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Mechanical characterization and inclusion based boundary element modeling of lightweight concrete containing foam particles

G. Song, L. Wang, L. Deng, H.M. Yin [*]

Department of Civil Engineering and Engineering Mechanics, Columbia University, 610 Seeley W. Mudd 500 West 120th Street, New York, NY 10027, United States

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ABSTRACT

This paper investigates the effective material properties of lightweight concrete containing polymer foam particles through both experiments and numerical modeling. Different volume fractions of foam particles have been added to cement paste to fabricate lightweight concrete samples. To interpret the experimental results, an inclusion method based boundary integral equation has been proposed. The effect of the material mismatch between the foam particles and the cement matrix can be simulated by an eigenstrain, which is a fictitious nonmechanical strain. Due to the interaction between particles and boundary effect, the eigenstrain on a particle is not uniform. An asymptotic analysis shows that a quadratic distribution of the eigenstrain over each particle provides very good accuracy. Since the discretization of particles is not needed due to applying an analytic form of eigenstrain field, a large number of spherical inhomogeneities can be simulated and the local field can be calculated in a lightweight concrete sample. The formulation has been implemented in a software package for the simulation of material samples and has been verified with the finite element method for two top-down particles embedded in a cylinder. The simulation results based on idealized microstructure exhibit a very good agreement with the experimental results of the effective elastic moduli. A simple and empirical study also predicts the strengths of the composites very well. The developed algorithm can be used for virtual mechanical experiments of particulate composites.

1. Introduction

Structural lightweight concrete (LWC) has an in-place density on the order of 90–115 lb/ft^3 which is smaller than normal weight concrete with a density in the range of 140–150 lb/ft^3. The primary use of structural lightweight concrete is to reduce the dead load of a concrete structure, so that the structural designers can reduce the size of columns, beams and other load bearing elements. While lightweight concrete may cost more per cubic yard than normal weight concrete, the total structure may cost less as a result of reduced size of load bearing elements and lower foundation costs (ACI, 1967). Lightweight concrete is mainly classified into two groups: lightweight aggregate concrete (LWAC) and autoclaved aerated concrete (AAC). Many types of lightweight aggregates are used in industry manufacture. The early lightweight aggregates (LWAs) were made of natural volcanics, such as pumice, scoria, tuff, etc. The Lightweight aggregate concrete can be expensive but it still exhibits a relatively high strength compared with another type of lightweight concrete, autoclaved aerated concrete. Autoclaved aerated concrete (AAC) is commonly manufactured from a mixture of portland

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[*] Corresponding author. Tel.: +1 212 851 1648; fax: +1 212 854 6267.
E-mail address: yin@civil.columbia.edu (H.M. Yin).

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cement, fly ash (or other sources of silica), quick lime, gypsum, water, and aluminum powder or paste (Bonakdar et al., 2013) and its strength can be significantly lower than the LWAC alternative.

Recent researchers in lightweight concrete have used recycled polymer foams, for example, expanded polyethylene (Perevozchikov et al., 2000), expanded polystyrene (Laukaitis et al., 2005) and polyurethanes (Mounanga et al., 2008), as an aggregate to produce lightweight concrete. Generally, commingled plastic waste (CPW) is difficult to recycle due to contamination, variability in composition and incompatibility of the various plastics in the waste stream. However it can be used as concrete aggregate, which does not involve the intimate human contact of consumer products. Using the CPW foam particles for lightweight concrete not only provides one way to reduce the concrete density, but also makes it possible to tailor the thermal resistance, acoustic insulation, and durability of the structural components. This technology requires a method to produce foam from commingled plastic waste, accomplished by the variability of plastic waste stream compositions. There exist two basic types of blowing agents to produce polymeric foams (Eaves, 2004). Chemical blowing agents undergo a chemical reaction to produce a gas that causes foaming. Physical blowing agents do not take part in a chemical reaction, but volatile liquids evaporate and make the foam expand. First generation physical blowing agents are mostly outruled because of their negative environmental impact on the ozone layer.

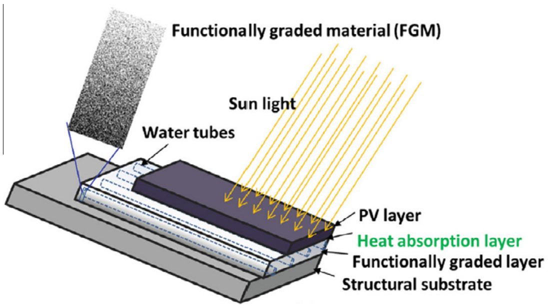

Fig. 1. Schematic illustration of the hybrid solar roofing panel prototype.

The present research is motivated by manufacturing a hybrid solar roofing panel as Fig. 1 (Yin et al., 2013; Yang et al., 2012; Yang and Yin, 2011). It includes a substrate made of a lightweight concrete panel to provide structural support to the roof load, above which is a functionally graded material layer with gradient thermal conductivity in the thickness direction, which gradually transitions from a well conductive side attached with PV solar cells laminated by a protective layer to another highly insulative side bonded to the lightweight concrete substrate. The water flowing through the FGM layer cools down photovoltaic (PV) cells and harvests the solar heat. Consequently, the efficiency of PV cell is improved while working under a moderate temperature condition; and the water flow through the FGM layer is useful for preheated water systems. The mechanical properties of the lightweight concrete panel are key parameters in panel design and manufacture.

This paper investigates the effect of the volume fraction of polymer foam particles on the effective material properties of lightweight concrete. For simplicity and consistency of the tests, Elemix XE concrete additive foam particles have been used in all tests. Because the mechanical loading resistance of foam particles is very low, this lightweight concrete could be treated as an aerated concrete. Compared with traditional AAC manufactured by chemical processes, this lightweight concrete is more environment-friendly and affordable in manufacturing. By mixing the cement paste with foamed polymeric particles, which have a very minimal or negligible cost, a lightweight concrete can be manufactured without any chemical reaction with additives and environmental costs. Moreover, its volume fraction can be easily controlled by weighting the polymer and cement; in contrast, it is very difficult to control the void ratio in AAC. So the variation in quality is significantly reduced compared with traditional AAC.

Previous studies on the effective elastic modulus and strength of lightweight concrete are basically about to simply develop empirical formulas by curve fitting the experimental results (Kockal and Ozturan, 2011; Zhang and Gjvorv, 1991; Yasar et al., 2003). Even though much data is available for lightweight aerated concrete, only very few analytical or numerical models exist in the literature to describe the effective mechanical behavior of this porous material due to the difficulty in simulating large number of the particles and the complexity of boundary conditions in a specific finite domain.

Micromechanics-based modeling provides an effective approach to correlating the effective material behavior with the microstructural parameters of composite materials. This lightweight concrete can be treated as a two-phase composite material with the foam particles as dispersed inhomogeneities and cement as the matrix. Given a composite specimen, one can apply a test load on the boundary, which is generally a uniform stress or displacement, to characterize the effective mechanical properties. At the macroscale, the composite can be considered as a homogeneous material; whereas at the microscale, the microstructure is heterogeneous. A representative volume element (RVE) (Hill, 1963; Willis, 1981; Mura, 1987; Nemat-Nasser and Hori, 1999) can be used to correlate the effective material behavior at the macroscale to the local mechanical field at the microscale. An RVE for a material point of a continuous mass is a material volume which is statistically representative of the mircostructure in the neighborhood of the infinitesimal material point. The microstructure can be periodic (Yin et al., 2002; Xia et al., 2003; Yin and Sun, 2005), random, or even a functionally graded materials (Reiter et al., 1997; Yin et al., 2004, 2007). Most classical approaches are to investigate the mechanical response of this RVE when far field stress or strain is applied (Eshelby, 1957; Eshelby, 1959). In other words, it assumes that the composite material size is much larger than the particles (Mura, 1987; Nemat-Nasser and Hori, 1999).

Many micromechanical formulas have been proposed to predict the effective elastic modulus of composites with different volume fractions. For the Voigt model (Voigt, 1889), it