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Constitutive theory for Recycled Aggregate Concretes subjected to high temperature

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HIGHLIGHTS

- A thermodynamically consistent gradient poroplastic model is proposed.
- The RAC effect is considered by a concrete mixture recycling factor.
- Numerical results demonstrate good accuracy to predict failure behavior.

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ABSTRACT

The use of recycled aggregates in concrete to partially substitute the natural ones has strongly increased in the last decades. Due to both, environmental and economical reasons, a relevant and increasing proportion of the concrete production in the developed countries is currently based on combinations between recycled and natural aggregates. As a result, a more eco-friendly constructive material is obtained which has gained significant impact in the construction market. Consequently, there is a need for accurate constitutive theories for predicting the mechanical behavior of Recycled Aggregate Concretes (RAC) subjected to severe loading conditions such as high temperature. In this work, a non-local gradient poroplastic material model is formulated for RAC composed by arbitrary proportions of recycled aggregates, when they are affected by long term exposures to high temperature. The model takes into account through one single parameter, the so-called *concrete mixture recycling factor*, the influence of the recycled aggregates proportion on the temperature-dependent yield condition, the local hardening/softening laws and the volumetric non-associativity. The last one accounts for the particular behavior of the plastic volumetric strains of RAC. The proposed dissipative constitutive theory is fully consistent with the thermodynamic laws. The predictive capabilities of the proposed constitutive formulation have been tested against experimental results on RAC specimens considering variable amounts of recycled aggregates in both, tensile and compressive regimes. Finally, the influence of the recycled aggregate inclusion and of its participation proportion on the localization properties and on the fundamental failure indicators is evaluated.

1. Introduction

Climate change and global warming represent important topics in the field of the so called *Climate Change Science*. Starting from 1992, several countries joined into an international cooperation through the United Nations Framework Convention on Climate Change (UNFCCC) group, to synergistically adopt actions to limit the global temperature increase and to mitigate the resulting climate change. One of the main objectives of the UNFCCC is to control Greenhouse Gas Concentrations (GGC) in the atmosphere to prevent dangerous interference with the climate system, see Bjornberg [1].

Nowadays, the construction sector is one of the industrial activities that more resources and energy consumes. Particularly, according to recent surveys, emissions of GGC due to the concrete industry correspond to about 10% of the total, and almost the half of this proportion is due to the cement production [2]. To enhance the sustainability of this sector, the design of integrated recycling processes aimed to reducing wastes and to produce new *eco-friendly* materials is of particular interest, see a.o. Proske et al. [3].

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As a matter of fact, the possible production of concrete with recycled constituents (not only aggregates, but also alternative binders and/or natural fibers) is a feasible solution to reduce the environmental impact of the construction industry. Recently, numerous researches have addressed the possible structural use of concrete buildings manufactured with recycled aggregates, see a.o. Breccolotti and Materazzi [4], Li [5]. Moreover, several national and international codes have contributed to improve the knowledge of the use of such concretes in building constructions, see a. o. RILEM-TC-121-DRG [6] and NTC-2008 [7]. On the other hand, in the last years numerous experimental tests aimed at investigating the physical, mechanical and durability proprieties of concrete incorporating recycled aggregates have been performed, a.o. by Kou and Poon [8] and Folino and Xargay [9]. These studies have demonstrated that some mechanical properties of RAC may be generally lower than those of Natural Aggregate Concrete (NAC), however they are still sufficient for structural uses in civil constructions.

In recent years, the performance of RAC subjected to long term exposure to high temperatures and fire has became a subject of increasing interest in the scientific community. Thereby, the attention is focused on the evaluation and prediction of the mechanical property degradations of this material and the main differences with those of NAC. For instance, studies on the compressive mechanical capabilities of RAC subjected to elevated temperatures have been made a.o. by Zega and Di Maio [10] and Guo et al. [11]. A full review of the state of the art of the subject has been done by Cree et al. [12]. In all cases, the experimental evidence shows that the degradation of the mechanical properties of RAC under increasing temperature (compressive strength, tensile strength and elasticity modulus) is considerably more important than those of NAC.

From the numerical point of view, some constitutive formulations have been proposed to predict the mechanical behavior of RAC based on empirical considerations and mainly related to the compressive stress–strain relationships, see a.o. Du et al. [13]. Another formulation based on microplane theory has been developed by Li et al. [14]. In fact, none of the recent proposals can accurately reproduce the entire spectrum of possible failure modes of RAC subjected to arbitrary temperatures and for arbitrary proportions of recycled aggregates.

In this work a thermodynamically consistent gradient poroplastic material model is proposed to predict the mechanical response of RAC subjected to long term exposures of elevated temperatures and for all possible stress path, considering variable amounts of recycled aggregates into the cementitious material. A reformulation of the so-called temperature-dependent Leon–Drucker–Prager (TD-LDP) model for NAC by Ripani et al. [15], based on non-local gradient and fracture energy-based concepts is proposed to account for the recycled aggregate content and of its effect on the pre-peak stiffness, maximum strength capacity and post-peak regime, as well as on the inelastic dilatancy, when subjected to coupled thermo-mechanical actions. To account for the thermal degradation, and following Coussy [16], frozen entropy is incorporated, which describes the thermo-mechanic softening behavior. An isotropic and local hardening formulation that turns non-local in the softening regime is also accounted. Particularly, the strength decohesion in post-peak regime is controlled by two independent mechanism: (i) micro o macrocracking process, described by a fracture energy-based plasticity formulation according to Willam et al. [17] and Etse and Willam [18]; and (ii) degradation of the continuum or material located in between cracks, formulated by means of the gradient-based non-local plasticity based on Vrech and Etse [19]. Two characteristic lengths are included, one related to the fracture energy released in the active cracks during coupled thermo-mechanical processes and the other related to the gradient-based formulation. To realistically reproduce the strong dependence of concrete failure modes on the acting confining pressure, temperature and initial porosity, both characteristic lengths are defined in terms of these variables.

The effects of the recycled aggregates and of the eventual presence of fly ash in the overall mechanical response behavior of RAC is taken into account by means of the so-called concrete mixture recycling factor which is introduced in the re-formulation of the hardening and softening laws, the maximum strength criterion and the non-associativity.

Fundamentals of the RAC mechanical behavior under room and high temperatures are described in Section 2. Basic assumptions of the constitutive theory and its formulation are highlighted in Sections 3 and 4. Section 5 reports the extension of the general constitutive gradient and fracture-based theory to account for RAC, which is the key contribution of this paper. Analysis of the numerical predictions of the proposed model is included in Section 7. Thereby, comparisons of the performances of the localization indicators for RAC and NAC are also included to illustrate the fundamental differences between the mechanical degradations in these two materials due to the combined action of temperature and mechanical loading. Finally the concluding remarks are discussed in Section 8.

2. Mechanical behavior of RAC

Experimental results on RAC samples in the literature, composed by different proportions of recycled aggregates lead to the following main conclusions regarding the mechanical response behavior of RAC. Under room temperature conditions, the failure behavior of RAC samples in the uniaxial compression test shows four main differences compared with that of the NAC, as follows: (i) reduced stiffness; (ii) smaller maximum strength; (iii) smaller ductility in post-peak regime, or smaller fracture energy; (iv) higher lateral deformation. This follows from the results by Rahal [20], Casuccio et al. [21], Folino and Xargay [9] and Lima et al. [22]. The last reference concludes also that the partial substitution of the finest portion of aggregates with fly ash, may lead to important increments of the uniaxial compressive strength of RAC, turning it similar to that of NAC. However, and due to the delayed binding action provided by the fly ash, the higher the content of this addition, the longer the time needed to achieve the maximum strength. Regarding the deformation capabilities of RAC, particularly the experimental campaign by Folino and Xargay [9] demonstrates that it considerably increases with the level of recycled concrete addition and this effect starts already in pre-peak regime. The inelastic volumetric expansion after peak reaches similar val-

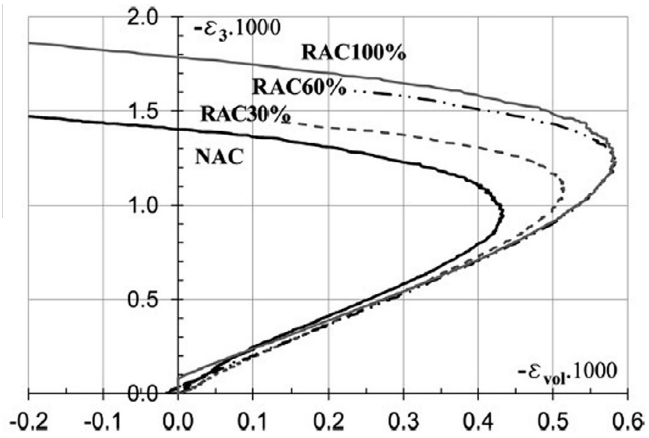

Fig. 1. Uniaxial compression: axial stresses vs. volumetric strain obtained from Folino and Xargay [9].