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Effects of nano-particles on failure process and microstructural properties of recycled aggregate concrete

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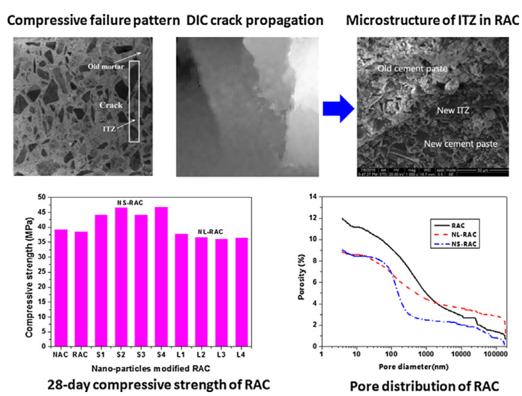
HIGHLIGHTS

- Failure process of RAC was influenced by the relative strength between new and old cement mortars.
- Colloidal NS could enter into ITZ regions in RAC to increased hydration products by secondary chemical reaction.
- Powdered NL could not enhance the compressive strength of RAC due to the particles agglomeration.
- Colloidal NS could effectively reduced porosity and water absorption of RAC.

GRAPHICAL ABSTRACT



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ABSTRACT

The effects of nano-particles including nano-silica (NS) and nano-limestone (NL) on the crack propagation and microstructure properties of recycled aggregate concrete (RAC) were experimentally investigated in this study. The crack initiation and propagation of nano-particles modified RAC with different nano-particle modification were evaluated using digital image correlation technique (DIC). The microstructures and porosity of interfacial transition zones (ITZ) in nano-modified RAC were also examined using scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP). It was found that the micro-cracks were typically derived from relatively weak ITZs in RAC, and then progressively propagated along the compressive loading direction. The meso-crack developments eventually led to final splitting failure. The results indicated that compared to NL, NS was more effective in improving the microstructure properties and enhance the mechanical strength of RAC. The porosity and water absorption of RAC were obviously reduced by the NS incorporation. However, due to particles agglomeration, NL could not effectively improve the microstructure of RAC for further enhancing the RAC mechanical properties. Furthermore, in terms of severe particles agglomeration, NL was even detrimental to the mechanical strength of RAC especially at the late-age.

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1. Introduction

The study on recycled aggregate concrete (RAC) have become a hot topic in the field of construction material. A lot of researchers realized that RAC can effectively recover waste into useful resources. However, compared to ordinary concrete, there are still some shortcomings of RAC for practical applications in terms of mechanical properties [1–5], which is one of the major factors limiting RAC in structural applications. To address this concern, a series of research studies had been conducted to develop methods to improve the RAC mechanical performance. Because the properties of the recycled aggregate to a large extent determines the performances of the RAC [6,7], increasing number of studies were carried out to improve the quality of recycled aggregate. These methods include microwave heating [8], chemical immersion [9], biological precipitation [10,11], carbonization [12,13], and surface treatment of recycled aggregate [14–17]. However, more effective methods are still needed to achieve better mechanical properties for RAC. For the failure mechanism of RAC, previous studies [18–21] have confirmed that the mechanical properties of RAC is closely related to the properties of the interfacial transition zone (ITZ) between new cement mortar and recycled aggregate [22–24].

Nano-particles can act as nuclei for cement phases, further promoting cement hydration process due to their high reactivity as filler and densifying the microstructure, thereby, and leading to reduce porosity number of nano-particle has been studied for incorporating in cement and concrete including nano-silica (NS) [25–27], nano-limestone (NL) [28–29], nano-metallic oxide [30–32], graphene oxide [33–35], carbon nano-tubes [36–37]. Two nano-particle types, NS and NL, are the most commonly used in cementitious material applications. Currently, there are typically two methods which have been reported for producing nanosized silica and limestone particles: (i) high energy milling of raw material (top-down approach); and (ii) chemical synthesis (bottom-up approach) [38,39]. Previous studies usually showed that they can act as nuclei for promoting cement hydration process. These nano-particles can also act as physical fillers for densifying the microstructure of the cement mortar and ITZs in RAC. Nano-particle has advantages in improving the mechanical properties of cementitious composites. The modifications of NS and NL have been demonstrated in NAC [26,28,29]. NS exhibits strong pozzolanic effect, which can promote the secondary hydration of cement, i.e. pozzolanic reaction, generating further calcium silicate hydrates (C-S-H), and fills the pore structures. On the other hand, NL has a strong effect of crystal nucleus and physical filling effects which can largely improve the concrete microstructure. RAC which is more porous than natural aggregate concrete is more likely to be improved by nano-particles. But further studies on the failure mechanism of nano-particles modified RAC are still necessary.

In this study, NS and NL at different dosages were used to enhance the properties of RAC. The effects of nano-particle on the mechanical strength and crack propagation of RAC were evaluated with incorporation dosages and mixing methods. Scanning electron microscopy (SEM) and mercury intrusion porosimetry (MIP) techniques were used to analyze the failure mechanism and microstructure properties of the nano-modified RAC with NS and NL. The related results can provide an insight into and enhancing RAC properties and promoting structural applications.

2. Material and method

2.1. Sample preparation

Ordinary Portland cement (OPC 42.5) was used in the experiments, and the chemical compositions are shown in Table 1. The fine aggregate used was common natural river sands, and the fineness modulus was 2.6. Natural gravel with continuous gradation from 5 to 26.5 mm was chosen as natural coarse aggregate. It had water absorption of 0.96% and bulk density of 1,395 kg/m^3. The recycled coarse aggregate (RCA) was obtained from the demolition of wasted concrete at the Shanghai Port wharf, China. The RCA had a water absorption value of 6.30%, and a bulk density of 1290 kg/m^3. The powdered NL was purchased from Xuan Cheng Jing Rui New Material Co., Ltd, China. The colloidal NS was purchased from Zhejiang Yuda Chemical Co., LTD, China. The physio-chemical properties of the nano-particles (powdered NL and colloidal NS) used are shown in Tables 2 and 3, respectively. A naphthalene based superplasticizer was used to improve the RAC workability and serve as the dispersant of NL powder in solution. After NL powder was mixed with a small amount of water. Then NL solution was subjected to ultrasonication to improve the dispersion by a Sonics Vibra-Cell vcx-500 ultrasonic processor (Vibra-Cell-Sonics & Materials, Inc.) with an energy intensity of 40,000 J with amplitude of 80% and pulse of 4 s.

2.2. Experimental program

The RCA was used to replace the natural coarse aggregate by weight at 30%. According to NS dosage (1.0 and 2.0% by weight of cement) and two different mixing methods, NS-RAC was divided into S1, S2, S3 and S4. According to the different NL dosages (1.0 and 2.0% by weight of cement) and superplasticizer addition (1.0% by weight of cement), NL-RAC was divided into L1, L2, L3 and L4. The compressive strength of the RAC was tested after 7-day and 28-day standard curing at 20 ± 2 °C and relative humidity of 90 ± 5%. Concrete cubes of 150 × 150 × 150 mm were cast using different dosages of nano-particles (powdered NL and colloidal NS), as shown in Table 4. Three cubes were tested to measure the compressive strength. To investigate the failure process of RAC, some cubes were cut into slices of 150 × 150 × 30 mm for uniaxial compression test. To study the effect of nano-particles on the RAC, the natural aggregate concrete (NAC), RAC, nano-silica modified RAC (NS-RAC) and nano-limestone modified RAC (NL-RAC) were prepared by an effective water to cement ratio of 0.5 for comparison.

Due to the high water absorption of RCA, an additional amount of water was added to assure the same effective water to cement ratio for all the nano-particles modified RAC specimens. The additional water was calculated by the water absorbed from air-dry condition to saturated-surface-dried (SSD) condition [5,23]. There were two mixing methods (Method 1 and Method 2) for the RAC preparation, as shown in Fig. 1. For the first mixing method with the insight from the two-stage mixing method developed by Tam et al. [5], RCA and nano-particles were firstly mixed for 60 s, and subsequently mixed for another 30 s with half of the mixing water added. Then, cement, sand and the remaining water were added and mixed for a further 60 s. For the second mixing method, RCA,

Table 1
Chemical composition of ordinary Portland cement.

	SiO_2	Al_2O_3	Fe_2O_3	SO_3	CaO	MgO	K_2O	Na_2O	Total
Composition (%)	21.00	5.40	2.20	2.00	65.40	3.40	–	–	99.40