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Composite behavior of concrete materials under high temperatures

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ABSTRACT

This study examines the performance of concrete under elevated temperatures at the meso-scale level of observation where aggregate particles and the embedding hydrated cement paste form interacting continua. Decomposing concrete into these two constituents leads to mismatch of the thermal and hydraulic transport properties and hence to self-equilibrating internal stresses introducing progressive damage of the mechanical response behavior of concrete. Thereby the internal stresses are disregarded by the macro-scale level approach when the heterogeneities are replaced by equivalent effective material properties using homogenization. In other terms, the macroscopic approach eliminates the contrast among the individual constituents and consequently negates the development of stresses causing pervasive microcracking in concrete.

The current study resolves concrete into its main components, the aggregate particles and the cement paste, bonded by a weak interface transition zone that reduces to some extent the mismatch between the two constituents. The study illustrates the magnitude of the stress state in representative concrete specimens and the resulting damage evolution under high temperatures.

1. Introduction

Although traditional engineering studies consider concrete as a homogeneous material, with effective (homogenized) properties (macroscopic approach), concrete is a highly heterogeneous material and its composite behavior is exceedingly complex. In Wittmann (1983) three levels of observations have been proposed for concrete: the microscopic level at the micro-meter scale, the mesoscopic level at the mm-cm scale and the macroscopic level at the meter scale. With regard to the macroscale, most of the research reported in literature assumes phenomenological relationships based on macroscopic observations. Even if this approach implies a series of simplifications, the use of continuum-type constitutive models renders a satisfactory description of the basic features of the mechanical behavior of concrete.

A more profound understanding of the macroscopic constitutive behavior of concrete is necessary, which can be reached at the mesoscale (Contri et al., 1983; Contri and Schrefler, 1984), also thanks to upgraded computer resources. Hence concrete becomes a mixture of cement paste, aggregates of different sizes and a thin layer of matrix material surrounding each inclusion, that is more porous than the bulk of the surrounding cement paste matrix. This layer is named interfacial transition zone (ITZ) (Scrivener, 1989, 1999; Bentz et al., 1992, 1993; Scrivener and Pratt, 1996; Scrivener and Nemati, 1996; Garboczi et al., 2000; Scrivener et al., 2004) and has relevant effects on the properties of concrete, being likely to act as the "weak link in the chain" when compared to the bulk cement paste and the aggregate particles.

A third level of observation is the microscopic one, in which the internal structure of the hardened cement paste or the ITZ is studied. At this level chemical processes during hydration and drying are significant features. Moreover, thanks to new development techniques such as nanoindentation or TEN (transmission electron microscope), concrete can be studied at a fourth level, i.e. the nanoscale.

In this paper a mesoscale approach is being followed, which provides a more realistic description of concrete and inherent stresses than the macroscale, influenced by the geometry and the properties of its multiple constituents. This could be expected, since the observed macroscopic behavior is a direct consequence of the phenomena which take place at the level of the material heterogeneities.

A thorough knowledge of concrete at the mesoscale level is in fact essential for a better understanding of specific processes in concrete, especially those where the aggregate performance and

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their thermal properties play a crucial role, e.g. for spalling (Khoury and Anderberg, 2000; Majorana et al., 2010). Spalling corresponds to the ablation of concrete segments from the surface of a structural element when it is exposed to high and rapidly rising temperatures. Many informations on this phenomenon, particularly on explosive spalling, have been obtained after damage caused by fire in tunnels, such as the Danish Great Belt one, the Channel Tunnel, Mont Blanc and Tauern tunnels.

Concrete properties and thermal response depend on its constituents characteristics, which can be significantly altered when exposed to high temperatures. Generally it can be said that concrete has good properties with respect to fire resistance; however the high temperature gradients and the hygral conditions developing during a fire can result in concrete spalling. Consequently, the reduction in cross-section reduces the load bearing area and hence the capacity.

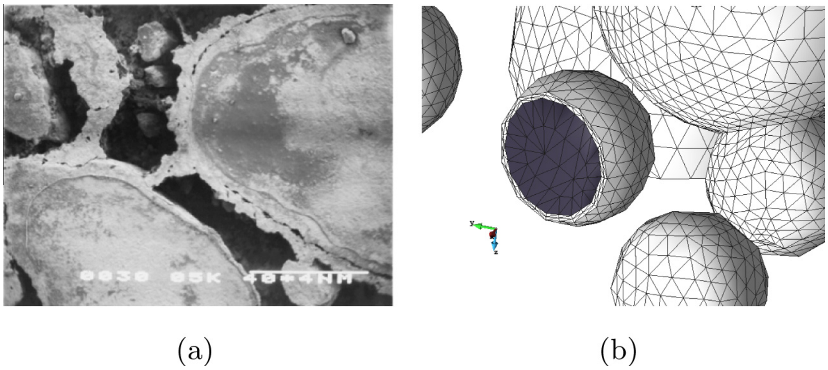
In this paper, two-dimensional macroscale studies are compared with corresponding mesoscale ones. Subsequently the effect of concrete components characterized by different porosities is investigated considering 3D mesoscale models, in order to capture the distinct damage scenarios related to different inclusion types and hence to understand the role of aggregate porosity on spalling when concrete is exposed to elevated temperatures. For this purpose a 3D fully coupled thermo-hygro-mechanical model of heated concrete is adopted and through this model each single composite constituent can be approached and fully characterized as a multiphase material.

In this F.E. code (Majorana et al., 1998; Xotta et al., 2013), concrete is treated as a multi-phase system, where the voids of the skeleton are partly filled with liquid and partly with a gas phase. As regards the mechanical field, the code couples creep, shrinkage and damage. Thereby, it is assumed that concrete creep and damage are associated to the cement paste and ITZ and that concrete creep may be described by the B3 model (Bažant and Baweja, 2000; ACI Committee 209, 2008), whereas damage by the Mazars' damage law with non-local correction (Mazars and Pijaudier-Cabot, 1989; Pijaudier-Cabot and Bažant, 1987).

2. ITZ characterization

Cement grain sizes range from less than a micron up to 100 microns, while aggregates are several orders of magnitude larger. This difference of size implies that the aggregate particle is an obstacle, which disrupts the packing of cement grains, resulting in the so called “wall effect” (Scrivener et al., 2004). The origin of the ITZ lies in this “wall effect” of packing against the relatively flat aggregate surface. The result is that the zone closest to the aggregate contains small grains and has a significantly higher porosity (often about two or three times larger than the cement paste), while larger grains are found farther away. This means that the size of the ITZ is comparable with the size of cement grains and that, since packing is a random process, each individual region of ITZ will be different. Anyway its thickness is typically in the range of $15 - 50\,\mu m$ (Garboczi et al., 2000), according to numerous researchers. In this study the ITZ has been assumed to be homogeneous and with a constant thickness around the grains, strictly linked to the diameter of each aggregate (thicker for larger diameters), see Fig. 1.

This increased porosity around the aggregates promotes also the deposition of more calcium hydroxide in this zone (Garboczi


(a)

(b)

Fig. 1. (a) ITZ formation (Nemati and Monteiro, 1997); (b) Numerical simulation of ITZ layer.

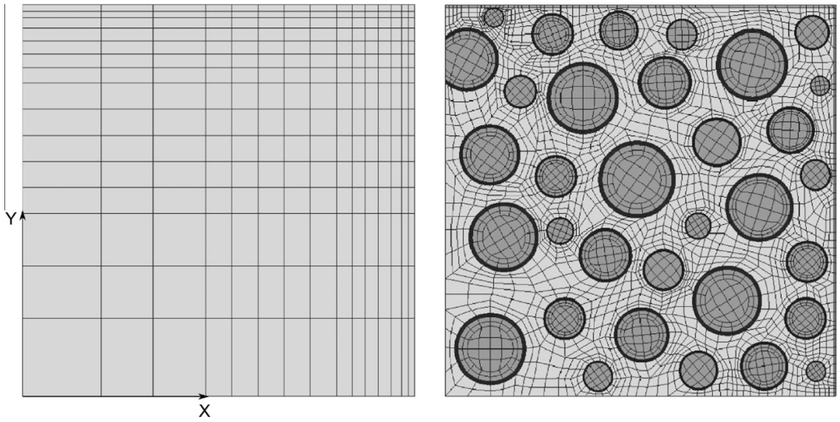


Fig. 2. Adopted discretization for the 1/4 macro and meso-scale samples.