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Air-void size distribution of cement based foam and its effect on thermal conductivity

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HIGHLIGHTS

- The air-void size distribution was evaluated with the help of X-ray Tomography (CT Scan) Technique.
- The air-void diameter of size 0.03 mm was optimal for all the mixes.
- The increase in median diameter value (D50) leads to a reduction in thermal conductivity.

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ABSTRACT

The study reported here characterizes the air-void size distribution in cement-based foam and examine its influence on thermal conductivity, density, and pozzolanic admixture. The cement-based foam was produced by replacing fly ash, silica fume, and metakaolin, up to 20% by weight, for densities range of 800–400 kg/m^3. Through, X-ray tomography technique the air-void distribution was evaluated while the thermal conductivity was measured using the transient plane source. The study results revealed that the air-void diameter of size 0.03 mm was optimal for all the mixes. Further, it was found that with an increase in the cast density, there was a drop in the median void diameter (D50) and for given density, the thermal conductivity decreases with an increase in the median void diameter. In addition, the data showed that the influence of pozzolanic admixture on the air-void size distribution was not significant.

1. Introduction

In recent years, the use of cement-based foam has noticeably increased due to their speed of production, easy compaction, low density, good insulation and with potential for utilization of industrial by-products such as mineral admixtures [1,2]. Cement-based foam comprises of Portland cement, water, and foam. The foam may be introduced either by adding surfactants to the mix constituents or by adding a "preformed foam" to the cement slurry. The cast density of such composites ranges between 300 and 1600 kg/m^3, the lighter densities (<800 kg/m^3) are attractive for thermal insulation purposes whereas, the heavier mixes are used for crash cushions, retaining walls, and fillers.

The thermal conductivity, which is a material property, has been subject to intensive study for decades especially for building materials. Past studies have reported the thermal conductivity of a cellular composite depend upon the volume fraction of its solid constituents and the geometrical distribution of the void phases [3,4]. In cement-based foam, the microstructure comprises of the solid phase representing the hydrated cement paste while the void phase denotes the air-void created by adding preformed foam to the mix. Note that the solid phase, which is composed of hydrated cement paste, is itself porous. The authors have previously illustrated the thermal conductivity of the solid phase which accounts for the inherent porosity in the hydrated cement paste [5].

Past research has characterized the air-void parameters and their influence on the strength [6–9] and density [6] of the cement-based foam. For instance, Nambiar and Ramamurthy [6] relate the median diameter, D50, with the strength of the foam composite. Similarly, Wei et al. (2013) [10] measured the air-void size for foamed concrete and reported an inverse relationship with porosity. These researchers reported air-void parameters as the properties influencing factor of cement-based foam. Although, the thermal properties of the cementitious system has been subject

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of intensive study for decades thus, so far hardly any study investigates the effect of the air-void size on the thermal conductivity of the cement-based system.

Previously researchers have employed the optical microscope and scanning electron microscope (SEM) to establish the microstructural parameters inside cement-based foams. These techniques may alter the microstructure details during sample preparation, especially for the lower densities. Recent advancements in X-ray tomography present a non-destructive technique through which the microstructural characterization of engineering materials has become possible [11–19]. X-ray tomography is a three-dimensional imaging technique that measures the internal structure of the material through its X-ray absorption [20]. In addition, this technique has certain specimen size limits due to the need for high-flux X-ray sources of narrow energy distribution, which increases with the larger specimen. Recently, Hoseini (2013) [19] identified the microstructure of cement-based foam and co-related it with the permeability property. Similarly, type of study was conducted by Bentz et al. (2000) [11] and Lu et al. (2006) [21] for bricks and concrete.

This study quantifies the air-void size distribution parameter and evaluates their influence on the thermal conductivity of the cement-based foam by using the X-ray tomography technique. The parameters associated with the air-void size distribution are related to the density, porosity, and pozzolanic admixture.

1.1. Research significance

The literature review reveals studies characterizing the air-void parameters and their influence on the mechanical and physical properties of the cement-based foam, but hardly any investigation explains the effect of the air-void network on the thermal conductivity. Moreover, the measurement techniques adopted by the past researchers alters the microstructure information of cement-based foam during the sample preparation. This paper report test results on the air-void size distribution for the cement-based foam generated through non-destructive technique. It is expected that this investigation will bridge the gap of knowledge and will lead to a better understanding of air-void parameters in general and its effect on conductivity in particular.

2. Experimental details

2.1. Materials and mix proportions

Three series of cement-based foams were prepared, with cast densities of 800 kg/m^3, 600 kg/m^{3,} and 400 kg/m^3. Type HE Portland cement conforming to CAN/CSA A3000 (2013) [22] was used in the preparation of the slurry to achieve immediate strength and enable demolding with a relative density of 3120 kg/m^3. Besides the reference mix containing Portland cement only, six other series were prepared by incorporating fly ash (FA), silica fume (SF) and metakaolin (MK) by replacing Portland cement with 10% and 20% by weight. Thus, in all 21 mixes were examined here as tabulated in Table 1. The fly ash met Class C-I, conforming to ASTM C618 (2012) [23] and silica fume conformed to ASTM C1240 (2012) [24].However, metakaolin conformed to ASTM C618 (2012) [23] Class N. The relative densities for fly ash, silica fume and metakaolin for this study are 2050,820 and 920 kg/m^3 respectively. The air-void network, created with the help of stable foam was prepared by using 3% solution of a synthetic foaming agent conforming to ASTM C869 (2011) [25]. The general description of ingredients in the foaming agent is found in [26]. In the production of cement-based foams, an optimal water-to-cementitious material ratio (w/cm) is desired. For, if the w/cm is too low, it leads to instability in the foam because of the binder's tendency to draw moisture away from the air bubble. Based on prior trials a w/binder ratio of 0.69 was used uniformly to prepare the slurry in this program, and it was found sufficient to render the cement-based foams workable.

2.2. Specimens

The cement-based foam mixes were prepared as follows. First, water was added to the cement (and the pozzolanic admixture, if any) to result in a slurry. Next, a stable foam was generated using a synthetic foaming agent mixed with water in a separate container. A mini ½ inch open air foam generating system activated by compressed air sourced at 0.70 MPa pressure was used to aerate the form to a density of 40 kg/m^3. Finally, this pre-formed foam was added gradually to the slurry in a rotating, inclined drum mixer. The mixing time was carefully monitored to avoid disturbing the internal air-void network through excessive agitation even as the foam was blended into the slurry. Moreover, the density of the resulting composite was checked intermittently until the desired cast density was reached. This initial density was determined by filling a small container of known weight and volume with cement-based foam from the mixer and measuring the change in weight. The resulting cement-based foam was cast into cylinders (150 mm × 75 mm) which were left covered with plastic sheets to avoid any loss of moisture. After 48 h these specimens were demoulded and stored in a water curing room and remain there at a controlled temperature of 22 ± 2 °C and humidity at 95 ± 5% for 28 days. Later all the samples were left for air drying at room temperature of 21 ± 2 °C with an average relative humidity of 65 ± 5%. Due to space limitation imposed by the scanning bed associated with X-ray tomography, square slices of size 35 mm × 35 mm × 20 mm were cut from these cylindrical specimens, as illustrated in Fig. 1. Thus, a total of 21 samples were prepared for X-ray tomography scanning and CT images were recorded at hydration age of 300th day.

2.3. Micro computed X-ray tomography (μCT)

The tomographic technique works by directing the X-rays through the specimen and collecting a large number of images from discrete viewing angles. The specimen is rotated around a single axis with an angular increment between 0° and 180° by using a rotating stage that keeps the axis of rotation perpendicular to the X-ray beam [19],[27]. A specialized algorithm was used to reconstruct the distribution of X-ray in the slice plane and as a result, the stack of 2D μCT images was obtained.

Fig. 2 shows the experimental setup of Skyscan 1076 X-ray computed tomography machine used for this study. This machine consists of a high-performance micro-CT scanner with X-ray source supply of 20–100 kV and X-ray detector of 4000 x 2672 pixels size. After preliminary trials, the X-ray voltage, and electric current were set at 100 kV and 100 μA, respectively. These settings were deemed suitable for the porous material and enabled 2D projections through a 1.0 mm aluminum filter, resulting in a spatial resolution of 9 μm. The SkyScan NRecon software reconstructs the μCT images (raw images). A total of 1500 reconstructed images referred to as the "image-dataset" were captured from within a width of 14 mm, as shown in Fig. 1.

Once the raw images were obtained, the 2D quantitative analysis of the air-void structure within the cement-based foam specimens was done by using the Skyscan CT-analyzer software. The image dataset of reconstructed raw images was loaded in the software as shown in Fig. 3a. Then those raw images were processed by first selecting a fixed circular region of interest (Fig. 3b). That selected region of the images was converted to a binary format