the volume of total capillary pores (i.e. pores with a diameter >0.01 μm) decreased with increases in slag fineness at all testing ages considered.

Journal Contact Details:
PO Box 75364
Lynnwood Ridge
Pretoria, 0040
South Africa
+27 12 348 5305

CONCRETE SOCIETY
OF SOUTHERN AFRICA

admin@concretesociety.co.za
www.concretesociety.co.za

Influence of GGBS Fineness on the Pore Structure OPC/GGBS Mortar

TECHNICAL PAPER

Folarin T Olorunsogo

SYNOPSIS

An investigation into the effects of ground granulated blastfurnace slag (ggbs) fineness has been carried out considering ggbs samples with fineness ranging from 4320 to 7500 cm²/g (Blaine). Mortar mixes were prepared using cement/sand and water/cement ratios of 3 and 0.45 respectively. In all mixes Ordinary Portland cement was replaced with 70% ggbs by mass. The pore structure of the mixes was studied at 3, 7 and 28 days by examining intrinsic oxygen permeability, total porosity and pore size distribution. The results show that at all ages considered, the hardened mortar became less permeable and less porous as the ggbs fineness increased: the relationship between intrinsic oxygen permeability and ggbs fineness being almost curvilinear at the age of 3 days whilst at later ages of 7 and 28 days it is almost linear. Furthermore, the results show that the volume of total capillary pores (i.e. pores with diameter > 0.01 μm) decreased with increases in slag fineness at all the testing ages considered.

1.0 INTRODUCTION

Ground granulated blastfurnace slag (ggbs) has been used successfully and extensively in the construction industry world wide as a cement extender. Its use is based primarily on the fact that it is cheaper to produce than ordinary Portland cement (OPC), and that when incorporated in concrete, may confer beneficial effects on certain properties of the concrete so derived. Some of the advantages of using ggbs in manufacture of concrete are: improved workability(1), reduced water demand for equivalent cohesion; flow and compaction characteristics(2) and increase in setting time as a result of slower rate with which ggbs reacts with water(3). Other advantages are lower level of heat evolution(4) and development of higher long-term compressive strengths(5,6). Pore structure of cement paste, mortar and concrete may be defined by material characteristics such as porosity, permeability and pore size distribution. By virtue of their compositions, cement paste, mortar and concrete are porous materials. According to Collins(7) a porous material is a solid containing holes or voids, either connected or unconnected, dispersed within the solid in either a regular or random manner, provided that such voids occur frequently within the material. Powers(8) classified pores in a hardened cement paste into two categories namely; gel pores and capillary pores. He defined the gel pores as the interstices among gel particles which are contained in the cement gel and, capillary pores as the interconnected channels formed by the residues of the originally water-filled spaces existing within the cement paste.

An intrinsic physical property, porosity is described as that fraction of bulk volume of a material that is occupied by voids. Compaction and sedimentation are the primary factors affecting porosity. Similarly, any chemical reactions that may occur from time to time in a given porous material may play a significant role in determining the magnitude of its porosity, as is the case with cement paste, mortar and concrete. Permeability is that property of a porous material which characterises the ease with which a fluid may be made to flow through the material under an applied pressure gradient. The term permeability is strictly related to the flow that occurs under a pressure differential, but frequently, it is also used to refer to transport mechanisms such as adsorption, and ionic and fluid diffusion.

Investigations including those of Powers(8), Danyushesvkii and Dzhabarov(9), Nyame and Illston(10), Dhir et al.(11), Cusens and Cabrera(12), Cabrera and Lynsdale(13), and Nyame(14), have been carried out on pore structure of cement paste, mortar and concrete containing OPC only. There is, however, little information on similar work with OPC/ggbs blends, particularly on the influence of ggbs fineness on pore structure of paste, mortar or concrete incorporating ggbs. In an attempt to fill this vacuum an investigation has been carried out on the effect of fineness of ggbs on the pore structure of OPC/ggbs mortar by considering properties such as porosity, permeability and pore size distribution on slag cement mortar specimens.

Table 1: Properties of GGBS and OPC

(a) Chemical Analysis		
	GGBS	**OPC**
Oxides	**Percentage by mass (%)**	
CaO	40.12	64.01
SiO_2	37.28	21.06
$A1_2O_3$	10.79	5.09
Fe_2O_3	0.43	3.01
MgO	8.83	2.58
MnO	0.68	–
TiO_2	0.58	–
K_2O	0.37	0.80
Na_2O	0.27	0.33
S(total)	1.04	–
SO^{2-}	0.98	–
SO_3	0.15	2.92
$C1^-$	–	0.03
C	0.12	–
Free CaO	0.06	1.20
L.O.I	1.03	–
Insoluble Residue	0.22	0.40
(b) Physical Properties		
Specific Surface Area (cm²/g, Blaine)	4320	3880
Relative Density	2.93	3.11

2.0 EXPERIMENTAL DETAILS

2.1 MATERIALS

The original ggbs, which was subsequently ground to different fineness, was obtained commercially along with the ordinary Portland cement. Washed sand was used as the fine aggregate throughout the experimental programme. Table 1 shows the chemical composition of the OPC and ggbs as supplied by the manufactures while Table 2 shows the physical properties of the fine aggregate. For each mix, five different size ranges of the aggregate as shown in Table 2 were recombined such that the resulting combination conformed with the zone M grading of the British Standard BS 882(15).

2.2 EXPERIMENTAL PROGRAMME

Four additional slag samples were made by grinding for different times the original slag sample (4320 cm^2/g, Blaine) using a 10 kg capacity ball mill. Fineness of the ground samples range from 5300 to 7500 cm^2/g, (Blaine). The properties of mortar which were examined on all the mixes are intrinsic oxygen permeability, total porosity and pore size distribution. Based on the results obtained from a previous investigation(16), tests were carried out on mortar mixes containing ground slag samples at 70% level of replacement and 0.45 water-cement ratio.

2.3 PROCEDURES

Table 2: Properties of Fine Aggregate

(a) Particle size distribution	
Size Range	**Percentage Passing by Mass (%)**
>2.36mm	100
1.18mm - 2.36mm	85
600μm - 1.18mm	65
300μm - 150μm	35
<150 μm	15
(b) Physical properties	
Relative Density	2.62
Water Absorption	0.13%
Fineness Modulus	2.00

2.3.1 Determination of packing density

The packing density of the OPC and all the slag samples were determined following the procedure specified by the British Standards BS 812(17). Table 3 shows the fineness, void percentage and relative density of all the ggbs samples together with OPC.

2.3.2 Mixing procedure

All the mortar mixes were prepared using a 25 kg capacity Cretangle mixer. The cementitious content (i.e. OPC and ggbs) and fine aggregate for each mix were first mixed in a dry state for about 30 seconds before water was added. The entire mixture was then mixed for another 90 seconds, after which the mortar was left in the mixer undisturbed for approximately 15 minutes before casting of mortar cubes.

Table 3: Fineness, packing and relative densities of OPC and GGBS samples

Sample Id.	Fineness Blaine (cm^2/g)	Percentage Void	Relative Density
OPC	3880	35	3.11
SL-A	4320	34	2.93
SL-B	5300	30	2.96
SL-C	6500	37	2.97
SL-D	7100	38	2.97
SL-E	7500	40	2.99

2.3.3 Casting of cubes

Three 50 mm cubes were cast from each mix. After casting and subsequently demoulding, all the cubes were cured at 22 °C and relative humidity of 100%. Cores (50 mm long and 25 mm diameter) were cut out of the cubes (as shown in Figure 1 (a)) at 3,7 and 28 days after casting.

2.3.4 Measurement of oxygen permeability

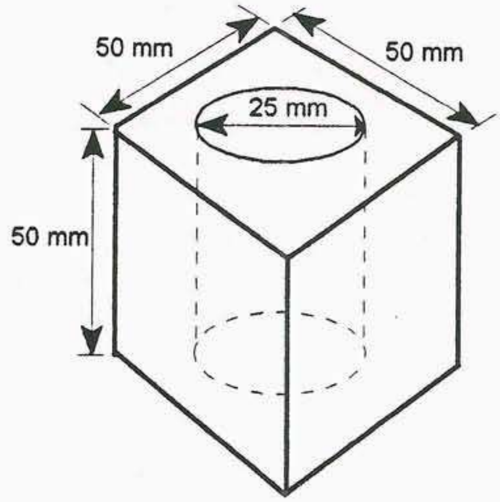
At ages of 3, 7 and 28 days, a 25-mm thick slice was cut 19 mm from the top of the as-cast face of each core, as illustrated in Figure 1 (b). The specimens were then oven dried at a temperature of 110 °C for at least 24 hours prior to testing.

Oxygen permeability of the mortar specimens was determined using modified equipment originally developed by Cabrera and Lynsdale(13). The technique involved the passage of oxygen under high pressure through a cylindrical sample of the mortar. Rates of oxygen flow at given pressures were measured and the coefficient of permeability of the mix was calculated using Darcy's Law, i.e. $K=(q\ P)/L$ where K is the coefficient of permeability, q, the gas flow rate in volume per unit time, L, the length of material in the direction of flow and, P, the pressure difference across the length L.

2.3.5 Measurement of porosity and pore size distribution

Mercury Intrusion Porosimetry (MIP) was used for the determination of the pore size distribution and total porosity of each mortar at the ages 3, 7 and 28 days. Specimens for this test were obtained from the same cores cut from the 50 mm cubes as used for the oxygen permeability test. Discs of 12 mm thickness were cut from the top 19 mm of each core as shown in Figure 1 (b). The discs were then oven dried for at least 24 hours at a temperature of 110 °C. After drying, the specimens were allowed to cool to room temperature in a desiccator so as to prevent them from absorbing moisture from the atmosphere.

(a) 50-mm mortar cube



(b) 25-mm diameter core (cylinder)

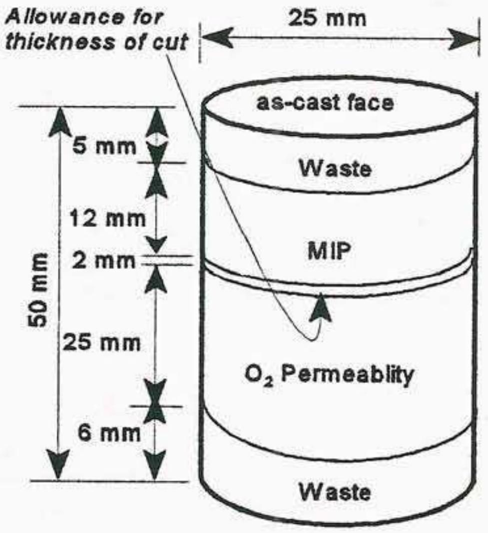


Figure 1: *Core samples from a mortar cube*

3.0 RESULTS AND DISCUSSION

3.1 OXYGEN PERMEABILITY

It was observed that increasing ggbs fineness from 4320 to 7500 cm^2/g resulted in 90, 47 and 35% decreases in permeability at 3, 7 and 28 days respectively. As shown in Figure 2 (a) and as might be expected (due to formation of small quantities of hydration products at early age which tend to block the pores), the effect of increasing the slag fineness was greatest at the age of 3 days; the relationship between the slag fineness and permeability being almost curvilinear. Figure 2 (a) also shows that there was only a marginal difference in permeability when the slag fineness was increased beyond the value of 6500 cm^2/g. At the ages of 7 and 28 days, the permeability decreased almost linearly with the slag fineness; the decreases being much smaller in comparison with the values obtained at 3 days of age.

The results obtained in this investigation are similar to those obtained previously by Wainwright and Olorunsogo(18). In their investigation, it was reported that for 70% slag mixes made to 1:3 cement:sand and 0.45 w/c, increasing the slag fineness from 3950 to 4850 cm^2/g, Blaine led to 38, 91 and 60% decreases in permeability of the specimens at the ages of 3, 7 and 28 days respectively. Wainwright and Olorunsogo also associated the tendency for reduced permeability of mortar mixes with increases in slag fineness to the fact that finer cementitious particles are quicker to hydrate, forming more hydration products which should reduce the volume and favourably alter the nature of the pore within the paste thus decreasing permeability of the mixes.

Comparing the permeability of the OPC (3880 cm^2/g, Blaine) control mortar with the ggbs mixes, Figure 2 (b) shows that at 3 days, mortar mixes containing ggbs with fineness 4320 and 5300 cm^2/g exhibited significantly higher values of oxygen permeability (15.10 x10-16 and 5.34 x 10-16 m^2 respectively) than the control (2.27x10-16 m^2) . At 7 days, however, variations between these mixes were marginal, with the OPC permeability only 12 and 14% respectively lower than these ggbs mixes. At 28 days, only the 5300 cm^2/g ggbs mix exhibited higher permeability than the OPC mix, with all other mixes exhibiting a very similar permeability of around 0.80 x 10-16m^2. The initial lower permeability of the OPC mix than the two ggbs mixes, as manifested at the age of 3 days, can be explained by the fact that activation of ggbs particles depends on $Ca(OH)_2$ which is liberated by earlier hydration of OPC. This means that formation of hydration products by the ggbs component of the combined cementitious particles is delayed until hydration of OPC has commenced. The same explanation holds for the observations made at 7 and 28 days by which time there would be abundant amount of $Ca(OH)_2$ for continuing hydration process of the ggbs particles. As for the other (6500, 7100 and 7500 cm^2/g) ggbs mixes, the lower permeability than the OPC mix at all testing ages may be attributed to the significantly higher ggbs fineness which would normally lead to faster rates of hydration and formation of hydration products.

Findings of an investigation carried out by Douglas and Hemmings(19) corroborates the results obtained in this study. In their investigation on the porosity and permeability of cement pastes made with ggbs samples of different fineness (4000 and 6000 cm^2/g, Blaine), it was reported that up to 7 days of age, water permeability decreased with increases in slag fineness. However, by 28 days, both slag cement pastes showed no measurable permeability with values less than 10-14 m/s compared with the higher permeability of 9.7 x10-13 m/s exhibited by the OPC paste.

3.2 TOTAL POROSITY

For total porosity, increasing the slag fineness from 4320 to 7500 cm^2/g led to 32, 30 and 50% reductions from initial porosity values of 24.1, 19.4 and 18.4 % at the ages of 3, 7 and 28 days respectively, as illustrated in Figure 3 (a). Furthermore, Figure 3 (a) shows that at all ages of testing, increasing ggbs fineness beyond 7100 cm^2/g resulted in increasing porosity, suggesting a pessimum value of ggbs fineness may exist. However, since there was only one ggbs fineness (i.e. 7500 cm^2/g) beyond the presumed pessimum value of 7100 cm^2/g in this investigation, an assumption of the existence of a pessimum value of ggbs fineness may be erroneous. Hence, further studies on ggbs samples finer than 7500 cm²/g will be required to verify this claim.

The general tendency for total porosity to decrease with increasing ggbs fineness, is supported by the findings of the another investigation(18). The study indicated that for mortar mixes prepared using similar mix proportions (to those in the present investigation), increasing ggbs fineness from 3950 to 4850 cm²/g resulted in decreases of 13, 17 and 3% in total porosity of mortar mixes at 3, 7 and 28 days respectively. The reason for this trend is, that finer cementitious particles are quicker to hydrate, thus forming more hydration products which should reduce the volume of pore within the paste and decrease porosity.

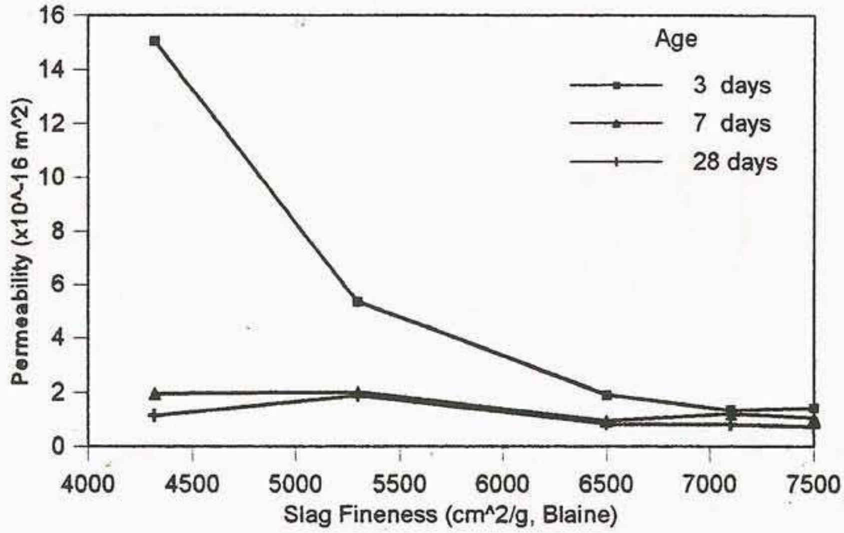
Figure 3 (b) shows the relationship between total porosity and age for all mixes. This figure shows that with the exception of the 4320 cm²/g ggbs mix (and 5300 cm²/g ggbs mix at 3 days), the OPC mortar mix displayed higher value of total porosity than all ggbs mixes at all curing ages. At 3 days of curing, the porosity of the OPC mix is the same as that of the 5300 cm²/g ggbs mix, whilst at 7 days, OPC mix displayed marginally worse porosity than the 5300 cm²/g ggbs mix. However, by 28 days of curing, the OPC mix exhibited much higher porosity value of 16.1% compared with 14.3% for the 5300 cm²/g ggbs mix. Again, similar explanations as offered for the behaviour of OPC and ggbs mixes when considering permeability also apply here for consideration of total porosity. The reasons being that hydration of ggbs particles is dependent upon availability of $Ca(OH)_2$ which is liberated by earlier hydration of OPC particles and that finer ggbs are quicker to hydrate thereby creating more hydration products which tend to block the pores.

3.3 PORE SIZE DISTRIBUTION

Four different pore size ranges as identified by Cusens and Cabrera(12) are considered when examining the results of pore size distribution of the mortar mixes investigated. These ranges are defined as; (i) gel pores: for pores with sizes < 0.01 μm, (ii) medium capillary pores: for pores with sizes ranging from 0.01- 0.05 μm, (iii) large capillary pores: for pores with sizes > 0.05 μm, and (iv) total capillary pores: for pores with sizes > 0.01 μm. Results of pore size distribution for all mixes are shown in Figure 4, which shows that of the pore size ranges considered, only the quantity of large and total capillary pores followed a consistent relationship with ggbs fineness. Increasing the slag fineness from 4320 to 7500 cm²/g (Blaine) led to reductions of 35, 60 and 37% in volume of large capillary pores at the ages of 3, 7 and 28 days respectively. As for the volume of total capillary pores the reductions were 27, 40 and 28% respectively. No specific trend as to the effect of slag fineness could be established in the cases of gel and medium capillary pores. It should be noted that as for porosity, the 7100 cm²/g slag cement mortar mix exhibited the lowest volumes of large capillary and total capillary pores at all the ages of testing.

Clearly, the tendency for volume of total capillary pores to decrease with increases in ggbs fineness may be associated to formation of larger amounts of hydration products as a result of quicker rate of hydration of finer cementitious particles. The effect of the large amount of hydration products is to reduce the volume of total capillary pores.

(a) Permeability versus fineness



(b) Permeability versus age

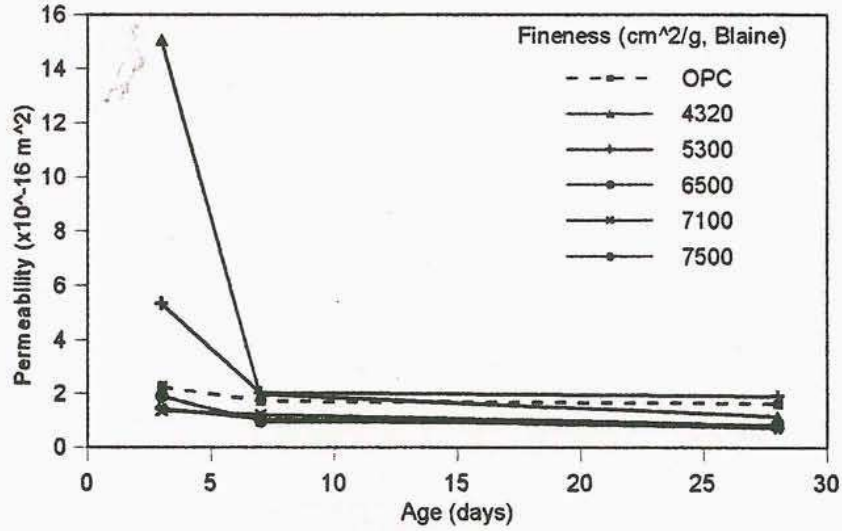
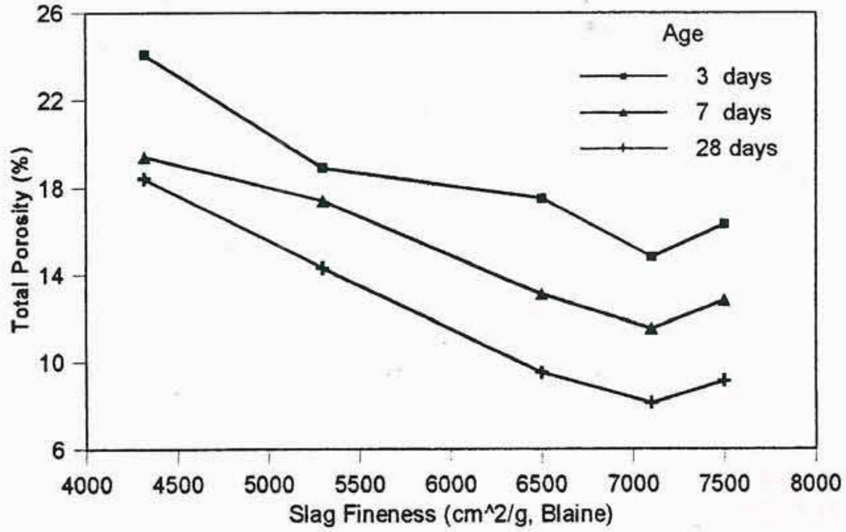


Figure 2: *Effect of slag fineness on oxygen permeability*

(a) Total porosity versus fineness



(b) Total porosity versus age

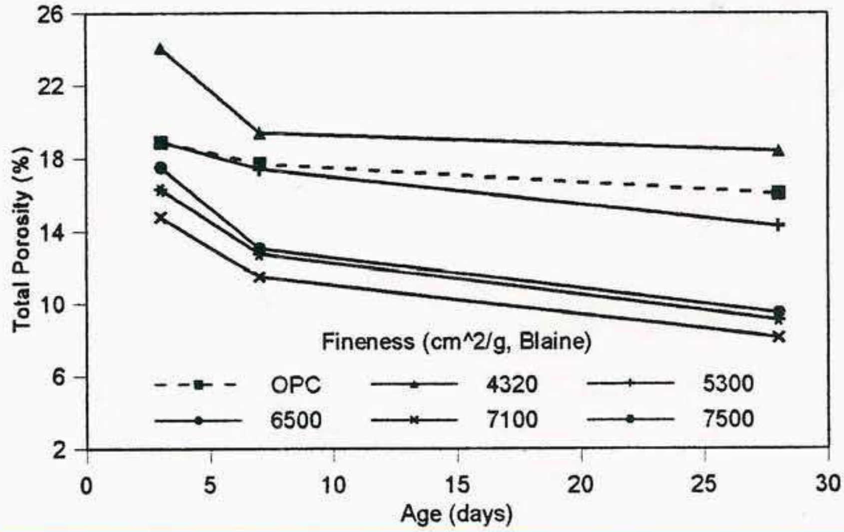


Figure 2: *Effect of slag fineness on total porosity*

In general, the improvement in the pore structure properties (as represented by the permeability, porosity and pore size distribution) of the mortar specimens with increases in ggbs fineness are attributed to increased rate of hydration, and development of a more compact pore structure by ggbs relative to the OPC as also suggested by Satarin(20), Syrkin et al.(21) and Frigione and Di Leva(22) quoting Regourd(23). As the results of this investigation show, the beneficial effects of increasing slag fineness are less noticeable with age. However, the trends suggest that in the long term there will still be a benefit but more data is required to quantify such effects.

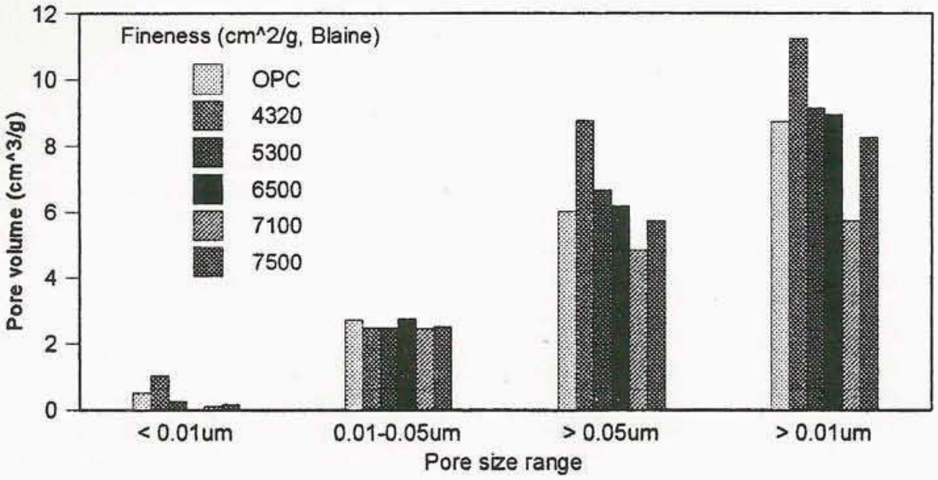
4.0 CONCLUSIONS

At all the ages of testing considered (i.e. 3, 7 and 28 days), slag cement mortar specimens were generally less permeable and less porous as the fineness of the ggbs incorporated in the mixes increased from 4320 to 7100 cm²/g (Blaine). These trends were due to the volumes of large and total capillary pores eability, the relationship between ggbs fineness and permeability was almost curvilinear at a testing age of 3 days whilst it was almost linear at later ages of 7 and 28 days.

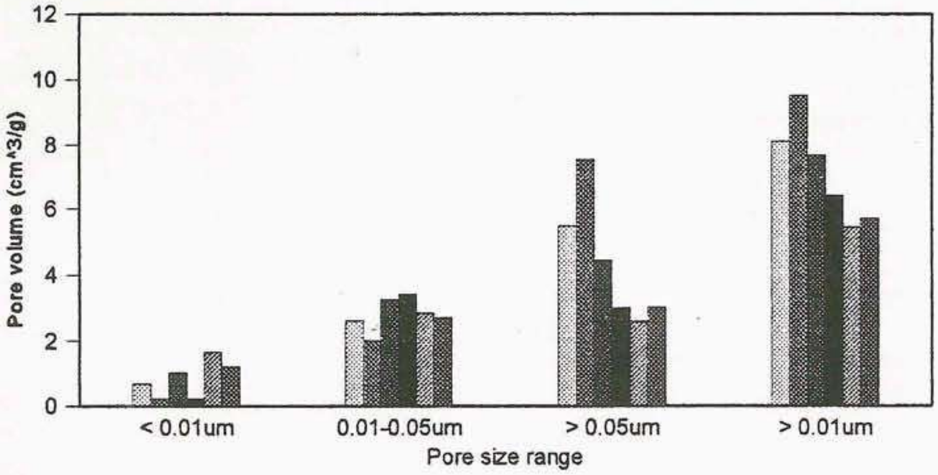
Although, the results obtained show conclusively that the finer the ggbs, the better the pore structure of slag cement mortar, one must consider the cost implications of manufacturing ggbs with fineness in the region of 7000 cm²/g (Blaine) for commercial use in normal or general purpose construction. Therefore, from a durability point of view, ggbs with fineness in the region of 4000 cm²/g (Blaine) may be employed for normal construction purposes. However, users must ensure that products (i.e. mortar, concrete, etc) derived from such ggbs are adequately cured, especially at early age, so as to facilitate sufficient formation of hydration products which would in turn lead to less permeable and less porous mix. ●

FOLA OLORUNSOGO lectures and carries out research in Concrete Structures and Materials at the University of Durban-Westville. Previously he was engaged in research activities in Structural Engineering and Concrete Technology at the Universities of Sussex and Leeds, both in the United Kingdom. He spent a brief time in industry with Pell Frischmann Consultants Ltd., also in the United Kingdom as an Engineer. Afterwards he was at the Obafemi Awolowo University, Ile-Ife, Nigeria where he also lectured and was the Chairman of the Civil Engineering Department.

(a) 3 Days



(b) 7 Days



(c) 28 Days

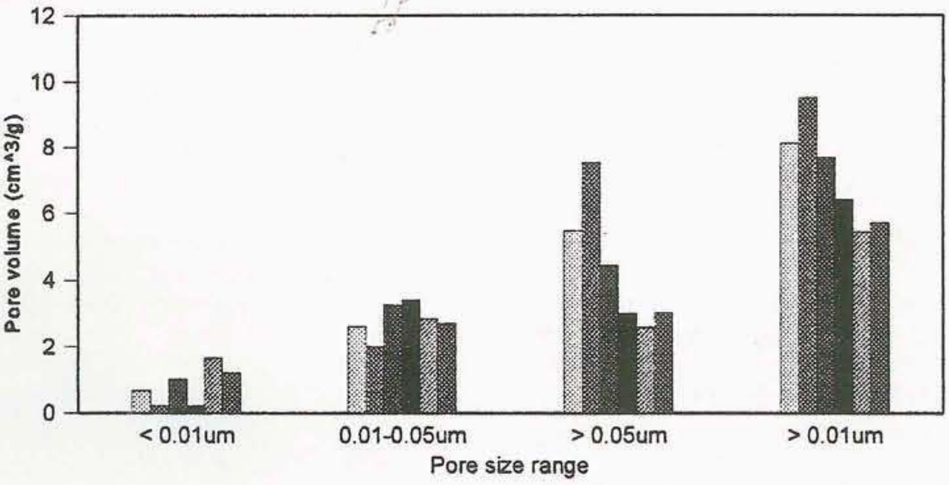


Figure 4 *Effect of slag fineness on pore size distribution*

REFERENCES

1) Wainwright, P.J. "Properties of Fresh and Hardened Concrete Incorporating Slag Cements" in Concrete Technology, vol. 3: Cement Replacement Materials. Ed. by R.N. Swamy, Surrey University Press, 1986, 259p.

2) Reeves, C.M. "The Use of Ground Granulated Blastfurnace Slag to Produce Durable Concrete", Durability of Concrete Conference: Institution of Civil Engineers, London, England, 1985.

3) Reeves, C.M. The Production, Properties and Applications of Blastfurnace Cement, Concrete, Mortar and Grouts Made with Cemsave. ACI Dissertation: Cement and Concrete Association, Slough, England, 1980.

4) Regourd, M. "Structure and Behaviour of Slag Portland Cement Hydrates", 7th International Congress on Chemistry of Cement, Paris, Principal Paper, vol. 1, 1980, pp III 9-26. 5 Atwell, J.S.F "Some Properties of Ground Granulated Blastfurnace Slag and Cement", Proceedings of Institution of Civil Engineers, vol. 57, 1974, pp 233-250.

6) Frigione, G. and Sersale, R. "Gypsum in Blastfurnace Slag Cements" American Society, Bulletin, vol. 62, 1983, pp 1275-1279.

13) Cabrera, J. G. and Lynsdale, C. J. "Particle Size Analysis of Civil Engineering Materials", Department of Civil Engineering, The University of Leeds, Leeds, England 1988.

14) Nyame, B.K. "Permeability of Normal and Lightweight Mortars", Magazine of Concrete Research, March 1985, pp 44-48.

15) British Standards Institution. "Specification for Aggregates from Natural Sources for Concrete". BSI, London. BS 882, 1983.

16) Olorunsogo, F.T. "Properties of Slag Cement Mortars Incorporating GGBS of Different Fineness", Concrete Beton - Journal of the Concrete Society of Southern Africa, No. 84, 1997, pp 10-18.

17) British Standards Institution. "Testing of Aggregates: Method of Determination of Physical Properties". BSI, London. BS 812: Part 102, 1975.

18) Wainwright, P.J. and Olorunsogo, F.T. "Effects of PSD of GGBS on Some Durability Properties of Slag Cement Mortars", Accepted for publication in Journal of the South African Institution of Civil Engineering, 1998.