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Microstructural analysis of recycled concrete using X-ray microtomography

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ABSTRACT

This paper reports an investigation of the recycled concrete (RC) microstructure using synchrotron microtomography (μCT) at the Advanced Light Source combined with Scanning Electron Microscopy analysis. The study evaluated the influence of 50% of recycled concrete aggregate (RCA) and its water absorption compensation on the RC microstructure. The following variables were studied: a) the compressive strength of the original concrete used to obtain the RCA (40 and 80 MPa) and b) the initial moisture condition of the RCA (Saturated Surface Dry and Oven Dry). The microtomographic images showed the mixtures cast with RCA in the dry condition developed an evident macropore network surrounding the RCA particle that was not observed in the mixtures using RCA in the SSD condition. SEM images confirmed the initial findings from μCT and showed that the thickness of the interfacial transition zone in RC is in the same order of magnitude as the reference concrete.

1. Introduction

The worldwide amount of construction and demolition waste (CDW) is one of the largest among the various types of waste. Therefore recycling CDW to produce new construction materials has become imperative. As a consequence, the number of studies on recycled concrete (RC) has significantly increased over the last two decades. Most of the studies agree that recycled aggregates (RA) are more heterogeneous, porous and less dense than natural aggregates. This higher porosity also leads to higher values of water absorption rate that can vary from 5 to 15% depending on the features of the material from which the recycled aggregate is derived [1–8]. The recycled aggregate can modify the effective content of water in the concrete mixtures, increase the mixing time, and affect the properties of fresh and hardened concrete due to the high water absorption rate [2,4,6,9]. The microstructure of the RC can also be strongly influenced by the water absorption and by the way this water absorption is compensated. Studies analyzing the microstructure of the recycled aggregate [3,8,10–14] reported that the RC made from recycled concrete aggregate (RCA) has two interfacial transition zones (ITZs): a) between the old natural coarse aggregate (NCA) and the old cement matrix (CM) and b) between the new CM and the RCA [10,13,14]. These two ITZs seem to have characteristics that influence the RC properties in different ways. The old ITZ makes the concrete microstructure more fragile due to higher porosity and cracks, which increases the water demand. These features ended up modifying the amount of water in this region [4,13]. According to these authors, the amount of water on the new ITZ is reduced because water is absorbed by the cement matrix of the RCA and potentially impairing the hydration process. On the other hand, Tegguer [1], Kohno et al. [15] and Barra [16] advocate that this absorbed water can help the hydration process at later ages by reducing the self-desiccation of the new CM. Therefore, RCA can promote the internal curing of the concrete and densify the ITZ.

To overcome the weaknesses of the RA, Poon et al. [8] and Tam et al. [13] suggested, respectively, to use high-strength concrete to produce RA, and to adopt a new concrete mixing approach in order to fill up the old cracks and voids in RA surface with a thin layer of cement slurry.

Poon et al. [8] reported that RA obtained from a high-performance concrete improves the recycled concrete compressive strength and also helps to make its ITZ denser than when RA comes from normal-strength concrete. The use of old high-quality original concrete to produce RA has been reported by Andreu and Miren [17], Dosho [18], Alaejos et al. [19] and ACI555R [20]. The highest original concrete compressive strength values reported were 100, 54, 43 and 85 MPa, respectively. Old concrete structures (bridges, factories, dams, concrete pavements) and waste from precasting factories can provide a good source of old higher strength concrete that can be recycled as good quality recycled concrete aggregates.

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According to Tam et al. [13], the two-stage mixing approach (TSMA) makes the ITZ in RC stronger because the cement slurry "gels up" the RA improving also the compressive strength. The improvements on the ITZ and the mechanical properties of RC made by TSMA were confirmed by Li et al. [10] who used nanoindentation to study the microstructure of the old and new ITZs of RC. Salas et al. [21] also reported the use of TSMA to produce recycled concrete used for airfield rigid pavement applications at Chicago O'Hare Airport.

The influence of the RA moisture condition on the fresh and hardened properties of the RC has been addressed by a number of researchers [2,9,22]. Saturation, pre-wetting, or mixing water compensation of RA absorption rate has been suggested to prevent decreases in workability and mechanical properties. The required RA pre-wetting, besides being widely discussed in the literature, is also identified as a key point in the current production of recycled concrete used in the construction industry. For example, in the construction of the Hong Kong Wetland Park which used 5000 m^3 of recycled concrete [23], the RA was pre-wetted both at the stockpiles of the recycling plant and by sprinkling water mist on the recycled aggregates during unloading at the receiving hopper at the batching plant before feeding to the overhead bin. Hansen [24] reported the results of several studies dealing with pre-wetting methods to reduce the absorbed mixing water by RA. However, subsequent studies pointed out that the water absorption of the RA inside a concrete mixture can be different from the free water absorption determined in the RA particle [2,16,25]. Considering that, research has been carried out using partial water compensation of RA absorption rate [2,7,9,14,26]. The aggregates were wetted prior mixing but not saturated. The pre-saturation occurred: 1 day before mixing [7,9,14]; or 5 to 8 min inside the mixers [2,26]. Then RC was produced using the same order of mix used to conventional concrete. The authors reported some improvements on ITZ of RC but the results are still controversial. Poon et al. [9] observed that the use of the recycled aggregate in air-dried condition, i.e. in semi-saturated condition (moisture content around 50%) showed the best behavior. Etxeberria et al. [7] and Leite et al. [26] suggest the use of 50% aggregate replacement and higher water partial compensation values in order to achieve better behavior either in fresh or mechanical properties. Ferreira et al. [2] reported that the recycled concrete using high values of water compensation (around 90%) in the pre-saturation showed slightly worse properties for both the fresh and hardened concrete.

In an attempt to improve the interfacial transition zone of RC, new mixing approaches also studied the effect of coating the RA surface with pozzolanic materials [3,4,6]. The results showed an enhanced ITZ, with denser packing, higher compressive and flexural strengths and better workability.

Most of the studies on RC microstructure investigations used secondary electron images from Scanning Electron Microscopy (SEM) or optical microscopy images to characterize the morphological features of the ITZ. The main shortcoming of these techniques is the lack of three dimensional information and the drying of the samples for SEM studies. It is necessary to study the pore formation and its spatial distribution on RC microstructure using 3D techniques like hard X-ray microtomography (μCT). Microtomography has been useful to investigate the hydrated microstructure of cement pastes, fracture, and the pore structure of conventional concrete for the last 15 years [27–29], but it has never been used to study RC.

This study evaluates the influence of 50% recycled concrete aggregate (RCA) replacement and its type of water absorption compensation on the RC microstructure. The research program used two grades of strength to produce RCA and two different initial moisture conditions of the RA. All concrete mixtures were produced using the *Two-Stage Mixing Approach* proposed by Tam et al. [13] in order to determine the influence of the mixing approach on the RC microstructure and its ability to overcome the RCA problems in producing new concrete. The RC microstructure was studied using hard X-ray microtomography (μCT) combined with Scanning Electron Microscopy (SEM).

2. Materials and methods

2.1. Materials

The recycled coarse aggregates (RCA) used in this experimental program were obtained by casting normal-strength concrete (40 MPa, labeled here T40) and high-strength concrete (80 MPa, labeled here T80). The materials used in these mixtures were ASTM portland cement Type I/II with a specific gravity of 3.15, quartz sand with a fineness modulus of 2.9 as natural fine aggregate (NFA), and a crushed basaltic gravel with maximum size of 19.0 mm as natural coarse aggregate (NCA). A high-efficiency polycarboxylate-based superplastisizer (ADVA-405®) with specific gravity of 1.04 also was used to produce the high-strength concrete. The mixture proportions and the 28-day compressive strength results of these two mixtures are presented in Table 1. The TSMA described by Tam et al. [13] was applied to make both mixtures. The TSMA consists of mixing all the aggregates for 60 s, followed by adding half of the mixing water, and then mixing the materials for 60 s. After that, the cement is added to the mix, which is then mixed for 30 s, and finally the remaining half of the mixing water is added and then mixed for another 120 s. Except for the aggregates, all materials are added without stopping the mixer; therefore the total mixing time was 4.5 min. After 28 days of moist curing, the two original concrete mixtures were crushed using a jaw crusher and sieved to achieve the two types of RCA, each of them reaching a maximum size of 19 mm. The RCA obtained was oven-dried under a temperature of 40 °C until reaching a constant weight. The specific gravity and water absorption rate of the T40 RCA were 2.73 and 7.2%, respectively. These values were 2.72 and 5.2%, respectively, for T80 RCA.

2.2. Mix proportions, concrete production and testing

The two types of RCA (T40 and T80) were used in the DRY and SSD initial moisture conditions, resulting in four recycled concrete mixtures made with the same mix proportions of the conventional concrete used as reference with 40 MPa compressive strength at 28 days. From now on, the conventional concrete will be labeled as 'reference concrete'.

The reference concrete proportion was established according to the method described by Monteiro et al. [30]. The concrete trial mixtures were prepared using the natural fine and the natural coarse aggregates presented in Item 2.1, to have a slump of 80 ± 20 mm [31]. All mixtures were produced using white portland cement. This type of cement was used in order to clearly delineate the interface between RCA (which the original concrete was prepared with gray portland cement as described in Item 2.1) and the new white cement matrix, as it can be seen in Fig. 1 which shows images taken using a Keyence VHX-2000 Digital Microscope. The white portland cement complied with ASTM Type I/II standard and had a specific gravity of 2.99.

As described before, recycled concretes were cast using the reference mix proportions with a 50% replacement of NCA by RCA. This substitution was done by a volumetric basis to keep a similar total aggregate volume. Also, the water content of recycled concretes using RCA in the DRY condition was adjusted to compensate for the water absorption rate of the aggregate. Based on the work of Leite et al. [26],

Table 1
Mixture proportions, slump and compressive strength results of original normal (T40) and high strength concretes (T80).

Mixture	Materials Content						
	Cement (kg)	NFA (kg)	NCA (kg)	Water (kg)	SP (%)	Slump (mm)	fcm ± sd(cv) MPa ± MPa(%)
T40	359	910	1158	229	–	80	43.3 ± 0.9(2.2)
T80	549	775	1226	189	0.27	85	79.7 ± 0.8(1.0)

NFA = natural fine aggregate/NCA = natural coarse aggregate/SP = Superplasticizer. fcm = average compressive strength, 28-days/sd = standard deviation/cv = coefficient of variation.