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Cement & Concrete Composites 22 (2000) 267–271

Cement & Concrete Composites

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# The effect of mineral admixtures on the properties of high-performance concrete

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**Abstract**

The paper presents a laboratory study on the influence of two mineral admixtures, silica fume (SF) and fly ash (FA), on the properties of superplasticised high-performance concrete. Assessment of the concrete mixes was based on short- and long-term testing techniques used for the purpose of designing and controlling the quality of high-performance concrete. These include compressive strength, porosity, oxygen permeability, oxygen diffusion and chloride migration. Measurements were carried out after curing at 20°C and 65% relative humidity up to the age of 1 yr. The results, in general, showed that mineral admixtures improved the properties of high-performance concretes, but at different rates depending on the binder type. While SF contributed to both short- and long-term properties of concrete, FA required a relatively longer time to get its beneficial effect. In the long term, both mineral admixtures slightly increased compressive strength by about 10%, but contributed more to the improvement of transport properties of concretes. 

*Keywords:* High-performance concrete; Durability; Mineral admixtures; Transport properties; Strength; Pore structure

## 1. Introduction

The premature deterioration of concrete structures in aggressive environments has led to the development of high-performance concrete. The production of high-performance concrete involves appropriate selection and proportioning of the constituents to produce a composite mainly characterised by its low porosity and fine pore structure. These, in turn, improve the resistance of concrete to the penetration of harmful substances such as chloride and sulphate ions, carbon dioxide, water and oxygen, and hence the enhanced durability performance [1,2].

The improved pore structure of high-performance concrete is mainly achieved by the use of chemical and mineral admixtures. Superplasticisers allow substantial reduction in the mixing water. Mineral admixtures, such as silica fume (SF) and fly ash (FA), provide additional reduction to the porosity of the mortar matrix and improve the interface with the aggregate [3]. Another factor influencing the quality of high-performance concrete is curing. In a review of high-performance concrete, Neville and Aitcin [4] highlighted the essential need of wet curing from the earliest possible moment.

Since high-performance concrete is a relatively recent development, there is a need for studying long-term behaviour in different environments. In this study the effect of mineral admixtures on the short- and long-term properties of high-performance concrete was investigated. Concrete mixes made with different binders (OPC, OPC/SF and OPC/FA) were prepared and air-cured at 20°C and 65% relative humidity. Evaluation was made by comparing the porosity, engineering (strength) and transport (permeability and diffusion) characteristics of the different mixes, up to the age of 1 yr.

## 2. Experimental work

### 2.1. Materials and properties

The cement used was ordinary Portland cement, which complies with the requirements of BS 12 [5]. FA was supplied by National Power from Drax Power Station and conformed to BS 3892: Part 1 [6]. The SF used was a dry powder, supplied by Elkem Chemicals. Table 1 gives the chemical composition of the three

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0958-9465/00/$ - see front matter 
PII: S0958-9465(00)00031-7

Table 1
Chemical composition of OPC, FA and SF (%)

| | OPC | FA | SF |
|---|---|---|---|
| $SiO_2$ | 21.03 | 49.9 | 90.00 |
| $Al_2O_3$ | 4.73 | 26.5 | 1.21 |
| $Fe_2O_3$ | 2.93 | 8.1 | 3.87 |
| CaO | 63.63 | 1.7 | 0.34 |
| MgO | 2.67 | 1.3 | 1.43 |
| $Na_2O$ | 0.30 | 1.5 | 0.46 |
| $K_2O$ | 0.65 | 3.6 | 1.49 |
| $SO_3$ | 3.00 | 0.9 | 0.31 |
| LOI | 0.97 | 3.8 | 2.17 |

binders. Quartizitic sand and gravel, conformed to BS 882 [7], were used as fine and coarse aggregates, respectively. The sand grading was medium (zone M), whereas the gravel had a nominal maximum size of 14 mm. The superplasticiser used was a naphthalene sulphonated polymer-based admixture and complied with BS 5075: Part 3 [8].

### 2.2. Concrete mixes

The constituents of the OPC mix were proportioned to achieve maximum packing of the particles and thus minimum porosity. Details of the mix design and procedure are given elsewhere [3]. The composition of the OPC mix was 1:2:3 by weight of cement:sand:gravel, with a cement content of 400 kg/m$^3$.

For the SF and FA concrete mixes, 10% and 30% by weight of the OPC were replaced by SF and FA, respectively. A high superplasticiser dosage (3 l per 100 kg of binder) was used, and the amount of mixing water was decided on the basis of equal workability. The w/b ratio was 0.32, 0.32 and 0.29 for the OPC, SF and FA concrete mixes, respectively. The workability of the concrete mixes ranged between 175 and 190 mm as obtained by the slump test, BS 1881: Part 102 [9].

Concrete cubes (100 mm) and slabs (400 × 250 × 40 mm$^3$) were cast out of each mix and compacted using a vibrating table. The specimens were covered overnight with wet hessian and plastic sheets. Twenty four hours after casting, they were de-moulded and air-cured at 20°C and 65% relative humidity until testing, which is considered as poor curing practice for high-performance concrete.

### 2.3. Methods of testing

Different testing techniques were used in the study to assess the engineering and performance properties of the mixes. These include compressive strength, porosity, oxygen permeability, oxygen diffusion and chloride migration. Testing was carried out at the ages of 1, 3, 7, 28 and 365 days.

The concrete cubes were used for the measurement of compressive strength in accordance with BS 1881: Part 116 [10]. Porosity testing was performed on cores (50-mm diameter and 40-mm height) using the Leeds vacuum saturation method [11]. Briefly, the test consists of subjecting the specimens to a vacuum (negative) pressure of 1 bar for 3 h, then introducing de-aired water to submerge the specimens and maintaining the negative pressure for a further 3 h. The pressure is then released to atmospheric level, and the specimens are left submerged overnight to ensure full saturation. The porosity is calculated from the weight measurements of saturated specimens in air and in water, and the dry weight (oven drying at 105°C to constant weight).

Measurements of oxygen permeability and oxygen diffusion were carried out on similar cores as were used for porosity testing. Conditioning of the specimens prior to testing has a great effect on the measured permeability and diffusion values. Previous work by drying concrete specimens to different moisture levels, including drying at 105°C, indicated correlation between oxygen permeability and degree of saturation [12,13]. In this study, the technique of oven-drying at 105°C was used as it provides a quick conditioning of the specimens and allows comparison between different mixes at early ages. Details of the Leeds permeability and diffusion cells together with the testing procedures are described in reference [11]. For the oxygen permeability testing, the curved surface of the specimen was sealed in the permeability cell and the measurements were conducted at a pressure of 2 bars absolute. The oxygen diffusion testing was carried out by exposing the opposite faces of the specimen to two streams of oxygen and nitrogen, maintained at the same pressure and flow. The oxygen concentration in the nitrogen stream was measured periodically using an oxygen analyser and used for the calculation of oxygen diffusion.

Concrete cores (100-mm diameter and 25-mm thickness) were used for the measurement of chloride transport. The specimen was placed in the diffusion cell between two compartments containing solutions of 3% sodium chloride and 0.1 mole of sodium hydroxide. A potential difference of 12 V was applied to two electrodes (anode and cathode) placed in the solutions, and the amount of chloride ions migrating through the specimens was monitored periodically using the technique of ion chromatography. The chloride migration coefficient ($D_{\mathrm{mig}}$) was calculated using the Nernst–Einstein equation [14]:

$$D_{\mathrm{mig}} = \frac{JRTL}{zFC_0E}, \tag{1}$$

where $J$ is the flux of chloride ions (mol/cm$^2$ s), $R$ the gas constant (8.314 J/K mol), $T$ the absolute temperature (K), $L$ the thickness of the specimen (cm), $z$ the valency of chloride ions ($z = 1$), $F$ Faraday's number ($9.648 \times 10^{-4}$ J/V mol), $C_0$ the initial chloride concentration (mol/l) and $E$ is the potential applied (V).

For the above testing, duplicate specimens were used at each testing age and the mean values were reported. The coefficients of variation were less than 8%, 10% and 15% for the measured properties of strength, porosity and transport, respectively.

Table 2
Compressive strength as fractions of OPC concrete

| Age (days) | OPC | FA | SF |
|---|---|---|---|
| 1 | 1 | 0.74 | 1.11 |
| 3 | 1 | 0.89 | 1.09 |
| 7 | 1 | 0.89 | 1.04 |
| 28 | 1 | 1.00 | 1.09 |
| 365 | 1 | 1.07 | 1.09 |

## 3. Results and discussion

The compressive strength results of the different concrete mixes up to 1 yr are presented in Fig. 1. The results show the general trend of increasing strength with age for all mixes. Minimum strength values of 80 MPa at 28 days and 90 MPa at 1 yr were achieved for the different mixes regardless of the binder type.

The SF concrete showed similar strength development to that of the OPC concrete, but with slightly higher values at all tested ages. The behaviour of the FA concrete was different, as it gave the lowest compressive strength at early ages. However, it showed similar strength to that of the OPC mix at 28 days and higher value at 1 yr.

Table 2 gives the compressive strength expressed as fractions of that of the OPC concrete. With the exception of the FA concrete at 1 day, the results varied between ±11% at the different tested ages. This indicates that at curing conditions of 20°C and 65% RH, mineral admixtures provide a slight improvement to the compressive strength of high-performance concrete. This might be attributed to the lack of moist curing at early ages. Khan and Ayers [15], based on compressive strength determinations and the guidelines of ACI 308-81(86), showed that the minimum lengths of curing required for the OPC, SF and FA concretes were 3.75, 3 and 6.5 days, respectively.

The porosity results are illustrated in Fig. 2. The values of the different mixes varied between 9% and 5% at the different ages tested (1–365 days). These relatively low porosity values indicate the effect of mix proportions and chemical admixture on reducing the porosity of concrete. The results also indicate that more reduction in porosity is achieved by the use of mineral admixtures.

The extremely fine SF particles, in addition to being highly pozzolanic material, improve the packing of the mortar matrix and at the interfaces with the aggregate, resulting in a denser concrete mix with finer pore structure [3,4]. In this study, SF was found to contribute more to the improvement of porosity than compressive strength. The SF concrete exhibited lower porosity values (up to 25%) when compared to the OPC concrete.

Unlike most other mineral admixtures, FA enhances the workability of fresh concrete. Hassan et al. [16] reported that for each 10% replacement of OPC by FA in a concrete mix, the water content reduces by 3–4%. This, in turn, improves the packing capacity of the concrete ingredients and reduces its porosity. Fig. 2 shows that FA concrete gave the highest porosity values at early ages. However, a significant reduction is clearly observed with age. In fact, the FA concrete was the only mix that showed noticeable reduction in porosity after 28 days.

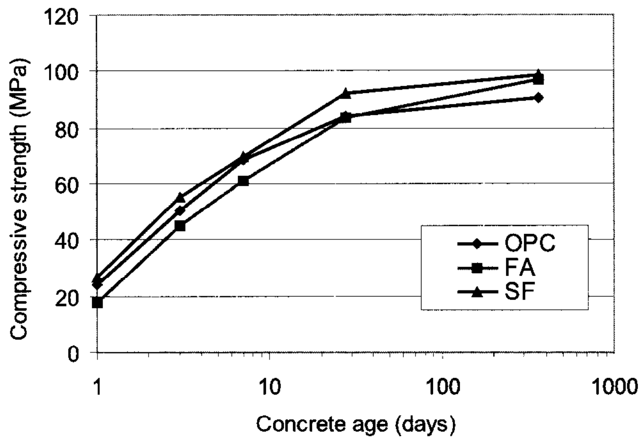


Fig. 1. Compressive strength of high performance concretes.

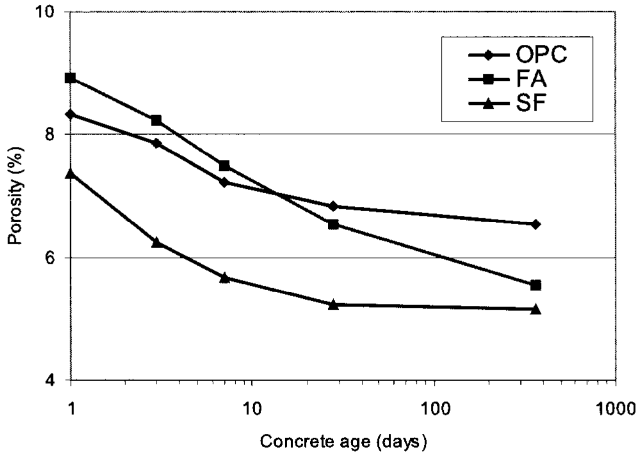


Fig. 2. Reduction in porosity with age.

The fine pore structure of high-performance concrete improves its transport properties and consequently increases its resistance to aggressive environments. The oxygen permeability results are plotted against age in Fig. 3, and presented as fractions of that of the OPC concrete in Table 2.

OPC concrete exhibited the highest permeability values, with a slight reduction with time. Both SF and FA concrete mixes showed lower permeability at early ages. After 28 days, the FA concrete was the only mix to show considerable reduction with time to reach a permeability value almost similar to that of the SF concrete at 365 days. Table 3 shows that SF and FA reduce the permeability by 87% and 84%, respectively, in the long term (365 days).

The oxygen diffusion and chloride migration coefficients are presented in Figs. 4 and 5, respectively. Similar to the permeability results, both SF and FA reduced the transport characteristics at early ages, and the reduction was more pronounced in the long term.

In general, the results obtained in this study clearly indicate that the addition of mineral admixtures provides additional improvement to the porosity, and hence the pore structure of high-performance concrete. This is reflected in the improved strength and transport properties. The compressive strength increased by a maximum of 10%, whereas a remarkable reduction was observed in permeability (>80%) in the long term.

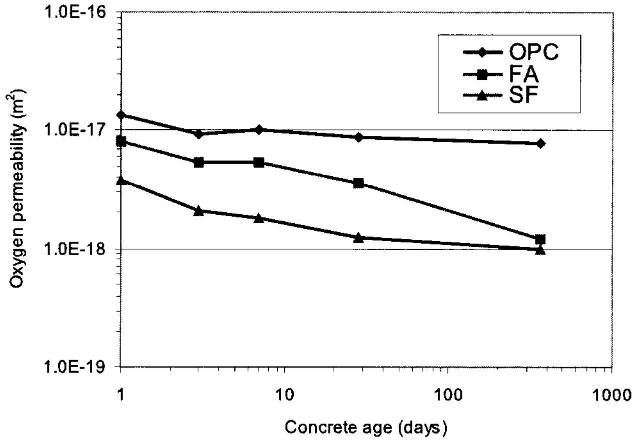


Fig. 3. Oxygen permeability vs. age for the different concrete mixes.

Table 3
Permeability as fractions of OPC concrete

| Age (days) | OPC | FA | SF |
|---|---|---|---|
| 1 | 1 | 0.60 | 0.29 |
| 3 | 1 | 0.57 | 0.22 |
| 7 | 1 | 0.53 | 0.18 |
| 28 | 1 | 0.30 | 0.14 |
| 365 | 1 | 0.16 | 0.13 |

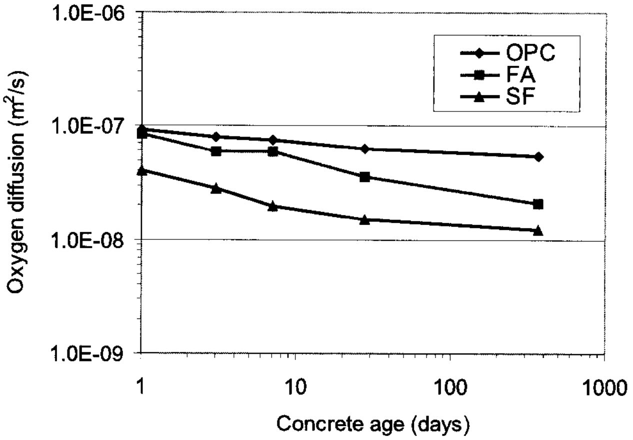


Fig. 4. Oxygen diffusion of high performance concretes.

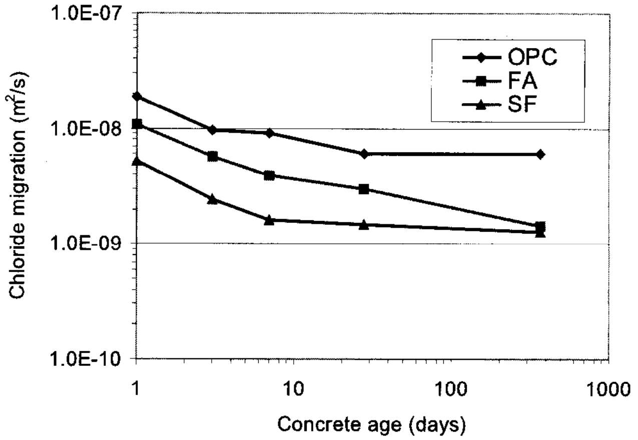


Fig. 5. Chloride migration of high performance concretes.

Attempts to correlate permeability with strength for different concrete types have indicated the difficulty of obtaining a unique relationship [1,13]. Consequently, durability specifications should consider the transport properties of concrete, in addition to compressive strength, together with environmental aspects to ensure long term durability performance of concrete structures.

## 4. Conclusions

1. Specifying concrete on the basis of 28-day compressive strength underestimates the general beneficial effects of mineral admixtures in improving the transport properties.
2. Under the curing conditions used in this study, the inclusion of 10% SF or 30% FA slightly improved the strength in the long run, but provided a significant improvement to the transport properties of high-performance concrete.
3. SF enhances the early ages as well as the long-term properties of concrete. It reduces the permeability

by 71% and 87% at 1 and 365 days, respectively, when compared to OPC concrete.

4. FA concrete has relatively poorer characteristics at early ages, but achieves similar strength and transport characteristics to SF concrete in the long term.

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