Research Article

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Improving recycled aggregate concrete by compression casting and nano-silica

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Abstract: Improving and reusing recycled aggregate concrete (RAC) is an ideal approach to develop sustainability in the construction industry. In this article, a newly proposed physical compression casting method was used in combination with a treatment of nano-silica (NS) particles to enhance the properties of RAC. Although using NS contributed to accelerating hydration, promoting pozzolanic reaction, and increasing calcium-silicate hydrate gel, the enhancement in strength and reduction in porosity was found to be limited. Thus, the compression casting method was used to compensate for the weaknesses. The effects of compression casting, NS, and their combinations on the properties of RAC were investigated. At the macro-level, the stress–strain responses were evaluated by examining the compressive strength, peak strain, and modulus of elasticity. At the micro-level, the porosity and pore distribution along the interface transition zones (ITZs) were investigated using mercury intrusion porosimetry analysis and scanning electronic microscope imaging technology. Compared with normal RAC, the compressive strength achieved by using NS particles, compression casting, and their combination were increased by 37, 88 and 143%, respectively. The compression casting or combination of compression casting and NS particles treatment can effectively reduce the total porosity of the mortar and pore ratio along the ITZs.

Keywords: recycled aggregate concrete, compressed recycled concrete, nano-silica

1 Introduction

According to a 2018 analysis of construction and demolition waste (CDW) worldwide, China produced 2.36 billion tons of CDW, followed by the United States (about 600 million tons), and India (around 530 million tons) [1]. The European Union also generated a large amount of CDW, where France and Germany were predominant contributors, reaching 240 and 225 million tons, respectively [1]. The deposition and disposal of such a huge amount of CDW is an urgent issue to be addressed globally. Traditionally, a large portion of CDW is sent to landfills, which will be hindered by the sharply increased cost and environmental concerns [2]. In addition, CDW is likely to contain hazardous substances, such as varnishes, sealants, adhesives, lead paint, or mercury, which can contaminate soil and groundwater [3]. Thus, more rational technologies (e.g., recycling and reuse of CDW) are urgently needed to deal with the enormous quantity of CDW waste.

A life cycle assessment of the environmental impact of recycled aggregate (RA) from CDW in Hong Kong showed that using recycled aggregate concrete (RAC) can reduce greenhouse gas emissions by 65% and lower non-renewable energy consumption by 58% compared to producing natural aggregate concrete (NAC) [4]. The production of RA requires the mechanical crushing of waste concrete, resulting in a layer of old mortar with many microcracks and high porosity that adheres to the surface of the original aggregate [3,5]. Existing findings indicate that this old layer of mortar, also known as interfacial transition zone (ITZ), is the weakest part of RA [6–8],...
resulting in poor performance of RAC. Therefore, it is necessary to improve the performance of RAC by improving the bonding properties between the RA and the old mortar matrix or the matrix properties of RAC [9–12].

Over the last few decades, methods that have been used to improve RAC can be divided into two main categories: physical and chemical treatments. Physical treatments aiming to improve the conformation of matrix or reduce the thickness of ITZ, include improving the mixing procedure [13,14], adding fibers [15–17], mechanical grinding [18], high-temperature heat treatment [19,20], and microwave treatment [21]. However, a suitable mixing procedure can only be obtained through a large number of preliminary tests, and the increment in compressive strength of RAC is limited [22]. Meanwhile, although adding fibers significantly improves the compressive strength and splitting tensile strength of RAC [17,23], the higher cost prevents this method from being prevalent in practice. Besides, the complex process of mechanical grinding and the high energy consumption associated with high-temperature and microwave treatments hinders the further application of these methods in practice [24]. Chemical treatments such as acid treatment [25–28], accelerated carbonation [29,30], incorporation of volcanic ash materials (silica fume, fly ash, etc.) [31–33], and microbial carbonate deposition [34–36] have proven to be effective in improving the quality of RAC to varying degrees. However, though these treatments are effective, they also suffered various drawbacks. For example, acid treatment of RA produces an acidic solution that will result in environmental concerns and make the treatment process more cumbersome; carbonation of RA takes much longer processing time and requires more sophisticated equipment [34,37–41].

In recent years, the use of nanomaterials to modify RAC has also been widely investigated. These include nano-calcium carbonate [42], nano-titanium dioxide [43], nano-alumina [44], and nano-clay [45], which can be used to not only fill interfaces, pores, and cracks but also as nucleation centers for crystallization in the hydration process of cement. In addition to the above-stated positive effects, silica nanoparticles also include the extra function of volcanic ash reaction [46,47]. Thus, nano-silica can further improve the microstructure and mechanical properties of the RAC, and the overall performance of nano-silica-modified RAC can be improved by up to 130% [48–52], nano-silica being one of the most commonly used nanoparticles for the modification of RAC. More recently, a physical method, named compression cast technology (CCT), was proposed by Wu et al. [53] and has been proven to be effective in enhancing the performance of various kinds of concrete without increasing the cost [53,54]. The CCT tightens the internal structure of the concrete through pressure, and the overall performance of the concrete can be improved by up to 130% [53]. A detailed description of the CCT can be found in ref. [53].

Although various physical and chemical approaches have been developed to improve the quality of RAC, an effective method that combines these two approaches is still an open issue. To fill this gap, this article proposes a new method that combines the nano-technology and CCT to improve the performance of RAC, aiming to achieve a goal of one plus one really is greater than two. To prove this conjecture, three main tests were carried out. First, uniaxial compressive tests were conducted to obtain the stress–strain responses of RAC under the modifications of CCT, silica nanoparticles, and their combination. Subsequently, the porosity of the mortar was measured and analyzed with a mercury intrusion porosimetry (MIP) test, aiming to evaluate the strength enhancement after different modifications. Finally, the backscattered electron (BSE) images were statistically analyzed to obtain the porosity and pore distribution near the ITZs between the old and new mortar to determine the mechanism of different modifications.

2 Experimental program

2.1 Specimen design

To ensure that the height of the specimen after CCT treatment reached the standard height of 300 mm, pretests were conducted to determine the amount (height) of fresh concrete needed to be filled in the designed mold before compression casting. In addition to the expected densified internal structure of concrete, a phenomenon of drainage was observed during compression casting. So, the improvement in concrete due to compression casting was divided into two parts, namely, one for the physical densification and another for the reduction of the water/binder ratio. In order to investigate how these two mechanisms contributed to the enhancement of RAC using CCT, three groups of RAC samples were designed. The first was the normal cast group, named RAC-N. The second group was the RAC modified by CCT, called RAC-P. The third group, RAC-CP, was normal cast RAC with the amount of water squeezed out under compression casting eliminated in the original mixture. Each group included a specimen modified by nano-silica (NS) at a dosage of 2% by weight of cement and denoted as 2%NS.
So, each specimen was labeled according to the above designations. For example, specimen RAC-2% NS-P represents the RAC modified by the combination of NS at a 2% dosage and CCT. Table 1 summarizes the detailed information of all the specimens.

Figure 1 illustrates the procedure of the CCT. The concrete was compacted by a tailor-made mold after mixing, which included a jack, an indenter, and a specially-designed cylinder mold (with a diameter of 150 mm and a depth of 400 mm). When the fresh concrete was filled in the cylinder mold, the fresh concrete was vibrated to make the concrete reach a specified height. Then, the concrete was compressed. The pressure from the jack with a controlled magnitude measured by the indenter was applied on the concrete in the cylinder mold. The depth of concrete under compression was determined in the pre-experiments. A specified height of concrete was reserved when filling in the mold, so the height of the specimen was the standard height (300 mm) after compression [53,54]. At the same time, the actual compression depth of the concrete was recorded. The volume of concrete under compression was converted from this compression depth. It is proposed that this volume is equal to the amount of water squeezed out under compression. The pressure value applied on RAC can be converted by the oil gauge of water squeezed out under compression. The pressure was maintained for 24 h, and then the specimen was de-molded. For the non-compression casting specimens, ordinary cylinder molds (150 mm in diameter and 300 mm in height) were used. After de-molding, all the specimens were placed in the curing room for 28 days, where the temperature and the relative humidity were 20 ± 2°C and 95%, respectively.

### 2.2 Material properties

The material constituents of the concrete mix used in the current tests include ordinary silicate cement (42.5R), colloidal NS, sand, and RA. Table 2 shows the properties of sand and recycled coarse aggregate, and Table 3 lists the material properties of NS. In this study, recycled aggregates were obtained by crushing waste concrete blocks from a building demolition site in Shenzhen. After cleaning, sieving, and drying, the maximum aggregate size of the recycled coarse aggregate was found to be 20 mm. The crushing index and water absorption of the recycled coarse aggregate were 15.8 and 5.5%, respectively. River sand with a water absorption rate of 1.2% was used. The above indicators were measured according to Chinese standards [55].

Table 1 summarizes the proportions of the raw materials used for all specimens. Considering the high water absorption of RA, an additional amount of water (62 kg/m³) was added to keep the actual water/binder ratio of the RAC close to the designed value during the mixing procedure. Both coarse and fine aggregates are dried at 60°C for 24 h to ensure that they reached a saturated dry state of surfaces. The RA and sand were initially mixed for 1 min, and subsequently, the cement was added to the concrete mixer. After 1 min of mixing, half of the water was added and mixed for another 1 min. Finally, the remaining water was gradually added and mixed for 2 min. Because NS was in colloidal form, it was first dispersed in half of the water in order to stir it into a homogeneous solution, which was then added into the mixer during the concrete mixing process.

### 2.3 Test setup and instrumentation

#### 2.3.1 Uniaxial compression test

The uniaxial compression test was carried out using an MTS machine (type: YAW63063051401) with a loading capacity of 3,000 kN to obtain the stress–strain relationships of specimens. Four linear variable differential transformers (type: DMWY-10) with a gauge length of 185 mm...
were installed to measure the axial deformation of the specimens, as illustrated in Figure 2. Besides, a digital image correlation (DIC) device (type: VIC-3D 6 M), which has been approved to be effective in capturing the strain of the concrete [56–58], was applied to measure the strain field of the specimens. The axial strain data presented in this article has been checked by DIC. All specimens were tested in a displacement-controlled loading manner at a rate of 0.3 mm/min, and the data acquisition rate was 5 Hz to record the applied load and deformation.

**2.3.2 MIP**

The MIP test is an effective method for evaluating the overall porosity and pore sizes of cement mortars [59,60]. After curing, the samples were broken into small pieces and stored in anhydrous ethanol to prevent further hydration. All samples were then dried in a vacuum oven at a temperature of 50°C for 48 h. A Poremaster-60 MIP (Quantachrome Instruments, Boynton Beach, FL, USA) was used in the tests, and the upper limit of mercury pressure was set at 30,000 psi during the tests.
Concrete blocks with suitable sizes containing the ITZ between the old and new mortar interfaces were prepared as the BSE samples, which were soaked in isopropyl alcohol to remove free water. Great care was given to this process for the selection of suitable samples that contain the ITZ for BSE characterization. The sample surface was pre-sanded using 320 grit SiC paper, followed by infusing the concrete block with resin under the vacuum condition. The resin was used to support the internal microstructure of the concrete. Once the resin hardened, the BSE samples were polished using 320 grit, 600 grit, and 1,200 grit SiC paper in order, and then 5.0, 3.5, 1.0, and 0.5 µm polishing pastes were used in sequence to achieve a smooth surface. Eventually, the samples were carbon coated and further tested under the electron microscope.

The instrument used for the tests was a Thermo Apreos, and the scanning electron microscope (SEM) parameters were set as follows: accelerating voltage (HV): 15 kV; magnification (MAG): 1,000x; working distance (WD): 12.7 mm; and the size of the photographic area (View field): 207 µm × 138 µm. During the test, photographs were taken along the ITZ between the old and new mortar interfaces, as shown in Figure 3. A total of 30 shooting areas were selected for subsequent statistical analysis of their porosity (Figure 3).

### 3 Mechanical performance and discussions

#### 3.1 Failure modes

Figure 4 shows the failure mode of concrete specimens in the RAC-N group (specimens RAC-N and RAC-2% NS-N), RAC-CP group (specimens RAC-CP and RAC-2% NS-CP), and RAC-P group (specimens RAC-P and RAC-2% NS-P) after the uniaxial compression test. Generally, all the specimens experienced a similar failure process. Discrete micro-cracks began to occur vertically as the stress caused by the applied external load approached the peak stress. The stress decreased shortly after the unstable point of inflection (peak point), which was attributed to the further propagation of large numbers of vertical cracks. As the axial compression straining continued, discontinuous vertical cracks linked to form a major inclined crack, which eventually resulted in the failure of a column. Similar phenomena have also been found in previous studies [61]. Compared with uncompressed specimens (RAC-N group and RAC-CP group), the failure process of compressed specimens (RAC-P group) was observed to be much more abrupt. Besides, spalling and falling of concrete chunks were found to occur for the specimen in the RAC group and RAC-CP group, whereas no such phenomenon was observed for the compressed specimens. Similar observations were recorded by Wu et al. [53]. Both these differ-
quences can be caused by the higher strength and much smaller strain at the ultimate point (the end of the stress–strain curve, as shown in Figure 5).

3.2 Stress–strain responses

Figure 5 shows the stress–strain curves for all specimens. For a more clear comparison, the curves were presented in different figures. The stress–strain responses of all the tested specimens are depicted in Figure 5(a). It is interesting that the shape (e.g., modulus of elasticity, peak stress, and corresponding strain as well as post-peak softening behavior) of the stress–strain curve was affected by compression casting, the addition of NS, and their combination. For specimens under normal casting (RAC-N and RAC-2% NS-N), the addition of 2% NS significantly enhanced the compressive strength of RAC, as shown in Figure 5(b). After the peak stress, major cracks extend continuously despite the reduced external loading. The post-peak deformation known as strain softening was characterized by a descending curve with negative tangential stiffness, which is an important indicator of the brittleness of the material \[62,63\]. Compared with RAC-N, the post-peak response shows that the RAC-2% NS-N experienced a much steeper branch of the stress–strain curve. The NS material not only enhanced the compressive strength but maintained a better toughness and a better energy absorption capacity, which is consistent with previous studies \[47,48\]. For
specimens under compression casting (RAC-P and RAC-2% NS-P), the addition of 2% NS significantly increased the compressive strength, which indicates that NS contributes to the enhancement in compressive strength for both normal and compression cast concrete (Figure 5(b)). However, higher compressive strength resulted in the increased brittleness of the compression casting specimens. The comparison among RAC-N, RAC-P, RAC-2% NS-N, and RAC-2% NS-P indicates that the combination of CCT and 2% NS contributed most to the enhancement of compressive strength, followed by separate use of CCT, and 2% NS in sequence. Figure 5(c) and (d) shows the effects of two mechanisms involved in the compression casting method on the stress–strain curves for normal RAC and NS-modified RAC specimens. As stated previously, the first mechanism is the reduced water/binder ratio caused by compression casting, and the second is the physical densification. The effects of reduced water/binder ratio and compression casting on the stress–strain responses of RAC without and with the modification of 2% NS were similar. Clearly, the second mechanism of compression casting showed a more significant influence on the compressive strength and post-peak behavior, which will be presented and discussed subsequently.

3.3 Compressive strength

Figure 6(a) and Table 4 compare the compressive strength (peak stress) for specimens caused by the individual and combined effects of reduced water/binder ratio, NS, and compression casting. Compared with specimen RAC-N, the compressive strength of specimens RAC-CP and RAC-P increased by 32.2 and 88.1%, respectively, indicating that both the reduced water/binder ratio and densification were effective [53,64] and that the strength enhancement under compression casting was mainly contributed by the densification. Compared with specimen RAC-2% NS-N, the compressive strength of specimens RAC-2% NS-CP and RAC-2% NS-P increased by 23.5 and 77.3%, respectively. Thus, similar trends and mechanisms can be found for specimens incorporating nano-silica. Notably, the densification involves mechanisms like the reduced total porosity and enhanced ITZ, which will be thoroughly presented and analyzed subsequently.

Under the same water/binder ratio, the compressive strength increases due to compression casting which was 42.3% for specimens without nano-silica (RAC-CP and RAC-P) and 43.5% for specimens with nano-silica (RAC-2% NS-CP and RAC-2% NS-P). Compared with specimen
RAC-N, RAC-CP, and RAC-P, the addition of 2% NS resulted in a strength increment of 37.1% (RAC-2% NS-N), 28.0% (RAC-2% NS-CP), and 29.2% (RAC-2% NS-P), respectively, indicating that the improvement in the compressive strength of the sample is attributed to the addition of 2% NS [47,48]. After compression casting, specimen RAC-N, which had the lowest strength of the original mix (20.10 MPa), had the highest strength enhancement rate of 88.1%, while specimen RAC-2% NS-N, which had the highest strength of the original mix (27.55 MPa), experienced a relatively lower improvement ratio of 77.3%. Notably, the combined enhancement due to the compression casting method and nano-silica (specimen RAC-2% NS-P) synthetically improved the compressive strength by 143% compared with specimen RAC-N.

### 3.4 Elastic modulus

Figure 6(b) and Table 4 show a comparison of the modulus of elasticity for all specimens. The histogram value

![Figure 6: Comparison of key points on stress–strain curves: (a) compressive strength, (b) modulus of elasticity, (c) peak strain, and (d) ultimate strain.](image)

**Table 4: Key points on stress–strain curves**

<table>
<thead>
<tr>
<th>Spec. ID</th>
<th>No. of samples</th>
<th>Compressive strength (MPa)</th>
<th>Peak strain (%)</th>
<th>Ultimate strain (%)</th>
<th>Modulus of elasticity (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAC-N</td>
<td>3</td>
<td>20.10</td>
<td>0.16</td>
<td>0.35</td>
<td>24.62</td>
</tr>
<tr>
<td>RAC-CP</td>
<td>3</td>
<td>26.58</td>
<td>0.20</td>
<td>0.36</td>
<td>26.99</td>
</tr>
<tr>
<td>RAC-P</td>
<td>4</td>
<td>37.81</td>
<td>0.21</td>
<td>0.32</td>
<td>23.14</td>
</tr>
<tr>
<td>RAC-2% NS-N</td>
<td>3</td>
<td>27.55</td>
<td>0.25</td>
<td>0.40</td>
<td>20.19</td>
</tr>
<tr>
<td>RAC-2% NS-CP</td>
<td>3</td>
<td>34.04</td>
<td>0.30</td>
<td>0.41</td>
<td>21.10</td>
</tr>
<tr>
<td>RAC-2% NS-P</td>
<td>4</td>
<td>48.85</td>
<td>0.30</td>
<td>0.37</td>
<td>20.14</td>
</tr>
</tbody>
</table>
of each specimen is the averaged elastic modulus of the three specimens (Figure 6(b)), and the value was determined in accordance with the regulations specified in ASTM C469 [65]. The modulus of elasticity for specimens RAC-N, RAC-CP, RAC-P, RAC-2% NS-N, RAC-2% NS-CP, and RAC-2% NS-P was 24.6, 27.0, 23.1, 20.2, 21.1, and 20.1 GPa, respectively. For specimens without (RAC-N) and with nano-silica (RAC-2% NS-N), the reduction in water/binder ratio increased the elastic modulus by 9.6% (RAC-CP) and 4.5% (RAC-2% NS-CP), respectively. This trend is consistent with that of the compressive strength. Under the scenario of reduced water/binder ratio, the increased compressive strength was associated with the denser ITZ between mortar and aggregate [64]. However, the compression casting decreased the modulus of elasticity by 6.1% for specimens without nano-silica (RAC-N and RAC-P) and by 0.3% for specimens with nano-silica (RAC-2% NS-N and RAC-2% NS-P). This phenomenon indicates that nano-silica offset most of the negative effect of compression casting on the modulus of elasticity. This negative effect of compression on the elastic modulus might be because high stress (triaxial compressive stress state) was applied during the compression casting and lasted for 24 h. After removing it from the mold, the specimen changed from a triaxial compressive stress state to an unloaded state, and un-restricted high residual internal stress began to release, resulting in a small expansion strain on the specimen that was eventually detrimental to the elastic modulus. Notably, the elastic modulus of concrete modified by compression casting will be affected by the values of compressive stress applied and the associated time of duration, thus more tests and experimental evidence are needed to further clarify this issue.

3.5 Strain corresponding to peak stress

Figure 6(c) shows a comparison of the averaged peak strain of all the specimens. A more detailed value of peak strain for each specimen can be found in Table 4. For specimens without NS, the peak strain increased from 0.16% (RAC-N) to 0.20% (RAC-CP) because of the reduced water/binder ratio and further increased to 0.21% (RAC-P) owing to the compression casting. For specimens incorporating NS, the degree of peak strain increases because of the reduced water/binder ratio and compression casting was less significant than the corresponding cases of the specimens without NS, as summarized in Table 4. With the addition of NS only, the peak strain grew from 0.16% (RAC-N) to 0.25% (RAC-2% NS-N) under a water/binder ratio of 0.53, and from 0.20% (RAC-CP) to 0.30% (RAC-2% NS-CP) under a water/binder ratio of 0.39. For specimen under combined modifications of compression casting and 2% NS (RAC-2% NS-P), the peak strain was 0.3%, which is the same as that of RAC-2% NS-CP. Thus, it can be inferred that the enhancement in peak strain is mainly contributed by the reduced water/binder ratio [64], whereas the physical compression led to a larger increase in the peak stress.

3.6 Ultimate strain

The ultimate strain was determined by taking a reading at point on the descending branch of a stress–strain curve where the stress equals 0.85 times of the peak stress [61, 66]. Figure 6(d) compares the ultimate strains for all specimens, and the averaged value of each specimen is also provided in Table 4. The ultimate strain values are given for reference only because the drop of the stress–strain curve for the concrete specimens depends partly on the stiffness of the testing machine [53]. Under normal casting, when the water/binder ratio decreased from 0.53 to 0.39, the ultimate strains increased from 0.35% (RAC-N) to 0.36% (RAC-CP) for specimens without NS as well as from 0.40% (RAC-2% NS-N) to 0.41% (RAC-2% NS-CP) for specimens with NS. With the addition of nano-silica, the ultimate strain increased from 0.35% (RAC-N) to 0.40% (RAC-2% NS-N) under a water/binder ratio of 0.53, and from 0.36% (RAC-CP) to 0.41% (RAC-2% NS-CP) under a water/binder ratio of 0.39. Thus, the extent of enhancement in ultimate strain due to the incorporation of NS is more significant than reducing the water/binder ratio. However, the compression casting decreased the ultimate strain for specimens regardless of whether NS was used or not. Compression casting enhanced the member compressive strength and simultaneously increased the brittleness [53], which eventually resulted in a small decrease in ultimate strain values.

4 Microstructure

4.1 Effect of nano-silica and compression casting on the porosity

The mortar samples used for the investigation of porosity were obtained from the cylinder specimens. Figure 7(a) depicts the cumulative porosity curves of the mortar from specimens RAC-P, RAC-CP, RAC-2% NS-P, and RAC-2% NS-CP.
Figure 7 shows the proportion of porosity under different pore sizes, which are further quantitatively summarized in Table 5. The pore sizes of the above specimens ranged from 0.007 to 100 µm (Figure 7(a)). The total porosity of uncompressed specimens RAC-CP and RAC-2% NS-CP was 15.58 and 12.73%, which was, respectively, decreased to 12.31% (RAC-P) and 10.76% (RAC-2% NS-P) by using compression casting. Thus, under the same water/binder ratio, the physical compression casting can reduce the total porosity of the RAC regardless of with and without 2% NS. After the addition of 2% NS, the porosity reduced from 15.58% (RAC-CP) to 12.73% (RAC-2% NS-CP) and from 12.31% (RAC-P) to 10.76% (RAC-2% NS-P), indicating that the NS can effectively fill the mortar matrix and make the internal structure denser. Thus, even in a denser matrix structure, the compression casting method can further improve the mortar compactness.

Table 5: Pore parameters in mortar measured by MIP

<table>
<thead>
<tr>
<th>Spec. ID</th>
<th>Total porosity (%)</th>
<th>Porosity ratio (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>&lt;0.01 µm</td>
</tr>
<tr>
<td>RAC-CP</td>
<td>15.58</td>
<td>5.32</td>
</tr>
<tr>
<td>RAC-P</td>
<td>12.31</td>
<td>6.55</td>
</tr>
<tr>
<td>RAC-2% NS-CP</td>
<td>12.73</td>
<td>2.33</td>
</tr>
<tr>
<td>RAC-2% NS-P</td>
<td>10.76</td>
<td>5.69</td>
</tr>
</tbody>
</table>

As summarized in Table 5, the proportion of large capillary pores was not reduced by the physical compression, instead, the percentage of large pores (>5 µm) increased by 3.9% for specimens without NS (RAC-CP and RAC-P) or 3.2% with NS (RAC-2% NS-CP and RAC-2% NS-P). As summarized in Table 5, the proportion of large capillary pores was not reduced by the physical compression, instead, the percentage of large pores (>5 µm) increased by 3.9 or 3.2% for specimens without (specimens RAC-CP and RAC-P) or with NS (specimens RAC-2% NS-CP and RAC-2% NS-P), respectively. The reason can be given as follows. In the process of compression casting, the pore pressure of the internal slurry increased, which caused the water discharge out of the mold. The discharged water impacted the slurry structure until forming the tiny connecting holes inside the slurry. However, the pores in the slurry cannot be completely and promptly backfilled by solid material after drainage, and they exist until the concrete hardens. These pores can be seen in the mercury injection test in the form of large pores. Although the compression casting method did not improve the percentage of pore distribution of the mortar, this method can further densify the mortar under conditions of equal water/binder ratio, thus achieving an increase in concrete strength.
Figure 8: Grayscale threshold values for determination of pore ratio along ITZ of RAC-CP based on 4 random BSE images (4 out of 30 shooting areas, refer to Figure 3): (a) brightness histogram for image 1, (b) cumulative grayscale histogram for image 1, (c) brightness histogram for image 2, (d) cumulative grayscale histogram for image 2, (e) brightness histogram for image 3, (f) cumulative grayscale histogram for image 3, (g) brightness histogram for image 4, and (h) cumulative grayscale histogram for image 4.
4.2 Effect of compression casting on ITZ

4.2.1 Determining the threshold value for pore ratio based on BSE images

The preparation of BSE samples was depicted in Section 2.3.3. In a BSE image, the pixel brightness varied with the number of atoms, so the darkest areas were pores or voids, followed by aggregate particles, hydration products, and unreacted cement in turn [68]. The upper grayscale threshold for porosity was determined by the turning point of the cumulative brightness histogram of the BSE image [69–73]. Threshold values for the determination of pore ratio are shown in Figure 8. Using RAC-CP as an example, Figure 8(a) represents the number of pixel points within a region that was segmented into 255 by grayscale value, and Figure 8(b) depicts the change in cumulative pixel shared at different grayscale threshold levels. As shown in Figure 8(b), the tangent slope method was used to determine the pores’ upper grayscale threshold, which has been verified by existing research works [69–73]. Notably, the upper limit of the grayscale threshold for porosity was related to its brightness and contrast. Thus, during the BSE imaging process, the brightness, contrast, and the related SEM setup parameters were kept the same for the same group of samples. Before analysis, the upper limit threshold of the pores was determined for each of the 30 BSE images using the tangent slope method [69–73], and the results of four randomly selected BSE images are shown in Figure 8. The upper grayscale thresholds of pores obtained from the 4 BSE images of RAC-CP were extremely close, at 124, 123, 119, and 123, respectively, indicating that the upper grayscale thresholds are stable in a very small range under the premise of the same shooting parameters. The same processes were adopted to determine the upper grayscale thresholds of specimens RAC-P, RAC-2% NS-CP, and RAC-2% NS-P. Using the above-stated method, the upper grayscale thresholds of specimens RAC-CP, RAC-P, RAC-2% NS-CP, and RAC-2% NS-P were 122, 115, 120, and 118, respectively.

Therefore, in the subsequent analysis of pore distribution based on the BSE images, the average upper limit of pore grayscale threshold obtained from any four BSE images was used for pore distribution analysis. It is worth noting that the upper grayscale threshold of the pore can be determined by the artificial threshold method, the tangent slope method, and the entropy maximization method. However, the tangent slope method was applied in the present work due to the inherent limitations of artificial thresholds and entropy maximization [71]. In this article, the porosity was statistically calculated by dividing the pore area by the total area in the BSE image. The porosity values were expressed as percentages. Notably, the BSE image analysis is affected by the resolution.

Figure 9: Pore distribution along ITZ based on two random BSE images of RAC-CP: (a) original BSE image 1, (b) pore distribution of BSE image 1, (c) original BSE image 2, and (d) pore distribution of BSE image 2.
Thus, the analysis only contains large capillaries and large pores \([74–77]\), which naturally caused the porosity obtained by backscattering to be slightly smaller than the porosity of MIP. A total of 30 BSE images were taken along the new ITZ (between the old and new mortar interfaces) for each specimen, as shown in Figure 3.

Figure 10: Pore distribution along ITZ based on two random BSE images of RAC-P: (a) original BSE image 1, (b) pore distribution of BSE image 1, (c) original BSE image 2, and (d) pore distribution of BSE image 2.

Figure 11: Pore distribution along ITZ based on two random BSE images of RAC-2% NS-CP: (a) original BSE image 1, (b) pore distribution of BSE image 1, (c) original BSE image 2, and (d) pore distribution of BSE image 2.
Figure 12: Pore distribution along ITZ based on two random BSE images of RAC-2% NS-P: (a) original BSE image 1, (b) pore distribution of BSE image 1, (c) original BSE image 2, and (d) pore distribution of BSE image 2.

Figure 13: Porosity at 30 shooting areas along ITZ according to BSE image analysis (30 shooting areas refer to Figure 3): (a) RAC-CP, (b) RAC-P, (c) RAC-2% NS-CP, and (d) RAC-2% NS-P.
4.2.2 Pore distribution along ITZ

Taking specimen RAC-CP as an example, Figure 9(a) shows the original BSE image, and Figure 9(b) illustrates the pore distribution pattern (dark areas) as calculated by setting the upper limit of the porosity grayscale threshold in a computer program. Figures 9–12 show the pore analysis of specimens RAC-CP, RAC-P, RAC-2% NS-CP, and RAC-2% NS-P, respectively. The ITZs were marked in Figures 9 and 11 for specimens under normal casting (without compression). It can be clearly seen that many pores and much cement slurry are continuously distributed along the ITZs of specimens RAC-CP and RAC-2% NS-CP. These continuous pores along the ITZs are the major reasons for the lower strength of RAC. However, after the treatment of compression casting, the RAs were much more tightly bound to the cement paste (Figures 10 and 12), and the pores were sparsely distributed in the ITZ areas. Some researchers have defined ITZ as a region with a certain width extending from the aggregate to the cement slurry [78–80]. The positive effect of the compression casting method on the RAC can be interpreted as a significant reduction in the width of the ITZ, resulting in a significant enhancement in the weak areas (or weakest link) between the RA and the cement paste. Thus, the bonding property of aggregate and paste is significantly improved under compression casting. However, the improvement in pore distribution along ITZs because of the addition of 2% NS was not as obvious as that of compression casting.

Figure 13 shows the calculated values of pore ratio based on the analysis of 30 BSE images for specimens RAC-CP, RAC-P, RAC-2% NS-CP, and RAC-2% NS-P. The average porosity of RAC-CP, RAC-P, RAC-2% NS-CP, and RAC-2% NS-P was 4.50, 3.92, 4.17, and 3.52%, respectively. Thus, it was clear that both the compression casting and nano-material modifications (2% NS) can reduce the pore ratio of ITZs, and more importantly, the combination of compression casting and 2% NS was most effective in this regard. Meanwhile, the variation in pore ratio against different modifications measured by the BSE image method was consistent with that obtained by MIP.

5 Conclusion

This study aims to improve the properties of RAC. To this end, the combination of compression cast technology and the addition of 2% NS was studied for the first time. To understand the enhancement mechanisms, uniaxial compressive tests (macro-level) and material characterizations (micro-level) were conducted to investigate the stress–strain behaviors and porosity as well as pore distribution along ITZ of RAC under different modifications (i.e., compression casting, the addition of 2% NS and their combination). Based on this work, the following conclusions were drawn:

1) The single-use of compression casting, single-use 2% NS, or the combined use of them can, respectively, enhance the compressive strength and reduce the porosity of RAC.
2) Two mechanisms were involved in the strength enhancement of RAC under compression casting. The first is the slightly reduced water/binder ratio because of compression drainage, and the second is the concrete densification. The first mechanism was found to be much less significant than the second one.
3) Compared with normal RAC (normal casting without 2% NS) under the condition of equal water/binder ratio, the compressive strength increased by 37% when incorporating 2% NS, increased by 88% when using compression casting, and increased by 143% under a combined modification of 2% NS and compression casting. For 2% NS modified RAC, the compression casting further enhanced the compressive strength by 77%.
4) The modulus of elasticity was slightly decreased by both the compression casting and 2% NS modification. Compared with normal RAC (normal casting without 2% NS), the peak strain (strain corresponding to peak stress of a stress–strain curve) increased from 0.1 to 0.21% under compression casting, to 0.25% using NS, and to 0.30% when combining compression casting and addition of NS.
5) Under the same water/binder ratio, the total porosity of the control specimen (RAC-CP) was 15.58%, which decreased to 12.31% for compression casting (decreased by 21%), 12.73% when adding 2% NS (decreased by 18%), and 10.76% when modifying with both compression casting and 2% NS (decreased by 31%).
6) In terms of the enhancement in ITZ of RAC, the combination of compression casting and the use of 2% NS was most significant, and the single-use 2% NS was least significant with the single-use of compression casting falling in between.

The conclusions drawn from the current study are based on the test results, discussions, and understanding presented above. However, since only limited parameters and small ranges of parameter variation were considered, additional studies are needed to consider more factors (e.g., environmental conditions, material dimensions,
and pressure as well as time duration in CCT) to further understand the behavior of RAC modified by compression casting and nano-silica.

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