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On entrained pore size distribution of foamed concrete

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HIGHLIGHTS

- Clear images of preformed foam were captured by treating with bitumen emulsion.
- Successful comparison between the foam bubble and concrete void size distributions.
- Voids circularity factor was successfully measured and related to added foam volume.
- Evidence was found for both bubble loss and bubble merging during the mixing process.

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ABSTRACT

The pore structure of foamed concrete is a significant characteristic since it affects properties such as strength and durability. To investigate these properties, the determination of total air voids content is not sufficient as the shape, size and distribution of air voids may also be influential. To understand the formation of voids after hardening, an investigation of the bubble size distribution of foam (before adding to the mixture) and the pore size distribution of the foamed concrete mixes (after hardening) is discussed in this paper. These distributions have been quantified by examining selected size parameters to make a comparison between them. In addition, void circularity factors have been determined to examine the phenomenon of voids merging. In order to investigate the foam structure before adding to the mix, it was found that by treating the foam with bitumen emulsion, a clear image of its structure can be captured using an optical microscope. Using this technique, a significant difference was found between the size distribution of foam bubbles and those of air pores within foamed concrete mixes. From circularity factor results, there is evidence for increased bubble merging with increased added foam volume (decreased density).

1. Introduction

Foamed concrete is a versatile material consisting of either Portland cement paste or cement filler matrix (mortar) with homogeneous pore structure created by entrained air voids roughly 0.1–1.0 mm size [1–4]. Nambiar and Ramamurthy [1], reported that the introduction of pores inside foamed concrete can be achieved mechanically either by preformed foaming (forming the foam before adding it to the mix) or mix foaming (mixing in a foaming agent). It should be noted that the foamed concrete investigated in this study has been manufactured using the preformed foaming method.

The pore structure of cementitious material is a very significant characteristic since it affects properties such as strength and durability due to their dependence on material porosity and permeability [2]. However, determination of the total air void content (porosity) is not sufficient as shape, size and distribution of voids may affect the strength and durability of concrete [5].

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

It seems likely that the pore structure and microstructure of foamed concrete has an important influence on its properties. It is usually classified into gel pores (<10 nm), capillary pores (<10 μm) and air voids (air entrained and entrapped pores). Although the gel pores do not influence the concrete strength, they are directly related to creep and shrinkage. On the other hand, capillary and other large pores are responsible for reduction in strength and elasticity [1]. In spite of this significant influence, evaluation of foamed concrete pore structure is seldom reported [6].

Nambiar and Ramamurthy [1] and Just and Middendorf [7] both mentioned that the pores of foamed concrete can be measured by

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several test methods such as: nitrogen gas absorption–desorption, optical microscopy with image processing, mercury porosimetry and X-ray computed tomography with image processing. In addition, for testing the pore structure and microstructure of foamed concrete, both scanning electron microscopy (SEM) and light microscopy combined with digital imaging were used by Yu et al. [6]. The results from both measurement techniques revealed that the pore diameters were mainly in the range of 100–200 μm.

In their investigation into the microstructure of foamed concrete produced with the inclusion of either classified (pfa) and unclassified (Pozz-fill) fly ash, Kearesely [5] concluded that there was no obvious difference between the void sizes observed in the two mixes and that for a 1500 kg/m^3 mix, the entrained air void diameters varied between approximately 40 and 300 μm.

Nambiar and Ramamurthy [1] also 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.

Thus, although the pore size distribution of foamed concrete has to some extent been investigated, a great deal remains to be understood, so this paper aims to investigate the formation of the voids during mixing. This is achieved by:

(1) Determining and comparing the size distributions of air voids in the foamed concrete mixes (after hardening) to those of bubbles in the preformed foam based on both number and area of bubbles/voids.
(2) Investigating the circularity of the voids within the mixes.

2. Experimental details

2.1. Constituent materials

The materials used were: ordinary Portland cement CEM I-52,5 N (3.15 S.G.) conforming to BS EN 197-1:2011 [8], natural fine aggregate (sand) (2.65 S.G.) conforming to BS 882:1992 [9], sieved to remove particles greater than 2.36 mm to help improve the flow characteristics and stability of the final product [10,11], potable water and foam. Three mixes of foamed concrete were made with nominal densities of 1300, 1600 and 1900 kg/m^3, designated FC3, FC6 and FC9. To achieve these target densities, the water cement ratios of these mixes were determined, by trials, ensuring the stability of the wet foamed concrete mix and also that the measured density was equal or nearly equal to the design density [12,13]. The materials required per m^3 of the selected mixes were calculated using the absolute volume method. An ordinary mixer was used to produce foamed concrete in the laboratory by the addition of preformed foam to a base mortar (sand-cement) mix. The required amount of foam was generated and added to the base mix and mixed until the foam was uniformly distributed and incorporated into the mix [12]. The mix proportions of the foamed concrete mixes investigated are given in Table 1 per m^3 of final concrete.

2.2. Specimen preparation

2.2.1. Foam

Pre-formed foam (at 45 kg/m^3) produced by blending a foaming agent, EABASSOC (1.05 S.G.), water and compressed air at predetermined proportions of 55: 1 (water: foaming agent by volume) in a foam generator. A STONEFOAM-4 generator was used in this study.

Table 1
Mix proportions of selected foamed concrete mixes.

	Mixes		
	FC3	FC6	FC9
Target density (kg/m^3)	1300	1600	1900
Cement content (kg/m^3)	500	500	500
W/C ratio	0.475	0.5	0.525
Water content (kg/m^3)	237.5	249.9	262.5
Sand content (kg/m^3)	562	850	1137.5
Foam (l/m^3)	424	295	166
Foaming agent (kg/m^3)	0.35	0.24	0.14

About a litre of foam has been taken from the foam generator and then put in a cylindrical plastic container (50 mm diameter and 20 mm height) for foam surface microscopic investigation. Due to the impossibility of capturing a clear image of the foam in its natural state using an optical microscope with low magnification, in was decided to impregnate it with a very small dose of bitumen emulsion, see Fig. 1. Bitumen emulsion was chosen since it contains carbon which, when using an optical microscope, gives an image of the free surface of the foam with good clarity and contrast between the edges and surfaces of individual foam bubbles, see Fig. 2. In addition, the production process of bitumen emulsion involves a surfactant (emulsifier) which surrounds individual bitumen droplets (of size <10 μm) within the water, which is essentially the same mechanism as used in foam production, see Fig. 3. The result is that the bitumen emulsion is compatible with the foam and spread easily through the bubble membranes, giving them colour.

2.2.2. Foamed concrete

For each foamed concrete mix, 3 slices (50 × 50 × 15 mm) were cut from the centres of three cured specimens, perpendicular to the cast face, and used for pore size investigation.

To make the boundaries between the air voids and the matrix sharp and easily distinguishable, the specimens were first polished and cleaned to remove any residues. Then, to enhance the contrast, the specimen surfaces were treated by applying two coats of permanent marker ink to them. After placing them in an oven at 50 °C for 4 h, a white powder (Sodium bicarbonate) with a minimum particle size 5 μm was pressed into the surfaces of the specimens and forced into the voids. This left the concrete surface black and the voids white, resulting in specimens with excellent properties for image analysis. This technique is described more fully in EN 480-1 [14,1].

2.3. Image capture, processing and analysis

A camera connected to an optical microscope and a computer was used to capture the images of both foam and foamed concrete mixes.

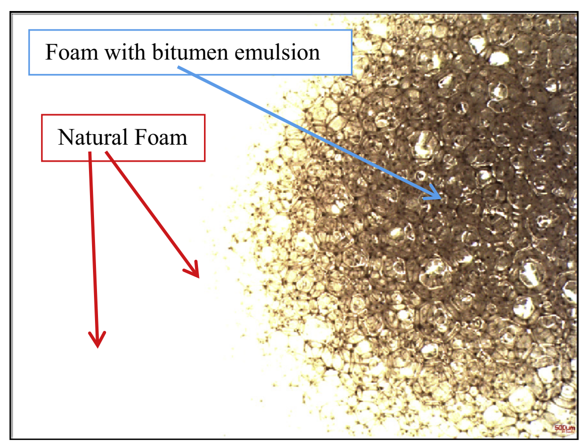

Fig. 1. Image of foam during bitumen emulsion application [15.43 mm × 11.57 mm].

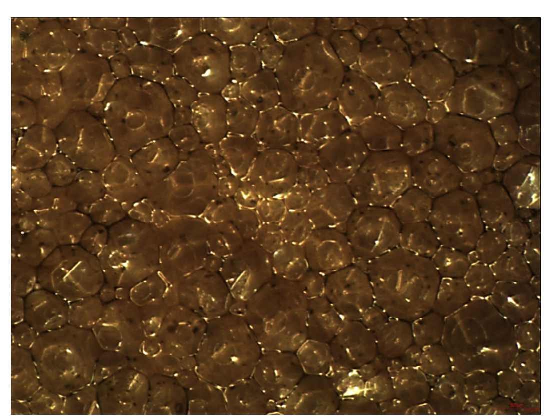

Fig. 2. Foam image of natural free top surface [6.14 mm × 4.60 mm].