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Strengthening Effect of Nano-materials on the Compressive Strength and Microstructure of Recycled Brick Aggregate Concrete

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To investigate the strengthening effect of different nano-materials on recycled brick aggregate concrete, this paper considered the influence of different nano-materials, different mixing amounts, and different mixing methods on the compressive strength and microstructure of recycled brick aggregate concrete. The results show that the 7-day, 14-day, and 28-day compressive strengths of recycled brick aggregate concrete increase to different degrees after adding nano-materials, but the improvement in early compressive strength is more obvious. The cubic compressive strength prediction model of three nanomaterial-reinforced recycled brick aggregate concretes is established using the compressive strength as the index. The optimum contents of nano-SiO_2, nano-$CaCO_3$, and nano-Al_2O_3 are 3 %, 2 %, and 3 %, respectively. Double-mixed nano-materials have a lower improvement effect on the compressive strength of recycled brick aggregate concrete at different ages than single-mixed nano-materials. The nanomaterials can not only promote the hydration reaction of cement but also fill the microcracks and micropores inside the concrete, making the structure denser and thereby improving the mechanical properties of recycled brick aggregate concrete. The 28-day compressive strength of recycled aggregate modified with nano-materials (nano-SiO_2 and nano-Al_2O_3) concrete is higher than that of recycled aggregate concrete mixed with nano-materials. The early compressive strength of recycled aggregate modified with nano-Al_2O_3 concrete is lower than that of recycled aggregate concrete mixed with nano-Al_2O_3.
Keywords: nano-material, recycled brick aggregate, compressive strength, microstructure.

1. INTRODUCTION

With the rapid development of the construction industry, the use of natural aggregates has increased dramatically, and the amount of natural resources such as sand and gravel has increased [1]. At the same time, a large amount of construction waste is produced in the process of construction and demolition. Waste concrete and waste clay brick are the main components of construction waste [2]. The resource utilization of waste concrete and waste clay bricks directly affects the degree of construction waste recycling and its industrialization process [3, 4]. Recycled aggregate made from waste concrete and waste clay brick instead of natural aggregate can reduce the emission of construction solid waste, reduce the consumption of natural resources and realize the sustainable utilization of resources [5].

The recycled concrete aggregate has high porosity and high water absorption due to its surface adhesion mortar [6 – 8]. There are multiple transition interface zones in recycled concrete aggregate concrete and a large number of microcracks and pores in the interface transition zone [9], which become weak links in concrete, resulting in the mechanical properties of recycled concrete aggregate concrete being generally inferior to those of ordinary concrete [10, 11]. Recycled brick aggregate has the disadvantages of high water absorption, many microcracks, and high porosity [12], which makes the mechanical properties of recycled brick aggregate concrete worse than those of ordinary concrete [13, 14]. At present, there is relatively much research on recycled aggregate concrete [15, 16], but there are few studies on recycled brick aggregate concrete. It is worth further studying to improve the mechanical properties of recycled brick aggregate concrete.

Nano-materials have the characteristics of small size, large specific surface area, and so on, which have the function of filling effect and surface activity during the cement hydration reaction. Nano-materials can improve the mechanical properties of concrete and have been widely used in concrete. Nano-SiO_2 can affect the formation law and microstructure of concrete hydration products, promote the hydration reaction of cement and the secondary

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hydration reaction with $Ca(OH)_2$ [17], produce more C-S-H gel to fill the internal pores of concrete [18], make the distribution of hydration products more uniform, reduce the connected pores, optimize the internal pore structure [19], and improve the mechanical properties of concrete [20, 21]. Sobolev et al. [22] used atomic force microscopy (AFM) to study the amorphous C-S-H gel in concrete, and the results showed that the C-S-H gel had a highly ordered structure at the nanoscale. A low content of nano-SiO_2 (0.25 %) could still improve the 1-day and 28-day compressive strength of Portland cement mortar. Adding nano-SiO_2 to lightweight self-compacting concrete could promote the hydration reaction, promote the formation of C-S-H gel, and fill the pores of cement paste [23], making the distribution of calcium hydroxide crystals more uniform [24]. Mohamed [25] found that adding 3% nano-SiO_2 could increase the compressive strength, splitting tensile strength, bending strength, and elastic modulus of dolomite coarse aggregate by 60.22 %, 129.27 %, 53.49 %, and 58.31 %, respectively, while it could increase the compressive strength, splitting tensile strength, bending strength and elastic modulus of granite coarse aggregate by 62.55 %, 67.92 %, 65.41 %, and 67.26 %, respectively.

Nano-SiO_2 could improve the hydration reaction speed of cement [26], which was beneficial to the early strength of concrete. However, when the amount of nano-SiO_2 was too high, the local hydration reaction of cement would be too fast, resulting in C-S-H gel wrapping the nonhydration reaction cement particles, affecting the late strength of concrete. At the same time, when the content of nano-SiO_2 was too high, agglomeration occurred, which reduced the mechanical properties and durability of the concrete [27, 28]. Ozyildirim [17] found that compared with recycled concrete, the strength of recycled concrete with 5 % nano-SiO_2 increased by 15 % after 14 days, while the strength increased by less than 5 % after 28 days. The 14-day strength of recycled concrete with 1 % nano-SiO_2 increased by 7.5 %, and the 28-day strength increased by 18 %. Mendes [29] pointed out that nano-SiO_2 could improve the compressive strength and dynamic elastic modulus of ultrahigh strength concrete.

Nano-$CaCO_3$ could be prepared by calcium carbide slag, which could play a chemical activity and filling effect in cement hydration, filling concrete micropores, and improving the pore structure of concrete [19], thereby improving the mechanical properties and durability of concrete [28]. Wu et al. [30] studied the effect of the amount of nano-$CaCO_3$ on the compressive and flexural strength of ultrahigh-performance concrete and found that when the content of nano-$CaCO_3$ was 2 %, the compressive and flexural strength of ultrahigh-performance concrete was improved; when the content of nano-$CaCO_3$ exceeded 3.2 %, the compressive and flexural strength of concrete decreased. Zhou et al. [31] found that when the content of nano-$CaCO_3$ was 1.5 %, the 7-day compressive strength and 7-day splitting strength of concrete were 29.70 MPa and 2.56 MPa, respectively, which were 13.92 % and 12.76 % higher than those of original concrete.

Nano-Al_2O_3 particles can promote cement hydration, thereby shortening the initial setting time of concrete [32 – 34]. Nano-Al_2O_3 had a great influence on the performance of concrete while controlling the setting time of concrete. The results of Li et al. [35] showed that when the content of nano-Al_2O_3 was 5 %, the elastic modulus of mortar at 3-day, 7-day and 28-day was the best, which was 154 %, 241 %, and 243 % of ordinary mortar, respectively.

Various admixtures have different chemical activities, and they play a complementary role in concrete, which is more conducive to the improvement of concrete strength. The synergistic effect of nano-SiO_2 and silica fume on the hydration performance of cement-based materials could make the cement paste more compact in the microstructure morphology [36]. The addition of fly ash could compensate for some performance degradation of recycled concrete caused by the single addition of nano-SiO_2. Nano-SiO_2 and 30 % fly ash could effectively improve the 28-day splitting tensile strength of recycled concrete [37, 38]. The flexural strength and splitting tensile strength of recycled concrete mixed with nano-SiO_2 and fly ash are also significantly improved [39].

At present, most of the research focuses on the application of nano-materials in ordinary concrete and recycled concrete aggregate concrete, and there are relatively few studies on nano-reinforced recycled brick aggregate concrete. Therefore, this paper carries out experimental research on the influence of different nano-materials (nano-SiO_2, nano-$CaCO_3$, and nano-Al_2O_3), different nano-material content (0 %, 1 %, 2 %, and 3 %), and different nano-material mixed methods (double-mixed nano-materials and single-mixed nano-materials) on the compressive strength of recycled brick aggregate concrete at different ages, and analyzes the microstructure of recycled brick aggregate concrete before and after nano-material strengthening by field emission environmental scanning electron microscopy. The influence of nano-materials on the microstructure was studied, and then the mechanism of nanomaterial strengthening recycled brick aggregate concrete was explored.

2. EXPERIMENT

2.1. Materials

The recycled brick aggregate was broken, cleaned, and graded waste red brick; the ordinary coarse aggregate was natural gravel, and the aggregate size was 5 mm – 26.5 mm. The basic properties of coarse aggregate are shown in Table 1 (NCA is ordinary coarse aggregate; RBA is recycled brick aggregate).

Table 1. Properties of coarse aggregate

Type	Crush index, %	Water absorption, %	Soil content, %
NCA	4.9	1.09	1.9
RBA	32.9	12.54	2.4

The fine aggregate was natural river sand, the fineness modulus was 2.7, which belongs to medium sand, and the mud content was 1.2 %. P.O 42.5 ordinary Portland cement produced by Zibo Luzhong Cement Co., Ltd. was used, and the chemical composition of the cement is shown in Table 2. The nano-materials used were nano-SiO_2, nano-Al_2O_3, and nano-$CaCO_3$, and the technical parameters are shown in Table 3.

Table 2. Chemical composition of the cement

Chemical composition	SO_3	Al_2O_3	Fe_2O_3	CaO	MgO	SiO_2	K_2O	TiO_2	MnO	Na_2O
Content, mass %	2.87	5.86	4.37	60.41	0.98	22.3	0.58	0.21	0.12	0.06

Table 3. Physical properties of nano-materials

Type	Particle size	Purity, %	Volume density, g/m^3	Color
Nano-SiO_2	20 nm	99.9	0.06	White
Nano-Al_2O_3	30 nm	99.9	1.50	White
Nano-$CaCO_3$	40 nm	95.0	0.40	White

2.2. Mixture ratio design

The mixture ratio of ordinary aggregate concrete and recycled brick aggregate concrete is shown in Table 4. Where NAC represents ordinary aggregate concrete; RBC represents recycled brick aggregate concrete; B represents nano-SiO_2; C represents nano-Al_2O_3; and A represents nano-$CaCO_3$. X represents nano-materials content in mass %. Among them, the brick aggregate was soaked in water for 24 hours to reach saturation surface dry before use. The production process of concrete was as follows[40]: (1) half of the needed water was added to the nanoparticles and stirred at high speed for 3 minutes; (2) cement and high-speed stirring nanosolution were added to the mixer and stirred for 3 minutes; (3) the remaining water was gradually added to the mixer and stirred for 4 minutes until a uniform cement paste was obtained; and (4) fine aggregate and coarse aggregate were added to the mixer in turn and stirred for 5 minutes until a uniform concrete slurry was obtained.

2.3. Specimen and test scheme

The standard cube test specimen with a size of 150 mm × 150 mm × 150 mm was poured. After pouring was completed, the specimens were placed in an air-conditioned room for 24 hours (the standard temperature was 20 ± 2 °C, and the relative humidity was above 95 %), and the mold was removed. The compressive strength test was carried out after watering and curing for 7-day, 14-day, and 28-day. When the concrete was cured for 14-day, the concrete sample was cut with a cutting machine and placed in anhydrous ethanol to stop hydration until the electron microscope scanning test began. The test equipment is shown in Fig. 1.

a b

Fig. 1. Test equipment: a – servo-hydraulic machine; b – scanning electron microscope

3. TESTS AND RESULTS

3.1. Specimen failure mode

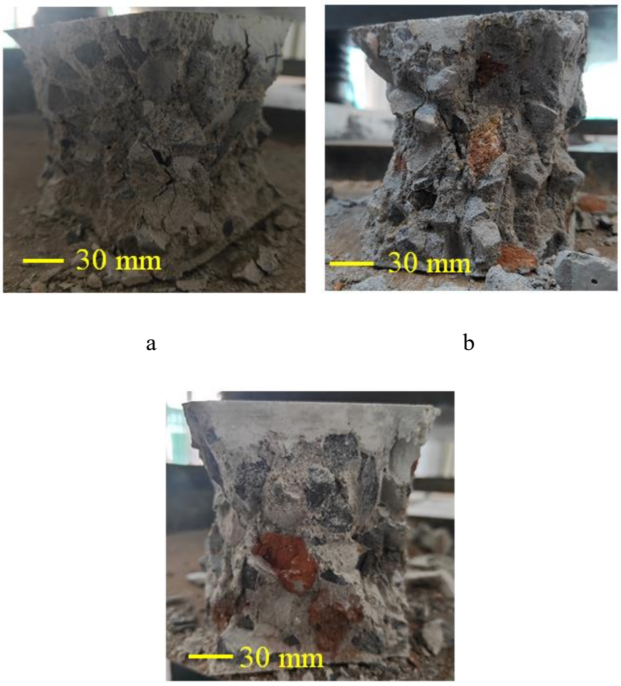
The failure modes of different concrete specimens were similar, as shown in Fig. 2. With increasing load, cracks gradually appeared on the side surface of the specimen, and then cracks developed at the end of the specimen. After reaching the ultimate load, the load growth rate slowed down, and the surrounding concrete fell off, while the specimen was intact.

The ordinary concrete showed great brittleness when it reached the ultimate load; that is, when the ultimate load was reached, the bearing capacity was suddenly lost. The brittleness of recycled brick aggregate concrete was relatively small at failure. In addition, the damage of ordinary concrete mostly occurred in the interfacial transition zone between coarse aggregate and mortar, and the aggregate was not damaged. When the brick aggregate concrete and nano-material-reinforced brick aggregate concrete were damaged, not only was the interface transition zone between coarse aggregate and mortar damaged, but some brick aggregates were also broken.

Table 4. Mixture ratio of concrete, kg/m^3

Type	Water	Cement	Sand	Ordinary coarse aggregate	Recycled brick aggregate	nano-SiO_2	nano-Al_2O_3	nano-$CaCO_3$
NAC	208	320.0	700	1120	0	0	0	0
RBC	208	320.0	700	784	336	0	0	0
RBC-B-1	208	316.8	700	784	336	3.2	0	0
RBC-B-2	208	313.6	700	784	336	6.4	0	0
RBC-B-3	208	310.4	700	784	336	9.6	0	0
RBC-C-1	208	316.8	700	784	336	0	3.2	0
RBC-C-2	208	313.6	700	784	336	0	6.4	0
RBC-C-3	208	310.4	700	784	336	0	9.6	0
RBC-A-1	208	316.8	700	784	336	0	0	3.2
RBC-A-2	208	313.6	700	784	336	0	0	6.4
RBC-A-3	208	310.4	700	784	336	0	0	9.6
RBC-AB-2	208	313.6	700	784	336	3.2	0	3.2
RBC-BC-2	208	313.6	700	784	336	3.2	3.2	0
RBC-AC-2	208	313.6	700	784	336	0	3.2	3.2

The reason is that the concrete interface transition zone first exhibits stress concentration and produces microcracks under load, and then the microcracks gradually develop. The aggregate will hinder the development of cracks, and then stress concentration will occur on the aggregate surface. The recycled brick aggregates are cut off by concentrated stress due to weak strength, while the natural aggregates can hinder the development of cracks, change the direction of crack development, and make cracks develop along the interface transition zone.



a b

c

Fig. 2. Specimen failure mode: a – ordinary concrete; b – brick aggregate concrete

3.2. Effect of nanomaterials on compressive strength at different ages

1. Effect of single-mixed nanomaterials on compressive strength at different ages.

The concrete compressive strength at different ages is shown in Fig. 3. The compressive strength of recycled brick aggregate concrete at different ages was less than that of ordinary concrete. The 7-day, 14-day, and 28-day compressive strengths of recycled brick aggregate concrete were 15.4 %, 15.7 %, and 10.0 % lower than that of ordinary concrete, respectively. The reasons for this situation are as follows: on the one hand, the recycled brick aggregate itself contains more pores, and the aggregate is damaged during processing, thereby reducing its strength. The crushing index of recycled brick aggregate is 6.7 times that of ordinary coarse aggregate. The characteristics of the high crushing index and low strength of recycled brick aggregate limit the compressive strength of concrete, which makes the compressive strength of recycled brick aggregate concrete prone to stress concentration, resulting in the compressive strength of recycled brick aggregate concrete being lower than that of ordinary concrete. On the other hand, due to the high water absorption of recycled brick aggregate, soaking treatment is carried out before use, which improves the effective water-cement ratio to a certain extent, and cement hydration slows down in the later stage of concrete curing. A large amount of water absorbed by recycled brick aggregate in the early stage is gradually released, which also improves the effective water-cement ratio of recycled brick aggregate concrete, thus reducing the strength of concrete.

The early and late compressive strengths of recycled brick aggregate concrete were improved to varying degrees after adding nano-materials, but the early compressive strength was more significant, which was consistent with the experimental results of Yang et al [41] and Li et al [42]. This is because nano-materials have the characteristics of small size and large specific surface area, which can provide crystal nuclei in the nucleation and growth stage of the hydration reaction crystal to promote the early cement hydration reaction, and nano-materials fill the micro cracks in concrete, which has a significant effect on the early strength of concrete [43]. Different nano-materials have different chemical properties, and their effects on improving the mechanical properties of concrete are also different. Nano-Al_2O_3 plays the role of dispersant in cement particles, and the incorporation of nano-Al_2O_3 greatly reduces the setting time of concrete [33]. The secondary hydration reaction between nano-SiO_2 and $Ca(OH)_2$ can produce more C-S-H gel to fill the internal pores of the concrete and optimize the internal pore structure. Therefore, nano-Al_2O_3 has a relatively good improvement effect on the 7-day compressive strength of concrete, while nano-SiO_2 has a relatively good improvement effect on the 28-day compressive strength of concrete. However, due to the rapid hydration reaction of cement in the early stage, the released heat leads to a certain degree of reduction in the internal compactness of concrete, and the formation of an early hydration product layer hinders the reaction between external water and internal cement clinker ions [43], so the effect of improving the later strength of concrete is not significant. In addition, it can be seen from the test results that the effect of adding nano-SiO_2 and nano-Al_2O_3 on the compressive strength of concrete was better than that of adding nano-$CaCO_3$.

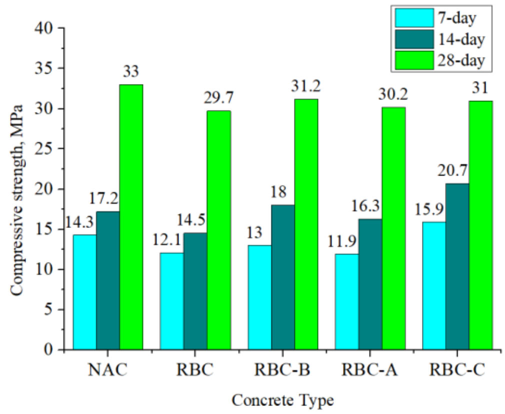


Fig. 3. Effect of single-mixed nano-materials on compressive strength

2. Effect of nano-materials content on compressive strength.

The relationship between nano-material content and the 28-day compressive strength of concrete is shown in Fig. 4. The addition of nano-materials to recycled brick aggregate concrete could improve the mechanical properties of concrete, and the improvement of concrete by various nano-materials with different dosages was also different. With increasing nano-material content, the 28-day compressive strength of both nano-Al_2O_3 concrete specimens and nano-SiO_2 concrete specimens showed an increasing trend; for the nano-$CaCO_3$ concrete specimen, when the nano-material content reached 2 %, the 28-day compressive strength no longer increased, which was consistent with the experimental results of Li et al. [42]. The reason for this situation is that on the one hand, nano-materials can improve the internal defects of brick aggregate concrete, accelerate the cement hydration reaction, and thus improve the mechanical properties of concrete. On the other hand, when there are many nano-materials, it is easy to exhibit an "agglomeration" phenomenon, which eventually leads to a decrease in the compressive strength of concrete. Therefore, to ensure better improvement of the mechanical properties of recycled brick aggregate concrete, the content of nano-materials should be controlled within a reasonable range.

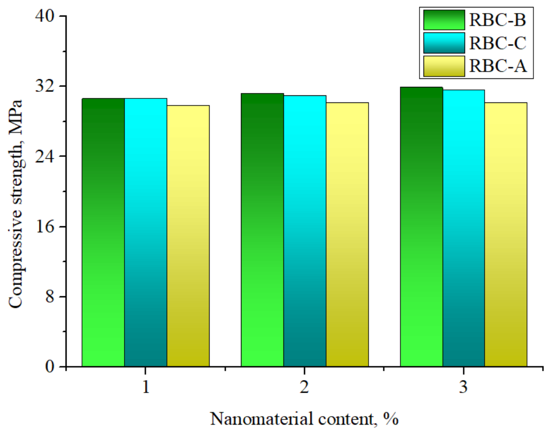


Fig. 4. Effect of nano-materials content on 28-day compressive strength

The relationship between the content of the three nano-materials and the compressive strength of the concrete is obtained by data fitting as follows:

Al_2O_3: $y = 0.5\,x + 30.067$; (1)

SiO_2: $y = 0.65\,x + 29.933$; (2)

$CaCO_3$: $y = -0.2\,x^2 + 1\,x + 29$. (3)

The coefficients of determination of the fitting function of Al_2O_3, SiO_2, and $CaCO_3$ were 0.9868, 0.9980, and 0.9989, respectively (Fig. 5), indicating that the fitting function could accurately represent the variation in the compressive strength of recycled brick aggregate concrete with the nano-materials content.

3. Effect of double-mixed nano-materials on compressive strength at different ages.

The effect of nano-materials on the compressive strength of concrete at different ages is shown in Fig. 6. The 7-day compressive strength and 14-day compressive strength of recycled brick aggregate concrete increased by 5.0 % and 12.4 %, respectively, after adding nano-SiO_2 and nano-$CaCO_3$ and increased by 1.7 % and 4.8 %, respectively, after adding nano-SiO_2 and nano-Al_2O_3, while they increased by -14.1 % and 3.4 %, respectively, after adding nano-$CaCO_3$ and nano-Al_2O_3.

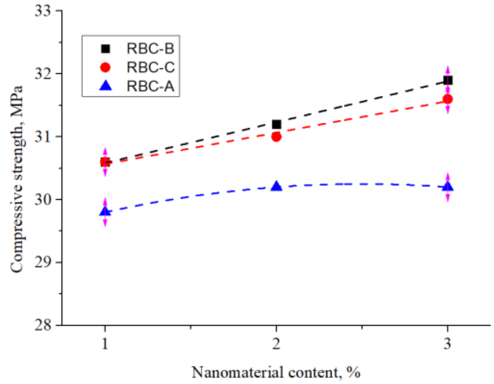


Fig. 5. Effect of nano-materials content on 28-day compressive strength

However, the addition of different nano-materials had little effect on the 28-day compressive strength of recycled brick aggregate concrete. The improvement effect of double-mixed nano-materials on the compressive strength of recycled brick aggregate concrete at different ages was inferior to that of single-mixed nano-materials. This may be due to the mutual reaction between nano-materials, which affects its improvement effect on the mechanical properties of concrete.

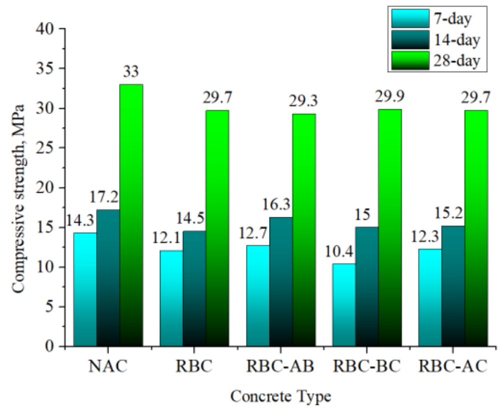


Fig. 6. Effect of double-mixed nanomaterials on compressive strength

3.3. Microstructure analysis

The microstructure of the concrete specimens is shown in Fig. 7. Fig. 7 a shows that the microstructure of recycled brick aggregate concrete was relatively loose, and there were some microcracks and micropores inside. In addition, although hydration products such as C-S-H and AFt were generated, the distribution was relatively dispersed, the microcracks and micropores were not effectively filled, and the hydration product $Ca(OH)_2$ in the interfacial transition zone was more abundant. Due to the special structure of $Ca(OH)_2$, it could not provide effective strength for concrete, which would reduce the mechanical properties of recycled brick aggregate concrete. The main reason for this situation is that the recycled brick aggregate reaches the saturated surface dry state before use; it contains more water to participate in the hydration reaction so that the actual water-cement ratio of the interface transition zone is high, and the interface transition zone forms a large number of water sacs to hinder the normal progress of the cement hydration reaction and gathers the Ca^{2+} generated by the hydration reaction, resulting in many interface transition holes and a wide distribution of $Ca(OH)_2$.

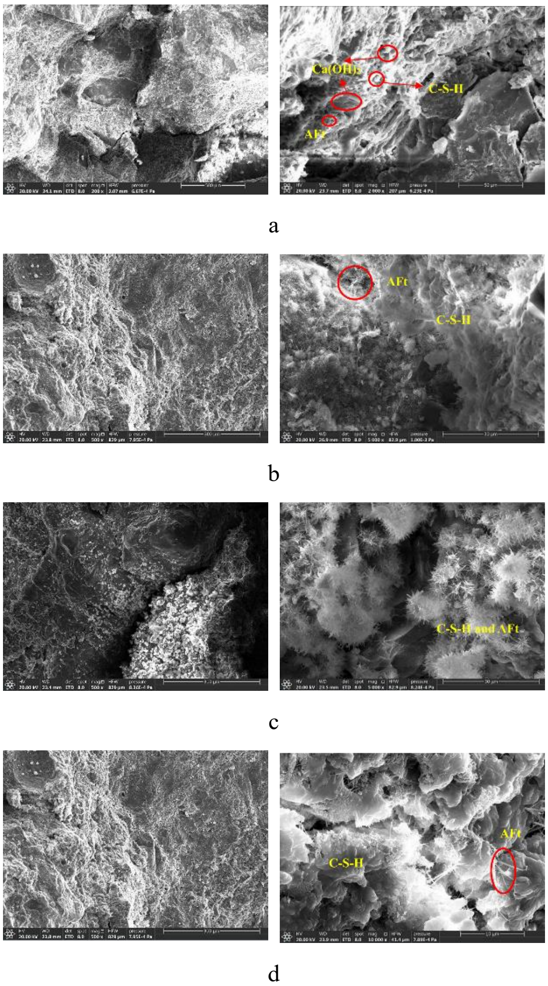


Fig. 7. SEM micromorphology of brick aggregate concrete: a – recycled brick aggregate concrete; b – recycled brick aggregate concrete with nano-SiO_2; c – recycled brick aggregate concrete with nano-$CaCO_3$; d – recycled brick aggregate concrete with nano-Al_2O_3

Fig. 7 b shows that the internal structure of the concrete was denser after adding nano-SiO_2. The reasons are as follows: on the one hand, the high pozzolanic activity of nano-SiO_2 can promote the hydration reaction of cement, and its role as a crystal seed can make the distribution of C-S-H gel more uniform, thereby reducing the concentrated distribution of pores [43] and secondary hydration reaction with $Ca(OH)_2$ to form C-S-H gel [44], improving the internal pore structure of concrete; on the other hand, nano-SiO_2 can fill the microcracks, micropores, and pores of the C-S-H structure inside the concrete, making the concrete structure denser, thereby improving its mechanical properties.

It can be seen from Fig. 7 c that the hydration products of concrete after adding nano-$CaCO_3$ are thorn-globular in shape, which had a certain filling effect on cracks and pores. The hydration products also filled the pores between cement, sand, and other materials, improved the compactness of the structure, improved the internal defects of brick aggregate concrete, and then improved the mechanical properties of concrete. Compared with Fig. 8 b, it was found that the hydrated products of recycled concrete mixed with nano-$CaCO_3$ are large in volume and loosely distributed.

The reason was that nano-$CaCO_3$ can accelerate the cement hydration reaction, which makes the early hydrated products wrap part of the cement and hinder its further hydration reaction. Compared with nano-SiO_2 and nano-Al_2O_3, nano-$CaCO_3$ reacts to generate thorn-globular shape hydration products, which are more likely to wrap the unhydrated cement particles and hinder their further hydration, so nano-$CaCO_3$ has a poor effect on improving the compressive strength of concrete. Fig. 7 d shows that after adding nano-Al_2O_3, the internal cracks and pores of the concrete were filled with flocculent particles, forming a relatively dense network structure. Nano-Al_2O_3 reacts with the hydration product C-S-H gel to generate C-A-H or C-A-S-H, improving the compaction effect, increasing the bonding strength of the cement mortar interface, and improving the compressive strength of concrete [44, 45].

4. COMPARISON OF MODIFICATION EFFECTS OF DIFFERENT NANO-MATERIALS MODIFICATION METHODS

The comparison of compressive strength between recycled aggregate modified with nano-materials concrete in reference [46] (RBC-MB represents recycled aggregate modified with nano-SiO_2 concrete; RBC-MC represents recycled aggregate modified with nano-Al_2O_3 concrete) and recycled aggregate concrete mixed with nano-materials (RBC-B and RBC-C) at different ages is shown in Fig. 8. The compressive strength at different ages of recycled aggregate modified with nano-SiO_2 concrete was higher than that of recycled aggregate concrete mixed with nano-SiO_2, especially in the early compressive strength of concrete. When the concrete age was 14-day, the compressive strength of recycled aggregate modified with nano-SiO_2 concrete was 7.2 % higher than that of recycled aggregate concrete mixed with nano-SiO_2. This is because the performance of recycled brick aggregates has significantly improved after nano-materials modification, and concrete relies more on aggregates to resist external loads in the early stages. Therefore, the performance of aggregates has a significant impact on the mechanical properties of concrete, resulting in a more significant strength advantage of recycled aggregate modified with nano-SiO_2 concrete.

The early compressive strength (7-day and 14-day ages) of recycled aggregate modified with nano-Al_2O_3 concrete was lower than that of recycled aggregate concrete mixed with nano-Al_2O_3, while the 28-day compressive strength of recycled aggregate modified with nano-Al_2O_3 concrete was higher than that of recycled aggregate concrete mixed with nano-Al_2O_3. This is because the addition of nano-Al_2O_3 greatly shortens the setting time of concrete [33], which reflects the strength advantage of cement paste earlier and plays a more important role in the stress process, improving the early strength of concrete, resulting in higher strength of recycled aggregate concrete mixed with nano-Al_2O_3. As the concrete age increases, the difference in cement paste strength between the two types of concrete is not significant, and the strength advantage of aggregates is reflected, resulting in higher strength of recycled aggregate modified with nano-Al_2O_3 concrete.

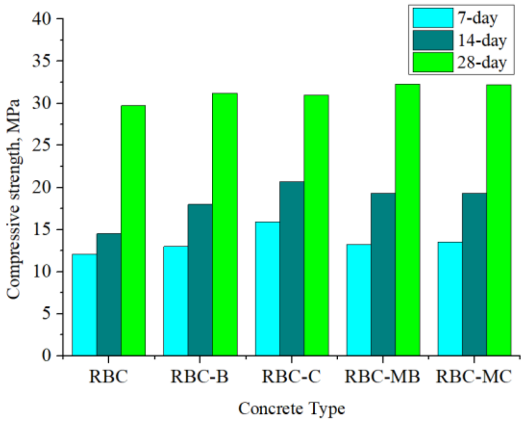


Fig. 8. Comparison of the modification effects of different nano-material modification methods

5. CONCLUSIONS

1. The compressive strength of recycled brick aggregate concrete at different ages was lower than that of ordinary concrete, and the compressive strength of recycled brick aggregate concrete at different ages after single-mixed nano-materials had been improved to different degrees.
2. With increasing nano-material content, for both nano-Al_2O_3 concrete specimens and nano-SiO_2 concrete specimens, there was an increasing trend; for the nano-$CaCO_3$ concrete specimen, when the nano-material content reached 2 %, the 28-day compressive strength no longer increased.
3. The improvement effect of double-mixed nano-materials on the compressive strength of recycled brick aggregate concrete at different ages was inferior to that of single-mixed nano-materials.
4. The nano-materials could not only promote the hydration reaction of cement but also fill the microcracks and micropores inside the concrete, making the concrete structure denser, thereby improving the mechanical properties of recycled brick aggregate concrete.
5. The 28-day compressive strength of recycled aggregate modified with nano-material concrete was higher than that of recycled aggregate concrete mixed with nano-materials, while the early compressive strength of recycled aggregate modified with nano-Al_2O_3 concrete was lower than that of recycled aggregate concrete mixed with nano-Al_2O_3.

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