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The modification effects of a nano-silica slurry on microstructure, strength, and strain development of recycled aggregate concrete applied in an enlarged structural test

Hongru Zhang [a], Yuxi Zhao [a,*], Tao Meng [b], Surendra P. Shah [c]

[a] Institute of Structural Engineering, Zhejiang University, Hangzhou 310058, Zhejiang, PR China
[b] Institute of Building Materials, Zhejiang University, Hangzhou 310058, Zhejiang, PR China
[c] Center for Advanced Cement-Based Materials, Northwestern University, Evanston, IL 60208, USA

HIGHLIGHTS

- Recycled aggregate concrete (RAC) modified by nano-silica was applied in a project.
- Mechanical properties of RAC were improved after modification.
- The cracking resistance of the modified RAC beam was enhanced.
- Nano-silica enhanced the new interface between the old and new mortars in RAC.

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ABSTRACT

The modification effects of a nano-silica slurry on properties of recycled aggregate concrete (RAC) were experimentally studied. Together with natural aggregate concrete (NAC), non-modified and modified RAC were applied in three beams in a real project. The beneficial effects of the nano-silica slurry on RAC's mechanical properties were certificated. *In situ* strain monitoring in the target beams showed the improved resistance to cracking of RAC after modification. Nanoindentation tests proved that the nano-silica slurry enhanced the new interface transition zone (ITZ) between the old and new mortars in RAC, and surface-strengthened the old mortar, while the old ITZ between old aggregate was not strengthened.

1. Introduction

To dispose of the huge amount of construction and demolition (C&D) wastes and to reduce the consumption of natural aggregate resources, an environmentally friendly construction material, recycled aggregate concrete (RAC), was developed. It has been widely accepted that RAC is generally inferior to natural aggregate concrete (NAC) in terms of its mechanical properties [1–4], e.g., compressive strength, tensile strength, and elastic modulus, and some durability properties, e.g., air permeability, resistance to Cl^- penetration, shrinkage, and freeze–thaw resistance [5–9], etc. The inferiority of RAC in material properties has adversely affected some structural performance of reinforced RAC members or structures. Sato et al. [10] have pointed out that though the ultimate flexural capacity of reinforced RAC beams is comparable to, that of the NAC beams, however, the deflection and the overall crack width of RAC beams under the same moment are significantly larger. Etxeberria et al. [11] have reported that the shear capacity of RAC beams without stirrups is smaller than that of NAC beams. The study carried out by Andrzej et al. [12] has confirmed that though loading capacity of the reinforced RAC beams or columns is comparable to that of the NAC members, however, the effects of RAC's inferiority in material properties on the deformability of reinforced members should be carefully considered, at beam deflection assessment, as well as at the column shortening analysis.

Considering the inferiority of RAC in material properties, and thereby the affected structural performance, especially in the deformability of reinforced RAC members, as referred above, it is necessary to raise effective techniques for modifying RAC. Till now, many types of modification techniques on RAC have been tried. Enhancing effects of slag, fly ash, and silica fume on either mechanical properties or RAC durability have already been reported [13–15]. Recently, another material, nano-silica, which

* Corresponding author.
E-mail address: yxzhao@zju.edu.cn (Y. Zhao).

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has been reported to have beneficial effects on natural aggregate concrete (NAC) [16–18], has caught RAC researchers' attention. Generally, it is believed that nano-silica particles primarily work at two levels in cement-based materials, known as the "filling effects" [19,20] and "accelerating effects" [21–24]. "Filling effects" mean that nano-silica particles can penetrate into the cementitious matrix and fill the pores inside, thanks to their small size (approximately 100 times smaller than cement particles [19]); the density degree of concrete can thus be improved [20]. "Accelerating effects" mean that the nano-silica particles can promote the hydration of cement in concrete, primarily because of their pozzolanic activity or perhaps because of their considerable surface activity [21–24].

Although the modification effects and the corresponding modification mechanism of nano-silica on NAC have been explored in depth, trials that apply nano-silica on RAC's modification have seldom been reported. It is now widely known that as a result of the introduction of recycled aggregate (RA), there are at least two types of ITZs in RAC, i.e., the old ITZ, which is between the old, virgin aggregate and the adhering old mortar, and the new ITZ, which is between the old mortar and the new mortar. In some cases, there exists the third type of ITZ in RAC, i.e., those located between the old aggregate in RA and the new cement mortar. By contrast, there is only one type of ITZ in NAC, which lies between the virgin aggregate and the cement mortar. Compared with NAC, more potential weak points exist in RACs, including more types of ITZs and the weak, porous old mortars adhering to virgin aggregate. Therefore, it can be seen that due to the introduction of RA, RAC's micro-structure is more sophisticated than that of NAC. Hence, whether nano-silica will modify the properties of RAC, and how it works, deserves exhaustive exploration.

Despite the various types of modification treatments that have been applied to RAC, as mentioned above, it should be noted that most studies on RAC modification are primarily limited to laboratory experimental practice. Until now, none of the modified techniques mentioned above have ever been applied in real reinforced concrete structures. As a result, reports have seldom been seen on the structural performance of modified RAC in real projects. The structural performance of reinforced concrete structures can be assessed in a number of ways, among which concrete's cracking resistance is of vital importance. Concrete cracking in reinforced concrete structures can accelerate the penetration of hazardous materials into concrete and thereby accelerate steel erosion. It is common knowledge that concrete cracks when its tensile strain exceeds the ultimate value. Therefore, it is worthwhile to monitor the *in situ* concrete strain in real structures in which the modified RAC is employed to evaluate the structural performance of the modified RAC, to predict cracking, and to reduce induced damages.

This paper aims at providing an efficient modification technique for RAC, with the incorporation of nano-silica and other composites, and exploring the modification effects of this technique on RAC's mechanical properties on the micro scale and material properties and structural performance on the macro scale, thereby revealing the employed technique's modification mechanism.

2. Materials

Three concrete groups were prepared in this study, i.e., the commercial natural aggregate concrete (CNAC), the original recycled aggregate concrete (ORAC), and the modified recycled aggregate concrete (MRAC). The percentage replacement of RA was 50% for both ORAC and MRAC.

2.1. Coarse aggregates

A concrete plant in Hangzhou produced the commercial natural aggregate concrete (CNAC). The coarse aggregate used for preparing CNAC was natural coarse aggregate (NA). The RA employed in the ORAC was original recycled aggregate (ORA) without strengthening, which was purchased from a recycled aggregate plant located in Shanghai, China. The size ranged from 5 mm to 31.5 mm for both NA and ORA particles. The mud contents of NA and ORA were 1.6% and 4.0%, respectively. The larger mud content of the ORA was mainly attributed to the crushing operation on the waste concrete, through ORA's producing procedure.

The RA used in the MRAC was strengthened recycled aggregate (SRA), which used the designed nano-silica slurry. The prepared strengthening slurry's proportions are shown in Table 1. The cement used for preparing the strengthening slurry was ordinary potland cement. The nano-silica dispersant was a water-based solution that was supplied by a company in Hangzhou. The content of this nano-silica dispersant was 30% (by weight), and the size of the nano-silica particles contained in this dispersant was 15 ± 5 nm. The PH value of this dispersant ranged from 9 to 11.

The materials listed in Table 1 were first mixed in a mixing machine for 120 s to get a slurry with nice dispersion. The ORA was then added into the strengthening slurry, and all of the materials were mixed three times. Each mixing lasted for 3 min, and the interval between two adjacent mixings was 1 min. Afterwards, the redundant slurry was removed, using a screen with a 5-mm sieve diameter. Finally, the freshly prepared SRA was spread on a dry, neat plastic cloth and dried naturally in the open air. All the three groups of coarse aggregates, i.e., NA, ORA, and SRA, were employed in air-dried condition.

The bulk density, the water absorption (by weight), and the crushing value of the three groups of coarse aggregates were tested according to the *National Specification Pebble and Crushed Stone for Construction* (*GB/T 14685-2011*). The testing results are listed in Table 2. According to Table 2, the bulk density of the two groups of RAs, i.e., the ORA and the SRA, was significantly lower than that of the NA, meanwhile the water absorption and the crushing value were much larger, compared with the NA. The presence of the porous old mortar adhering to RA is the predominant reason for the much lower bulk density, the higher water capacity, and the inferior anti-crushing strength of RA. The bulk density of the SRA and the ORA was almost the same, according to Table 2, demonstrating that the employed strengthening slurries had not induced great changes in density of coarse aggregates. The enhancement of SRA's resistance to water absorbing and crushing, after strengthening by the employed nano-slurry, indicates that the old mortar adhering to the SRA may have been densified and strengthened, to some extent, compared with the ORA. However, based on the information in Table 2, the changes in RA's physical and mechanical properties after strengthening are not significant, demonstrating that the direct strengthening effects on the old mortar might be limited. Such results will be further discussed, according to the nanoindentation test results on the old mortar, in Section 5.3.2.

2.2. Other materials

The fine aggregate used in this study was natural river sand. The water content (by weight) of the fine aggregate was 7.6% and the fineness modulus was 2.7. The cement used in the three concrete groups was ordinary potland cement with a grade of 42.5 MPa. Slag of Class S95 and fly ash of Class II were added as mineral admixtures. A MTWF-8 superplastizer was added to guarantee the workability of the fresh concrete mixture.

2.3. Mixture proportions of concrete

To make reasonable comparisons among the three concrete groups that were prepared in this study, i.e., CNAC, ORAC, and MRAC, the mixture proportions were kept the same by referring to those of the CNAC mixture. The mixture proportions are shown in Table 3. The target compressive strength of the three concrete groups was 30 MPa, as required by the project in which they would be applied. For the three concrete groups in this study, the dosages of each single component of these mixtures were kept the same, thereby to ensure that the comparisons among the three concrete groups in either the macro properties or the ITZ properties would not be disturbed by the mixture proportions.

3. Information for the applied project

To compare the performance of ORAC and MRAC when serving in real projects, they were applied in two secondary beams in a reinforced concrete building in Hangzhou, China. The CNAC applied in a third beam worked as the control. The three beams were designed to bear similar loads. The applied project was an 8-story frame structure, and the three target beams were located

Table 1
The proportions of the strengthening slurry prepared for this study (unit: kg).

Cement	Water	Superplastizer	Nano-silica dispersant
100	50	1	1