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Hardened behavior of mortar based on recycled aggregate: Influence of saturation state at macro- and microscopic scales

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HIGHLIGHTS

- Effect limits the strength of RCA can be identified by using the De Larrard's approach.
- Microstructure of RAC can be analyzed by image analysis and nano-indentation test.
- Initial moisture content of recycled sand little affect on mortar's hardened behavior.

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ABSTRACT

The influence of saturation state of recycled concrete aggregate (RCA) on the hardened behavior of mortar was investigated at macroscopic and microscopic scales.

At the macroscopic scale, a good adhesion between the RCA and the new cement matrix at 28 days of hydration is observed. However due to its intrinsic strength; a limiting effect of the RCA is found in comparison to natural aggregates (NA). This effect limits the strength of mortars for small values of effective water to cement ratio. In parallel, a low influence of moisture condition of used RCA on the mechanical properties is observed.

The microstructure of interfacial transition zone (ITZ) is characterized by image analysis of backscatter scanning electron microscopy (SEM) images at 2 and 28 days of hydration and nano-indentation test under SEM at 28 days of hydration. For mortars based on RCA, the average porosities in the ITZ of mortars with dried and over-saturated aggregates are identical. But the saturation state of aggregates has a significant influence on the distribution of porosity in the ITZ. The porosity in the ITZ of mortars containing RCA is larger than that of mortars made with NA. This difference can be explained by a higher effective water to cement ratio in the mortar based on RCA. This excess may be due to a lower value of absorption of RCA than that provided by the absorption estimated on RCA. The nano-indentation test under the SEM shows that the initial saturation state of recycled sand (dry or over-saturated) does not influence the micro-hardness of the new cement matrix.

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1. Introduction

The construction industry is a large consumer of natural resources. In the same time, it generates large amounts of construction and demolition wastes that eventually end up in landfills without any form of recovery. According to the European Union directive 2008/98/EC, one aim is to increase recycling of construction and demolition waste to at least 70% by the year 2020 [1]. The recycled concrete aggregates (RCA) have the potential to replace natural resources however it is necessary to assess the effect of recycled aggregates on the final concrete.

RCA are composed of a mixture of natural aggregates roughly coated with hardened cement paste. The presence of cement paste which is very porous leads to a greater absorption of water that must be taken into account in the formulation of concrete. In concrete, the amount of water available for cement hydration, the quality of the bond zone between aggregates and cement paste and the quality of the RCA strongly influence the mechanical properties.

The quality of this bond zone depends on the presence or not, between the aggregate and the bulk cement paste, of a more porous cement paste zone than the bulk paste called interfacial tran-

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sition zone (ITZ). Several authors [2–5] have studied in details, experimentally and numerically, the microstructure of the ITZ, its formation mechanisms and its properties.

The ITZ is constituted by a cement paste with a microstructure gradient between the bulk cement paste and the aggregate: the porosity and the Portlandite content increases in the ITZ from the bulk cement paste to the aggregate surface. This microstructure gradient is mainly the consequence of the "wall effect" exerted by the aggregate on the fine cement particles. Because of this "wall effect" the initial cement content decreases and respectively the water content increases from the bulk cement paste to the aggregate surface. The thickness of the disturbed area by the "wall effect" is of several tens of microns and corresponds to the initial thickness of the ITZ. During the hardening and because of a filling of the porosity by the hydrated products the depth of the ITZ generally decreases. A mechanism of transport of the hydration products (mainly Portlandite) which occurs from the rich to the poor cement area is also observed. Because of the Portlandite transport, the formation of a "duplex film" of a few microns rich in Portlandite can be observed at the aggregate surface. In the case of recycled aggregate concrete, three different kinds of ITZ are present (Fig. 1): ITZ within the RCA (old ITZ), ITZ between the old and new cement paste (new ITZ), ITZ between the new paste and natural aggregate (NA) present in the RCA.

The strength of recycled aggregate concrete may depend on the strength of the old ITZ within the RCA, the new ITZ between the old and new cement paste or between the new cement paste and NA, the mechanical properties of the new cement paste, or the intrinsic mechanical properties of RCA. In the literature, some studies shown that the weak link in the recycled aggregate concrete is the new ITZ between the new cement paste and RCA [6]. However, the weak link depends also on the relative strength between old and new ITZ [7,8]. RCA contains part of adherent cement paste that could reduce their mechanical properties. Microcracks due to the crushing process are also one of the reasons of the lower strength of RCA in comparison to natural aggregates [7,9–11]. This weak link could be responsible for the limitation of strength of recycled aggregate concrete, called "ceiling effect", which characterizes the intrinsic properties of aggregates [12].

The difficulty to control the quality of recycled aggregate leads to different conclusions in the literature. Contradictory opinions on the influence of absorption on the quality of ITZ and on mechanical properties can be found [9,13,14]. The influence of the saturation state of natural aggregates with different absorption coefficients on the properties of mortars prepared with the same effective water content has been studied by Nguyen [13]. In the case of low porosity aggregate, a little or no difference in the porosity of the ITZ between mortars based on dry and wet sand all along the distance from aggregate is observed. However, in the case of more porous aggregates, the porosity in the ITZ is much higher for the mortars based on wet sand than for mortars based on dry sand. In the case of large absorption coefficient, the higher porosity in the ITZ obtained for saturated aggregates in comparison to dry ones could explain the lower mechanical strengths in the former case. Zhao et al.[14] obtained similar results with mortars containing RCA. On the contrary, Tam et al. [9] showed that the quality of the new ITZ, between the new and old cement paste, is improved by using wet aggregates.

As a conclusion, the quality of ITZ depends on the surface characteristics of aggregate particles, chemical bonding, absorption and saturation state of aggregate. A few qualitative studies have been carried out on the new ITZ in the recycled aggregate concrete and on the influence of saturation state of aggregate on its properties. However, there is no quantitative study of new ITZ in RAC and very few studies carried out on the "ceiling effect" of RCA [15].

The aim of this work is to characterize the influence of moisture condition of recycled aggregates on the hardened behavior of mortars at macro and microscopic scales. Firstly, the possible influence of RCA on the limitation of strength of recycled aggregate concrete ("ceiling effect") is studied. The influence of moisture conditions of recycled aggregate on the macroscopic properties is also investigated. Secondly, the microstructure of recycled mortars is characterized by image analysis of the ITZ and by nano-indentation test under the SEM. The ITZ between the old and the new cement paste for different ages of curing and different initial saturation states of recycled sand is characterized at a micro scale by image analysis. Then it is compared to ITZ of mortar based on natural aggregates. The micro-hardness of different phases in the mortar based on recycled aggregates (natural aggregate, old and new cement pastes) is then characterized by nano-indentation test under the SEM. Finally, the link between the saturation state, the macro and microscopic properties is discussed.

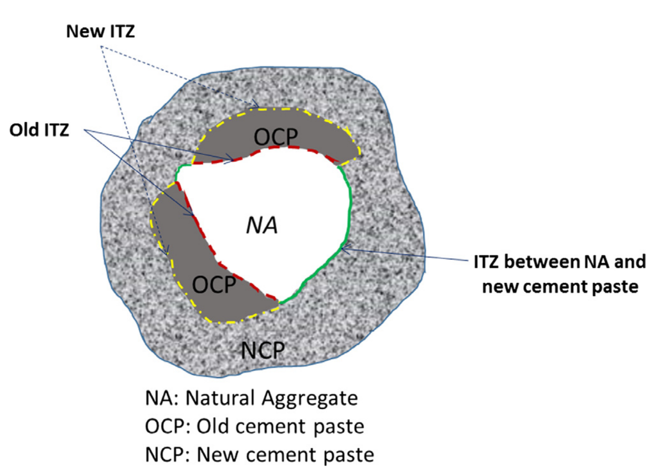

Fig. 1. Illustration of different ITZs in RAC.

2. Materials and methods

2.1. Properties of raw materials

The RCA (RS_1) and natural sand (NS) are provided by the French National Project RECYBETON [16]. The RCA was crushed on the site of DLB Gonesse (France) from the destruction of real concrete structure. No washing was used in the production process. For the preparation of mortars, the RCA (RS_1) was sieved and recomposed from six size fractions to obtain the same particle size distribution as the natural sand (NS) (Fig. 2). The recomposed recycled sand is labeled RS_2. The physical properties of the sands are given in Table 2. The cement used in the study is an ordinary Portland cement OPC (CEM II/A-L 42,5N). The mineralogical composition is shown in the Table 1. The class of cement at 28 days (noted Rc^{ci}_{28}), measured according to European Standard EN 196-1 [17], is 51.3 MPa.

Measurement of the moisture content and absorption coefficient of aggregates is essential, because if the methods of formulation enable determination of the optimum dosage of water in concrete, it should take into account the water contained or absorbed by the aggregates to determine the effective water content. The effective water content is defined in the case of absorbing aggregates as the difference between the total water present in the fresh concrete and the water absorbed by aggregates.

In order to study the effect of saturation degree of aggregates on the microstructure and mechanical properties, wet and dry sand (respectively labeled WS and DS) have been used. DS was obtained by oven drying at 105 °C until constant mass. WS was pre-saturated in a sealed plastic box and stored in a room at 20 °C for one week. The amount of water added to the pre-saturation is equal the amount of absorbed water (WA_{24h}) plus 10%, so the water content is equal to WA_{24h} + 10%. We can note that we obtain a supersaturated state in comparison to the saturated surface dry state (SSD state). The water absorption of NS was determined by standard method EN 1097-6. However, in the case of RS_1 and RS_2, the water absorption was measured by extrapolation [18,19]. The measure and comparison of the water absorption coefficient of the present recycled sand by different methods have been already discussed in a previous paper [18]. So the water absorption of RS_1 and RS_2 are 9.0 and 10% respectively. Table 2 presents the physical properties of the used sands in this study.

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