Pergamon

Cement and Concrete Research 32 (2002) 241–246

CEMENT AND CONCRETE RESEARCH

Ash content for optimum strength of foamed concrete

E.P. Kearsley[a], P.J. Wainwright[b,*]

[a]Department of Civil Engineering, University of Pretoria, Pretoria 0001, South Africa
[b]Department of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK

Received 14 August 2000; accepted 20 August 2001

Abstract

A study has been undertaken into the properties of foamed concrete in which large volumes of cement (up to 75 wt.%) have been replaced with both classified and unclassified fly ash. This fourth paper in the series examines the effects of increasing the levels of ash on the compressive strength of the concrete. Twenty-seven different mixtures were cast with varying ash contents and densities, and the results used to develop models that have been used to predict the compressive strength of the foamed concrete. The output from the models predicts an optimum ash content for maximum strength at a given porosity and age and shows that the optimum value increases with increasing age.

Keywords: Foamed concrete; Porosity; Compressive strength; Fly ash

1. Introduction

This is the fourth paper in a series reporting on the results of an investigation into the effects on the properties of foamed concrete of replacing large volumes of the cement with both a classified (pfa) and unclassified (pozz-fill) fly ash. The first paper [1] reported on the effects on the compressive strength, the second [2] on the relationship between the porosity and permeability and the third [3] investigated the relationship between porosity and compressive strength and presented a mathematical model that has been developed to describe this relationship. The aim of this paper is to determine the effect of high levels of unclassified fly ash on the properties of foamed concrete. Twenty-seven different mixtures were cast with varying ash contents and densities, and the results obtained from these mixtures have been used to develop models that can be used to predict the compressive strength of foamed concrete. Through computer simulation, the output of these models was used to determine optimum ash contents and to establish the effect of high contents of ungraded ash on the compressive strength of foamed concrete.

* Corresponding author. Tel.: +44-113-2332294; fax: +44-113-2332265.

E-mail address: p.j.wainwright@leeds.ac.uk (P.J. Wainwright).

2. Experimental procedure

2.1. Mix compositions

The following mixtures were cast [1–4]:

- Cement pastes with water/cement ratios of 0.3, 0.4 and 0.6.
- Mixtures with pfa where 50, 66.7 and 75 mass% of the cement had been replaced with pfa (ash/cement ratios of 1, 2 and 3). The water/binder ratio was kept constant at approximately 0.3.
- Mixtures with ungraded ash (pozz-fill) where 50, 66.7 and 75 mass% of the cement had been replaced with ungraded ash (ash/cement ratios of 1, 2 and 3). The water/binder ratios of these mixtures were the same as that of the mixtures containing pfa.
- Foamed concrete mixtures of different casting densities (1000, 1250 and 1500 kg/m3) with different percentages of ash replacement (50%, 66.7% and 75%).

2.2. Test procedures

2.2.1. Compressive strength

The compressive strength of foamed concrete was determined from 100-mm cubes. The cubes were cast in steel moulds, demoulded after 24 ± 2 h, wrapped in poly-

0008-8846/02/$ – see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S0008-8846(01)00666-4

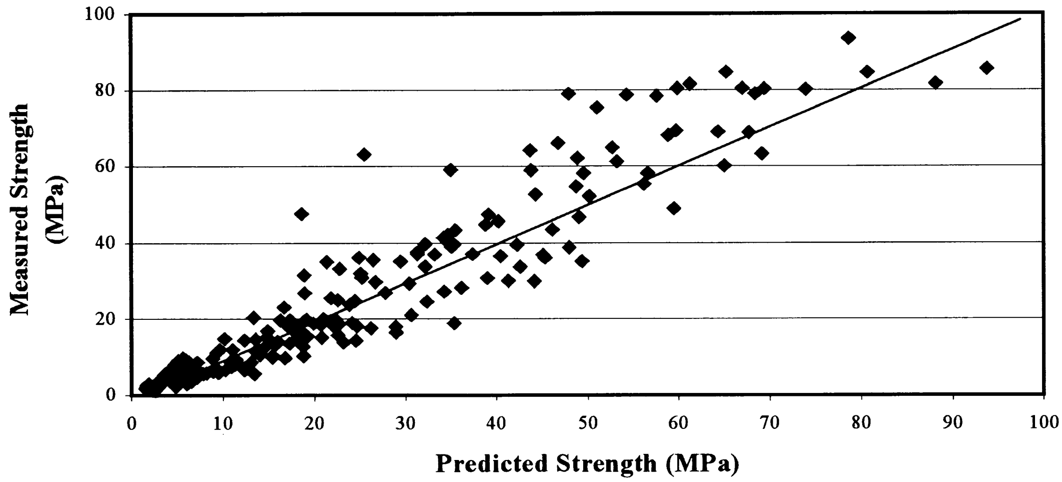

Fig. 1. Predicted versus measured strengths [3] (not taking ash content into account).

thene wrapping and kept in a constant temperature room at 22 ± 2 °C up to the day of testing. The compressive strengths recorded are the average of three cubes (with the difference between the average and the individual values limited to less than 10%). The cement paste cubes were crushed using a standard cube press. Since the foamed concrete strengths were relatively low, these cubes were crushed using a more sensitive testing machine. This machine had a 500-kN (50 MPa for 100-mm cubes) capacity and stress was recorded to the nearest 0.1 MPa. Cubes were crushed after 7, 28, 56, 84, 168, 270 and 365 days. Details of the compressive strengths measured can be found in a previous publication [1].

2.2.2. Porosity

The porosity of the foamed concrete was determined using the Vacuum Saturation Apparatus as developed by Cabrera and Lynsdale at the University of Leeds [5], details of which have been given in previous publications [2,3].

3. Compressive strength model

The compressive strength of concrete is not only a function of time but also of porosity and ash content. Previously [3], it has been established that the function that best describes the relationship between porosity and strength of foamed concrete is a multiplicative function, while the relationship between time and strength is best fitted by a logarithmic function of the form:

$$f_c = 39.6(\ln(t))^{1.174}(1-p)^{3.6} \quad (1)$$

where f_c = compressive strength of foamed concrete (MPa), t = time since casting (days) and p = mature porosity (measured after 365 days).

The R^2 statistic indicates that this model, as fitted, explains 89.6% of the variability in compressive strength. The correlation coefficient is .946. The relation between the compressive strength as predicted using Eq. (1) and the actual measured values is shown in Fig. 1.

The effect of ash content on the compressive strength has not yet been quantified in the previous publications by the authors, and this is the main objective of the work presented in this paper. In order to achieve this, results from all 180 strength tests have been used taking into account simultaneously the effect of ash type, ash content, porosity and age. The fact that the variables are not only interdependent but that their influences are also nonlinear complicated the interpretation of results, and it ruled out the use of a standard statistical program to conduct multiple linear regression analysis. The general shape of the age–porosity relationships as established before [1,3] was used for fitting the model. The two different types of ash used were treated as two separate samples. It was decided to use a second order polynomial function to represent the effect of ash content on the compressive strength because the best-fit result of the third (or quadratic) term would be zero unless there is an optimum ash content. If both the third and the second (or linear) term are zero, one could conclude that the ash content has no influence on the compressive strength.

Table 1
Constants for compressive strength model

Constant	Pfa	Pozz-fill
α	3.7	3.7
β_1	24.91	23.74
β_2	52.89	56.78
β_3	− 12.27	− 14.31
λ_1	172.8	176.9
λ_2	− 196.0	− 229.7
λ_3	34.02	46.04

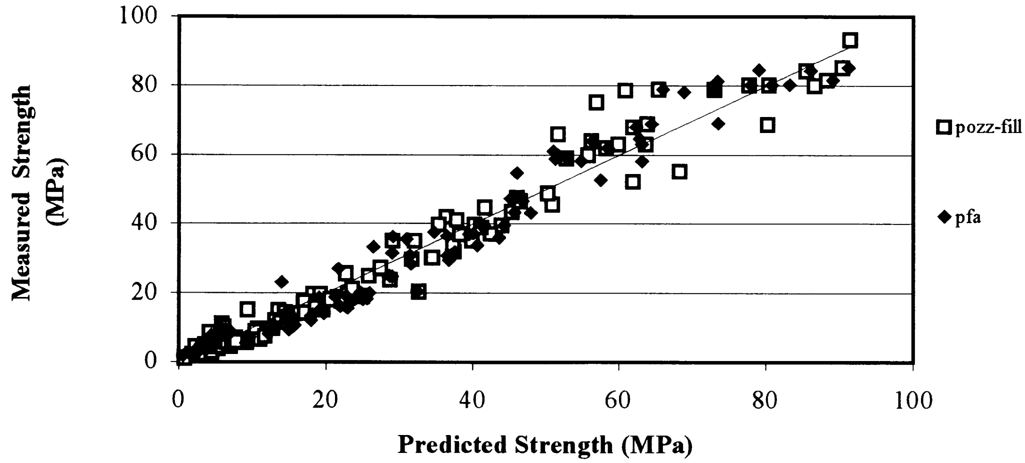

Fig. 2. Predicted strength versus measured strength (taking ash type and content account).

The strength of foamed concrete was represented by the following equation:

$$f_c = (\lambda + \beta \mathrm{Ln}(t))(1-p)^{\alpha} \quad (2)$$

with

$$\beta = \beta_1 + \beta_2(a/c) + \beta_3(a/c)^2 \quad (3)$$

$$\lambda = \lambda_1 + \lambda_2(a/c) + \lambda_3(a/c)^2 \quad (4)$$

where f_c = compressive strength (MPa), t = time since casting (days), p = porosity (as a fraction), a/c = ash/cement ratio (by weight) and α, β and λ are constants.

The test results were divided into two groups representing samples containing pfa and pozz-fill. The two groups of results were used separately, and a set of constants was determined for each of these groups. Default values were used to calculate the first set of fitted strengths and, thereafter, an iterative calculation was used in the model-building process. The differences between the actual measured strengths and the calculated values were taken as the errors, and the squares of these errors were summed. Stepwise regression was used to alter one variable at a time by one increment at a time, and each time, the new sum of the square of the errors was compared to the previous value. The process was repeated until the sum of the square of the errors was minimized. The constants that produced the best fit for each of the sets of data are listed in Table 1.

The function as fitted for the pfa explains 96.3% of the variation in compressive strength while the function as fitted for the pozz-fill explains 95.9% of the variation. The strengths as predicted using the model are plotted against the measured strengths in Fig. 2; as can be seen, the variation between the predicted and measured strengths increases as the strength increases. The reason for this may possibly be due to the form of Eqs. (1) and (2) and their sensitivity to changes in porosity at the lower end of the porosity range. For example, at a porosity of say 30%

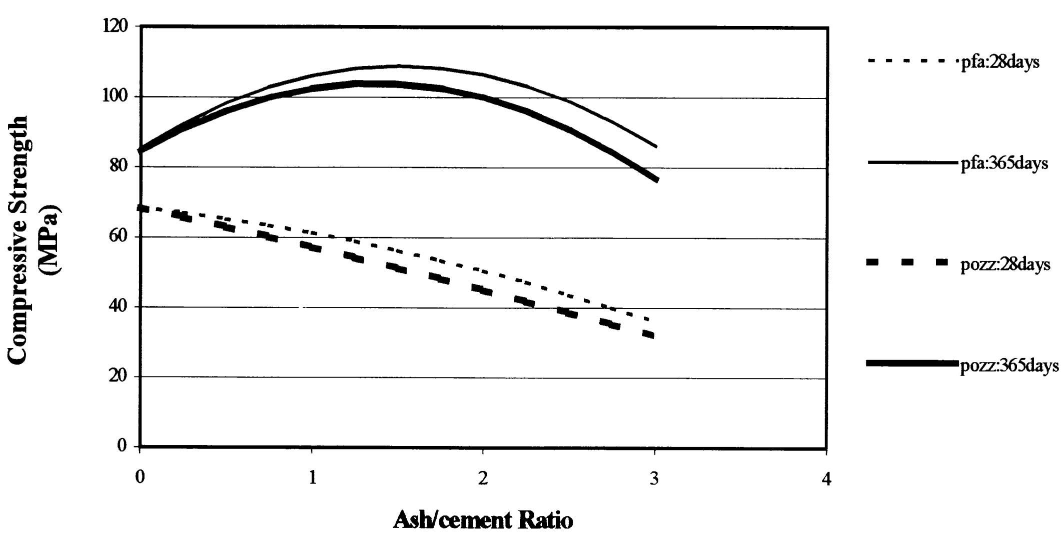

Fig. 3. Effect of ash type on calculated compressive strength for 30% porosity.

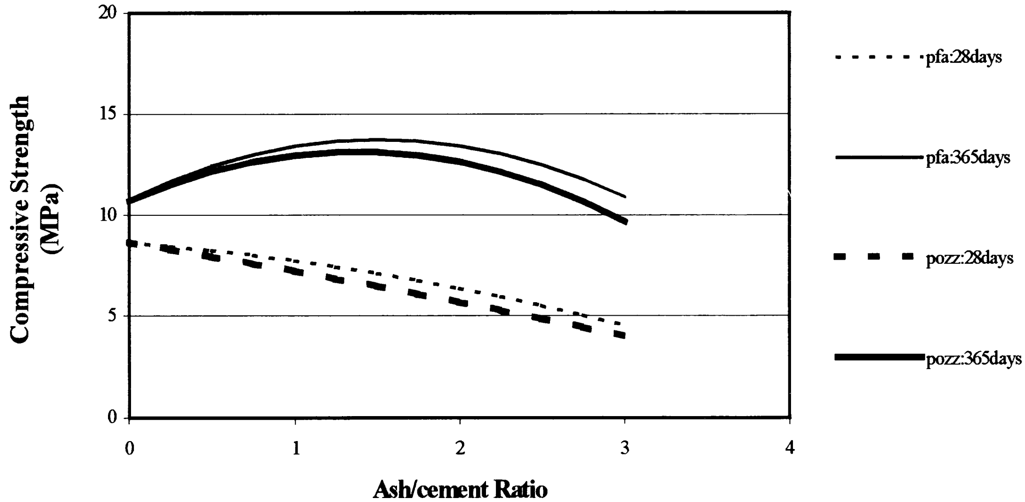

Fig. 4. Effect of ash type on calculated compressive strength for 60% porosity.

(i.e. a strength of approximately 90 MPa), a variation in porosity of about 1% would result in a change of approximately 10 MPa in the calculated strength, while at the higher porosity range, say at 60% (i.e. a strength of approximately 10 MPa), the same variation in porosity would result in only a about a 2-MPa change in strength. As described in a previous publication [2], porosities were measured only at an age of 365 days on separate samples to those used for measuring strength, it is possible then that the measured porosities do not truly represent those of the cubes used to measure strength. All the mixtures were though manufactured using the same equipment and all the porosities were tested in the same way, which means that the effect of within-batch and test variations increases with reduced porosity (or increased measured strength). It should also be pointed out again that the main aim of this investigation was to determine the effect of ash content on compressive strength of foamed concrete and that the larger variations discussed above occur in those mixes with low porosities that do not, in fact, contain any foam. It can, however, be concluded that there is no skewness in fit and the model can be used to predict the compressive strength of foamed concrete (with relatively high porosities). This model can now be used to evaluate the effect of ash type, ash content, porosity and age on the compressive strength of foamed concrete. The constants used in the model were derived for the materials and mix proportions used in this investigation and these constants could change for other mix proportions.

3.1. Effect of ash type and content

The effect of ash type on the compressive strength of foamed concrete can be established by comparing the calculated strength of pfa and pozz-fill mixtures for a given porosity, age and ash/cement ratio. In Fig. 3, the 28- and 365-day compressive strengths of mixtures with a porosity of 30% are plotted as a function of ash/cement ratio. From this graph, it can be seen that the 28-day compressive

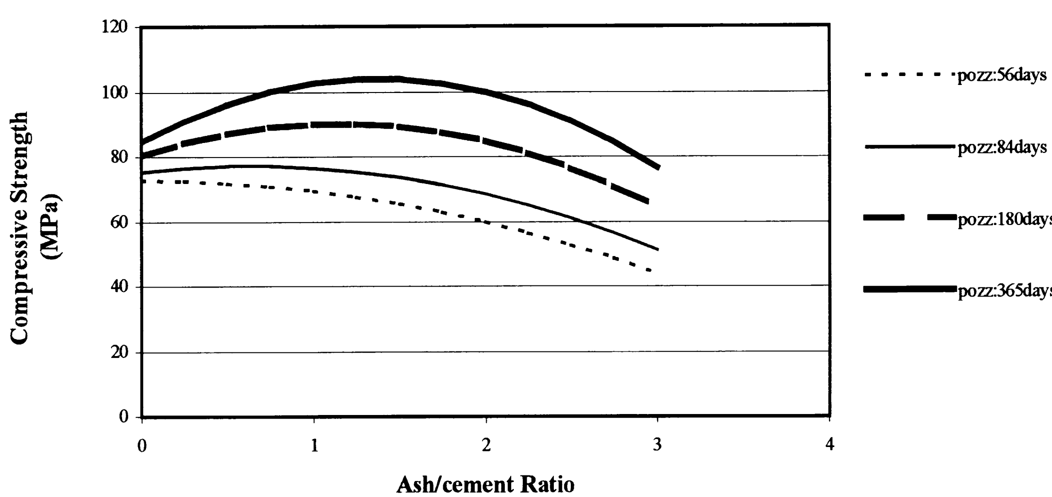

Fig. 5. Effect of age on calculated strength development of foamed concrete.

Table 2
Calculated constants and optimum ash contents at different ages

	Age	56	84	180	270	365
Pfa	l	−4.107	−5.437	−7.936	−9.265	−10.254
	m	4.516	10.247	21.018	26.748	31.009
	n	72.971	75.67	80.743	83.46	85.449
	Optimum a/c	0.550	0.942	1.324	1.443	1.512
	Maximum a/c	1.100	1.885	2.649	2.887	3.024
Pozz-fill	l	−3.090	−4.640	−7.555	−9.105	−10.258
	m	−0.305	5.847	17.411	23.563	28.137
	n	72.808	75.38	80.215	82.787	84.7
	Optimum a/c	–	0.630	1.152	1.294	1.371
	Maximum a/c	–	1.260	2.305	2.588	2.743

strength decreases with increased ash content, and the highest 28-day strength is achieved with no ash in the mixture. In contrast, the 365-day strengths show an optimum ash content with maximum strength obtained at ash/cement ratios in the region of 1.5. The trends observed are similar regardless of the ash type used, but the compressive strengths obtained when using the pozz-fill are marginally lower than when using pfa. Although pozz-fill yields marginally lower strengths than pfa, the 365-day strength of mixtures containing pozz-fill for mixtures with ash/cement ratios below 2.75 are higher than those of mixtures containing no ash. The trends observed for mixtures with 30% porosity are not unique, and although increased porosity results in decreased strength, the trends remain unchanged with changes in porosity. In Fig. 4, the effect of ash type and content on the compressive strength of mixtures with 60% porosity can be seen.

3.2. Effect of age on optimum composition

The effect of age on the strength development of foamed concrete with 30% porosity containing pozz-fill is shown in Fig. 5 from which it can be seen that the ash content resulting in the maximum strength increases with time. Similar trends were found for other porosities. These findings correlate with the findings of Hassan et al. [6] for normal concrete where up to 70% of the cement was replaced by ash.

The optimum composition at a given time and porosity can be determined by fitting a second-order polynomial function through the strengths obtained at different ash/cement ratios from the simulation model. The function fitted has the general form:

$$f_c = l(a/c)^2 + m(a/c) + n \tag{5}$$

where f_c = compressive strength (MPa), a/c = ash/cement ratio (by weight) and l, m and n are constants.

The values calculated for l, m and n at different ages, using the strengths obtained from the simulation model for pfa and pozz-fill, can be seen in Table 2. The optimum ash content at any given age can be determined by calculating the maximum of the polynomial function by setting the slope of the strength function (the derivative of Eq. (5)) zero. These calculated optimum ash contents are plotted as a function of time in Fig. 6. The same values for l, m and n were obtained for different porosities, indicating that the optimum ash content was independent of the porosity.

From Fig. 6, it can be seen that the optimum ash/cement ratio increases to a value of approximately 1.5, indicating that the highest long-term compressive strength is obtained for mixtures where 60 mass% of the cement has been replaced with ash. The optimum ash/cement ratio of pozz-fill follows the same trend to that of pfa, with the optimum ash content for the pozz-fill always being marginally lower than for pfa. The difference in optimum ash/cement ratio between the two types of ash decreases with increasing age. Curing temperature is also known to have a considerable influence on the strength development of mixtures containing large volumes of fly ash [6], an increase in curing

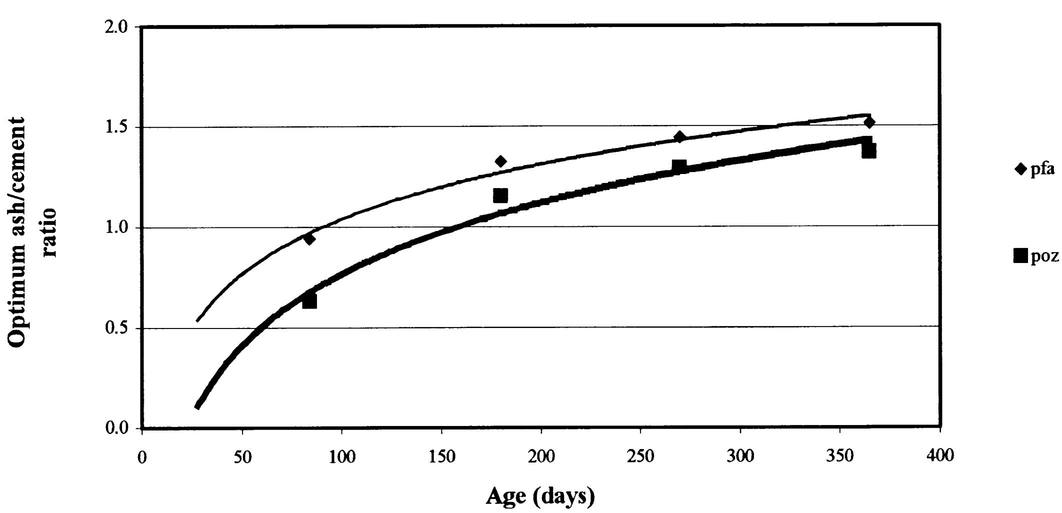

Fig. 6. Calculated optimum ash content as a function of time.

temperature will reduce the time that it takes for the ash to start contributing towards the compressive strength; the time scale of Fig. 6 will therefore be temperature dependent.

The optimum ash content at a specific age is the ash/cement ratio that yields the highest strength at that age, but equal strengths to the mixture containing no ash is obtained at much higher ash/cement ratios. The maximum ash/cement ratios that yield strengths equal to or higher than those obtained when no ash is used at different ages are shown in Table 2. These values indicate that mixtures where up to 75% of the cement has been replaced with pfa achieve higher 1-year strengths than those obtained from mixtures containing no ash. This maximum value is marginally lower (at approximately 73%) for pozz-fill.

4. Conclusions

Based on the compressive strengths calculated using the simulation model, the following can be concluded.

• High ash content results in a reduction in compressive strength at early ages. Long-term strength (say after 1 year) was improved by replacing up to 75 wt.% of the cement with ash.

• An optimum ash content was observed that resulted in the highest compressive strength for a given porosity, and this optimum increases with increased age. This optimum content is dependent on age only and although the porosity affects the compressive strength it does not affect the optimum ash/cement ratio.

• The trends observed for classified ash (pfa) and unclassified ash (pozz-fill) were similar, with the pozz-fill mixtures yielding marginally lower strengths than the mixtures containing pfa. The pozz-fill mixtures (with up to more than 70% of the cement replaced with pozz-fill) still achieved higher long-term strengths than the mixtures containing no ash.

References

[1] E.P. Kearsley, P.J. Wainwright, The effect of high fly ash content on the compressive strength of foamed concrete, Cem. Concr. Res. 31 (2001) 105–112.

[2] E.P. Kearsley, P.J. Wainwright, Porosity and permeability of foamed concrete, Cem. Concr. Res. 31 (2001) 805–812.

[3] E.P. Kearsley, P.J. Wainwright, The effect of porosity on the strength of foamed concrete. Cem. Concr. Res. 32 (2002) 233–239.

[4] E.P. Kearsley, The effect of High Volumes of Ungraded Fly Ash on the Properties of Foamed Concrete. PhD Thesis, Department of Civil Engineering, University of Leeds, UK, 1999.

[5] J.G. Cabrera, C.J. Lynsdale, A new gas permeameter for measuring the permeability of mortar and concrete, Mag. Concr. Res. 40 (144) (1988) 177–182.

[6] K.E. Hassan, J.G. Cabrera, Y.M. Bajracharya, The influence of fly ash content and curing temperature on the properties of high performance concrete. Deterioration and repair of reinforced concrete in the Arabian Gulf, in: J.S. Maso (Ed.), Proceedings of the 5th International Conference, Bahrain, vol. 1, Chapman & Hall, New York, 1997, pp. 345–365.