Pergamon

Cement and Concrete Research 31 (2001) 805–812

CEMENT AND CONCRETE RESEARCH

Porosity and permeability 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, England, UK

Received 14 August 2000; accepted 20 February 2001

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 permeability and porosity measured up to an age of 1 year on well-cured concretes. Porosity was found to be dependent mainly on the dry density of the concrete and not on ash type or content. Permeability was measured in terms of water absorption and water vapour permeability. The volume of water (in kg/m^3) absorbed by foamed concrete was approximately twice that of an equivalent cement paste but was independent of volume of air entrained, ash type or ash content. The water vapour permeability increased with increasing porosity and ash content.

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

1. Introduction

This is the second 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 cement with both classified (pfa) and unclassified (pozz-fill) fly ash. Foamed concrete is manufactured by entraining relatively large volumes of air into the cement paste by the use of a chemical foaming agent. High air contents result in lower densities, higher porosities and lower strengths. The previous paper by the authors [1] showed that although the rate of gain in strength of the foamed concrete was reduced by the use of large volumes of ash, up to 67% of the cement could be replaced without any significant reduction in the long-term strength.

Many authors have investigated the relationship between porosity and permeability of mortar and concrete. The *permeability* of concrete gives an indication of the ease with which fluids, gases or vapours can enter into and move through the concrete and it is therefore a good indicator of the quality of the concrete [2]. If the porosity is high and the pores are interconnected the permeability is also high, but if the pores are discontinuous the permeability of the concrete is low although the porosity is high.

Nyame [3] investigated the permeability of normal and lightweight mortars. It was found that the permeability of mortar increased as the porosity was reduced by the addition of aggregates which have a lower porosity than the mortar. Nyame suggested that the inclusion of the aggregate creates microcracks at the interface with the mortar resulting in increased permeability. By increasing the aggregate volume there are more interfaces resulting in higher permeability. Aggregates therefore have two opposing influences upon permeability: size and volume obstructions can reduce permeability but interfacial effects and aggregate properties can increase permeability. In the case of foamed concrete the small air voids that are entrained can effectively be considered as an aggregate, their inclusion might not reduce the permeability by obstructing flow but they are also unlikely to lead to an increase because of the absence of microcracking.

According to Neville [2], entrained air in concrete produces, in the cement paste, discrete, nearly spherical bubbles approximately 50 micrometer in diameter resulting in the formation of very few channels for the flow of water and very little increase in the permeability. The volume of air normally associated with air entrainment is no more than

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

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

0008-8846/01/$ – see front matter
PII: S0008-8846(01)00490-2

about 6% and what needs to be established is whether or not this statement holds true for foamed concretes which contain much larger volumes of air.

In their study on capillary pore structure and permeability of hardened cement paste Nyame and Illston [4] concluded that porosity is not a unique function of permeability. They concluded that total porosity of hardened cement paste is not uniquely related to permeability but depends on whether the change in porosity derives from differences in the water/cement ratio or hydration times [5]. They identified well-defined trends for the effect of the time of hydration at constant water/cement ratio on permeability.

The porosity and permeability of concrete is strongly affected by its moisture content: a change from near saturation to an oven-dried condition has been reported to increase the permeability by nearly two orders of magnitude. For this reason a clearly defined condition of testing should be used for all tests. Conditioning a specimen in air at a constant relative humidity, even for as long as 28 days, does not necessarily result in a uniform moisture condition within the concrete [2]. Incomplete drying (conditioning specimen at a particular relative humidity), results in residual water being present in the pore system, usually in the smaller pores. The residual water can block the passage of gas through certain routes, and hence reduce the flow through the specimen. On the other hand, complete drying (e.g. at 105°C) can result in shrinkage cracking which modifies the pore structure, leading to artificially high porosity and permeability values. Measurements of samples pre-dried at different temperatures (25°C, 50°C, 80°C and 100°C) show that gas permeability increases with increased temperature of drying. The shrinkage cracking that occurs as a results of drying does not, however, falsify the results of the gas permeability measurement on the ranking of different mixtures, but the results of such an evaluation are specific to the treatment of the samples to achieve equilibrium [6].

The volume of pore space in concrete, as distinct from the ease with which fluid can penetrate it, is measured by absorption. Absorption is usually measured by drying the specimen to a constant mass, immersing it in water and measuring the increase in mass as a percentage of dry mass. Various procedures can be used, resulting in widely different results. One reason for the variation in the values of absorption is that drying at ordinary temperatures may be ineffective in removing all the water; on the other hand, drying at high temperatures may remove some of the combined water.

Day and Marsh [7] assessed porosity measurements made using several testing methods. They concluded that water porosity by oven drying or by re-saturation after oven drying are equivalent methods. Marsh conducted research on the pore structure characteristics affecting the permeability of cement paste containing fly ash. He concluded that the pozzolanic reaction of fly ash in blended cement pastes can cause substantial reductions in permeability.

From the standpoint of ease of testing and consistency of results, conditioning the specimens using oven drying is the preferred procedure for both porosity and permeability measurements and was the procedure adopted by the authors. It is, however, appreciated that this condition is not representative of the concrete in service, if anything it is probably more severe. The aim of this investigation was to determine whether or not the high porosity associated with the foamed concrete also results in high permeability. The porosity, permeability and absorption of the foamed concretes were compared to those of cement pastes with different water/cement ratios and ash contents. It was the intention therefore to obtain information on the relative changes in these properties rather than actual values themselves and it was considered that comparisons made in this way would not be significantly influenced by the way in which the specimens were conditioned.

2. Experimental work

2.1. Mix compositions

More details relating to the materials used and casting procedure can be found in the previous publications [1,8], but in summary the following mixtures were cast:

- 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.
- 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%).

2.2. Test procedures

2.2.1. 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 [9,10]. 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 Eq. (1) [9]:

$$P = \frac{(W_{\mathrm{sat}} - W_{\mathrm{dry}})}{(W_{\mathrm{sat}} - W_{\mathrm{wat}})} 100 \qquad (1)$$

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

Table 1
Mix proportions and hardened concrete properties

Mix no.	Type of ash	Target density (kg/m^3)	a/c	w/c	w/binder	Vapour permeability (after 365 days) (kg s MN/m^3)	Porosity 365 days (%)	Dry density (kg/m^3)	Saturated density (kg/m^3)
1	none	full	0	0.30	0.30	0.0045	28.2	1958.3	2057.5
2	none	full	0	0.40	0.40	0.0062	31.0	1817.3	1968.5
3	none	full	0	0.60	0.60	0.0163	37.2	1450.3	1753.0
4	pfa	full	1	0.60	0.30	0.0059	29.8	1751.0	1920.0
5	pfa	full	2	0.86	0.29	0.0047	27.0	1715.5	1889.5
6	pfa	full	3	1.17	0.29	0.0114	30.6	1570.8	1819.0
7	pfa	1500	1	0.60	0.30	0.0183	43.3	1287.3	1530.5
8	pfa	1500	2	0.86	0.29	0.0204	43.6	1273.3	1509.5
9	pfa	1500	3	1.17	0.29	0.0164	43.1	1274.3	1531.5
10	pfa	1250	1	0.60	0.30	0.0255	48.4	1055.8	1304.5
11	pfa	1250	2	0.86	0.29	0.0405	52.5	1023.5	1254.0
12	pfa	1250	3	1.17	0.29	0.0351	49.5	1040.8	1318.5
13	pfa	1000	1	0.60	0.30	0.0539	59.3	833.0	1079.0
14	pfa	1000	2	0.86	0.29	0.0677	62.6	820.8	1064.5
15	pfa	1000	3	1.17	0.29	0.0698	61.9	810.0	1111.0
16	pozz	FULL	1	0.60	0.30	0.0077	31.7	1695.5	1871.5
17	pozz	FULL	2	0.86	0.29	0.0031	31.6	1561.0	1800.0
18	pozz	FULL	3	1.17	0.29	0.0087	33.2	1524.5	1789.0
19	pozz	1500	1	0.60	0.30	0.0131	43.0	1341.5	1545.5
20	pozz	1500	2	0.86	0.29	0.0125	41.1	1327.0	1537.5
21	pozz	1500	3	1.17	0.29	0.0170	38.2	1308.5	1560.5
22	pozz	1250	1	0.60	0.30	0.0275	50.0	1058.0	1303.0
23	pozz	1250	2	0.86	0.29	0.0339	51.1	1055.0	1281.0
24	pozz	1250	3	1.17	0.29	0.0368	48.3	1014.0	1280.5
25	pozz	1000	1	0.60	0.30	0.0537	58.7	823.5	1097.5
26	pozz	1000	2	0.86	0.29	0.0575	60.6	849.5	1088.0
27	pozz	1000	3	1.17	0.29	0.0724	62.6	772.5	1023.5

2.2.2. Absorption and permeability

The ease with which a fluid can penetrate foamed concrete was determined by measuring both the water absorption and the water vapour permeability.

The water absorption was measured on 100-mm cubes which had been cured under sealed conditions at 20°C for 28 days. The cubes were oven-dried at 100 ± 5°C for 7 days (to a constant mass) and then immersed in water for 7 days (to a constant mass). The water absorption was expressed as the increase in the mass as a percentage of the oven dry mass.

A water vapour permeability test was set up in accordance to the RILEM recommendation LC7 for autoclaved aerated concrete [11]. The water vapour permeability can be defined as "the amount of mass transfer due to diffusion of water vapour resulting from a difference in water vapour pressure on the two parallel surfaces of a disc of aerated concrete"[11]. Twenty-eight days after casting, a core with a diameter of 100 mm was drilled from a 150-mm cube and sliced into 40 ± 2 mm slices. Specimens were dried at 50 ± 3°C and then stored over a saturated solution of potas-

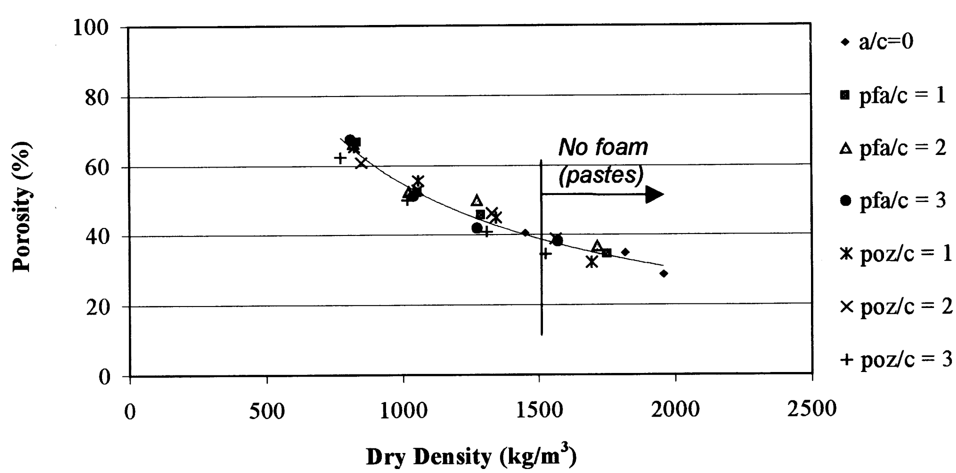

Fig. 1. Porosity as a function of dry density.

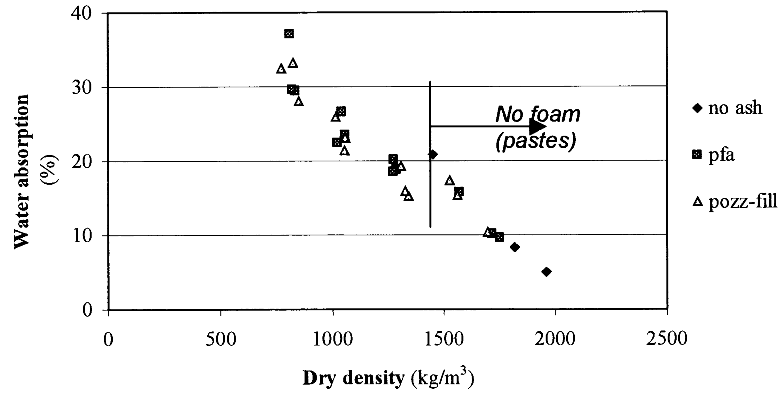

Fig. 2. Effect of dry density on percentage water absorption.

sium nitrate, in a closed container at 92% relative humidity for 7 days. After conditioning, the samples were placed in plastic containers filled with a saturated solution of potassium nitrate to a depth of 30 ± 2 mm below the bottom surface of the specimen. The sides of the specimens were covered with vapour-impermeable tape and rubber packing where after the assemblies were placed in the constant temperature room at 22 ± 2°C and 60 ± 5% humidity. Each assembly was weighed every 48 h until a constant rate of weight loss was obtained. After completion of the test each sample was removed and dried at 100 ± 5°C in order to determine the dry density.

The water vapour permeability k_d is a material constant which is a function of the density of the aerated concrete and its pore structure. The permeability can be calculated using Eq. (2):

$$k_d = \frac{Gd}{A_c t \Delta p} \quad (2)$$

where: k_d = time rate of vapour flow through unit area; G = weight loss during t hours; A_c = cross-sectional area of specimen perpendicular to flow (m^2); d = thickness of specimen in m; t = time in hours; and Δp = difference in water vapour partial pressure (millimetre of mercury) between the dry side and the moist side of the specimen.

The results shown are the average of two specimens.

3. Results

Details of mix proportions and selected hardened concrete results are shown in Table 1.

3.1. Porosity

The porosity of the foamed concrete is the sum of the entrained air voids and the voids within the paste. The relationship between dry density and porosity of both pastes and foamed concrete can be seen in Fig. 1. From this figure it can be seen that there is a strong relationship between porosity and dry density which is largely independent of ash type, ash content, or the inclusion of the foam. The porosities varied 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, of 29%, was for the cement paste mixture with a water/cement ratio of 0.3 containing no ash. This value correlates well with the 28% porosity that is characteristic of the volume of gel water in fully hydrated cement paste. The cement paste with a water/cement ratio of

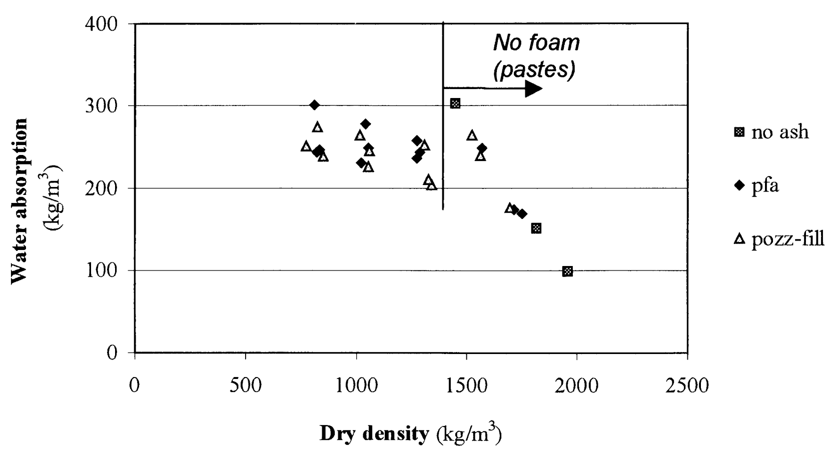

Fig. 3. Effect of dry density on water absorption.

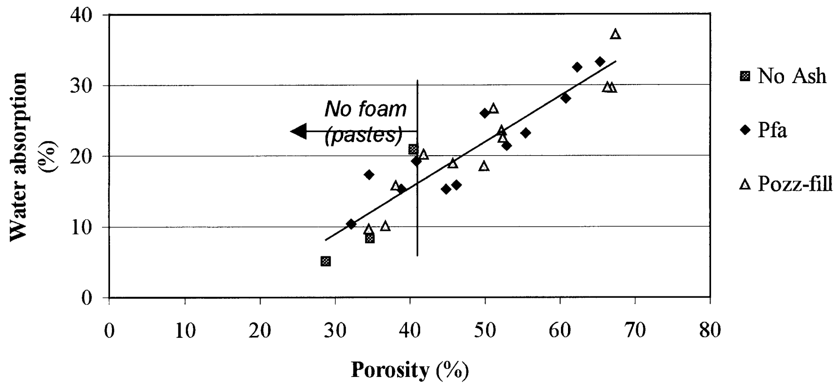

Fig. 4. Relationship between porosity and water absorption (percentage per weight).

0.6 had a porosity of 40%, which was very similar to the porosity of the foamed concrete mixtures with a casting density of 1500 kg/m^3 and an ash/cement ratio of 3. The expected reduction in porosity with increased ash content as reported in other investigations [1,12,13] was not observed here because, unlike other authors, the mixes in this investigation were based on equal water/binder ratio and not on equal workability. The relationship between porosity and dry density as shown in Fig. 1 can best be described using the following equation:

$$\rho = 18700\ \gamma_d^{-0.85} \quad (3)$$

where: ρ = porosity (%); γ_d = dry density (kg/m^3).

Regression analysis shows that comparing the actual measured porosities to the values calculated using Eq. (3) yields an R^2 value of .95, indicating a relatively strong relation between dry density and porosity.

3.2. Water absorption

The water absorption of the pastes and the foamed concrete mixtures (as expressed by the increase in mass as a percentage of dry mass) is plotted as a function of dry density in Fig. 2. The relationship between the two variables is almost linear, with the lower density mixtures absorbing significantly higher percentages of water than those with higher densities. From these results it could be concluded that because the mixtures with lower densities absorb more water they are potentially less durable than the mixtures with higher densities. However, water absorption may be expressed either as the increase in mass per unit of dry mass (as in Fig. 2) or as the increase in mass per unit volume. For conventional concrete where densities normally vary very little, the results are likely to be similar no matter which way they are expressed. However, for the foamed concrete mixtures reported here there are significant differences in density (1000 to 1500 kg/m^3) and expressing water absorption as the increase in mass per unit volume (see Fig. 3) presents a different picture from that discussed previously in Fig. 2. It is now apparent that the foamed concrete mixtures with low densities absorb only marginally more water than those with higher densities. It is also apparent that the cement paste mixture containing no ash (w/c = 0.6) absorbs more water than any of the foamed concrete mixtures. From Fig. 3 it can also be seen that there is a trend of increased absorption with decreasing density for all mixtures but the

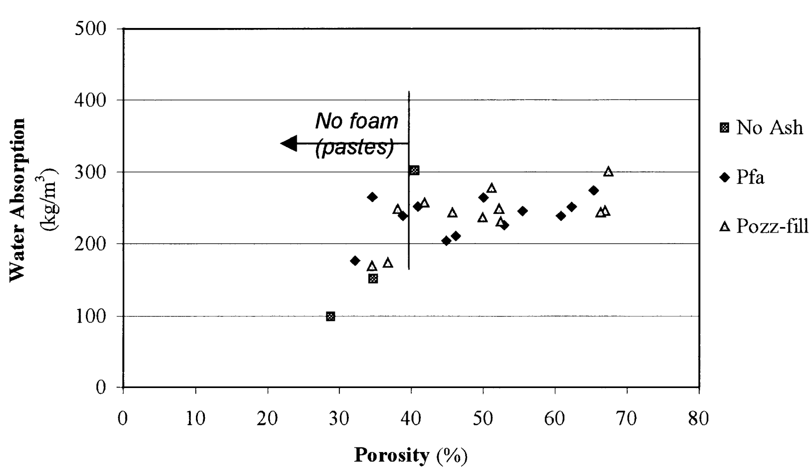

Fig. 5. Relationship between porosity and water absorption (percentage per volume).

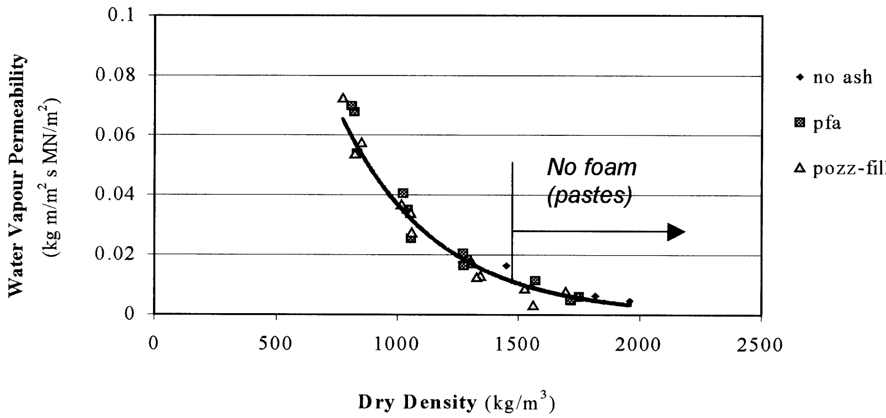

Fig. 6. Water vapour permeability as a function of dry density.

increase in absorption is much more significant in the paste (no foam) mixtures than in the foamed concrete mixtures.

The relationship between porosity and water absorption, per unit weight and per volume, are shown in Figs. 4 and 5, respectively, and it is not surprising to see similar trends to those for dry density shown in Figs. 2 and 3. Fig. 4 shows a linear relationship between porosity and water absorption (% increase per unit weight) and linear regression indicates that 85.9% of the variation in water absorption can be explained by the variation in porosity. The relationship between porosity and the water absorption (percentage increase per unit volume) is shown in Fig. 5 and this confirms the fact that for foamed concrete mixtures higher porosity does not necessarily result in higher water absorption. The majority of the foamed concrete mixtures have water absorption values between 200 to 280 kg/m^3 which are greater than that of the cement paste with a water/cement ratio of 0.30 (100 kg/m^3) but less than that of the paste with water/cement ratio of 0.6 (300 kg/m^3).

As the water/binder ratio of all the foamed concrete mixtures were nominally the same at 0.30, these results would suggest that about 50% of their water absorption can be accounted for by their paste fraction. The inclusion of the entrained air results in an approximate doubling of the water absorption but the fact that this increase appears to remain almost the same regardless of the amount of air entrained would suggest that only some of the voids are either filled or partly filled with water. Neither the ash type nor content seems to have a significant effect on the water absorption.

3.3. Water vapour permeability

The water vapour permeability of the foamed concrete is plotted as a function of dry density in Fig. 6. There is a strong relation between dry density and permeability with the water vapour permeability of foamed concrete with dry densities above 1250 kg/m^3 being approximately the same as that of cement paste with a water/cement ratio of 0.6. Foamed concrete is therefore not necessarily more permeable than cement paste.

A similar but slightly less well-defined trend is observed when plotting water vapour permeability against porosity (Fig. 7). It is interesting to note that the same trend line fits the results both with and without foam, which is in contrast to the case for water absorption (Fig. 3). An increase in the volume of voids (as indicated by a reduction in density or

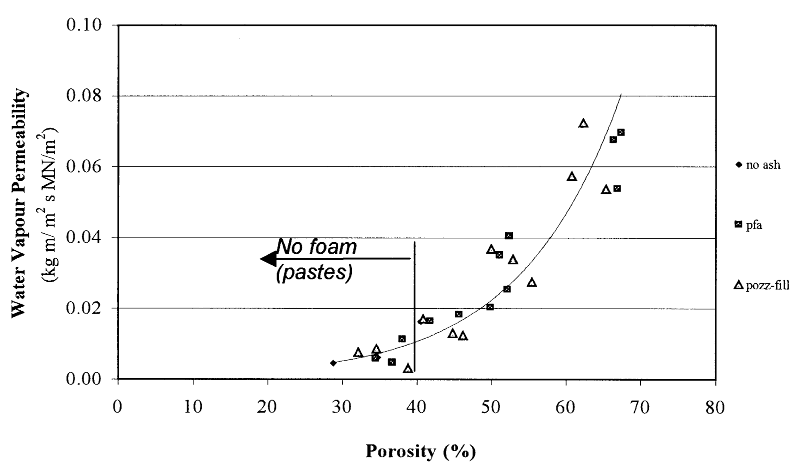

Fig. 7. Water vapour permeability versus porosity.

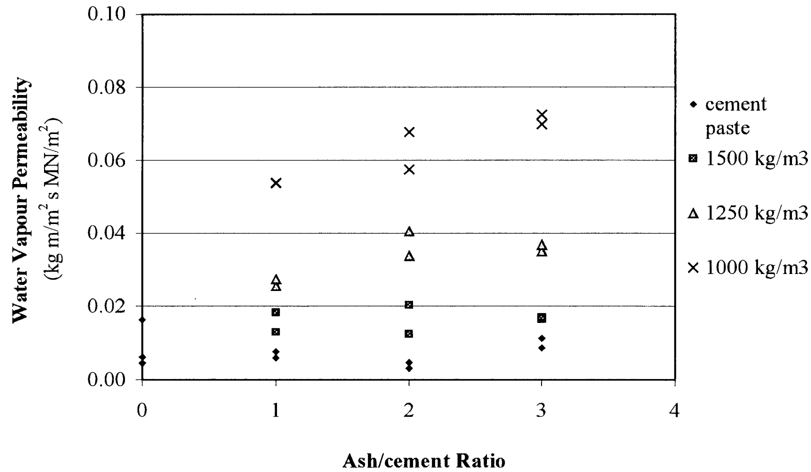

Fig. 8. Effect of ash/cement ratio on water vapour permeability.

increase in porosity) leads to a marked increase in water vapour permeability. This suggests that perhaps all the voids are playing a part in the transfer mechanism of water vapour through the specimen, which does not appear to be the case with water absorption.

The volume of ash (pfa or pozz-fill) used does have an effect on the water vapour permeability of foamed concrete as can be seen in Fig. 8. The water vapour permeability of the foamed concrete mixtures increase with increasing ash/cement ratio and this trend becomes more significant at the lower densities.

The relationship between the water absorption and the water vapour permeability of foamed concrete can be seen in Fig. 9. For the mixtures containing no foam there is little increase in permeability with increasing water absorption whereas for those mixtures containing foam a relatively small increase in water absorption results in a significant increase in water vapour permeability. These results would suggest, as discussed earlier, that the mechanisms of water absorption and water vapour permeability are fundamentally different and influenced by different factors.

Of the two tests reported in this section the water vapour permeability tests could arguably be considered to be the more realistic in terms of reproducing the conditions that concrete might be subjected to in service. The results from this test might have implications regarding corrosion of any reinforcing steel that may be embedded in the concrete and this is an area that warrants further investigation. It should be remembered, however, that the test results reported were obtained from specimens that had been conditioned by oven drying, conditions that are more severe than those likely to be experienced in practise.

4. Conclusions

From the tests carried out on foamed concrete mixtures in which up to 75% of the cement has been replaced by fly ash, the following conclusions can be drawn:

- Porosity is largely dependent on dry density and not on ash type or content.
- Expressing water absorption as a percentage increase in mass can give misleading results where foamed concrete is concerned because of the large differences in density between the different mixtures.

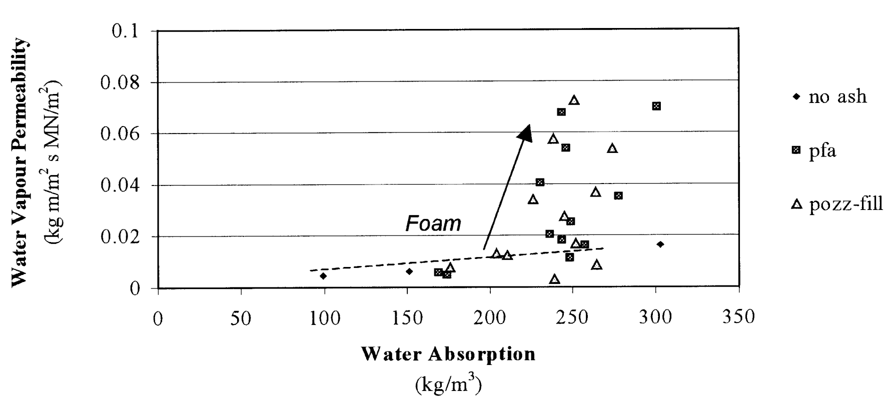

Fig. 9. Water absorption versus water vapour permeability.

- The volume of water, expressed in kg/m^3, absorbed by the foamed concrete is approximately twice that absorbed by a cement paste with similar water/binder ratio. The volume of water, expressed in kg/m^3, absorbed by the foamed concrete appears to be little influenced by the volume of air entrained, which suggests that not all the voids are filled with water.
- Neither ash type nor content has an effect on the water absorption (per unit weight or volume) of foamed concrete. The fact that the water/binder ratio was kept constant with changing ash content possibly eliminated any reduction in water absorption that might result from the use of ash.
- The water absorption per unit volume of cement pastes increased with increasing porosity, whereas there was little change in the case of the foamed concrete mixtures.
- Water vapour permeability increases with increasing porosity (or reducing density) and the trend lines appear to be similar for mixtures both with and without foam.
- The water vapour permeability of foamed concrete mixtures increase with increasing ash/cement ratios and this trend becomes more significant at lower densities.
- The water vapour permeability of mixtures containing pozz-fill is marginally lower than that of mixtures containing pfa.
- For mixtures containing no foam large increases in water absorption per unit weight results in marginal increases in water vapour permeability, whereas for mixtures containing foam small increases in water absorption results in significant increases in water vapour permeability.

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 (1) (2001) 105–112.

[2] A.M. Neville, Properties of Concrete, fourth ed., Longman Group Limited, Essex, England, 1995.

[3] B.K. Nyame, Permeability of normal and lightweight mortars, Mag. Concr. Res. 37 (130) (1985) 44–48.

[4] B.K. Nyame, J.M. Illston, Relationship between permeability and pore structure of hardened cement paste, Mag. Concr. Res. 33 (116) (1981) 139–146.

[5] B.K. Nyame, J.M. Illston, Capillary pore structure and permeability of hardened cement paste, Seventh International Symposium on the Chemistry of Cement, Paris, Paris Editions Paris, Septima, vol. 3, 1980, pp. 181–186.

[6] 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.

[7] R.L. Day, B.K. Marsh, Measurement of porosity in blended cement pastes, Cem. Concr. Res. 18 (1) (1988) 63–73.

[8] E.P. Kearsley, The effect of high volumes of ungraded fly ash on the properties of foamed concrete, PhD Thesis, Dept. of Civil Eng., University of Leeds, UK, 1999.

[9] 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.

[10] B.A. Gaafar, The effect of environmental curing conditions on the gas and water permeability of concrete, PhD Thesis, Dept. Civil Eng., University Leeds, UK, 1995.

[11] RILEM Recommendation LC7: Water vapour permeability of autoclaved aerated concrete, 1978.

[12] 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, Proc. 5th Int. Conf. on Deterioration and Repair of Reinforced Concrete in the Arabian Gulf, The Bahrain Society of Engineers, Bahrain, vol. 1, 1997, pp. 345–365.

[13] P.J. Wainwright, J.G. Cabrera, A.M. Alamri, Performance properties of pozzolanic mortars cured in hot dry environments, Concrete in Hot Climates: Proc. 3rd Int. RILEM Conf., E & FN Spon, Torquay, England, 1992, pp. 115–128.