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Mechanical Properties of Recycled Aggregate Concrete Modified with Nanosilica and its Bonding Properties with Steel Bars

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To improve the performance of recycled concrete materials and structures and achieve the widespread application of recycled concrete technology, this study comprehensively analyzes the influence of different concentrations of nanosilica-modified recycled aggregates on the mechanical properties of recycled concrete and its bonding performance with steel bars. These results indicate that nanosilica can significantly improve the performance of recycled aggregates, and the mechanical properties of recycled aggregate concrete, thereby enhancing the bonding performance between recycled aggregate concrete and steel bars (which was mainly reflected in the increase in bonding strength the increasing slope and the reduction in bonding slip). As the concentration of the nanosilica solution increases, the improvement effect of the nanosilica shows a trend of first increasing and then decreasing. In addition, a relationship model between the concentration of nanosilica and its bonding performance is established.
Keywords: mechanical performance, bond performance, nanosilica, recycled coarse aggregate.

1. INTRODUCTION

The utilization of recycled concrete (RAC) is an important way for the construction industry to achieve sustainable development, which can avoid excessive exploitation of sand and gravel resources, realize the resource utilization of construction waste, and reduce carbon emissions. Compared with natural aggregates (NCAs), recycled aggregates (RCAs) have old mortar attached to their surface, resulting in greater water absorption and porosity [1]. The RAC prepared by RCA has multiple interface transition zones, and there are many microcracks in the interface transition zones, resulting in lower mechanical properties and bonding performance between RAC and steel bars than those of ordinary concrete (NAC) [2]. Reinforced concrete structures are the most widely used composite materials in the field of civil engineering, and good bonding performance between concrete and steel bars is a prerequisite for the synergistic effect of these two materials [3]. To accelerate the promotion and application of RAC, how to improve the mechanical properties of RAC and its bonding performance with steel bars has attracted widespread attention from scholars around the world.

Nanomaterials have been introduced into the field of concrete modification because of their unique surface effects and small size effects. For example, nanosilica (NS) can consume calcium hydroxide in cement paste through pozzolanic reactions [4], generate more hydrated calcium silicate (C-S-H) gel [5], fill the micropores inside the concrete, compact the interface transition zone (ITZ) structure [6], and improve the mechanical properties of the concrete and its bond strength with reinforcement [7]. Compared with traditional additives, the dosage of nanomaterials is low, the effect is significant, and they can meet environmental protection requirements, providing new ideas for the efficient utilization of RAC.

Previous studies have shown that the application of nanomaterials in concrete can effectively improve its mechanical properties [8, 9]. NS has a wide range of applications [10, 11]. NS has advantages such as high permeability and high reactivity [12] and can also accelerate the hydration rate of cement [4]. The incorporation of NS into RAC can effectively fill micropores and microcracks and improve the mechanical properties of RAC by enhancing the pore structure [13].

Some scholars have conducted relevant research on the changes in the compressive strength of concrete with different replacement rates of recycled aggregates after adding NS [14, 15]. The results show that adding a small amount of NS particles can significantly improve the compressive strength of RAC. Under the same NS content, the compressive strength of RAC decreases with increasing RCA content. Under the same RCA content, the compressive strength of RAC first increases but then decreases with increasing NS content. The NS content corresponding to the maximum compressive strength increases with increasing RCA content. NS particles cannot fully compensate for the defects of RCAs. The number of microcracks and surface old mortar in the RCA increases with increasing RCA substitution rate, and NS particles cannot effectively fill these cracks and old mortar [16]. When many NS particles are added, their hydration activity cannot be effectively exerted due to agglomeration, resulting in a decrease in the nucleation effect; thus, the enhancement effect on the compressive strength is

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significantly reduced [17, 18].

Research has shown that within the range of 0.75 % to 8 % NS content, the compressive strength of RAC can increase by 2 % – 53 % [19]. Gao et al. [20] conducted a 2 % NS modification test, and the results revealed that the 28-day splitting tensile strength of RAC increased by 16.4 %. Mukharjee et al. [21] and Feng et al. [22] both confirmed that the addition of NS can effectively improve the bending strength of RAC. Zhao et al. [23] developed an NS immersion treatment method for RCAs, established optimal modification conditions, and significantly improved the flexural strength of the obtained concrete. Bao et al. [24] and Fan et al. [25] reported that RCA exhibited the best mechanical properties when the NS content was 3 %. In addition, Hou et al. [26] reported that the hydration products of NS can encapsulate and prevent the hydration of cement particles, thereby hindering the later strength development of mortar. However, according to Elkady et al. [27], these aggregated NS particles reduce porosity through filling in the early stages, and the density of C-S-H slightly increases in plastic form and transforms into a denser compressive structure after hydration, which increases the strength of the concrete in the later stage.

The bonding performance between RAC and steel bars is a key parameter for evaluating whether recycled concrete reinforced structures can meet practical engineering requirements [28]. Most studies have shown that the bonding performance between RAC and steel reinforcement is usually lower than that of NAC [29], which limits its application in practical engineering structures. Old mortar adheres to the surface of the RCA, resulting in insufficient hydration of the ITZ, forming more microcracks and weak areas, and reducing the grip force of the RAC on the steel bars [30]. The stress transmission efficiency of RAC decreases, resulting in a reduction in the mechanical biting force and friction force between it and the steel bars [31]. Therefore, the addition of recycled coarse aggregate usually reduces bond strength and increases slip, posing structural safety risks. Research on the bond performance between RAC and steel bars shows that as the RCA substitution rate increases, the bond strength between steel bars and RAC gradually decreases [32], and the slip amount of recycled concrete reinforced structures under maximum bond stress increases with increasing RCA particle size [33].

Starting from enhancing the structural performance of RAC and improving its practical applicability [34], scholars have proposed methods to improve the bonding performance between RAC and steel bars through aggregate treatment, the addition of additives, and preparation processes [35 – 37]. Related studies have shown that adding NS to RAC can eliminate poor pores and cracks in the structure, thereby enhancing the bonding performance between RAC and steel bars [24]. Meng et al. [38] impregnated RCAs in NS solution and reported a 44.2 % increase in the bond strength between RAC and steel bars, as well as a 25.0 % increase in the ultimate stress. Wang et al. [39] conducted in-depth research on the bonding characteristics and modification mechanism between nanomaterial-modified reactive powder concrete and ordinary steel bars. The experimental results revealed that the addition of nanomaterials improved the bonding strength of the structure and reduced steel slip. Alhawat et al. [40] studied the effect of adding NS on the bonding performance between RAC and steel bars. The results showed that replacing 1.5 % of the mass fraction of NS with cement increased the bonding strength between the RAC and steel bars from 8 % to 21 %. Fan et al. [25] studied the bonding performance between RAC composed of 100 % RCA and steel bars with different NS contents (0 %, 1 %, 2 %, and 3 %) as cement substitutes. The results revealed that the optimal NS content was 3 %. Compared with the RAC control without NS, the addition of NS increased the bonding strength of the RAC by 20.92 %.

However, the current research on the combination of nano modification technology and recycled concrete technology is not systematic enough, which hinders its application in engineering. This paper comprehensively analyzes the influence of nanosilica on the properties of recycled coarse aggregates, recycled concrete, and the bond performance between recycled concrete and steel bars and constructs a calculation model for bond strength and bond slip. This study provides theoretical support for improving the bonding performance between recycled concrete and steel bars, thereby expanding the application scope of recycled concrete.

2. EXPERIMENTAL DETAILS

2.1. Materials

The recycled coarse aggregate used in this test is recycled coarse aggregate obtained via manual classification, crushing (Fig. 1), screening and cleaning of waste materials from the demolition of an old residential area in Shouguang city. The original strength grade of recycled concrete is C30. The natural coarse aggregate used in the test was taken from a concrete mixing station in Shouguang city. The particle size of recycled coarse aggregate is 5 – 26.5, and the properties are shown in Table 1. P O 42.5 ordinary Portland cement produced by Huaxin Cement Co., Ltd. was used as the test cement, and its chemical composition and properties are shown in Table 2 and Table 3, respectively.

Table 1. Properties of coarse aggregate

Type	Apparent density, kg/m^3	Crushing index, mass %	Water absorption, mass %
Recycled coarse aggregate	2430	14.5	6.8

Table 2. Chemical composition of the cement

CaO, %	SiO_2, %	Al_2O_3, %	Fe_2O_3, %	SO_3, %
61.4	22.1	5.67	4.35	2.34

Table 3. Properties of the cement

Specific surface area, m^2/kg	Initial setting/final setting time, min	28 d compressive/flexural strength, MPa
335	225/276	48.7/8.6

Nanosilica was selected as the nanomaterial, as shown in Fig. 1. The technical parameters of the nanomaterials (Fig. 2) are shown in Table 4.

Fig. 1. Recycled coarse aggregate

Fig. 2. Nano silica

Table 4. Properties of the nanomaterials

Diameter, *u*m	Density, g/cm^3	Elastic modulus, GPa	Length, mm	Tensile strength, MPa
11	2.63	95	6	2800

The center pull-out steel bar is an HRB400 grade threaded steel bar with a diameter of 18 mm. The performance of the steel bars is shown in Table 5.

Table 5. Properties of the steel bars

Tensile strength, MPa	Yield strength, MPa	Elastic modulus, GPa
657	487	200

2.2. Modification method for recycled aggregate

Water was added to the high-speed mixer, nanosilica powder was added to the batches at intervals of 2 minutes each, and the mixture was stirred for 30 minutes. An ultrasonic disperser (20 kHz, 500 W power) was used for 15 minutes to eliminate particle agglomeration, as shown in Fig. 3. Then, the cleaned and dried recycled coarse aggregate was soaked in nanosolution for 2 days, and natural air drying was carried out. The concentrations of nanosilica used were 1 %, 2 %, 3 % and 4 %.

Fig. 3. Nanosilica solution

2.3. Mix proportion and specimen design

The mix design of recycled concrete is shown in Table 6, in which the recycled aggregate is replaced by equal-quality recycled concrete. Notably, N0, N1, N2, N3 and N4 refer to the recycled aggregates modified with nanosilica solutions with concentrations of 0 %, 1 %, 2 %, 3 % and 4 %, respectively.

The compressive strength and splitting tensile strength of the 150 mm × 150 mm × 150 mm concrete cube samples were tested. The bond strength between the concrete and steel bars is tested with 150 mm × 150 mm × 150 mm pull-out samples (install stirrups in the tensile test specimen to prevent splitting damage).

A microcomputer-controlled electronic universal hydraulic testing machine was used to test the compressive strength, and the control stress was 0.3 MPa/s. A splitting tensile strength test was carried out, and the control stress was 0.03 MPa/s.

The results of the bond strength test between the concrete and reinforcement are shown in Fig. 4.

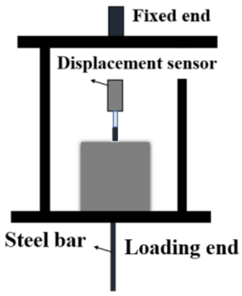


Fig. 4. Schematic diagram of the bond performance test device

The specific loading process is as follows:

1. Preload: load to 10 % of the estimated ultimate load at a rate of 0.5 – 1.0 kN/s, unload to zero after 1 minute of pressure stabilization, and record the initial displacement.
2. Formal loading: continuous loading at 0.5 ~ 1.0 mm/min (displacement control);
3. Data acquisition: an automatic acquisition system is used for real-time recording, and the data acquisition frequency is 10 Hz.

Table 5. Mix proportion

Type	Cement, kg/m^3	Water, kg/m^3	Sand, kg/m^3	Natural aggregate, kg/m^3	Recycled aggregate, kg/m^3	Water reducing agent, kg/m^3
RAC-N0	360	175	720	0	1185	3.2
RAC-N1	356.4	175	720	0	1185-N1	3.2
RAC-N2	360	175	720	0	1185-N2	3.2
RAC-N3	360	175	720	0	1185-N3	3.6
RAC-N4	360	175	720	0	1185-N4	3.2

3. RESULTS AND DISCUSSION

3.1. Recycled aggregate performance

The changes in the apparent density, water absorption and crushing index of recycled aggregates after modification with nanomaterials are shown in Fig. 4. Fig. 5 a shows that the apparent density of recycled coarse aggregates after nanomaterial modification significantly improved, and with increasing nanomaterial solution concentration, it first increased but then decreased.

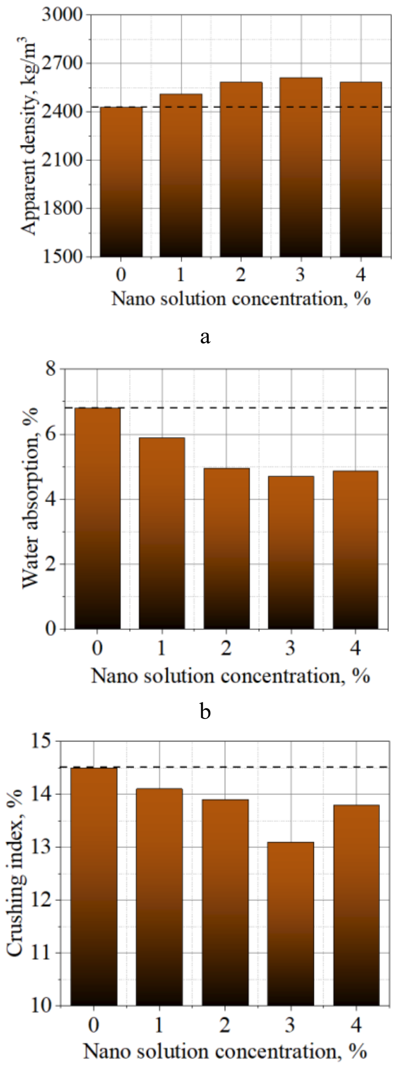


Fig. 5. Recycled aggregate performance: a – apparent density; b – - water absorption; c – crushing index

When the concentration of the nanomaterial mixture was 3 %, the maximum apparent density of the recycled coarse aggregate was 2610 kg/m^3, which was 7.4 % greater than that of the unmodified aggregate. When the concentration of the nanomaterial mixture was 4 %, the apparent density decreased slightly to 2582 kg/m^3, but it was still 6.25 % greater than that of the unmodified aggregate.

Fig. 5 b and Fig. 4 c show that the water absorption and crushing indices of recycled coarse aggregates after nanomaterial modification decreased, and with increasing nanomaterial solution concentration, the improvement in the water absorption and crushing indices first increased but then decreased. When the concentration of nanosilica solution was 1 %, 2 %, 3 % and 4 %, the water absorption of the recycled coarse aggregate was 5.89 %, 4.96 %, 4.71 % and 4.86 %, respectively. The crushing indices of the recycled coarse aggregates were 14.1 %, 13.9 %, 13.1 % and 13.8 %, respectively. When the concentration of the nanomaterial mixture was 3 %, it had the greatest effect on improving the water absorption and crushing index. At this time, the water absorption reduction rate is 30.7 %, and the crushing index reduction rate is 20.6 %. This is higher than the improvement effect of nano-Al_2O_3 [41] on recycled aggregates. When the concentration of the nanomaterial mixture was 3 %, the water absorption reduction rate is 24.2 %.

In conclusion, the performance of recycled coarse aggregate is improved after nanosilica modification. With increasing nanosilica solution concentration, the improvement effect first tends to improve but then decreases. This is because when the concentration of nanosilica is within a certain range, well-dispersed nanosilica particles can fully penetrate and fill the pores of recycled coarse aggregate and react with the old mortar on the surface to produce dense hydration products, which can improve the aggregate performance through "filling strengthening". However, when the concentration of nanosilica solution is too high, the nanosilica particles are prone to agglomeration and are unable to penetrate into micropores and form a loose stacking structure. Moreover, excessive reactions may lead to an imbalance between the surface and internal properties, but the performance of recycled aggregates is reduced because of the "agglomeration barrier" effect. Wang [41] also reported that nanomaterials could reduce the water absorption and crushing index of recycled aggregates when they were modified with nanomaterials.

3.2. Workability of recycled aggregate concrete

The slump of recycled concrete modified with nanosilica is shown in Fig. 6.

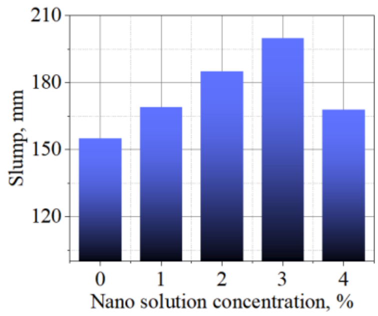
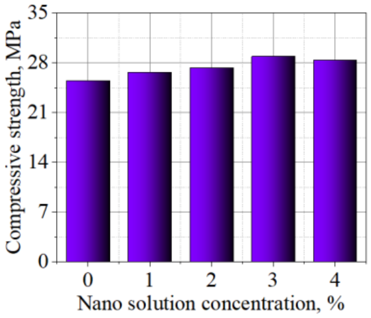


Fig. 6. Workability of recycled aggregate concrete

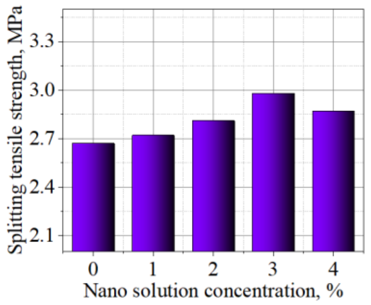
The influence of nanosilica on the slump of recycled concrete can be described as "lowly promoting high inhibition". When the concentration of nanosilica is low, the water absorption of the recycled aggregate soaked with nanosilica decreases by 20 % – 40 %, which reduces the instant adsorption of the mixed water and allows more water to enter the slurry. Moreover, the evenly dispersed nanoparticles reduce the internal friction of the slurry through the "ball effect", and the slump can be increased by 9 % – 29 % under the double action. When the concentration reaches 4 %, the nanoparticles easily agglomerate to form micron-sized flocs, which not only lose the "ball effect" but also adsorbs a large amount of free water through the surface hydroxyl, resulting in a sharp increase in the viscosity of the slurry and a significant decrease in the slump

3.3. Recycled aggregate concrete performance

The compressive strength and splitting tensile strength of recycled concrete modified with nanosilica are shown in Fig. 7. Nanosilica-modified recycled aggregate can improve the compressive strength and splitting tensile strength of recycled concrete; in particular, the compressive strength of recycled aggregate concrete modified with 3 % nanosilica solution can reach 28.9 MPa, which is 13.3 % greater than that of unmodified concrete.



a



b

Fig. 7. Basic mechanical properties of recycled concrete

The splitting tensile strength can reach 2.98 MPa, which is 11.6 % greater than that of unmodified concrete. The compressive strength and splitting tensile strength of recycled concrete modified with 4 % nanosilica solution were 28.4 MPa and 2.87 MPa, respectively, which were still 11.4 % and 7.5 % higher than those of unmodified concrete, although there was a certain degree of decline. Wang [41] and Cui [42] reached similar conclusions. Wang [41] noted that both nanosilica and nano alumina can effectively improve the mechanical properties of recycled concrete, whereas Cui [42] reported that nanoactivated calcium carbonate, nanosilica, and nano alumina can improve the mechanical properties of recycled brick bone materials. However, to ensure the optimal improvement effect, the content of nanomaterials needs to be controlled within a certain range.

This phenomenon is due mainly to triple synergy: nanosilica particles can penetrate into the micropores and cracks on the surface and inside of the recycled aggregate, reduce the porosity through physical filling, react with the residual $Ca(OH)_2$ of the aggregate to form a dense C-S-H gel, strengthen the structure of the aggregate and reduce its crushing index. The results show that the surface of the modified recycled aggregate is more compact, the interface transition zone (ITZ) with the new cement paste is optimized, the microcracks in the interface zone are filled with nanoparticles, and the C-S-H gel enhances the adhesion between the aggregate and mortar, reduces the thickness of the interface transition zone [10], reduces the stress concentration point. The high pozzolanic activity of nanosilica can accelerate the hydration process of the cement, promote the formation of more hydration products, and further compact the overall structure of the concrete. These three aspects work together to significantly improve the compressive strength and splitting tensile strength of recycled concrete.

3.4. Bond performance between recycled aggregate concrete and steel bars

3.4.1. Bond failure mode

The failure modes of the recycled concrete samples in each group are similar: when the reinforcement is in tension, its transverse deformation is restrained by the concrete, which produces radial tension on the concrete; when the radial tensile force exceeds the tensile strength of the concrete, the concrete cracks along the longitudinal direction of the reinforcement (extending from the surface of the member to the reinforcement interface); after the crack appears, the constraint of the concrete on the reinforcement suddenly weakens, and the bonding force decreases sharply. Finally, bonding failure is caused by crack penetration, as shown in Fig. 8. The addition of nanomaterial-modified recycled coarse aggregate has no significant effect on its failure mode. Although nanomaterial-modified recycled coarse aggregate can improve the mechanical properties of recycled concrete, it does not have a decisive effect on the failure mode of the bond between recycled concrete and reinforcement.

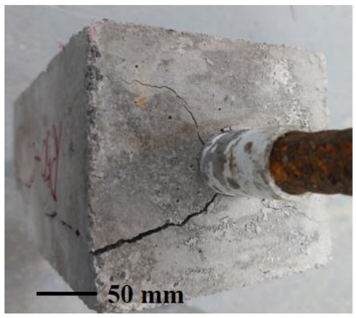


Fig. 8. Bond failure mode

3.4.2. Bond strength

The change trend of the bond strength between recycled concrete and reinforcement is shown in Fig. 9. In general, the addition of nanosilica-modified recycled coarse aggregate can effectively improve the bond strength between recycled concrete and steel bars. After the addition of 1 %, 2 %, 3 % and 4 % nanosilica-modified recycled coarse aggregate, the bond strengths of the recycled concrete and reinforcement improved by 1.03 %, 4.12 %, 10.31 % and 1.04 %, respectively. The results indicate that the 3 % nanosilica-modified recycled coarse aggregate has the best effect on improving the bond performance. The ability of nanosilica-modified recycled coarse aggregate to improve the bond performance between recycled concrete and steel bars stems from its multidimensional optimization of the interface transition zone and the performance of the concrete body.

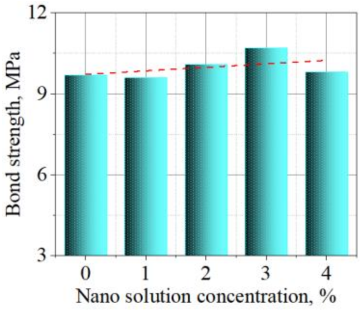


Fig. 9. Bond strength

First, nanosilica can react with cement hydration products with ultrahigh activity to generate denser C-S-H gel, which can fill the pores and microcracks remaining on the surface of recycled coarse aggregate due to destruction of the primary interface transition zone [2], significantly reducing the interface porosity, enhancing the compactness of the interface between steel and concrete, and increasing the chemical bonding force and friction force. Second, its nanometer size effect can refine the internal pore size distribution of concrete, reduce the number of surface dry shrinkage cracks caused by recycled aggregate water absorption [41], strengthen the binding ability of the reinforcement, increase the difficulty of the radial expansion force to cause concrete splitting, and indirectly improve the playing space of the mechanical bite force. In addition, the surface roughness of the modified recycled coarse aggregate was moderately increased due to gel filling and reaction product adhesion, and the toothed bite with the ribbed reinforcement was relatively close, which further increased the transmission efficiency of the mechanical bite force. Moreover, nanosilica can optimize the microstructure of cement paste, improve the strength of the concrete matrix, and increase the degree of stress when the steel bar is stressed to improve the bond performance between the concrete and the steel bar.

The relationship between the bond strength between the recycled concrete and reinforcement and the concentration of nanosolution of the modified recycled coarse aggregate can be obtained via data fitting (Fig. 10), such as via Eq. 1.

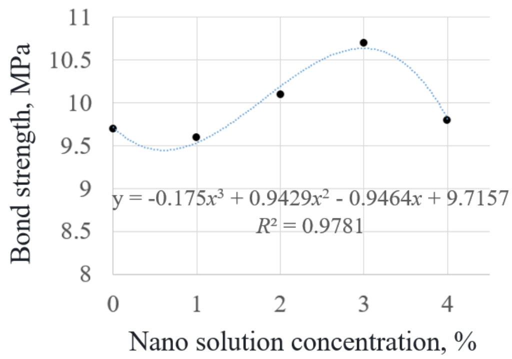


Fig. 10. Relationship between bond strength and nanosolution concentration

The correlation coefficient R^2 is 0.9781, which shows that it has a high correlation (it can be used under the same operating conditions in this experiment).

$$y = -0.175x^3 + 0.9429x^2 - 0.9464x + 9.7157. \quad (1)$$

3.4.3. Bond slip

The variation trend of the bond slip between the recycled concrete and reinforcement is shown in Fig. 11. The addition of nanosilica-modified recycled coarse aggregate can reduce the degree of bond slip between recycled concrete and reinforcement.

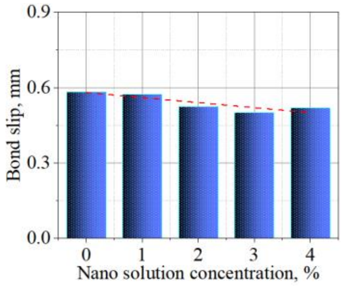


Fig. 11. Bond slip

After the addition of 1 %, 2 %, 3 % and 4 % nanosilica-modified recycled coarse aggregate, the degree of bond slip between the recycled concrete and steel bars decreased by 1.54 %, 9.95 %, 14.07 % and 10.98 %, respectively. This occurred because nanosilica can fill the pores and microcracks on the surface of recycled coarse aggregates and produce more C-S-H gel via pozzolanic reactions with cement hydration products, which significantly improves the compactness of the interface transition zone and reduces the initial slip space caused by the interface porosity. In addition, the surface roughness of the modified recycled coarse aggregate increases, and the mechanical biting force with ribbed reinforcement increases. The strengthening effect of nanosilica on cement improves the stiffness of the concrete matrix, makes the interface stress transfer more uniform when the reinforcement is stressed, delays the degradation rate of friction and the mechanical biting force, and effectively inhibits the relative slip between the reinforcement and the concrete.

The relationship between the bond slip between recycled concrete and reinforcement and the nanosolution concentration of modified recycled coarse aggregate can be obtained via data fitting, such as via Eq. 2 (Fig. 12).

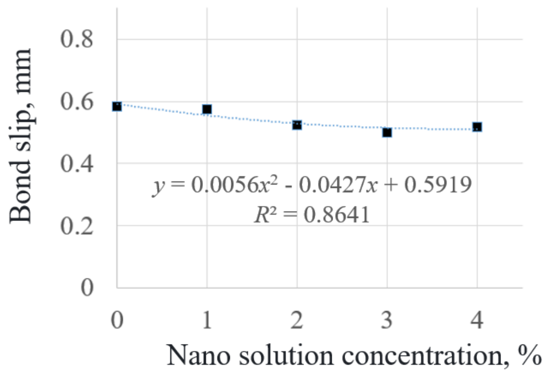


Fig. 12. Relationship between bond slip and nanosolution concentration

The correlation coefficient R^2 is 0.8641, which shows that it has a high correlation (it can be used under the same operating conditions in this experiment).

$$y = 0.0056x^2 - 0.0427x + 0.5919. \quad (2)$$

3.4.4. Bond–slip curves

The bond-slip curves between the recycled concrete and reinforcement before and after nanosilica modification are shown in Fig. 13. The bond-slip curves of each group can be roughly divided into a microslip linear stage, a slip stage, a slip acceleration stage, a nonlinear descent stage and a residual stage [39].

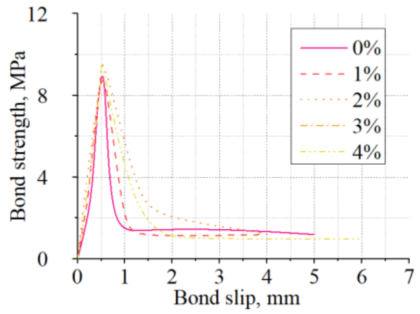


Fig. 13. Bond–slip curves

In the linear stage of microslip, at the initial stage of loading, the chemical bonding force is mainly controlled between the reinforcement and the concrete, the slip is very small, and the free end has not yet moved [40]. In the slip stage, the chemical bonding force gradually fails, the free end begins to slip, the slip is slow, and the bonding stress increases rapidly. In the slip acceleration stage, with increasing load, the slip speed is obviously accelerated, the growth of the bond stress is slowed, and the slope of the curve is reduced. In the nonlinear descent stage, after the peak load is reached, the bond stress decreases rapidly, the slip continues to increase, and the concrete crack expands. In the residual stage, the bonding stress tends to be stable, the slip continues to increase, but the bonding force no longer changes significantly, and the curve tends to be horizontal.

However, Fig. 13 shows that the slope of the rising section of the bond-slip curve between recycled concrete and reinforcement after nanosilica modification increases, and with increasing nanosilica concentration, it generally tends to first increase and then decrease. This is due to the improvement of the properties of recycled concrete itself after modification with nano silica, while optimizing the bonding performance between recycled concrete and steel bars. The combined effect of the two makes it more difficult for the interface to undergo relative slip under load, manifested as a significant increase in the slope of the rising section. When the concentration of the nanomaterial mixture was 4%, the slope of the rising section decreased because the bond strength was lower than that when the concentration of the nanomaterial mixture was 3%, whereas the slip value increased.

5. CONCLUSIONS

1. After nanosilica modification, the performance of the recycled aggregate significantly improved. With increasing nanosilica solution concentration, the modification effect of the nanosilica solution on the aggregate first increased but then decreased.
2. The addition of nanosilica-modified recycled aggregate can improve the compressive strength and splitting tensile strength of recycled concrete. When the concentration of nanosilica solution was 3%, the improvement in the mechanical properties of recycled concrete was the greatest.
3. The addition of nanosilica-modified recycled aggregate can improve the bond performance between recycled concrete and reinforcement, which is reflected mainly in the improvement in bond strength and the reduction in bond slip.
4. A model of the relationship between the concentration of nanosilica solution and the bonding properties was established.
5. The addition of nanosilica-modified recycled coarse aggregate can increase the slope of the bond slip section, and with increasing nanosilica solution concentration, it first increases but then decreases.

The application of this technology in engineering still requires a comprehensive analysis of its structural performance, which will be the direction of future research.

Acknowledgments

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