Mechanical properties and microstructure of nano-strengthened recycled aggregate concrete

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Abstract: The surface adhesion mortar of recycled coarse aggregate (RCA) is the main factor leading to poor aggregate quality, and it also affects the internal structure and mechanical properties of recycled aggregate concrete (RAC). To improve the quality of RCA and mechanical properties of RAC, self-developed mortar removal equipment was used to strengthen the RCA. Then, the RCA was soaked in 1, 2, and 3% nano-silica solutions, and the vibration-mixing process was used to improve the quality of RAC. In addition, the microstructure of the RCA was examined via scanning electron microscopy to observe its improvement effect on the microstructure of the RAC. The results indicated that the quality of the RCA was improved by mechanical and physical strengthening, and the water-absorption rate and crushing value decreased by 32.9 and 23.9%, respectively. The improvement effect of nan-immersion on the RAC was obvious. The optimal condition was a combination of physical strengthening, 2 days of immersion in 2% NS solution, and vibration stirring. The 28 day compressive strength increased by 31.3%, the splitting tensile strength increased by 23%, and the flexural strength increased by 49%. The proposed strengthening method improves the mechanical properties and microstructure of RAC. The results of this study provided a technical reference for the mechanical strengthening of RAC and promotion of the application and popularization of RAC.

Keywords: recycled coarse aggregate, nano-SiO₂, mechanical strengthening, compound strengthening, mechanical properties, microstructure

1 Introduction

With the promotion of urban-rural integration and infrastructure creation, a large amount of construction materials has been consumed, and a large amount of abandoned construction waste has been produced. If not treated, construction waste will not only cause serious environmental pollution but also occupy a considerable amount of farmland. Therefore, the effective recycling of construction waste is an urgent engineering problem that must be solved for sustainable development [1–3]. After the simple crushing of recycled coarse aggregate (RCA), the surface becomes not only rough with multiple edges and corners but is also attached to a large amount of cement mortar. In the preparation, owing to external forces, numerous microcracks are generated, resulting in the defect of a high water-absorption rate. To improve the quality of RCA, many physical and chemical methods have been proposed for removing or strengthening the old RCA mortar. The main methods for removing the mortar are heating [4] and acid treatment [5]. The main methods for strengthening RCA are carbonization [6] and solution strengthening [7]. The main crushing mode of concrete is mechanical crushing. When subjected to an external force, the waste concrete is forced to separate. Although this method can realize RCA mass production and reduce the production cost, the RCA produced has a large amount of adhered mortar, which affects the quality of the recycled concrete. The performance of the RCA can be improved by secondary slurry removal [8,9]. Marta and Pila [10] heated the saturated RCA at 500°C and soaked it in hydrochloric acid for de-pulping the RCA. The acid solution strengthening method can improve the quality of RCA without changing its morphology, but this method damages the internal structure of the RCA, affecting its performance. In conventional heating, RCA is heated at two different temperatures (300 and 500°C) and then cooled in water at 25°C [11]. In mechanical friction, RCA is put into a machine. After grinding, the old mortar on the RCA surface is removed, which improves the combined effect of the RCA and new mortar.
Akbarnezhad et al. [12] treated the adhered mortar layer on the RCA surface with microwave heating and mechanical grinding, effectively improving the physical properties of the RCA. Microwave weakening pretreatment can improve the mechanical properties of recycled aggregate concrete (RAC) [4]; however, the cost of this method was relatively high and the operation was complicated. The performance of RCA is improved by solution immersion, which is facile and requires little equipment. Owing to the relatively high and the operation was complicated. The improvement effect on RCA is also different. Many scholars have used nano-solutions to improve RCA and RAC. Studies have indicated that nano-silica (NS) can consume Ca(OH)$_2$ in RCA to improve its quality and can also react with Ca(OH)$_2$ – the hydration product of cement – to form calcium silicate hydrate (C-S-H) gel, improving the compactness and strength of RAC [13]. Shaikh et al. [14] used pre-immersion and incorporation methods to strengthen RAC and reported that the compressive strength of the RAC was increased by approximately 5% after soaking in an NS solution. In addition, the composite strengthening effect of the two methods was more obvious than the effects of the individual methods. The addition of a sufficient amount of fine-grained pozzolanic additive in the form of fly ash that contain active silica (SiO$_2$) causes a gradual reaction with calcium hydroxide (CH), consequently forming significant amounts of the calcium silicate hydrate phase. As a result, there is not only an improvement in the quality of the hydrates but also quantitative changes in the structure of the cement matrix [15–17]. Gao et al. [18] used a nano-CaCO$_3$ solution to strengthen RCA; the compactness of the RCA was increased, and the compressive strength and compactness of the RCA were improved. Shaban et al. [19] soaked RCA in different types of volcanic-ash solutions to improve the performance of the RAC. When 40% mud and 3% nano-silicon powder were mixed, the strengthening effect was optimal. Mukharjee and Barai [13] found that when NS was added to RAC, the gap of the RAC was filled with NS particles and reaction products, and the strength and compactness of the interfacial transition zone (ITZ) were improved. The peak flexural tensile strength of the RAC reached 4.97 MPa – an increase of approximately 15%.

Zeng et al. [20] found that soaking RCA in a nano-solution can increase the compressive strength of the RAC, enhance the strength of the ITZ between the old and new mortar, and reduce the width of the ITZ. Li et al. [21] added NS particles to RAC, and the compressive strength of the RAC was increased by 21.6%. Nuaklong et al. [22] found that the compressive strength of RAC was increased by 13% after the incorporation of NS, but the resistance to chloride ions was reduced. The addition of fly-ash changes the consistency of RAC and improves its mechanical properties [23–25].

Most of the previous studies involved single reinforcement of RCA, and the reinforcement effect was not obvious. In this study, the quality of RCA was improved by physical slurry removal and soaking in NS solutions with different concentrations for different amounts of time, and the mechanical properties of the RAC were enhanced by a vibrational stirring process. The improvement effects of single and compound strengthening on the mechanical properties of the RAC were studied, the internal microstructure of the RAC was examined via scanning electron microscopy (SEM), and the mechanisms whereby the different strengthening methods improved the internal microstructure of the RCA were studied.

## 2 Experimental investigation

### 2.1 Raw materials

RCA was obtained by crushing waste concrete at a construction site in Henan Province, China, and then processed by secondary slurry removal equipment. The physical properties of the RCA before and after slurry removal are presented in Table 1. P.O 42.5 ordinary Portland cement was used, and its performance indicators were in accordance with the specifications of “General Portland Cement” (GB175-2007). The fine aggregate was natural river sand, with a fineness modulus of 2.67. The NS solution was the HTSI-11L solution produced by Nanjing Haitai Nanomaterials Co., Ltd. The physical properties of the NS solution are presented in Table 2. The water used was laboratory

### Table 1: Physical properties of the RCA before and after slurry removal

<table>
<thead>
<tr>
<th></th>
<th>Absorption rate (%)</th>
<th>Apparent density (kg/m$^3$)</th>
<th>Packing density (kg/m$^3$)</th>
<th>Crush value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RCA</td>
<td>7.9</td>
<td>2,600</td>
<td>1,253</td>
<td>16.3</td>
</tr>
<tr>
<td>RCA (after slurry removal)</td>
<td>5.3</td>
<td>2,710</td>
<td>1,305</td>
<td>12.4</td>
</tr>
<tr>
<td>RCA (modified by 2% NS solution)</td>
<td>3.7–4.2</td>
<td>2,730–2,763</td>
<td>1,323–1,361</td>
<td>10.5–11</td>
</tr>
</tbody>
</table>
tap water. The chemical strengthening of the RCA was conducted as follows: the RCA (particle size of 5–20 mm) was cleaned and air-dried and then immersed in a 1, 2, or 3% NS solution for 24 or 48 h, as shown in Figure 1. After the immersion, the RCA was spread in a ventilated place to air-dry naturally.

2.2 Mix proportions

The design strength grade of the RAC was C30. The mix proportion was designed according to JGJ55-2011 “Ordinary Concrete Mix Design Regulations.” The water-cement ratio was 0.5, and the sand ratio was 36%. The RCA replacement rate was 100%, and the particle size of the RCA was 5–20 mm. The mix proportions are presented in Table 3.

To investigate the effects of different strengthening methods on the early and late strengths of the RAC, 16 groups of tests were conducted, and each group was divided into three ages: 7, 14, and 28 days. For each age, three specimens were produced; thus, the total number of test blocks was 432.

2.3 Grinding test of RCA

The grinding equipment used in this test is a self-developed RCA grinding machine, as shown in Figure 2. When RCA was given an external force (between the strengths of coarse aggregate and the bonding surface), the attached mortar and aggregate separated under the action of force, and the RCA after removing the mortar was obtained. The machine was turned at a frequency of 18 Hz. After the simple crushing of RCA, the surface was rough, with multiple edges and corners, and was also attached to a large amount of cement mortar. After the equipment treatment, the old mortar on the surface of RCA was significantly reduced and the particle shape was better. The quality of RCA was effectively improved, and the water absorption and crushing value were reduced. The effect of removing mortar is shown in Figure 3.

2.4 Vibration stirring process

In vibration mixing, the optimal arrangement of blades in the mixer led the mixture to undergo forced circulation and countercurrent movement, so that the process was uniform. Vibration mixing can enhance the convective and diffusion motion between RCA and cement mortar. The protective film on the surface of the cement paste got destroyed, allowing water to enter the cement paste more easily. This made the cement paste more evenly distributed and allowed the hydration reaction to progress, further improving the structure of the ITZ and the overall performance of the mixture. The vibration mixer was a 60 L double-horizontal shaft vibration mixer with an input power of 4 kW and a vibration input power of 3 kW.

2.5 Compressive strength test

The size of the compressive-strength test specimens was 150 mm × 150 mm × 150 mm. The compressive strength test was performed using a WHY-2000 concrete pressure test machine, in accordance with the GB/T50081-2002 specifications. After the specimen was removed from the maintenance room, its surface was cleaned. The specimen was placed at the center of the press cap so that the center of the specimen was aligned with that of the upper and lower caps of the testing machine. The contact surface of the specimen subjected to the load was perpendicular to the forming surface of the specimen. The arithmetic mean value of the three specimens was taken as the test result.

2.6 Splitting tensile strength test

The size of the splitting tensile strength test specimens was 100 mm × 100 mm × 100 mm. The splitting tensile

Table 2: Physical properties of NS solution

<table>
<thead>
<tr>
<th>Appearance</th>
<th>Density (g/cm³)</th>
<th>Size (nm)</th>
<th>pH</th>
<th>Purity</th>
<th>Price/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS White flocculent powder</td>
<td>1.1–1.2</td>
<td>15–30</td>
<td>9–10</td>
<td>≥99</td>
<td>$13</td>
</tr>
</tbody>
</table>

Figure 1: Soaking of RCA.
Table 3: Mix proportions of RAC

<table>
<thead>
<tr>
<th>Mix type</th>
<th>Water-cement ratio</th>
<th>Water (kg/m³)</th>
<th>Cement (kg/m³)</th>
<th>Sand (kg/m³)</th>
<th>RCA (kg/m³)</th>
<th>Solution concentration (%)</th>
<th>Immersion time (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>ZP</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>CP1-1</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CP1-2</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CP2-1</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>CP2-2</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CP3-1</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>CP3-2</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>NZ</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>CZ</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>\</td>
<td>\</td>
</tr>
<tr>
<td>CZ1-1</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>CZ1-2</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>CZ2-1</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>CZ2-2</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CZ3-1</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>CZ3-2</td>
<td>0.5</td>
<td>210</td>
<td>420</td>
<td>619</td>
<td>1151.3</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

Note: N represents the original RCA, C represents the treated RCA, P represents ordinary stirring, and Z represents vibration stirring; for example, CP1-2 represents RAC produced by RCA ordinary stirring after soaking in the 1% NS solution for 2 days (48 h).

Figure 2: (a) RCA slurry removal equipment and (b) workflow.
strength of the RAC was tested in accordance with GB/T50081-2002. The test block was placed in the center of the testing machine. A circular arc pad and pad bar were mounted on and below the specimens. The fracture surface of the splitted cubic specimen was perpendicular to the upper surface of the specimen.

2.7 Flexural strength test

The size of the flexural-strength test specimens was 100 mm × 100 mm × 400 mm. This test was conducted in accordance with GB/T50081-2002. After the specimens were removed from the curing room, the surface was wiped clean. The test was performed using a WHY-300/10 microcomputer-controlled pressure test machine.

3 Results and discussion

3.1 Compressive strength

Compared with untreated RCA, the compressive strength of the RAC after physical strengthening increased by 18.19, 14, and 7.64%, respectively. The enhanced RCA can effectively improve the compressive strength of RAC, particularly the early compressive strength. Cementing force between RCA and new cement mortar was strengthened after slurry removal [26,27].

The compressive strength of the CZ group was higher than that of the CP group at each age, indicating that vibration stirring can enhance the compressive strength of RAC. This is because the energy generated by vibration stirring was transmitted to the RAC through the stirring shaft, which increased the friction and frequency of collision between the mixtures, dispersing the cement particles and facilitating the hydration process [28]. The exciter designed with the mechanism of dynamic balance was built into the center of the mixing drum so that the vibration energy could be better absorbed by mixtures, boosting the uniformity of fresh concrete. Meanwhile, the energy also caused the cement particles to continuously flutter around an unbalanced middle position. With the increase in frequency of vibration of the particles, the density of RAC was increased and the microstructures of RAC can be improved. The products can fill the pores in the RAC and the microcracks in the ITZ. When only physical and production strengthening were used, the strength of the CZ group was increased by 25, 19.4, and 16.1% for the ages of 7, 14, and 28 days, respectively, compared to the NP group, and the effect of the composite strengthening was more significant than that of single strengthening.

As shown in Figure 4, the compressive strength of the RAC was improved more effectively when a nano-solution was used for strengthening, which is consistent with the results of Gao et al. [18]. The improvement effect of the NS on the early compressive strength was better than the late, possibly owing to the active participation of NS in the early cement hydration, the filling of the fine pores, and the better spray effect. In the later stage, the cement hydration was sufficient, and the hydration products were dense. In addition, the NS adhered to the outside of the voids owing to its strong cohesion; it formed a film preventing cement hydration and slowed down the increase.

![Figure 3: Comparison before and after removing mortar: (a) original RCA and (b) treated RCA.](image-url)
of strength [29,30]. The CP2-2 group had the best 28-day compressive strength (24.3% higher than that of the NP group). For 1 day of soaking in a nano-solution, the compressive strength of the RAC increased with the concentration of the NS solution. The effect of 2 day immersion was better than that of 1 day immersion. However, the compressive strength of 3% immersion for 2 days was slightly lower than that of 2% immersion for two days. Thus, when the concentration was high, a longer soaking time was not better. This is explained as follows: when the RCA was immersed in a high-concentration solution for a long time, it was filled with numerous NS particles, which accumulated on its surface. In the reaction with cement, the NS particles on the RCA surface underwent a secondary reaction with the hydration product of cement, that is, Ca(OH)$_2$, to form C–S–H which prevents the NS particles from continuing to reflect on it. Excess NS will accumulate in the RAC, adversely affecting its strength [31]. Byung-Wan et al. [32] reported that an appropriate amount of NS can fill the cracks of RAC, and the products generated by the reaction of Ca(OH)$_2$ improved the microstructure, compactness, and compressive strength of the RAC.

Under composite strengthening, the CP2-2 and CZ2-2 groups had higher compressive strengths. Between them, the CZ2-2 group had a higher 28-day compressive strength (31.3% higher than that of the NP group). The results of Li [33] indicate that when the NS concentration was 2%, the compressive strength maximized by 21.6%. The composite strengthening method of physical slurry removal, nano-immersion, and stirring had a better effect on the RAC. Vibrational stirring can make NS particles attached to RCA react fully with hydration products of cement while improving the microstructure and strength of the RAC [34].

### 3.2 Splitting tensile strength

As shown in Figure 5, physical slurry removal enhanced the splitting tensile strength at each RAC age by 10.85, 7.31, and 6.53%, particularly the splitting tensile strength at the early stage. Less mortar is attached to the RCA surface after slurry removal, which improved the particle shape of the RAC and strengthened the cementing force between the RCA and the new cement mortar [35]. The splitting tensile strength of RAC can also be improved by vibrational stirring. Compared with the NP group, the strength of the CZ group was increased by 18.9, 14, and 12.1%, respectively. The effect of composite strengthening was more significant than that of single strengthening.

When chemical strengthening was used, the splitting tensile strength changed in accordance with the compressive strength at each RAC age. In the case of soaking for 1 day, the splitting tensile strength of the RAC increased with the soaking concentration, but with an increase in the soaking time, the splitting tensile strength was the highest for the concentration of 2%, with a value of >3%. The 28-day splitting tensile strength of the CP2-2 group was increased by 18.2% compared to the NP group. This is because, with the increase in the immersion concentration and time, a large number of NS particles were accumulated on the RCA surface, exceeding the amount of Ca(OH)$_2$ involved in the reaction [15–17]. The excess part had caked, affecting the binding force of the RCA and mortar, generating numerous cracks, and affecting the strengths of the ITZ and RAC [32].

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**Figure 4:** Compressive strengths of the RAC at various ages. (a) Ordinary mixing mode and (b) vibration mixing mode.
CZ2-2 exhibited the highest tensile strengths of 2.85, 3.25, and 3.58 MPa, which were increased by 34.4, 25, and 23% compared with the NP group. The composite strengthening improved the bonding force inside the RAC and enhanced the cracking resistance \[35\]. The splitting tensile strength of the RAC was significantly improved.

### 3.3 Flexural strength

As shown in Figure 6, the cracking of unstrengthened RAC mostly occurs at the interface between the RCA and cement mortar, because there is a large amount of old mortar attached to the untreated RCA surface \[8,9\], which reduced the binding force between the RCA and the new cement mortar \[36\] and affected the flexural strength of the RAC. The section of RAC after composite strengthening was relatively complete, with most of them being integral fractures, and a small part occurring at the ITZ of the RAC. It can be concluded that the physical slurry removal, NS immersion, and vibration stirring significantly improved the compaction performance of the RAC, enhanced the cementation capacity of the RCA and new mortar \[18\], and improved the bending strength of the RAC.

In general, physical strengthening improved the flexural strength of the RAC at all ages. In comparison with the NP group, the flexural strength of the CP group increased by 14.47, 14.17, and 9.1% for the ages of 7, 14, and 28 days, respectively. This was mainly because the
RCA surface adhered to the old mortar, leading to low strength and high water-absorption rate. When the cement reacted, untreated RCA released a part of water, forming holes and fine cracks, which reduced the cementing capacity and strength of the RCA and new mortar. However, with strengthened RCA, these shortcomings were mitigated, enhancing the strength of the RAC \cite{12,36}. The flexural strength of RAC can also be improved by vibrational stirring. The 28 day flexural strength of the CZ group was 34.6\% higher than that of the NP group, and the composite strengthening effectively improved the flexural strength of the RAC.

As shown in Figure 7, after chemical strengthening, the 28-day flexural strength of CP2-2 was 39.1\% higher than that of the NP group. The effect of the chemical strengthening on the flexural strength was similar to that of the splitting tensile strength. It was optimal when the immersion concentration was 2\% and the immersion time was two days. This is because NS particles attached to the RCA surface reacted with Ca(OH)$_2$ in RCA to improve the defects of RCA’s performance and simultaneously reacted with cement hydration products to improve the structural strength of the ITZ between the RCA and the new cement mortar. The cement particles and NS particles in the agglomerated state were dispersed by vibrational stirring, which promoted the aforementioned hydration reaction. NS particles could better fill the pores of C–S–H and act as crystal nuclei to form a denser structure, improving the RAC microstructure and enhancing the strength of the ITZ \cite{34,37}.

4 Microstructure of RAC

The microstructure characteristics of RAC determine its macroscopic properties \cite{38} to a certain extent, thus affecting the mechanical properties of the RAC. The microstructure of the interface was composed of CH crystals, pores, and C–S–H gel \cite{39–41}. The microstructure study is often based on a single method, with complex external factors, and the research results are not uniform. Many scholars have studied the composition, porosity, hydration products, strength, and density of the RAC microstructure – particularly weak structures such as the ITZ \cite{12,19,20}. The microstructure characteristics are related to the chemical and physical changes of the cement slurry and the aggregate \cite{42} and are closely related to the water-cement ratio, admixtures, and external influencing factors.

As shown in Figure 8(a), in the NP specimen, the ITZ between the RCA and the new mortar had a crack that started from the ITZ and extended from the mortar, spreading around. The crack was large, and the fit between the RCA and the cement mortar was poor. Under a load, the ITZ was prone to the generation of penetrating cracks. As shown in Figure 8(b), the number of pore cracks in the interface area between the RCA and the new mortar was reduced. The ITZ width was small and the structure was relatively dense.

The hydration reaction of RAC prepared by ordinary stirring was not uniform, and there were large and small internal pores and cracks. As shown in Figure 8(a), the surface uniformity was poor, and there were agglomerated cement particles and large water cluster particles. The RAC prepared by vibration stirring had a uniform microstructure, dense internal structure, and no dense distribution of voids and cracks. In addition, the agglomeration phenomenon and large water cluster phenomenon...

![Figure 7: Flexural strengths of the RAC at various ages. (a) Ordinary mixing mode and (b) vibration mixing mode.](image-url)
caused by the cement in the RAC were eliminated; thus, the hydration reaction of the RAC cement slurry was sufficient, and the surface was smooth.

As shown in Figure 8(d) and (e), the chemical strengthening increased the density of the RAC microstructure. The C–S–H gel generated by NS particles consuming Ca(OH)$_2$ in the ITZ can fill the pores on the surface and make the mortar matrix denser [37]. Floccule C–S–H gelled and overlapped to form a network structure with different CH crystal shapes. In addition, acicular ettringite (AFt) was distributed in the holes, and the ITZ had good bonding properties [42]. Vibrations mixing was conducive to promoting the hydration process of cement and increasing the amount of C–S–H cementing [43]. The bonding force of the mortar matrix was strengthened, and the ITZ properties were improved. The mortar matrix was closely composite with the RCA, with a small number of microcracks and fewer holes. Also, with the soaking of NS solution, the bonding force of the mortar matrix can be strengthened further, and the internal defects of RAC will be reduced [44–46].

Figure 8: Microstructure of RAC. (a) N-P, (b) C-P, (c) C-Z, (d) CP2-2, and (e) CZ2-2.
5 Cost analysis of NS solution

At present, the price of NS is higher than other materials in the method of modifying concrete [47–51]. There is some limitation to the application of NS in RCA soaking. Due to the high cost of the NS solution at present [18], the NS solution used for soaking RCA was recycled and used in the next round of soaking to reduce test and production costs. For example, when soaked in 1% concentration, there were still a large amount of NS particles in the solution. Assuming that the solution was homogeneous, the residual amount of the NS solution after soaking was 80%, and the concentration of the NS solution remained unchanged. An appropriate amount of NS solution and water can be added to the recovered solution, and the solution with a concentration of 2% can be continuously configured. The costs are shown in Table 4. In later studies, some tap water can also be replaced with a residual solution during RAC production [14]. The improvement effect of this method on the mechanical properties of RAC can be studied to improve the quality of RAC [52].

6 Conclusions and future perspectives

6.1 Conclusions

The improvements in the mechanical properties of RAC due to physical slurry removal, soaking in NS solutions with different concentrations for different amounts of time, and vibration stirring was systematically studied. Using SEM, the effects of the different strengthening methods on the RAC microstructure were analyzed. The following conclusions were drawn:

1) The water-absorption rate and crushing index of the RCA were improved by physical slurry removal. The water-absorption rate was reduced by 32.9%, and the crushing index was increased by 23.9%.

2) Nano-solution strengthening can fill the microcracks and pores in RCA and RAC and effectively improve the mechanical properties of RAC – particularly the early strength. In this study, the optimal improvement was achieved when the concentration was 2% and the soaking time was two days; the 28-day compressive strength, splitting tensile strength, and flexural strength was increased by 24.3, 18.2, and 39.1%, respectively.

3) Vibration stirring can effectively improve the internal microstructure of RAC, increase the compactness of RAC, and reduce the number of cracks and pores. The 28 day compressive strength, splitting tensile strength, and the flexural strength of the optimal group was increased by 5.6, 4, and 10.6%, respectively.

4) The mechanical properties of RAC can be effectively improved by the combination of physical slurry removal, NS solution treatment, and vibration stirring. The 28 day compressive strength increased by 31.3%, the splitting tensile strength increased by 23%, and the flexural strength increased by 49%.

5) Physical slurry removal, NS solution soaking, and vibration stirring reduced the number of internal microcracks, increased the density of the RAC, improved the structure of the ITZ, and improved the strength of the RAC.

6.2 Future perspectives

Overall, this study confirmed that the NS solution modified RCA is promising for engineering applications with desirable mechanical properties. However, there are still some shortcomings in this study:

1) The modification effect of the NS solution on RCA from various sources needs to be studied.

2) Different nano-solutions can be used to improve the RCA, and the best nano-solution can be obtained.

3) The durability of RAC strengthened by NS solution needs to be studied.

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References


[38] Li C. Mechanical and transport properties of recycled aggregate concrete modified with limestone powder. Compos Part B-Eng. 2020;197:108189.


