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The effect of high fly ash content on the compressive strength of foamed concrete

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Abstract

A study has been undertaken to investigate the effects, on the properties of foamed concrete, of replacing large volumes of cement (up to 75% by weight) with both classified and unclassified fly ash. This paper reports only on the results of the compressive strength of concretes cured under sealed conditions and shows that up to 67% of the cement could be replaced without any significant reductions in strength. There appears to be little difference in the performance of the ungraded and the graded fly ashes used in this investigation. Equations based on effective water/cement (w/c) ratio and binder ratio have been developed to predict the strengths up to 1 year, of foamed concretes made with densities ranging from 1000 to 1500 kg/m^3. The calculated results compare well with the experimental results.

Keywords: Foamed concrete; Compressive strength; Fly ash

1. Introduction

Foamed concrete consists of cement paste and voids and the properties of both these components will have a measurable effect on the properties of the combined material. Literature reviewed [1–5] indicates that replacing up to 60% (by mass) of cement with fly ash (pfa) can enhance the properties of cement paste. The main aim of this investigation was to determine whether the use of unclassified fly ash as replacement for large percentages (i.e. up to 75%) of the cement in foamed concrete has a significant influence on the compressive strength of the material.

Properties of mortars containing different percentages of fly ash were compared to cement paste with the same water/binder ratio to determine the effect of fly ash replacement. Thereafter, the properties of mortars containing fly ash were compared with those of mortars containing ungraded ash (Pozz-fill). Once the effect of high ash content had been determined, the effect of adding foam to the mortar was established. The target casting densities used in this investigation were 1000, 1250 and 1500 kg/m^3 unless stated differently. The water/binder ratio was kept constant for the different casting densities and the compressive strength of the mixtures were determined after 7, 28, 56 days, 3, 6, 9 months and 1 year [6].

2. Materials

Tests have shown that the production of foamed concrete with predictable densities and strengths is only possible with prefoamed protein foams [7]; this investigation was therefore conducted using only this type of foaming agent. All the materials used are produced or manufactured in South Africa, and only one source of foaming agent, cement and ash was used.

Foamed concrete is produced under controlled conditions from cement, filler, water and a liquid chemical [8] that is diluted with water and aerated to form the foaming agent. The foaming agent used was "Foamtech," consisting of hydrolyzed proteins and manufactured in South Africa. The foaming agent was diluted with water in a ratio of 1:40 (by volume), and then aerated to a density of 70 kg/m^3.

The cement used in this investigation was rapid hardening Portland cement from Pretoria Portland Ce-

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Table 1
Properties of cementitious constituents

Oxides	RHPC from PPC Hercules (%)	Processed fly ash from Lethabo (%)	Pozz-fill from Lethabo (%)
CaO	61.7	4.7	5.0
SiO_2	21.2	53.9	54.8
Al_2O_3	4.6	33.5	31.7
Fe_2O_3	1.8	3.7	3.8
Na_2O	0.1	0.7	0.8
K_2O	0.7	0.7	0.8
MgO	4.3	1.3	1.1
SO_3	2.0	0.1	0.3
CO_2	2.6		
Free CaO	1.2		
Loss On ignition		0.8	0.8
Blaine surface area (m^2/kg)	431	350	280
Relative density	3.15	2.2	2.2

ment (PPC), Hercules, Pretoria. The cement can be classified as CEM I 42,5R according to the South African Specification SABS EVN 197-1:1992 [9]. Both the fly ashes used in this investigation were obtained from the Lethabo power station in South Africa. One was a graded ash (pfa) complying with SABS 1491 [10] and the second was an ungraded ash (Pozz-fill) from the same source. The chemical properties and the particle size distributions of all three binders are shown in Table 1 and Fig. 1, respectively.

3. Composition of mixtures

Twenty-seven mixtures were cast with cement, ash, water and foam contents as listed in Table 2. The water/cement (w/c), ash/cement (a/c) and water/binder ratios as shown in Table 2 are weight ratios, and the binder content is taken as the sum of the cement and the ash. The first three mixtures contained only water and cement with different w/c ratios and these mixtures were used to determine the cementing efficiency of the ash used. Mixture numbers 4 to 15 contained classified fly ash while mixtures 16 to 27 contained the unclassified ash (Pozz-fill). The first three mixtures cast for each type of ash were used to establish the effect of ash content on the properties of cement paste while the remaining nine mixtures cast with each ash type were used to establish the effect of varying foam contents.

4. Tests conducted

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 polythene wrapping and kept in a constant temperature room at 22°C up to the day of testing. Before testing each cube was unwrapped and weighed.

5. Results

5.1. Pastes containing ash

The compressive strength of paste mixtures containing fly ash is plotted as a function of time in Fig. 2. Although the a/c ratio of these mixtures varies from 1 to 3, the water/binder ratio was kept constant at approximately 0.3 and the strength development of the paste mixture with the

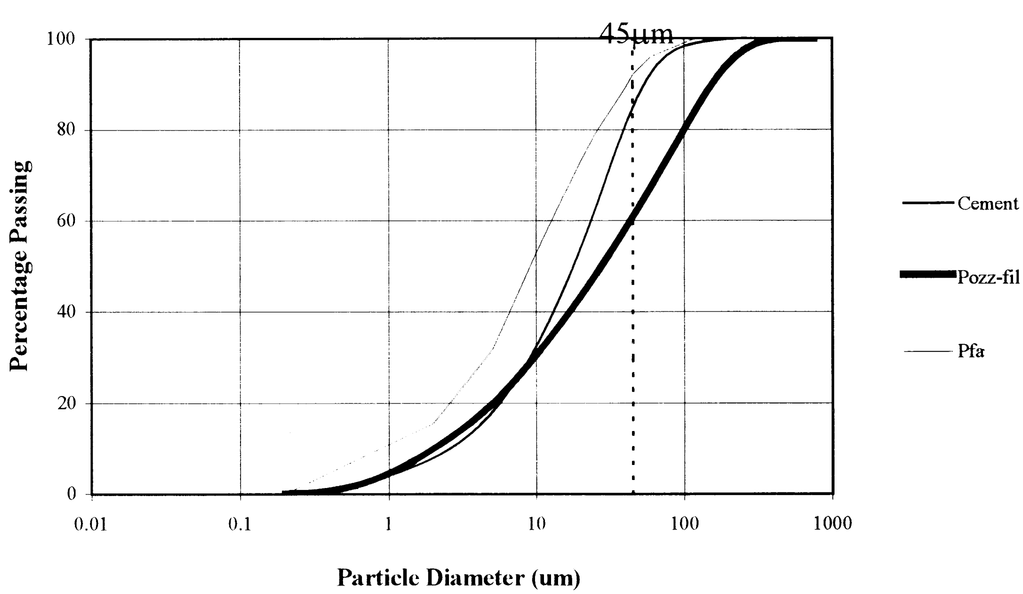

Fig. 1. Particle size distribution of cementitious constituents.

Table 2
Composition of mixtures

Mixture no.	Target density (kg/m^3)	a/c	w/c	water/binder	Composition of mixture (per m^3) Water (l)	Cement (kg)	Ash (kg)	Foam (l)
1	Full	0	0.30	0.30	486	1620	0	0
2	Full	0	0.40	0.40	558	1394	0	0
3	Full	0	0.60	0.60	654	1090	0	0
4/16	Full	1	0.60	0.30	437	729	729	0
5/17	Full	2	0.86	0.29	412	479	958	0
6/18	Full	3	1.17	0.29	411	351	1053	0
7/19	1500	1	0.60	0.30	346	577	577	208
8/20	1500	2	0.86	0.29	335	389	778	188
9/21	1500	3	1.17	0.29	339	290	870	173
10/22	1250	1	0.60	0.30	289	481	481	340
11/23	1250	2	0.86	0.29	279	324	648	324
12/24	1250	3	1.17	0.29	283	242	726	310
13/25	1000	1	0.60	0.30	231	385	385	472
14/26	1000	2	0.86	0.29	223	259	518	460
15/27	1000	3	1.17	0.29	226	193	579	450

Mixtures 4 to 15 contain fly ash and mixtures 16 to 27 Pozz-fill.

same w/c ratio but containing no ash is shown for comparison. From this graph, it is clear that the compressive strength of the ash mixtures increases over a much longer period of time than that of mixtures containing no ash. The gain in strength between 28 and 365 days is 37 and 44 MPa for the mixtures with the a/c ratios of 1 and 2, respectively, and after 270 days they have reached strengths of approximately 80 MPa, which is similar to that of the cement paste (containing no ash) with the w/c of 0.3 at the same age. After a period of 1 year, the paste with an a/c ratio of 3 has achieved a strength of only 58 MPa compared with 80 MPa for the other two mixes. This difference in strength remains approximately the same for all ages of testing. The compressive strength of mixtures containing Pozz-fill is plotted as a function of time in Fig. 3. These results show a similar trend to that observed for the mixtures containing fly ash. As far as ultimate compressive strength is concerned, there seems to be no significant difference between the mixtures containing fly ash and those containing Pozz-fill. These results seem to indicate that the classification of the ash does not improve its effectiveness as far as contribution towards compressive strength is concerned.

The mathematical analysis used to determine the contribution of the ash towards the compressive strength of the cement paste was simplified by assuming that the w/c and age of the paste are the only factors affecting the compressive strength. A fraction of the ash was taken to be active, and this fraction was added to the actual cement content when the w/c ratio was calculated. The compressive strength was used to determine what the actual size of the active fraction at any given time should be. The effective w/c ratio of the cement paste at any given age can be calculated

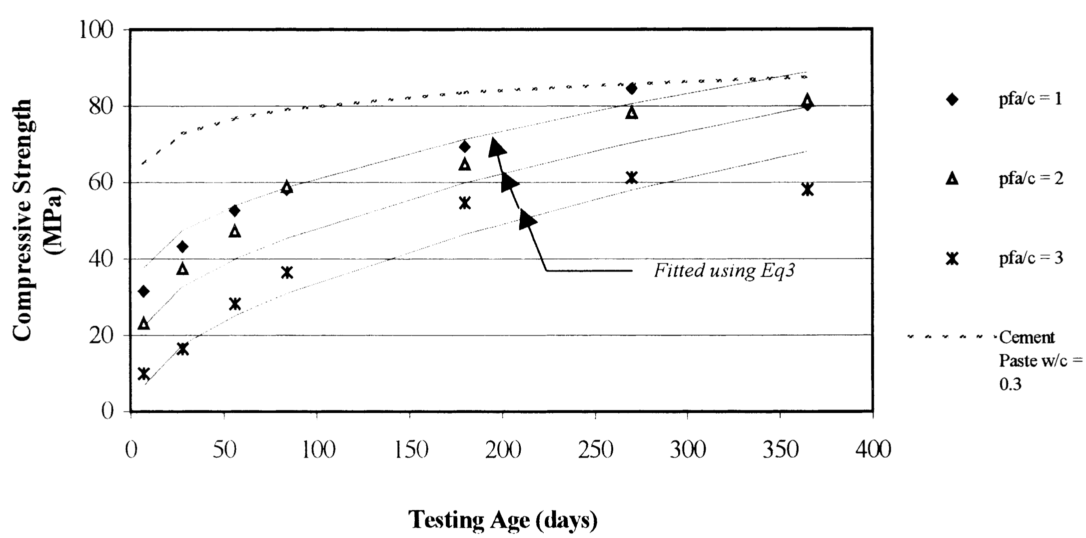

Fig. 2. Compressive strength of pastes containing fly ash (pfa).

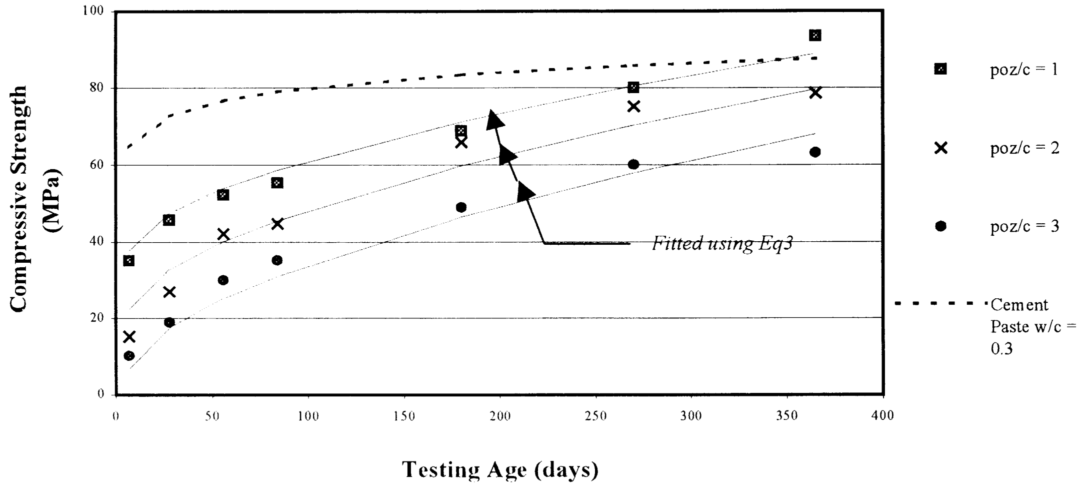

Fig. 3. Compressive strength of pastes containing Pozz-fill.

(based on the work conducted by Smith [11]) using the following equation [Eq. (1)]:

$$W/C\ (w/c;\ k;\ a/c) = w/c\left[\frac{1}{1+k(a/c)}\right] \quad (1)$$

where: W/C = effective water/cement ratio; w/c = actual water/cement ratio; a/c = ash/cement ratio; k = cementing efficiency.

The cementing efficiency is dependent not only on the source and quality of the ash but also on the age, the w/c ratio and the a/c ratio of the paste. Mathematical modelling was simplified by assuming that there is no marked difference between the cementing efficiency of fly ash and that of Pozz-fill. The cementing efficiency for the mixtures containing ash was determined using a multiple linear regression model and the following equation was derived [Eq. (2)]:

$$k\ (t;\ a/c) = \left(0.457 + 0.00315\frac{t}{(a/c+1)}\right)^2 \quad (2)$$

where: k = cementing efficiency; t = time since casting (days); a/c = ash/cement ratio (by weight).

The R^2 statistic indicates that the model as fitted explains 85.6% of the variability in k. The k value increases from approximately 0.21 after 7 days to between 0.55 and 1.1 after 365 days. Smith [11] recommended a k value of 0.25 based on 7- and 28-day concrete strengths and these results seem to confirm his recommendation. These results do however suggest that his assumption of a constant k value might be conservative as the efficiency definitely increases with time up to ages of at least 1 year.

A new relationship between compressive strength, effective w/c ratio and time can now be established using the calculated k value. The k value is used to calculate an effective w/c ratio that can be used as an independent variable in a multiple regression analysis. The relationship between compressive strength and time since casting as well as effective w/c ratio can be expressed using the following equation:

$$f_c\ (t;\ W/C) = 88.04 + 6.569\ln(t) - 130.5W/C \quad (3)$$

Where: f_c = cube compressive strength (MPa); t = time since casting (days); W/C = effective water/cement ratio.

The R^2 statistic indicates that the model as fitted explains 96.3% of the variability in strength, while the adjusted R^2 statistic is 96.2%. The standard error of the estimate shows the standard deviation of the residuals to be 4.2 MPa. Stepwise regression indicates that 83.5% of the variation in compressive strength can be explained by the variation in effective w/c ratio. Adding the time since casting as a second independent variable increases the percentage variation in compressive strength that can be explained by the fitted equation to 96.3%. The calculated k values were used to adjust the w/c ratios of the mixtures containing ash, and the effective w/c ratios were used in Eq. (3) to calculate the compressive strengths as indicated with the solid lines on the graphs in Figs. 2 and 3.

5.2. Strength of foamed concrete

The compressive strengths of foamed concrete mixtures with different ash contents and casting densities of 1500 and 1000 kg/m^3 are plotted as function of time in Figs. 4 and 5, respectively. The top graph in each of these figures is for mixtures containing fly ash while the bottom graph is for mixtures containing Pozz-fill. The results for casting density of 1250 kg/m^3 have been omitted for brevity but show a similar trend to that of 1500 kg/m^3. From Fig. 4 it can be seen that after 1 year (365 days), the compressive strengths of all six mixtures with casting densities of 1500 kg/m^3 is approximately 40 MPa. Neither the a/c ratio nor the type of ash used (fly ash or Pozz-fill) seems to have a significant effect on the long-term strength of these foamed concrete mixtures. After 9 months, the compressive strengths of the

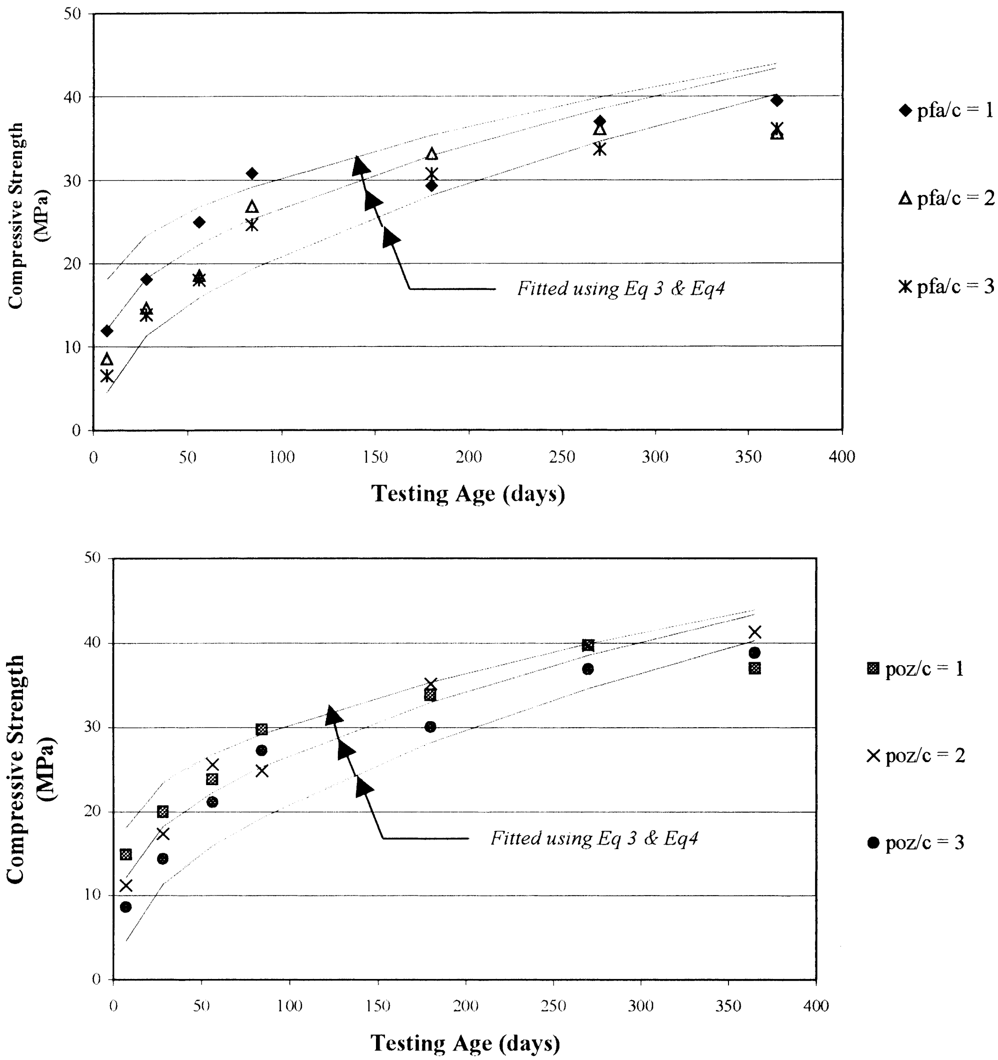

Fig. 4. Compressive strength of 1500 kg/m^3 mixtures as a function of time.

mixtures containing fly ash is slightly lower than that for mixtures containing Pozz-fill but this difference is not significant. The 1-year compressive strengths of the mixtures is approximately double the 28-day strengths, indicating a similar trend in long-term strength gain to that observed for the mortars containing ash (see Figs. 2 and 3).

From Fig. 5 it can be seen that after 1 year, the compressive strengths of the mixes with casting densities of 1000 kg/m^3 varies between 6 and 10 MPa. Although the a/c ratio does not seem to have a significant effect on the compressive strength, the type of ash used (fly ash or Pozz-fill) does; the compressive strength of mixtures containing Pozz-fill are significantly lower than those of the mixtures containing fly ash. It is interesting to note that, unlike those mixtures with higher casting densities, there seems to be virtually no increase in compressive strength after more than 180 days. The contribution to the long-term gain in strength of the ash seems to be reduced at these low densities.

The compressive strength of concrete is not only a function of the w/c ratio but also a function of the density ratio of the concrete [12]. The density ratio is defined as the ratio between the actual density of the concrete and the density of the concrete when fully compacted. The compressive strength of the paste in the foamed concrete can be expressed in terms of the age and the effective w/c of the paste. If one assumes that the paste in the foamed concrete has the same strength as the paste on its own, the only factor that should cause a reduction in strength should be the volume of air added to the mixture. As even the mixtures containing no foam might contain significant volumes of entrapped air, the theoretical volumes of binder were used as a base for comparison. The binder contents (by volume) of the foamed concrete mixtures were expressed as a fraction of the binder content of the pastes and the compressive strengths as calculated with [Eq. (3)] for pastes containing ash were adjusted taking the binder ratios into account. The effect of binder ratio on the compressive strength of foamed concrete can be expressed as follows:

$$fc_c = 1.172 f_c \alpha_b^{3.7} \quad (4)$$

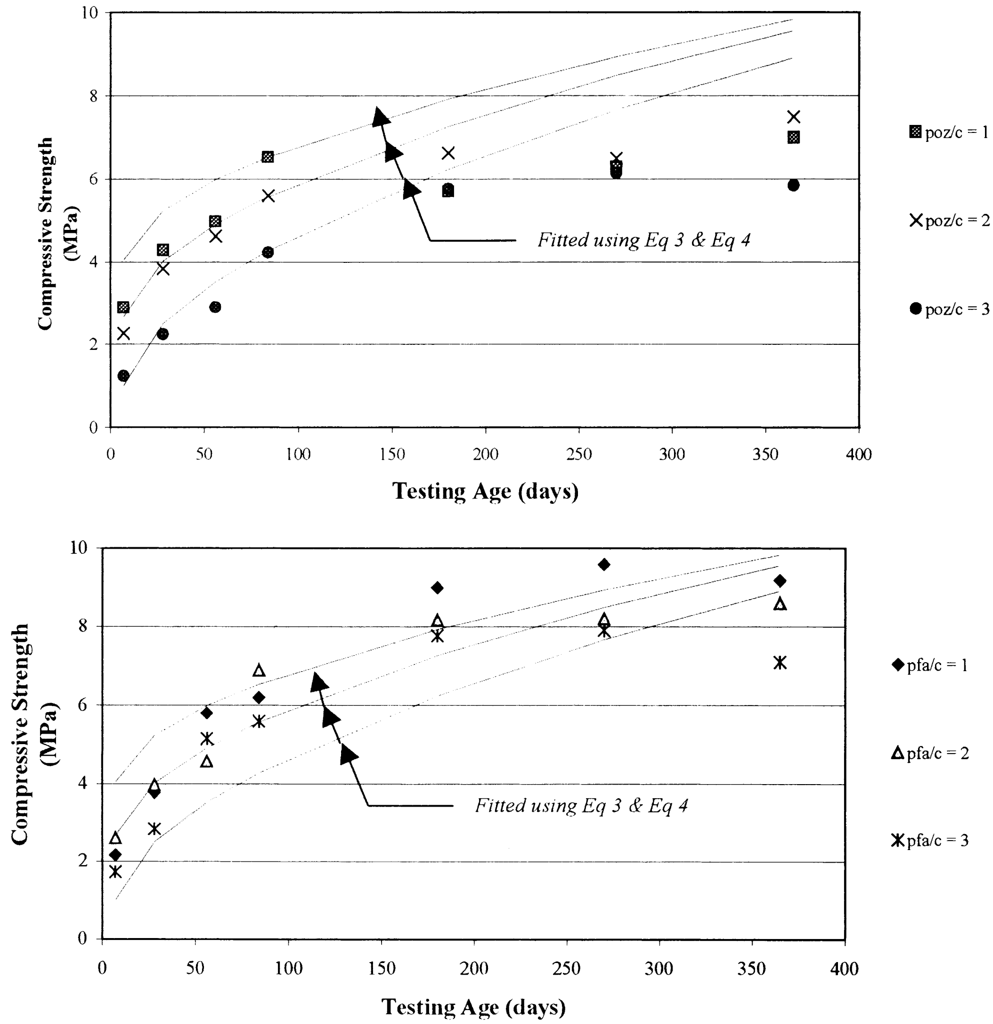

Fig. 5. Compressive strength of 1000 kg/m^3 mixtures as a function of time.

where: fc_c = compressive strength of foamed concrete; f_c = compressive strength of paste as calculated using Eq. (3); α_b = binder ratio.

Regression analysis was conducted on all the compressive strengths obtained for foamed concrete mixtures and it was concluded that the combination of equations Eqs. (3) and (4) explains 97.9% of the variation in compressive strength of the foamed concrete. Since Eq. (4) does not contain a constant, the correlation percentage as calculated cannot be compared to that of models containing a constant, and the value of 97.9% might be misleadingly high. The solid lines plotted on the graphs in Figs. 4 and 5 were calculated using Eqs. (3) and (4). On each graph, three lines are shown with the top line (the highest compressive strength at any given age) representing an a/c ratios of 1, while the bottom line (the lowest compressive strength at any given age) represents a/c ratios of 3. Relatively large differences occurred between some of the calculated strengths and the actual measured values, suggesting that some factor other than age, effective w/c ratio and binder ratio may be having an effect on the compressive strength of the foamed concrete mixtures. The difference between the predicted and the actual behaviour of the foamed concrete seems to increase with increased air content, indicating that the nature as well as the volume of air voids might have an effect on the compressive strength. In the volumetric approach used here, only the volumes of binder were taken into account and it was assumed that the water/binder ratio remains constant and therefore, does not influence the results.

5.3. Effect of dry density on compressive strength

The 28-day and 1-year compressive strengths are plotted as a function of dry density in Fig. 6 where the top graph shows the results obtained for fly ash and the bottom the results obtained for Pozz-fill. The dry density was only determined from cubes that were cured for 28 days before drying and it has been assumed that the dry density will not change significantly with longer periods of curing.

From Fig. 6, it can be seen that there is an exponential relationship between dry density and the 28-day compres-

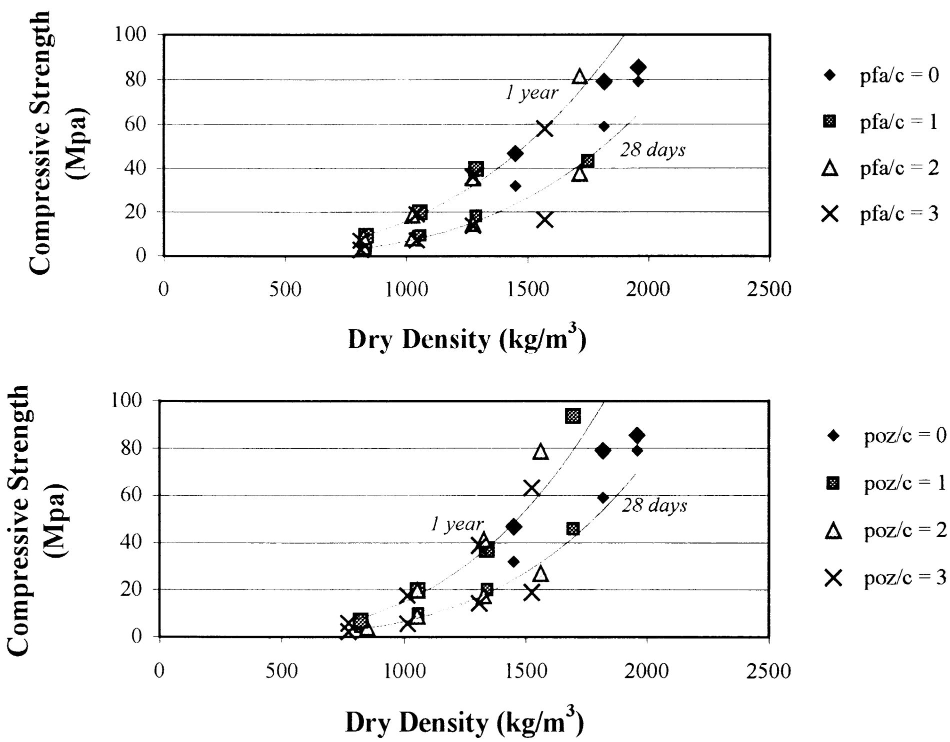

Fig. 6. Compressive strength at 28 days and 1 year as a function of dry density.

sive strength and there seems to be little difference between the strengths obtained from mixtures containing fly ash and those containing Pozz-fill. The mixtures containing no ash seem to have slightly higher strengths than the mixtures containing ash, confirming the fact that the early strength (up to 28 days) is reduced with high ash contents. The 28-day strengths of all the foamed concrete mixtures are, however, significantly higher than those obtained by other researchers. The strengths shown in Fig. 6 (15 MPa for a dry density of ±1250 kg/m^3) are approximately double those published previously for other protein foams (7 MPa for a dry density of ±1200 kg/m^3) [13].

From Fig. 6, it can also be seen that after 1 year, for the same dry density, the mixes containing ash have marginally higher compressive strengths than those without ash. As before there is virtually no difference between the fly ash and the Pozz-fill mixtures, with the Pozz-fill mixture strengths being marginally higher than those of the fly ash at higher densities.

6. Conclusions

Both the 28-day and 1-year results indicate that the compressive strength of foamed concrete is primarily a function of dry density and is little affected by the percentage cement replaced by ash. Based on the results of this investigation, it can therefore be concluded that replacing high proportions of cement with fly ash does not significantly affect the long-term compressive strength of well-cured foamed concrete. Equations have been derived that can be used to predict the strength of foamed concrete of different densities at different ages.

The results presented in this paper show that although the foamed concrete mixtures with high ash contents might need a longer period of time to reach their ultimate strength, this strength could be higher than the ultimate strength that can be achieved using only cement. The long-term gain of strength observed was for well-cured samples and this gain of strength might not be as great with specimens that have not been so well-cured. The fact that ungraded ash (Pozz-fill) yields similar results to pfa indicates that the cost of foamed concrete mixtures could be reduced by replacing large volumes of cement with Pozz-fill, without significantly affecting the long-term strength.

Further results from this investigation covering such aspects as: pore structure, shrinkage and creep will be published in later papers.

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