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Durability Study Partially Saturated Fly Ash Blended Cement Concrete

N. Shafiq, M. F. Nuruddin and S. C. Chin

***Abstract*—**This paper presents the experimental results of the investigation of various properties related to the durability and long-term performance of mortars made of Fly Ash blended cement, FA and Ordinary Portland cement, OPC. The properties that were investigated in an experimental program include; equilibration of specimen in different relative humidity, determination of total porosity, compressive strength, chloride permeability index, and electrical resistivity. Fly Ash blended cement mortar specimens exhibited 10% to 15% lower porosity when measured at equilibrium conditions in different relative humidities as compared to the specimens made of OPC mortar, which resulted in 6% to 8% higher compressive strength of FA blended cement mortar specimens. The effects of ambient relative humidity during sample equilibration on porosity and strength development were also studied. For specimens equilibrated in higher relative humidity conditions, such as 75%, the total porosity of different mortar specimens was between 35% to 50% less than the porosity of samples equilibrated in 12% relative humidity, consequently leading to higher compressive strengths of these specimens.A valid statistical correlation between values of compressive strength, porosity and the degree of saturation was obtained. Measured values of chloride permeability index of fly ash blended cement mortar were obtained as one fourth to one sixth of those measured for OPC mortar specimens, which indicates high resistance against chloride ion penetration in FA blended cement specimens, hence resulting in a highly durable mortar.

***Keywords*—**chloride permeability index, equilibrium condition, electrical resistivity, fly ash

I. Introduction

OVER the last few years the use of agricultural and industrial wastes with pozzolanic reactivity such as fly ash, FA, and silica fume, SF, as a partial replacement of cement are becoming very popular in producing high strength and high performance cement mortar and concrete. Many studies have shown that the addition of pozzolanic materials in concrete tighten the pore structure and hence reduced the total porosity. This tight pore structure of concrete and mortar increases its resistance against the penetration of aggressive fluid and ions, which results in a high performance concrete. Porosity and pore structure perhaps more than any other characteristics affect the behaviour of concrete [1]. Total porosity, pore size and their distribution directly control both the engineering and transport properties of concrete and mortar and therefore set the performance criteria of its durability.

N. Shafiq is with the Department of Civil Engineering, Universiti Teknologi Petronas, Malaysia (corresponding author phone: +605-368 7289; fax: +605-365 6716; e-mail: nasirshafiq@petronas.com.my).

M.F. Nuruddin is with the Department of Civil Engineering, Universiti Teknologi Petronas, Malaysia (e-mail: fadhilnuruddin@petronas.com.my)

S.C. Chin is presently a PhD student in Department of Civil Engineering, Universiti Teknologi Petronas, Malaysia (e-mail: brigitchin@gmail.com).

Porosity and pore structure, in turn, are influenced by the original packing of cement, mineral admixtures, and the aggregate particles; the water-to-solid ratio; the rheology; and the curing conditions [2].

The compressive strength of concrete is not the sole parameter to define the quality of concrete as stated in some codes and specifications. However, there are other parameters, such as the transport properties, which are very important to assess the durability and long-term performance of concrete structures.

Corrosion of embedded steel reinforcement in concrete is one of the major threats to its durability. Cabrera and Ghoddoussi [3] stated that the rate of corrosion is controlled by the ease with which ions can pass through the concrete cover from a cathodic region to an anodic one. Hence a larger potential gradient associated with a low concrete resistivity will normally result in a high rate of corrosion. The humidity of concrete and the presence of ions in the pore solution of concrete affect its electrical resistivity.

In this study total porosity, compressive strength, electrical resistivity and the chloride permeability index of mortar samples made of different mixes composed of 100% OPC, 50% OPC + 50% FA, and 60% OPC + 40% FA were investigated. All samples were cured for 28 days in fog room then dried in 75%, 65%, 40% and 12% relative humidity until equilibrium conditions were attained, which took nearly 12 weeks. All samples used for measuring of total porosity, compressive strength and electrical conductivity were tested at equilibrium condition, whereas the chloride permeability index test was conducted on fully saturated samples. The experimental tests were carried out partly in the department of civil engineering, Universiti Teknologi PETRONAS and partly at the University of Leeds, UK.

II. Experimental Investigations

A. Materials and Mix Proportions

Mortar mixes were obtained after wet sieving the coarse aggregate for concrete mixes. These were prepared with OPC and/or OPC + FA, sand and gravel using a weight ratio of 1:2.33:3.5. The OPC used complied with the requirements of BS 12 [4]. A Quartzitic sand and gravel conforming to BS 882 [5] were used as fine and coarse aggregates respectively. All mortar mixes were designed to have the same workability, i.e. a targeted slump of 55±5 mm. Details of all mixes used in this investigation are given in TABLE I.

TABLE I
CONCRETE/MORTAR MIX PROPORTIONS

MIX TYPE	OPC kg/m^3	FA kg/m^3	SAND kg/m^3	GGRAVEL kg/m^3	W/C
OPC	325	0	757	1137	0.55
PFA40	195	130	757	1137	0.49
PFA50	162.5	162.5	757	1137	0.48

B. Specimen Casting, Curing and Equilibration

Cubes of dimensions 50mm x 50mm x 50mm were cast for compressive strength and electrical resistivity tests. All cubes were cured for 28 days in a fog room, followed by equilibration in 75%, 65%, 40% and 12% relative humidity (RH) for nearly 12 weeks. Similarly 600mm x 250mm x 40mm thick mortar planks were cast and cured for 28 days in a fog room, then 100mm diameter and 25mm thick circular discs were cored out for equilibration in different relative humidity conditions.

C. Determination of Compressive Strength

Equilibrated mortar samples of 50mm x 50mm x 50mm dimensions were tested using a universal testing machine in accordance with the British Standards BS 1881: Part 116, 1983 [6].

D. Measurement of Total Porosity

In this investigation, a vacuum saturation apparatus was used, which is similar to that developed by RILEM [7] for measuring the total porosity. The mortar samples equilibrated in different RH were weighed in the air, W_i. Then the specimens were vacuum saturated in water, in a fully saturated condition; the specimens were weighed in the air, W_{SA} and in the water, W_{SW}. Finally, they were dried in an oven at 105°C to constant weight, W_d. The total porosity, P was calculated as:

$$P = \frac{W_{SA} - W_d}{W_{SA} - W_{SW}} 100$$

E. Measurement of Chloride Permeability Index

After equilibration of mortar specimens in different relative humidity conditions, they were saturated using vacuum saturation before the test was conducted. The Chloride Permeability Cell developed at the University of Leeds [8] was used in this investigation. Two samples from each of the mortar mixes were tested at an applied voltage of 30 volts for 6 hours to determine the chloride permeability index. The samples were fixed between the two compartments, the one bearing sodium hydroxide (NaOH) solution and the other bearing sodium chloride (NaCl) solution, the cell was tightened using long screws and nuts within the holes provided at the corners of the compartments, and the edges and gaps were completely sealed using silicon rubber in order to prevent any leakage during the test. The test was conducted according to the procedure as illustrated by Cabrera and Lynsdale [8].

F. Measurement of Electrical Resistivity

The moisture within concrete and the presence of ions in the pore solution, primarily affect the resistivity of concrete. Tutti [9] mentions that the electrical resistance of concrete is more sensitive to the equilibrium relative humidity than any other parameters. Cabrera and Ghoddoussi [3] reported that all those factors controlling the permeability of concrete also affect its resistivity. Moist concrete behaves essentially as an electrolyte with a resistivity in the order of 100 ohm-m, a value in the range of semi conductors. Oven-dried concrete has a resistivity in the order of 109 ohm-cm, like a good insulator. For very high resistivity of concrete and mortar, the corrosion-induced current is very small; therefore, the chances of significant corrosion are unlikely to occur [10]. In general, Vassie [11] suggested that if the resistivity is greater than 120 ohm-m, significant corrosion is unlikely to occur.

Berke et.al.[12], reported that from the measurements made on 36 trial concrete mixes containing micro silica, severe corrosion occurred in two mixes which exhibited resistivity values of 480 ohm-m and 730 ohm-m. Besides moisture content, the resistivity of concrete is a function of other factors, including temperature and water-cement ratio, which are directly proportional to resistivity. Bamforth and Pocock [13] investigated the effect of fly ashes on the resistivity of concrete, they found that at 2 years of age, fly ash concrete exhibited resistivity values in the order of 100 ohm-m or greater and the OPC concrete showed resistivity in the range of 100 to 300 ohm-m.

In this investigation, the relative electrical resistance of the mortar specimens was measured using an instrument based on Wheatstone Bridge, at a frequency of 1 KHz and 10 volts.

III. RESULTS AND DISCUSSION

A. Total Porosity of Mortar Samples

Table II is showing the experimental results of total porosity, P of the mortar samples equilibrated in different relative humidity conditions. As shown in TABLE II, the total porosity of fly ash blended cement mortar was 10% to 15% lower than the corresponding OPC mortar specimens.

It is also noted that the ambient relative humidity also significantly affected the total porosity of the samples. Porosity was 7% to 9% lower in mortar samples equilibrated at 75% RH as compared to samples equilibrated at 12% RH.

TABLE II
TOTAL POROSITY, P (%) OF MORTAR MIXES

RH (%)	Total Porosity, P, % Of Mortar Mixes		
	OPC	40% FA	50% FA
75	18.51	16.73	17.73
65	19.83	17.36	17.84
40	20.56	17.60	18.06
12	21.10	18.08	19.05

B. Compressive Strength of Equilibrated Mortar Samples

Table III shows the values of the compressive strength of mortar cubes equilibrated at different relative humidity. Since the compressive strength is a function of the total porosity, therefore a similar trend for fly ash blended cement mortar and OPC mortar was observed. The mortar cubes equilibrated at 75% RH showed the lowest porosity. Therefore, such mortar cubes displayed the highest compressive strength. Since both compressive strength and total porosity were significantly affected by the ambient relative humidity, compressive strength may be statistically correlated with a parameter termed as open porosity, V_e, which is defined as the fraction of unsaturated pores [14] and mathematically expressed as:

$$V_e = p\left(1 - \frac{S}{100}\right)$$

Where, P is the total porosity and S, is the degree of saturation of the equilibrated samples, and V_e is the open porosity.

The compressive strength, f_{cu} of different mortar mixes was plotted against the corresponding values of open porosity, V_e and a valid statistical correlation was obtained as:

$$f_{cu} = 62.27 - 0.805V_e$$
$$R^2 = 87.9\%$$

TABLE III
COMPRESSIVE STRENGTH, f_{cu} (MPA) OF EQUILIBRATED MORTAR SAMPLES

RH (%)	Compressive Strength, f_{cu} Mpa		
	OPC	40% PFA	50% PFA
75	58.1	61.6	60.1
65	53.2	57.1	54.3
40	50.7	54.9	52.5
12	46.7	51.4	49.7

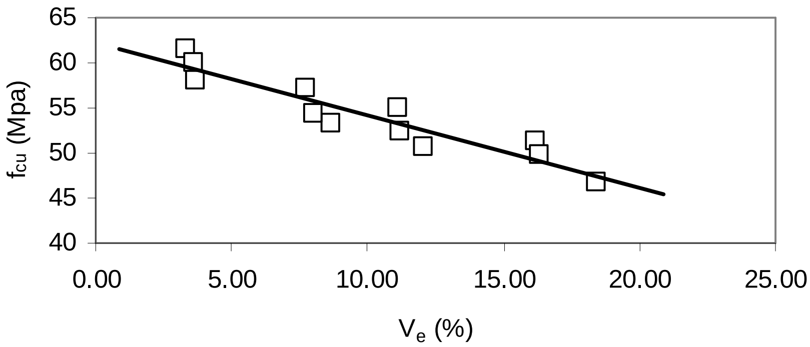

Fig. 1 Compressive strength, f_{cu} versus open porosity, V_e of equilibrated specimens

C. Chloride Permeability Index (CPI)

It is noted from Fig. 2 that that the fly ash blended cement lowered the chloride permeability index to one fourth to one sixth as compared with that the values obtained for specimens made of 100% OPC mortar. Therefore fly ash blended cement mortar offers high resistance against the penetration of chloride ions.

Although the specimens were fully saturated after reaching the equilibrium condition in different relative humidity, the effects of ambient relative humidity are prominent for all mixes as shown in Fig. 2. Chloride permeability index values nearly two times higher were obtained for samples equilibrated in 12% relative humidity compared to values obtained for samples equilibrated in 75% relative humidity. One of the obvious reasons is the higher porosity of samples equilibrated in dry ambient air.

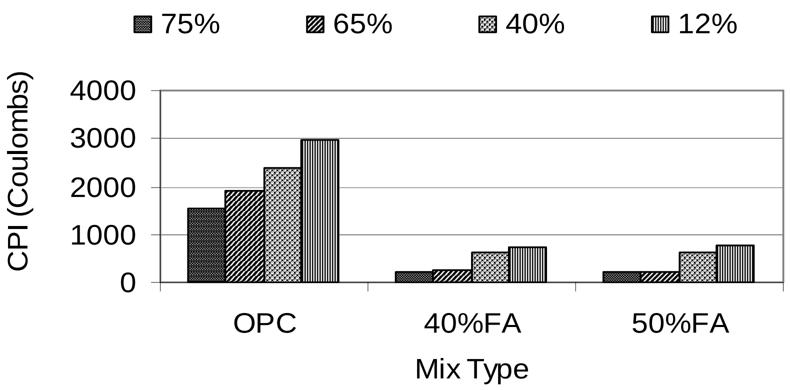

Fig. 2 Chloride permeability index (CPI) of equilibrated mortar samples

D.Electrical Resistivity of Mortar

As resistivity is inversely proportional to the chloride permeability index a similar trend was observed for electrical resistivity of the different mortar samples, as shown in Table IV. The specimens made of fly ash blended cement mortar displayed 4 to 7 times higher resistivity as compared to the resistivity values measured for corresponding OPC mortar samples. Similarly, the effects of equilibrium conditions were also significant as observed in Table III, for OPC mixes, samples equilibrated in 75% RH showing twice the resistivity of that samples equilibrated in 12% relative humidity, whereas, for fly ash blended cement mixes, electrical resistivity of samples equilibrated in 75% increased by more than 3 times the resistivity of those samples equilibrated in 12% relative humidity. Electrical resistivity ρ was plotted against the chloride permeability index, CPI as shown in Fig. 3 and a valid statistical correlation was obtained as:

$$\rho = 2.0x10^{7}\left(CPI\right)^{-0.97}$$
$$R^{2} = 0.98$$

TABLE IV
ELECTRICAL RESISTIVITY, Ρ (OHM-CM) OF EQUILIBRATED MORTAR SAMPLES

RH (%)	ELECTRICAL RESISTIVITY, ρ ohm-cm		
	OPC	40% PFA	50% PFA
75	12106	91860	84452
65	9879	75884	79333
40	7896	29582	30800
12	6309	25053	24467

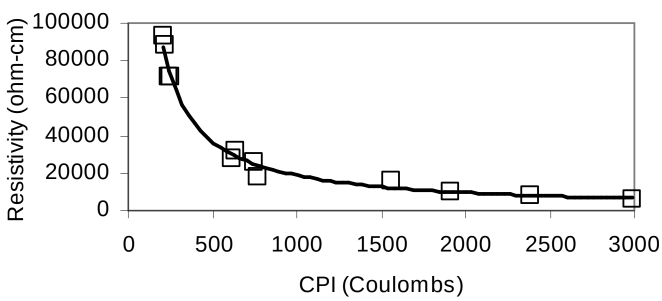

Fig. 3 Electrical resistivity, ρ versus chloride permeability index, CPI

IV. Conclusion

From the above results and discussions, the following major conclusions were made:

1. Partial replacement (40% and 50%) of cement with fly ash refines pore structure, enhances the compressive strength, and increases resistance to chloride ion penetration, resulting in a durable and high performance cement mortar.
2. A partial replacement of 40% fly ash content produces better result than 50% partial replacement. Therefore, 40% partial replacement of cement with fly ash is most suitable.
3. The effects of ambient relative humidity during equilibration of mortar samples were significant on all the characteristics of mortar investigated. Equilibration in wet conditions enhanced the properties of concrete, whereas dry ambient air caused an increase in the porosity of mortar, resulting in lower performance mortar.
4. Valid statistical correlations were obtained between compressive strength and open porosity and between chloride permeability index and electrical resistivity of mortar samples.

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