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On void structure and strength of foamed concrete made without/with additives

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HIGHLIGHTS

- Successful comparison between the void size distributions of mixes without/with additives.
- Significance difference in air void structure with additives in combination was achieved.
- Effect of additives on cement paste microstructure and air void structure was investigated.
- Evidence was found for the effect of both paste microstructure and void structure on strength.

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ABSTRACT

A study has been undertaken to investigate the effect of different additives on the strength foamed concrete by characterising air-void size and shape parameters and identifying the influence of these parameters and changes to cement paste microstructure on strength. Nine different mixes, made using a preformed foam, were investigated with varying density (nominally 1300, 1600 and 1900 kg/m^3) without/with additives (silica fume, fly ash and superplasticizer), used either individually or together. Optical microscopy and scanning electron microscopy were used in this investigation. Compared to the conventional mixes, inclusion of additives (individually or in combination) helped to improve both the cement paste microstructure and air-void structure of foamed concrete. For a given density, although the additives in combination led to increased void numbers, higher strength was achieved due to reduced void size and connectivity, by preventing their merging and producing a narrow void size distribution. Furthermore, superplasticizer has the most beneficial influence on voids when used alone and it further improves void structure (smaller and number voids) when used in combination with other additives. Not only enhancement of void structure but also improved cement paste microstructure both contribute to the strength of the foamed concrete.

1. Introduction

In aerated concrete, the structure is affected by the method of pore-formation (gas or foaming) and is characterised into a micro-porous matrix and macropores [1]. Foamed concrete is a particular example of aerated concrete in which addition pores have been introduced by the introduction of either preformed foam or by chemical action after mixing. In the study reported here, preformed foam was applied.

Ramamurthy et al. [2] and Nambiar and Ramamurthy [3], mentioned that air-void distribution is one of the most significant micro-properties influencing strength of foamed concrete and Ramamurthy et al. [2] found that foamed concrete with narrower air-void size distribution shows higher strength.

The pore structure of foamed concrete is classified as gel pores, capillary pores and air-voids (air entrained and entrapped pores) [2,4]. In addition, the air-voids in the foamed concrete may be characterised by parameters such as volume, size, shape, size distribution and spacing between air-voids [3]. To investigate this, image analysis software was used on images of specimens captured by using an optical microscope.

Although the compressive strength of porous materials has been expressed as a function of porosity by many researchers, some have mentioned that determination of total air void content

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(porosity) is not sufficient as shape, size and distribution of voids may affect the strength and durability of foamed concrete [5].

Kearsley [5] investigated the microstructure of foamed concrete produced with the inclusion of either classified (pfa) or unclassified (Pozz-fill) fly ash with nominal densities 1000, 1250 and 1500 kg/m^3. It was found that, at any given density, there was no obvious effect of *median* void diameter on the compressive strength.

Nambiar and Ramamurthy [3] determined the air void size distribution of foamed concrete mixes with different added foam volumes (10%, 30% and 50%) and found that the size of the larger voids increased sharply with an increase in foam volume, while for the same foam volume they were smaller for a cement–fly ash mix compared to a cement–sand mix. In addition, D_{90} (90th percentile) correlated better with strength than D_{50} (median pore size) indicating that it was the larger pores that influenced the strength more than the smaller pores.

Thus, it is well known that with the same matrix and void volume (porosity), the strength of material containing more large-size voids is lower. This paper aims to investigate, from pore structural and cement paste microstructural points of view, the strength of foamed concretes having the same air void contents, for a given density, but different matrices produced by using different additives (individually and in combination). This will be achieved by:

- Determining and comparing the size distributions of air voids of the foamed concrete mixes without/with different additives.
- Identifying the influence of size parameters on strength.
- Investigating the effect of cement paste improvement on foamed concrete strength.

2. Materials, mix proportions and production

Full details of the materials used, mix proportions and production process can be found in a previous publication [6], but essential information can be summarised as follows:

2.1. Materials

To produce conventional foamed concrete, the following constituent materials were used in this study.

- Portland cement, CEM I-52,5 N (3.15 S.G.) conforming to BS EN 197-1:2011 [7].
- Natural sand (2.65 S.G.) conforming to BS 882:1992 [8] with additional sieving to remove particles greater than 2.36 mm.
- Fresh, clean and drinkable water.
- Foam (45 kg/m^3) was produced by blending the foaming agent, EABASSOC (1.05 S.G.), water and compressed air in predetermined proportions (45 g water to 0.8 ml foaming agent) in a foam generator, STONEFOAM-4.

Then, to improve the cement paste microstructure and the air-void structure, the following additives were used individually or together depending on the desired mixes (see Table 1):

- *Silica fume*: Elkem Microsilica (2.2 S.G., 92% SiO_2, mean particle size 0.15 μm and specific surface 20 m^2/g).
- *Fly ash*: CEMEX fly ash-class S (2.09 S.G.) conforming to BS EN 405-1:2005 [9].
- *Superplasticizer*: MIGHTY 21 EG made by Kao Chemical GmbH of density 1.1 g/cm^3, compatible with the EABASSOC foaming agent.

2.2. Mix proportions

In this study, nine differently proportioned mixes were designed as follows: conventional mixes FC and modified mixes using all additives together FCa at three nominal wet densities ("low", "median" and "high"), 1300 (FC3 and FCa3), 1600 (FC6 and FCa6) and 1900 (FC9 and FCa9) kg/m^3; three further mixes at 1600 kg/m^3 with individual additives, silica fume (FCs6), fly ash (FCf6) and superplasticizer (FCp6), see Table 1. Actual achieved wet (Υ_{wet}) and dry (Υ_{dry}) densities are given in Table 2.

Mix proportioning began with the selection of the target density (1300–1900 kg/m^3), the cement content and the water to cement ratio. The mix was then proportioned by the method of absolute volumes. For each mix the water/binder ratio required to produce a stable mix (fresh density to target density ratio close to unity) was determined by trials while the required foam volume was determined from the mix design. A dosage of superplasticizer (1.5% of binder weight) was adopted for all relevant mixes. Silica fume was added to four of the mixes at 10% of the cement weight (see Table 1). Fly ash replacement was limited to 20% by weight of sand.

2.3. Production

Component materials were added into the mixer in the following sequence: dry materials (including additives, if any), water with dissolved admixture to produce the base mix (mortar) and then foam to produce the foamed concrete. The foamed concrete mix was placed in cube moulds in two approximately equal layers. The sides of the moulds were lightly tapped after placing each layer until the surface of the layer had subsided approximately to level [10]. After levelling the specimens' surfaces, all specimens were covered with thick nylon to prevent evaporation and then removed from moulds within 24 h. Because sealed-curing reflects typical industry practice for foamed concrete [11], all specimens were sealed-cured (wrapped in cling film) and stored at about 20 °C until testing.

3. Experimental details

3.1. Strength test

For both foamed concrete and unfoamed (mortar) mixes, compressive strength testing was carried out on 100 mm cubes in accordance with BS EN 12390-3:2002 [12] and in each case the results quoted are the average of three specimens.

3.2. Entrained air-void structure investigation

For the void size investigation, three slices (50 × 50 × 15 mm) were cut, perpendicular to the cast face, from the centres of three cured foamed concrete specimens. To enhance the contrast between the air voids and the matrix, the specimens were first polished and cleaned to remove any residues and then treated by applying two coats of permanent marker ink to them. Finally, after drying, a white powder (Sodium bicarbonate) with a minimum particle size of 5 μm was pressed into the surfaces of the specimens and forced into the voids leaving the concrete surface with excellent properties for image analysis, namely a black surface and white voids. This technique is described in details in BS EN 480-11 [13] and by Nambiar and Ramamurthy [3].

Table 1
Mix proportions of the all selected foamed concrete mixes.

	Mixes								
	FC3	FCa3	FC6	FCs6	FCf6	FCp6	FCa6	FC9	FCa9
Target density (kg/m^3)	1300	1300	1600	1600	1600	1600	1600	1900	1900
Cement content (kg/m^3)	500	450	500	450	500	500	450	500	450
Silica fume (kg/m^3)	–	50	–	50	–	–	50	–	50
w/b ratio*	0.475	0.3	0.5	0.5	0.5	0.325	0.325	0.525	0.35
Superplasticizer (kg/m^3)	–	7.5	–	–	–	7.5	7.5	–	7.5
Water content (kg/m^3)	237.5	150	250	250	250	162.5	162.5	262.5	175
Sand content (kg/m^3)	562	514	850	850	680	930	744	1137.5	974
Fly ash (kg/m^3)	–	128.5	–	–	170	–	186	–	243.5
Foam (kg/m^3)	19.4	19.4	13.3	13.3	13.3	13.3	13.3	7.6	7.6
Foaming agent (kg/m^3)	0.35	0.35	0.24	0.24	0.24	0.24	0.24	0.13	0.13
Foam (m^3)	0.424	0.424	0.295	0.295	0.295	0.295	0.295	0.166	0.166

* w/b ratios required to achieve a density ratio of about unity for the selected mixes.