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The effect of porosity on the strength of foamed concrete

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

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

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Abstract

A study has been undertaken to investigate the effects of replacing large volumes of cement on the properties of foamed concrete (up to 75% by weight) with both classified and unclassified fly ash. This is the third paper in a series; it investigates the relationship between porosity and compressive strength and presents mathematical models that have been developed to describe this relationship. The compressive strength of the foamed concrete was shown to be a function of porosity and age, and a multiplicative model (such as the equation derived by Balshin) was found to best fit the results at all ages up to 1 year. In addition, it was concluded that the equation derived by Hoff could effectively be used to predict the compressive strength of foamed concrete mixtures containing high percentages of ash.

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

1. Introduction

This is the third 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, while the second [2] on the relationship between porosity and permeability. This third paper investigates the relationship between porosity and compressive strength and presents mathematical models that have been developed to describe this relationship. The main aim of this part of this study was to investigate what effects the addition of the foam had on porosity and its relationship with strength.

The strength and porosity of foamed concretes with different casting densities were compared to those of cement pastes with different water/cement ratios. Different percentages of both pfa and unclassified ash were used to establish the effect of ash content on the strength–porosity relationship.

* Corresponding author. Tel.: +44-113-233-2294; fax: +44-113-233-2265.

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

2. Background

When concrete is fully compacted, the strength is taken to be inversely proportional to the water/cement ratio (Abrams rule) [3]. In 1896, René Féret formulated the following rule to relate the strength of concrete to the volumes of water, cement and air in the mixture (Eq. (1)):

$$f_c = K\left(\frac{c}{c+w+a}\right)^2 \quad (1)$$

where: f_c = concrete compressive strength (MPa); c, w, a = absolute volumetric proportions of cement, water and air; K = a constant.

The strength of concrete is influenced by the volume of all voids in the concrete (entrapped air, capillary pores, gel pores and entrained air) and a number of functions, including the following, have been proposed to express this strength–porosity relationship [4,5] (Eqs. (2)–(5)):

$$f_c = f_{c,0}(1-p)^n \qquad \text{(Balshin)} \quad (2)$$

$$f_c = f_{c,0}e^{-k,p} \qquad \text{(Ryshkevitch)} \quad (3)$$

$$f_c = k_s \ln\left(\frac{p_0}{p}\right) \qquad \text{(Schiller)} \quad (4)$$

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$$f_c = f_{c,0} - k_H p \qquad \text{(Hasselmann)} \tag{5}$$

where: f_c = compressive strength of concrete with porosity p; $f_{c,0}$ = compressive strength at zero porosity; p = porosity (volume of voids expressed as a fraction of the total concrete volume); n = a coefficient, which need not be constant; p_0 = porosity at zero strength; k_r, k_s, k_H = empirical constants.

Rößler and Odler [4] determined the relationship between porosity and strength for a series of cement pastes with different water/cement ratios after different periods of hydration. They concluded for porosities between 5% and 28% that although all four of the strength–porosity equations shown above could be used, the relation between compressive strength and porosity can best be expressed in the form of a linear plot. Fagerlund [5] stated that it often seems as if one equation fits experimental data for porosities below a certain limiting porosity and another for porosities above this limit. At high porosities, it is normally necessary to use an equation, which indicates a critical porosity while these equations are too insensitive to change for use with low porosities. An equation that takes into consideration the effect of high as well as low porosity will include a critical porosity as well as a stress concentration factor.

After studying aerated concrete manufactured at factories in China, Baozhen and Erda [6] concluded that the compressive strength decreases as the porosity increases with the same relationship as indicated in the strength–porosity equation derived by Balshin (Eq. (2)). It was found that n varied from 1 to 2.2 in different ranges of porosity, indicating that the strength of mixtures with low porosity was influenced more by small changes in porosity than the strength of mixtures with higher porosity.

Hengst and Tressler [7] concluded that the dominant parameter in controlling the strength of a foamed Portland cement at a given bulk density is the flaw size, which correlates with the pore size.

Hoff [8] conducted research on the porosity–strength relationship of cellular concrete and concluded that there is a single strength–porosity relationship for given cement and this relationship can be expressed in terms of water/cement ratio and density. Hoff [8] expressed the theoretical porosity of cellular concrete containing only water, cement and foam as the volume of voids as a fraction of the total volume. He used an average value of 0.2 for the ratio of the water bound by hydration to cement (by weight) and derived the following equation:

$$n = 1 - \frac{d_c(1 + 0.20p_c)}{(1 + k)p_c\gamma_w} \tag{6}$$

where: n = theoretical porosity; d_c = concrete density; p_c = specific gravity of the cement; γ_w = unit weight of water; k = water/cement ratio (by weight).

In the design of foamed concrete, the use of the space occupied by the evaporable water plus the air void space as the total void space in the concrete permits the determination of a single strength–porosity relationship for a given cement. The strength of cellular concrete in relation to any given cement can, according to Hoff, be expressed using the following equation:

$$\frac{\sigma_y}{\sigma_0} = \left(\frac{d_c}{1 + k}\right)^b \left(\frac{1 + 0.2p_c}{p_c\gamma_w}\right)^b \tag{7}$$

where: σ_y = compressive strength; σ_0 = theoretical paste strength at zero porosity; k = water/cement ratio (by weight); p_c = specific gravity of the cement; d_c = concrete density; γ_w = unit weight of water; b = empirical constant.

This equation does, however, only hold true for foamed concrete containing only air, water and cement. Adjustment will be required if additional components, such as fillers, are used. Hoff evaluated bag-cured samples manufactured using different cements with water/cement ratios varying from 0.66 to 1.06 and casting densities varying from 320 to 1000 kg/m^3. The analysis produced values of σ_0 = 245 MPa and b = 2.7 with a correlation coefficient of .95 for cement with a Blaine fineness of between 4500 and 4650 cm^2/g.

3. Experimental procedure

3.1. Mix compositions

Foamed concrete is produced under controlled conditions from cement, filler, water and a liquid chemical 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 (RHPC) from Pretoria Portland Cement (PPC), Hercules, Pretoria. Both the fly ashes used were obtained from the Lethabo power station in South Africa. One was a graded ash (pfa), which was screened to remove some of the larger particles (thus reducing the particles larger than 45 μm in diameter to less than 12.5%), and the second was an unclassified ash (pozz-fill). The chemical properties of all three binders are shown in Table 1.

The compositions by mass of the different mixtures cast are shown in Table 2; a total of 27 mixes were made as summarised below:

- Cement pastes with water/cement ratios of 0.3, 0.4 and 0.6;
- Paste mixtures in which 50%, 66.7% and 75% of the cement (by weight) was replaced with pfa and pozz-fill (ash/cement ratios of 1, 2 and 3). The water/binder ratio was kept constant at approximately 0.3; and

Table 1
Binder properties

Oxides	RHPC from PPC Hercules (%)	Processed fly ash (pfa) 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	1.11
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
Particles > 45 μm (%)		8	39
Calculated surface area (m^2/kg)		408	540

- Foamed concrete mixtures of different casting densities (1000, 1250 and 1500 kg/m^3) with different percentages of ash replacement (50%, 66.7% and 75%).

More details relating to the materials used and casting procedure can be found in the previous publications [1,9].

3.1.1. Compressive strength

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

Table 2
Mix proportions and hardened concrete properties

Mix number	Type of ash	Target density (kg/m^3)	a/c	w/c	w/binder	Compressive strength (365 days) (MPa)	Measured porosity (365 days) (%)	Dry density (kg/m^3)	Saturated density (kg/m^3)
1	none	full	0	0.30	0.30	85.4	28.2	1958.3	2057.5
2	none	full	0	0.40	0.40	78.9	31.0	1817.3	1968.5
3	none	full	0	0.60	0.60	46.7	37.2	1450.3	1753.0
4	pfa	full	1	0.60	0.30	80.3	29.8	1751.0	1920.0
5	pfa	full	2	0.86	0.29	81.5	27.0	1715.5	1889.5
6	pfa	full	3	1.17	0.29	58.1	30.6	1570.8	1819.0
7	pfa	1500	1	0.60	0.30	39.5	43.3	1287.3	1530.5
8	pfa	1500	2	0.86	0.29	35.6	43.6	1273.3	1509.5
9	pfa	1500	3	1.17	0.29	36.1	43.1	1274.3	1531.5
10	pfa	1250	1	0.60	0.30	19.8	48.4	1055.8	1304.5
11	pfa	1250	2	0.86	0.29	18.4	52.5	1023.5	1254.0
12	pfa	1250	3	1.17	0.29	19.1	49.5	1040.8	1318.5
13	pfa	1000	1	0.60	0.30	9.2	59.3	833.0	1079.0
14	pfa	1000	2	0.86	0.29	8.6	62.6	820.8	1064.5
15	pfa	1000	3	1.17	0.29	7.1	61.9	810.0	1111.0
16	poz	full	1	0.60	0.30	93.4	31.7	1695.5	1871.5
17	poz	full	2	0.86	0.29	78.7	31.6	1561.0	1800.0
18	poz	full	3	1.17	0.29	63.1	33.2	1524.5	1789.0
19	poz	1500	1	0.60	0.30	37.0	43.0	1341.5	1545.5
20	poz	1500	2	0.86	0.29	41.3	41.1	1327.0	1537.5
21	poz	1500	3	1.17	0.29	38.8	38.2	1308.5	1560.5
22	poz	1250	1	0.60	0.30	19.8	50.0	1058.0	1303.0
23	poz	1250	2	0.86	0.29	19.8	51.1	1055.0	1281.0
24	poz	1250	3	1.17	0.29	17.6	48.3	1014.0	1280.5
25	poz	1000	1	0.60	0.29	7.0	58.7	823.5	1097.5
26	poz	1000	2	0.86	0.29	7.5	60.6	849.5	1088.0
27	poz	1000	3	1.17	0.29	5.8	62.6	772.5	1023.5

crushed on a standard cube press, but as the foamed concrete strengths were relatively low, these cubes were crushed on a more sensitive machine with a 50-MPa capacity and recorded to the nearest 0.1 MPa. Cubes were crushed after 7, 28, 56, 84, 168, 270 and 365 days.

3.1.2. Porosity

The porosity of the foamed concrete was determined using the Vacuum Saturation Apparatus as developed by Cabrera and Lynsdale [10] at the University of Leeds [11]. Porosity measurements were conducted on slices of 68-mm diameter cores that were drilled out of the centre of a 100-mm cube. The slices were dried at 100 ± 5 °C until constant weight had been achieved and were then placed in a desiccator under vacuum for at least 3 h, where after the desiccator was filled with de-aired, distilled water. The porosity was calculated using the following formula [10] (Eq. (8)):

$$P = \frac{(W_{sat} - W_{dry})}{(W_{sat} - W_{wat})} \times 100 \qquad (8)$$

where: P = vacuum saturation porosity (%); W_{sat} = weight in air of saturated sample; W_{wat} = weight in water of saturated sample; W_{dry} = weight of oven-dried sample.

4. Results

Details of mix proportions and selected hardened concrete results are shown in Table 2. The porosity of the foamed concrete is the sum of the air voids and the voids in the paste. The relationship between dry density and porosity is shown in Fig. 1 from which it can be seen that porosity is largely dependent on dry density and not on ash type or ash content. The porosities vary between 29% (for cement paste with a water/cement ratio of 0.3) and 67% (for foamed concrete with a casting density of 1000 kg/m^3 and a pfa/cement ratio of 3). The lowest porosity, at 29%, was measured for the cement paste with a water/cement ratio of 0.3 containing no ash. The cement paste with a water/cement ratio of 0.6 had a porosity of 40%, which is virtually the same as the porosity of the foamed concrete mixtures with a casting density of 1500 kg/m^3 and an ash/cement ratio of 3.

4.1. Effect of porosity on compressive strength

The relationship between measured porosity and the compressive strength (after 1 year) of foamed concrete is shown in Fig. 2. From this graph, it can be seen that the relationship is not significantly influenced by the use of pfa or pozz-fill. Mixtures with an ash/cement ratio of 2 seem to yield marginally higher strengths for a given porosity and mixtures with no ash or an ash/cement ratio of 3 seem to yield marginally lower strengths for a given porosity. These differences are, however, only small and it can be concluded that for the results available, the volume of ash used does not significantly influence the porosity–strength relationship of foamed concrete.

Rößler and Odler [4] used four expressions that had been derived by other workers to express the relationship between porosity and compressive strength of porous solids. They determined the optimum values of the constant terms and sought the equation that best expressed the existing relationship between strength and total porosity for their set of Portland cement pastes.

The same procedure was used to determine whether these equations could be used to express the relation between porosity and strength of the author's foamed

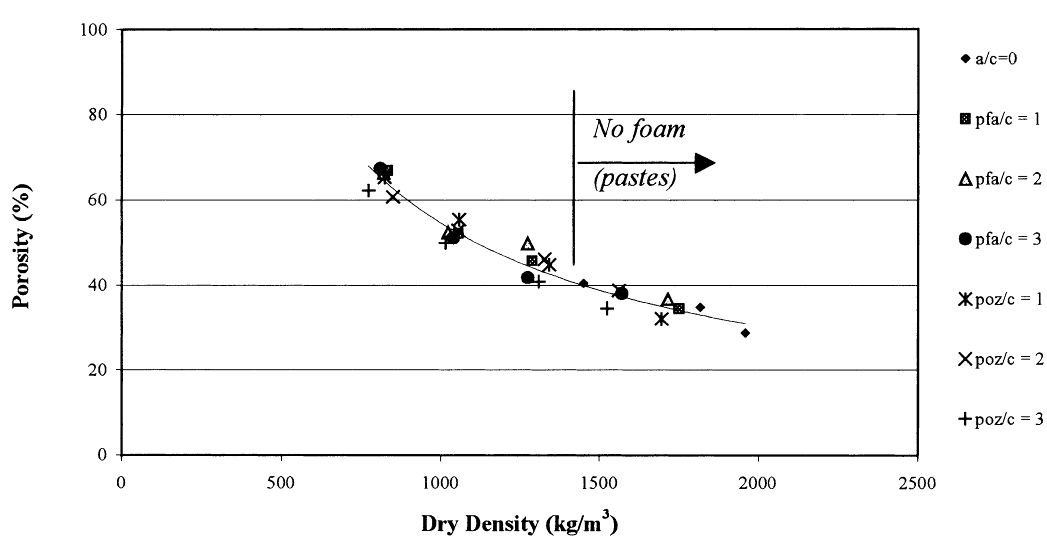

Fig. 1. Porosity as a function of dry density.

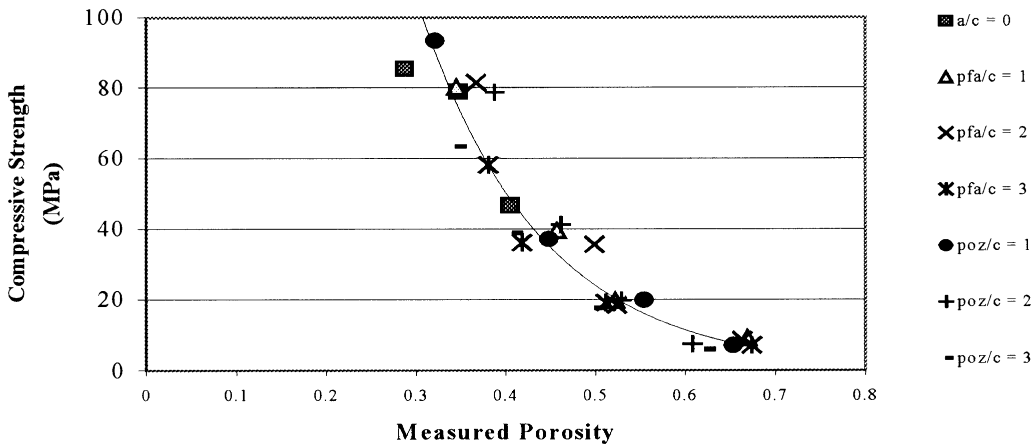

Fig. 2. Effect of porosity on compressive strength at 1 year.

concrete mixtures with high ash contents. The results in Table 3 indicate that for the 1-year results, any one of the four equations can be fitted, resulting in a relatively strong relationship between the compressive strength and the porosity of the foamed concrete. While Rößler and Odler [4] concluded that the linear relation (Hasselmann) fits their results best, the author's results are best fitted to an exponential function (Ryshkevitch). The solid line in Fig. 2 fits the exponential function ($f_c = 981e^{-7.43p}$) as shown in Table 3. The porosities of the cement pastes analysed by Rößler and Odler were below 0.3 (30%), while the porosities of the authors' foamed concrete samples were as high as 0.66 (66%). From Fig. 2, it can be seen that a linear function would fit the foamed concrete mixtures with lower porosities (say below 0.4) and these results do therefore seem to concur with the conclusions drawn by Rößler and Odler.

The multiplicative model (Balshin), fitted as shown in Table 3, has a power of 3.6, which is much higher than the values of up to 2.2 calculated for aerated concrete by Baozhen and Erda [6]. The fact that the authors' investigation contains data with a larger spectrum of porosities as well as higher strengths could explain this difference. For the foamed concrete mixtures used in this investigation, the strength–porosity equation fitted using an exponential function best explains this relationship with a high correlation coefficient of .967.

All the authors' foamed concrete strengths and porosities used to fit these functions were, however, measured 1 year after casting. The compressive strength of the mixtures increased significantly between 28 and 365 days, while based on literature reviewed [12,13], it was assumed that the change in porosity during this period would be negligible. The equations as fitted can therefore only be valid for the 1-year results and another factor will have to be added to the equation, taking time since casting into account. When the equations shown in Table 3 are fitted for strengths at different ages, the equation derived by Balshin gives the best result for the combination of all ages. The effect of age can be taken into account by taking the equation as derived by Balshin (Eq. (2)) and expanding it to use a variable strength at zero porosity (changing σ_0 to a function of time instead of using the fixed value of 321 that was derived for the 1-year strengths). Fitting a multiplicative model through linear regression results in the following:

$$f_c = 39.6(\ln(t))^{1.174}(1-p)^{3.6} \quad (9)$$

where: f_c = compressive strength of foamed concrete (MPa); t = time since casting (days); 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. A correlation coefficient of .946 indicates a relatively strong

Table 3
Equations for the strength–porosity relationship of foamed concrete

		Authors' foamed concrete		
Equation	Equation fitted by Rößler and Odler	Equation fitted	R^2	Correlation coefficient
Balshin	$\sigma_c = 540(1-p)^{14.47}$	$f_c = 321(1-p)^{3.6}$	.926	.962
Ryshkevitch	$\sigma_c = 636e^{-17.04p}$	$f_c = 981e^{-7.43p}$	.936	.967
Schiller	$\sigma_c = 81.5\mathrm{Ln}(0.31/p)$	$f_c = 109.5\mathrm{Ln}(0.66/p)$	.89	.943
Hasselmann	$\sigma_c = 158 - 601p$	$f_c = 147 - 226p$	.848	.921

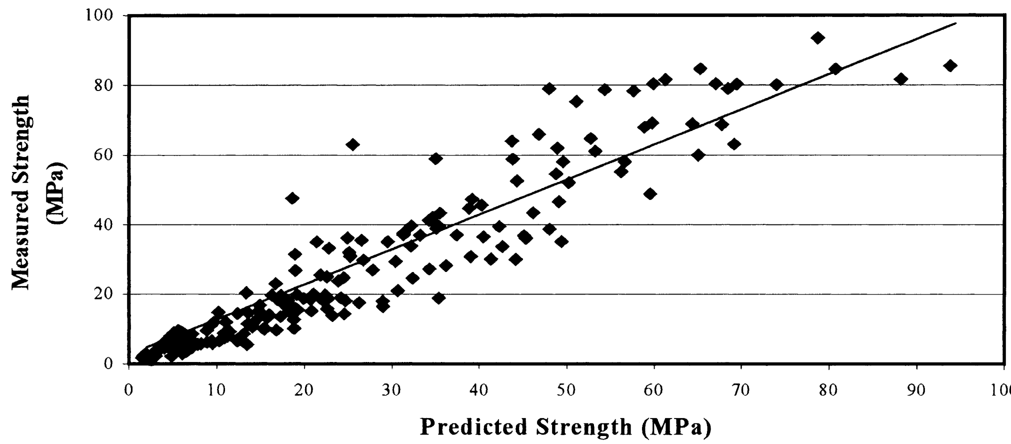

Fig. 3. Predicted versus measured strengths.

relationship between these variables. The relation between the compressive strength as predicted using Eq. (9) and the actual measured values can be seen in Fig. 3. Although the equation predicts the strengths reasonably accurately at low values, the compressive strength is underestimated at higher strengths (between 50 and 80 MPa).

Although from Eq. (9) it is possible to obtain a fairly accurate assessment of the compressive strength of the foamed concrete at any age, it does require a measurement of porosity to be made in order to solve the equation. Porosity is a property rarely measured outside the laboratory, and a model for predicting strength that requires a knowledge of more easily measured properties may be of more use to the concrete producers.

Using the equations derived by Hoff [8] (see Eqs. (6) and (7)), a theoretical porosity can be calculated for any mixture provided the dry density, water/cement ratio and cement specific gravity are known. The equations though were derived for foamed concrete mixtures made only with cement and may not therefore be valid for the authors' mixtures made with high volumes of ash. Eq. (6) was used to calculate the theoretical porosity for each mix, where k was assumed to be equivalent to the water/binder (cement + ash) ratio. The binder specific gravity (p_c) was calculated by dividing the total binder (cement + ash) weight by the total binder volume. In calculating the volumes of cement and ash, relative densities of 3.14 and 2.2, respectively, were used. The points in Fig. 4 have been plotted using the calculated porosity and measured compressive strength for each mixture. Using multiple regression analysis on Eq. (7), the line of best fit was derived, which is the solid line shown in Fig. 4. The values of the σ_0 and b used to derive this line were 188 MPa and 3.1, respectively. In Hoff's original work, he used a variety of different cements and derived a range of values of σ_0 and b from 115 to 290 MPa and 2.7 to 3.0, respectively, depending on the cement type. It is interesting to note that the values obtained by the authors lie almost within the ranges quoted by Hoff, which suggests

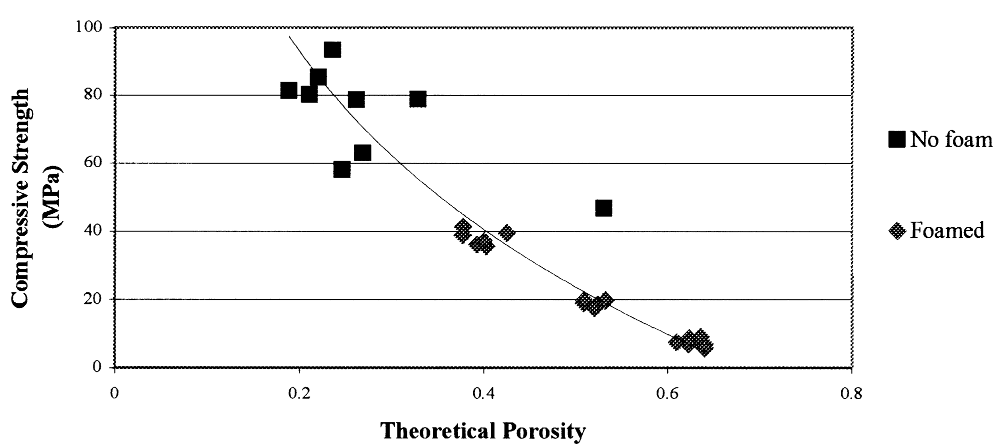

Fig. 4. Compressive strength–theoretical porosity relation at 365 days.

that his equation may well be valid for mixtures containing fly ash. However, looking more closely at Fig. 4, two things are evident:

- The two data points furthest from the line of best fit are for mixtures with water/binder ratios of 0.40 and 0.60 compared with 0.30 for all the other mixtures. This would suggest that the relationship is only valid for a given water/binder ratio.
- The variability about the fitted line for mixtures without foam (at water/binder ratio 0.3) is greater than for all the foamed concrete mixes. This might suggest that the equation is only valid for foamed concrete.

However, the R^2 statistic indicates that the model, as fitted, explains 92.3% of the variability in compressive strength, and the correlation coefficient equals .961, indicating a relatively strong relationship between theoretical porosity and compressive strength. It can be concluded that the equation as derived by Hoff can effectively be used to predict the compressive strength of foamed concrete mixtures containing high percentages of ash.

5. Conclusions

- Porosity is largely dependent on dry density and not on ash type or content.
- The compressive strength of foamed concrete was shown to be a function of porosity and age. A multiplicative model (such as the equation derived by Balshin) best fits the results at all ages of this investigation.
- The effect of ash/cement ratio has not yet been established and an attempt should be made to establish whether there are optimum ash contents at different ages and porosities.
- The equation as derived by Hoff can effectively be used to predict the compressive strength of foamed concrete mixtures containing high percentages of ash.

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