Pergamon

Cement and Concrete Research 30 (2000) 19–23

CEMENT AND CONCRETE RESEARCH

The influence of mineral additives on the strength and porosity of OPC mortar

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Received 4 December 1998; accepted 10 August 1999

Abstract

Mercury intrusion porosimetry study was carried out on samples of ordinary Portland cement mortars made with mineral additives such as fly ash, granulated blast furnace slag, phosphorous furnace slag, limestone, and lime sludge. The total porosity and compressive strength of all the blended cement mortar samples were determined at 7, 28, and 90 days of hydration. The porosity and mean pore diameter were found to increase with the addition of fly ash and slags, although the total pore volume was almost the same. The strength was found to decrease with the increase in porosity, but the extent of decrease in strength was more closely related to slags and fly ash addition than to limestone and lime sludge. Acceleration of the strength development of ordinary Portland cement was also observed with limestone and lime sludge addition.

Keywords: Mercury porosimetry; Pore size distribution; Fly ash; Granulated blast furnace slag; Mortar

1. Introduction

It is well known that strengths of Portland cement paste depend on porosity, pores size distribution, and pore shape [1–3]. Mineral additions such as fly ash, slags, and limestone influence the pore size and pore size distribution and, accordingly, the strength [4–10]. In this communication the effect of fly ash, granulated blast furnace slag, granulated phosphorous furnace slag, limestone, and lime sludge on the compressive strength and porosity of Portland cement has been studied and an attempt has been made to correlate compressive strength with porosity and pore size distribution.

2. Materials and experimental procedures

2.1. Materials

Ordinary Portland cement (OPC) and five other mineral additives, namely fly ash, granulated blast furnace slag, granulated phosphorous furnace slag, powdered limestone, and lime sludge, were collected from different sources. After examining their chemical and physical properties (Table 1), additives were ground to the workable fineness in the laboratory ball mill and mixed with OPC in 10% quantity on weight replacement basis. Samples were named as: OPC, control sample without additives; FA, OPC with fly ash; BFS, OPC with blast furnace slag; PFS, OPC with phosphorous furnace slag; LS, OPC with limestone; and SL, OPC with lime sludge.

2.2. Measurement of compressive strength and porosity

Compressive strength tests were conducted for all the samples with and without mineral additives according to IS 4031-1988 part VI [11]. For porosity measurement, a representative mortar sample of 10-mm size was obtained from each broken specimen from the compressive strength test. The sample was treated with acetone several times to remove the capillary water and then was subjected to vacuum drying in a vacuum desiccator for 2 h. After that they were preserved in vacuum desiccator until the porosity measurements were conducted with AMNICO mercury porosimeter as described elsewhere [7].

3. Results and discussion

3.1. Porosity and strength of mortar

It was observed that addition of fly ash and other additives in OPC increased the total porosity of mortar (Fig. 1). There was a decrease in the porosity of all the samples with the advancement of hydration period, due to the gradual filling of large pores by the hydration products of cementitious

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0008-8846/00/$ – see front matter
PII: S0008-8846(99)00180-5

Table 1
Chemical and physical properties of OPC and mineral additives

Contents	OPC	GGBFS	GGPFS	Fly ash	Limestone	Lime sludge
LOI	2.67	−0.83	0.24	3.50	37.5	38.17
SiO_2	21.14	32.06	41.29	59.64	10.91	8.45
CaO	61.20	32.05	48.55	1.98	48.0	45.45
MgO	2.67	10.05	1.92	0.85	0.79	3.20
Fe_2O_3	3.92	3.47	0.25	4.38	0.65	0.87
Al_2O_3	4.80	18.03	3.82	27.0	1.25	2.02
SO_3	2.08	–	–	–	0.20	0.10
Na_2O	0.20	0.7	0.65	0.23	0.08	0.68
K_2O	0.80	0.85	1.05	1.28	0.04	0.80
Cl	0.008	0.014	0.005	0.01	0.005	0.015
P_2O_5	0.32	0.17	1.08	0.45	traces	0.90
TiO_2	0.10	0.73	0.05	traces	0.05	0.12
Mn_2O_3	0.07	0.67	0.12	traces	traces	0.02
IR	3.06	0.96	1.26	90.41	11.38	12.50
Free CaO	0.50	–	–	–	–	–
Sulphide	–	0.75	0.09	–	–	–
Mineral composition		X-ray amorphous, a little FeS and crystalline material is present.	X-ray amorphous, small % of crystalline phases also present, which are not identifiable	Quartz and mullite predominant phases, magnetite, hematite in small amount. Some X-ray amorphous material is also present.	Calcite, quartz, muscovite	Calcite, dolomite, quartz, muscovite
C_3S	44.65					
C_2S	26.92					
C_3A	6.09					
C_4AF	11.93					
Glass content		93	94	32	–	–
Density	3.14	2.94	2.97	2.25	2.61	2.70
Fineness (cm^2/gm)	3044	3850	4000	3650	4550	4650

Abbreviations: GGBFS, ground granulated blast furnace slag; GGPFS, ground granulated phosphorous furnace slag; LOI, loss of ignition at 1000°C; IR, insoluble residue.

materials [1,12–14]. The total porosity of all the samples with additives increased at the respective period of hydration, but the extent of increase was variable; there was a greater increase for samples mixed with fly ash and slags and comparatively less for samples mixed with limestone and lime sludge. The strength was also found to decrease with the increase in porosity (Fig. 1), and the decrease was greater with slag and fly ash addition and less with limestone and lime sludge.

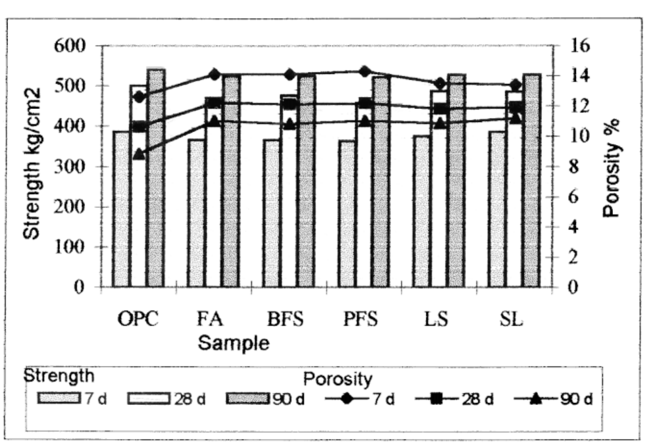

Fig. 1. Strength and porosity of OPC mortar with mineral additives.

To appreciate the nature of pores and its distribution, volumes of mercury intrusion (cc/g) in a specified range of pores are plotted against the pore range, obtained from the semilog curve of pressure (psi) and mercury intrusion volume (cc/g). These histograms have been plotted for each mortar sample, keeping in mind the progress of hydration with mineral additives (Fig. 2). A co-relation between pore volume of a particular range of pores and their relation with the mortar strength at a particular age has also been identified.

3.2. OPC mortar

The histogram (Fig. 2) of volume and pore diameter shows that at the age of 7 days of hydration, there was a larger penetration of mercury in the pore range of 1,000 to 2,000 Å, corresponding to the mean pore diameter of 1,500 Å. The volume of small pores was minimum, but pores of greater than 5,000 Å were abundant at this stage of hydration. As the hydration advanced, the larger pores were converted into smaller ones by the gradual filling of pores with cement hydrate materials such as ettringite, Portlandite, fine crystalline C-S-H, and others. The histogram of mortar samples at 28 days shows a shift of larger pores in the pore range of 500 to 1,000 Å, with mean pore diameter of 750 Å. The volume of smaller pores below 200 Å also increased due to the conversion of each single large pore into many

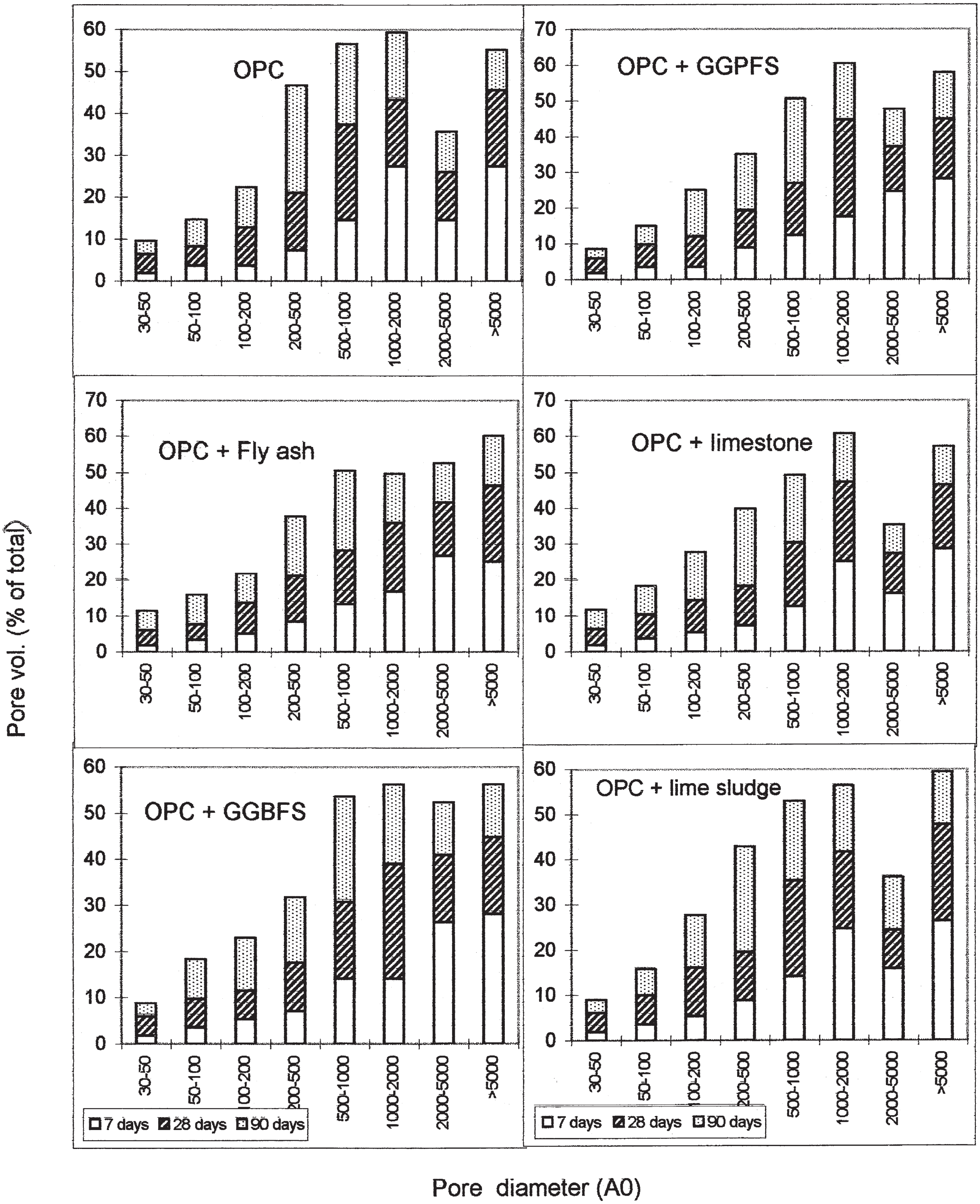

Fig. 2. Pore size distribution of OPC mortar with mineral additives.

smaller pores by the fine crystalline network of CSH (Fig. 3). There was a reduction in the total volume of pores at this stage. At the age of 90 days there was a further shifting of mean pore diameter in the pore range of 200 to 500 Å (mean pore diameter 350 Å) due to the deposition of more hydrated products in the larger capillaries. The total pore volume as well as large size pores of greater than 5,000 Å diameter also reduced considerably.

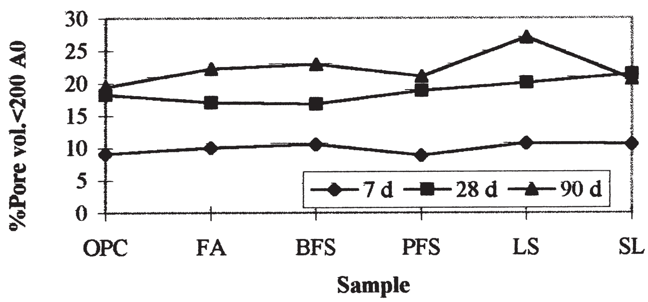

Fig. 3. Pore volume and compressive strength.

3.3. OPC with fly ash

At the age of 7 days (Figs. 1 and 2) the porosity of cement mortar mixed with fly ash was found to be slightly higher than that of OPC, and the pore size distribution shifted toward larger pores. There was a larger penetration of mercury in the pore range of 2,000 to 5,000 Å that corresponds to the mean pore diameter of 3,500 Å and was higher than that of the control OPC mortar. This was probably because of voids around fly ash particles and pores inside; this was also responsible for the increase in the number of pores greater than 5,000 Å.

The porosity and pore size distribution of cement with added fly ash was greater than that of cement without fly ash at the age of 28 days. The mean pore diameter shifted toward the lower range of pores, 1,000 to 2,000 Å, with the mean pore diameter of 1,500 Å. There was a reduction in the total pore volume but still it was greater than that of the control sample, which indicates that the pores were not filled with hydrated products as a result of pozzolanic reaction. However, at 90 days and later, due to the formation of more pozzolanic reaction products, the interspace was gradually filled up and porosity approached near values of control OPC mortar, which was also indicated by increased pore volume of <200 Å. There was greater penetration of mercury in the pore range of 500 to 1,000 Å, corresponding to the mean pore diameter of 750 Å, slightly higher than that of control OPC mortar.

3.4. OPC with slags

From Fig. 2 it is observed that at the age of 7 days there was a greater penetration of mercury in the pore range of 2,000 to 5,000 Å, with mean pore diameter of 3,500 Å. The increase in mean pore diameter and the volume of pores >2,000 Å was due to the slower rate of hydration of slag particles, filling the wide pores at a slower rate. At the age of 28 and 90 days the mean pore diameter shifted to 1,500 and 750 Å, respectively, with the corresponding decrease in total pore volume, approaching equivalence to that of OPC. It is also evident that the trend of pore size distribution was similar to that of samples with fly ash added, due to the delayed hydration and slower rate of filling of larger pores (Figs. 1 and 2).

3.5. OPC with limestone and lime sludge

At the age of 7 days, a larger penetration of mercury occurred in the pore range of 1,000 to 2,000 Å, with the mean pore diameter of 1,500 Å, which shifted to 750 Å at the age of 28 days and shifted further to 350 Å at the age of 90 days (Fig. 2). The overall histogram of pore range and volume at the ages of 7 and 28 days is very similar to that of OPC due to the increase in the rate of hydration. It can be observed from the Fig. 3 that the volume of pores <200 Å was greater at 7 and 28 days compared to other samples that indicated rapid conversion of larger pores into smaller pores due to the formation of hydration products.

3.6. Strength and porosity relationship

The strength of cement mortar or paste is more heavily influenced by the volume and number of large size pores and mean pore diameter than by smaller pores. As seen in Fig. 2, the pore size distribution of OPC mortar with fly ash and slags shifted toward the larger size pores, with an increase in mean pore diameter at all stages of hydration up to 90 days, causing a decrease in strength.

The strength of the mortar at 7 days seems to be influenced by the volume of pores >2,000 Å as observed from Fig. 4. The greater the volume of pores above 2,000 Å, the lower the compressive strength at 7 days. Fly ash and slags showed a decrease in strength at early age because of the presence of a large number of such pores, whereas the strength of samples with lime sludge and lime stone did not seem to be heavily influenced because of their pore volume, comparable with that of OPC mortar sample. The strength at 28 days seems to be related to the pores of >1,000 Å. With the advancement of hydration, the volume of large pores decreased and the volume of smaller pores (<200 Å) increased (Fig. 3). OPC with addition of fly ash and slags showed higher pore volume at >1,000 Å with lower strength, whereas samples with lime sludge and limestone were little affected (Figs. 2 and 4). At the age of 90 days the strength seems to be more heavily influenced by the pores of >500 Å. The pore volume >500 Å was still higher in all the fly ash and slag samples, whereas in samples with lime sludge and limestone, it was comparatively less, indicated by the strength results also (Fig. 4).

4. Conclusion

1. The addition of mineral additives in OPC increased the total porosity of mortar during the early hydration period.
2. The strength decreased with the increase in porosity.
3. In the presence of fly ash and slags the strength seems to be affected by pores >2,000 Å in diameter at the age of 7 days, whereas 28- and 90-day strength depended on pores of >1,000 and 500 Å, respectively.
4. The total volume of pores <200 Å in diameter at the age of 90 days of hydration increased in all the sam-

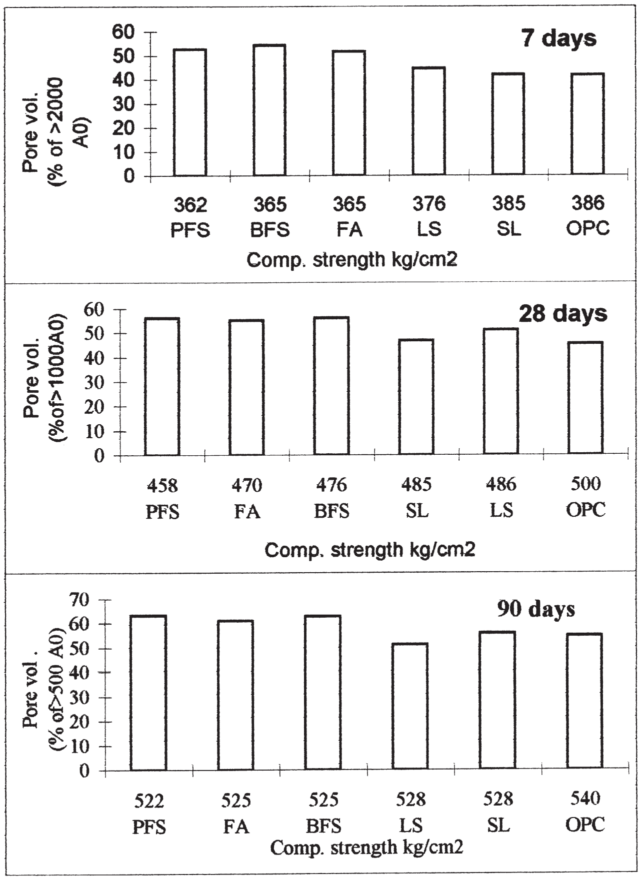

Fig. 4. Pore volume of <200 Å in different samples.

ples, indicating improvement in the hydration and ultimately the strength properties of cement with mineral additives.

5. Porosity and mean pore diameter did not seem to be affected by the addition of limestone and lime sludge in OPC.

Acknowledgments

The experimental work reported here is part of a Ph.D. thesis of one of the authors (R.L. Sharma), who would like to thank National Council for Cement and Building Materials, Ballabgarh (India), for extending the laboratory facilities. The authors are deeply indebted to Prof. N.B. Singh, head of Chemistry Department, Gorakhpur University Gorakhpur 27009 (U.P.) India, for his valuable guidance and suggestions while preparing this manuscript. Thanks are also due to shri C.P. Jajoo, Sr. Executive President, Vikram Cement, for granting permission to publish this paper.

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