Construction and Building Materials 59 (2014) 180–187

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Numerical model for mechanical behavior of lightweight concrete and for the prediction of local stress concentration

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HIGHLIGHTS

- A numerical model of lightweight concrete which respect a granular model.
- Influence of Young's modulus contrast in mechanical behavior of lightweight concretes.
- Tensile and compressive stresses around lightweight aggregates identified.
- Hypothesis of rupture only in mortar for lightweight concretes studied.

ARTICLE INFO

Article history:
Received 21 August 2013
Received in revised form 21 January 2014
Accepted 24 January 2014
Available online 19 March 2014

Keywords:
Numerical modelization
Lightweight concrete
Compressive strength prediction

ABSTRACT

In this study a numerical approach to simulate elastic behavior of lightweight concrete, is presented, at mesoscopic level. Concrete is considered as a bi-phasic material, composed of a granular skeleton dispersed in a mortar. Aggregates generation should respect a granular model where a maximum distance between aggregates is imposed. The granular media is also defined by a granular curve and a compacity. A numerical concrete sample is carried out, using three-dimensional finite element mesh. Here lightweight concretes are considered, where Young's modulus of natural sand based mortar is higher than the modulus of the lightweight coarse aggregates. Different concretes are carried out, according to experimental studies from literature, in order to distinguish the influence of Young's modulus contrast, and of the concrete compacity, on mechanical behavior. Then numerical compressive tests are realized until an experimental value of compressive strength, and the local stress and strain distribution around aggregates is studied, still remaining in the elastic domain. According to these results, breaking of this kind of concrete occurs when the maximum strain is reached in the lightweight aggregates surrounded mortar.

1. Introduction

At mesoscopic level, concrete could be described as a group of aggregates (inclusions) surrounded by a continued phase (matrix). In our model, this phase is considered as the mortar, and the inclusions are only the coarse aggregates. The elastic mechanical behavior of this composite depends both on material and structural properties:

- the elastic modulus for the inclusions and the matrix respectively,
- the volume fraction for both the inclusions and the matrix,
- the shape of inclusions,
- the granular distribution of the inclusions,
- the realistic location of the inclusions in the composite material.

The characterization of the elastic behavior of concrete, must be divided in two parts. First, the determination of a homogeneous elastic behavior is overall influenced by the two first parameter listed above. Several results have been carried out on this way, by analytical homogenization methods based on the representative volume element behavior and related to the hydrostatic forces as the Hashin and Shtrikman bounds [1], the two-sphere model proposed by Hashin [2] and the three-sphere model introduced by De Larrard [3] and Le Roy [4]. These models are less accurate when the contrast between the moduli of the inclusions and the matrix is important especially when the phenomenon of creep in the matrix

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http://dx.doi.org/10.1016/j.conbuildmat.2014.01.067
0950-0618/

leads to important drop of the modulus as shown in [5]. More sophisticated homogenization models based on the tensor of Eshelby [6] consider the shape of the particles (spheres for the Mori–Tanaka model [7,8] or polygonal shapes for the auto coherent model [9]) and allow to apply any stress field on the VER. In a previous work [10], a homogeneous elastic modulus of concrete was determined by a numerical model and compared with the analytical homogenization model [7].

On the other hand, the estimation of local stress concentration around aggregates, needs to characterize accurately the elastic behavior. For that, the shape, the granular distribution and the location of inclusions must be taken into account. In this case, numerical approaches take the place of analytical ones. Numerical models, based on three-dimensional microstructures, obtained by microtomography, are among the more accurate for the representation of a realistic granular skeleton [5]. The classical finite element approaches, allow to describe a material with at most a thousand of inclusions. Indeed, the high number of finite elements needed for the discretization, tends to limit the number of aggregates represented in a concrete sample. Finally, concrete could be described as a granular skeleton based on coarse aggregates and embedded in a mortar compound by a cement paste and sand [11,12]. Aggregates are rather represented as spheres, dispersed randomly in the mortar [12–15]. In order to represent the mesostructure in a realistic way, a granular model could be adopted [16]. In this model, called the "De Larrard model", a thickness is imposed between coarse aggregates [17,18].

The purpose of this paper, is to propose a numerical model which gives a characterization of the mechanical behavior of these lightweight concretes. This kind of mesoscopic description, is particularly well suited to concrete constituted by low rigid lightweight coarse aggregates, coated with a more rigid mortar based on natural sand. These families of lightweight concretes, are useful to reduce thermal bridge in the concrete structure [19]. Rupture mechanics on lightweight concrete, have provided various studies and interpretations in literature. Unlike traditional concretes, some studies observed compression rupture inside aggregates [20–23]. Others explained the rupture by the tensile stress concentration on the top of aggregates [24]. On the other hand, works of De Larrard [3], proposed a model with a perfect interface between mortar and aggregates, and supposed that the rupture was induced by compression inside mortar. An experimental study [25] showed that three ruptures modes, binded to the ratio between Young's modulus of aggregate and mortar, could be observed:

- tension rupture inside the bond aggregate/mortar for important ratios,
- compression rupture inside the mortar and the aggregates for intermediate ratios,
- compression rupture inside the aggregates for low ratios.

Experimental values of mechanical properties, provided by [21–23], will be used on the following to calibrate the numerical model.

In a first time, a numerical generation of different concrete samples, will be carried out, taking into account the granular model of De Larrard [16]. Lightweight concrete samples, will be considered as bi-phasic material, with a perfect mechanical link between aggregates and mortar. In a second time, using a finite element software, numerical simulation will be realized, based on experimental data quoted previously, in order to visualize the repartition of the principal stresses and strains inside mortar and aggregates, and in a geometrical transition zone between aggregates and mortar, called transition zone in the following. An interpretation of the rupture mode will be proposed, from the numerical results.

2. Material and methods

2.1. Generation of concrete

Numerical generation of concrete, is carried out with an open platform called "LMGC90", developed at the University of Montpellier [26]. The numerical concrete sample generated, should respect both the granular model of "De Larrard" [16] and a granular curve imposed. Let us first briefly recall the main properties of the granular model.

2.1.1. Granular model of "De Larrard"

This model requires to respect a distance between two adjacent coarse aggregates, in order to save the granular skeleton from the segregation phenomenon and optimize the compacity. This distance, called the Maximum Mortar Thickness (*MMT*), see Fig. 1, depends on the compacity of a sample, called g, and the virtual compacity, g^*. Compacity g is the ratio between the volume of aggregates, V_{agg}, and the total volume of a sample, V, such as:

$$g = \frac{V_{agg}}{V} \tag{1}$$

The virtual compacity is defined as the maximum density for a given mixture, and its expression for rounded aggregates, as lightweight aggregates, is defined in [16] as:

$$g^* = 1 - 0.47\left(\frac{d_{min}}{d_{max}}\right)^{0.22} \tag{2}$$

where d_{min} and d_{max} are the minimum and maximum aggregates' diameter.

The distance MMT is depending on g, g^* and d_{max} by the mathematical relationship:

$$MMT = d_{max}\left(\sqrt[3]{\frac{g^*}{g}} - 1\right) \tag{3}$$

2.1.2. Generation of a granular curve

As explained previously, the granular skeleton generated, needs to respect a granular curve, depending on the spreading and the shape of volume distribution. A method to generate this curve has been proposed by [27], based on the mathematical theory of distribution functions, and applied to granular media. A cumulative distribution function β is used, defined by the Eq. (4):

$$\beta(d_r, a, b) = \frac{1}{B(a,b)}\int_0^{d_r} t^{a-1}(-t)^{b-1}dt \quad \text{with} \quad a > 0, b > 0 \tag{4}$$

where a and b are the parameters of the distribution allowing to control the shape of the granular curve. The variable d_r is the reduced parameter, defined as follow:

$$d_r = \frac{d - d_{min}}{d_{max} - d_{min}} \tag{5}$$

with d the aggregate diameter. The function $B(a,b)$ is a weight function, according to distribution theory. The different shapes of the cumulative function β are represented by Fig. 2.

2.1.3. Generation of concrete at mesoscale level

The generation of concrete at mesoscale level, is now performed, according to

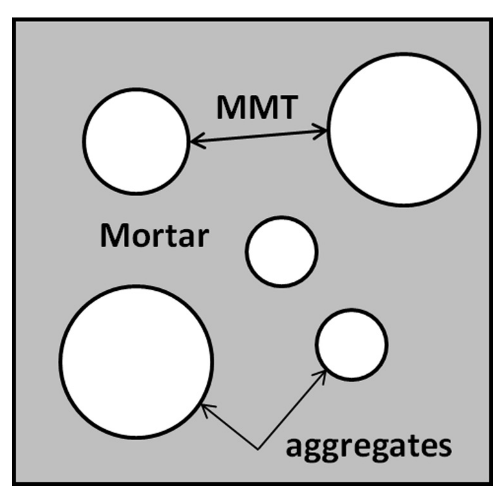

Fig. 1. Maximum mortar thickness between two aggregates.