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Bonding Performance Between Nanomaterial-reinforced Recycled Aggregate Concrete and Rebar

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Effectively improving the bonding performance of rebar in recycled coarse aggregate concrete is the key to the application of Recycled Aggregate Concrete (RAC) in engineering. This paper aims to improve the mechanical properties of Recycled Coarse Aggregate (RA) by strengthening recycled aggregate with nanomaterials and then improving its bonding performance with rebar. The results show that nanomaterials can fill cracks in aggregates and promote hydration reactions and can reduce the crushing index and water absorption performance of RA by 25.5 % and 14.5 % respectively, increase the compressive performance and splitting tensile performance of RAC by 9.4 % and 13.2 %, and increase the Ultimate Bond Strength (UBS) of RAC and rebar by 12.8 % and 11.2 %, respectively. However, the relationship between the concentration of the nanomaterial solution and the improvement effect is not constant. The concentration of the nanomaterial solution should not exceed a certain range (3 %) to avoid agglomeration of the nanomaterial and improve the effect. In addition, this paper also investigated the strengthening mechanism of nanomaterials and the relationship between nanomaterial-reinforced RA properties, mechanical properties of nanomaterial-reinforced RAC and bonding performance of nanomaterial-reinforced RAC specimens.

Keywords: nanomaterial-reinforced aggregate, nanomaterial solution concentration, rebar, mechanical property, bonding performance.

1. INTRODUCTION

The development of cities will inevitably lead to the renewal of old buildings, and the problem of handling solid waste will arise [1]. Moreover, a large amount of non-renewable aggregate resources is needed in the process of building renewal [2]. When subjecting solid waste from construction to secondary treatment and using it as aggregate, and then applying it to concrete, not only can the problem of solid waste disposal be solved, but also sand and gravel aggregates can be saved [3]. Research has revealed that concrete made from recycled aggregates has poor mechanical and durability properties, ultimately due to initial defects in the recycled aggregates themselves [4, 5]. This leads to severe deterioration of the bonding performance of Recycled Aggregate Concrete (RAC) specimens, affecting the safety of reinforced RAC structures [6, 7].

The key to improving the bonding performance of RAC specimens is to improve the mechanical properties of the concrete itself. Research had found a strong correlation between the properties of RA and RAC [8, 9].

Nanomaterials can improve the performance of Recycled Coarse Aggregate (RA), and it can accelerate the hydration rate of cement [10, 11]. Therefore, they have been widely used in the modification of recycled concrete [12, 13]. Gao [14] modified recycled clay brick aggregate concrete with different nanomaterials. Different nanomaterials improved the compressive strength of RAC. In addition, the splitting tensile strength increased with increasing nano-SiO_2 or nano-$CaCO_3$ content. Zhou [15] used a 2 % nano-SiO_2 solution to prepare RA to improve the deformation resistance of concrete. The results show that when all natural aggregate was replaced with nanomaterial-reinforced recycled aggregate, the creep and shrinkage deformation were reduced by 7 % compared with those of recycled coarse aggregate concrete. Wang [16] combined with vacuum impregnation technology to improve RA performance. The results show that the performance of concrete prepared by RA produced by this technology has been significantly improved. Zhang [17] studied the fatigue performance of nano-SiO_2-reinforced RAC and reported that a sample with a nano-SiO_2 immersion concentration of 2 % presented the highest fatigue strength. Chen [18] improved the performance of RAC by combining fiber materials and nanomaterials. The results show that nanomaterials improved the degree of hydration of cementitious materials, enhanced the microstructure and interfacial bonding ability between the fiber materials and the RAC mortar, and improved the performance of the RAC. Singh [19] modified the performance of RAs by nanosilica and urea/nonurea bacteria and found that the performance of modified RA was significantly improved, with the soaking method showing a more significant improvement effect. Whether the bonding performance between recycled concrete and rebar can be guaranteed is one of the key factors to ensure that recycled concrete can be used in reinforced concrete structures [20, 21]. Dong [22] found

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that the replacement rate of RAs is inversely proportional to the bond strength, but for specimens with low W/B ratios, the reduction rate decreased. Prince [23] studied the effect of concrete strengths on the bonding performance between rebar and RAC through pull-out tests. For all concrete with different strength, the bond resistance mechanism of RAC was not unique. RAC specimens can be used in ordinary concrete samples similar to the anchorage length of rebar. Qi [24] studied the effect of nanomaterials on the bonding performance between steel bars and concrete and found that the optimal dosage of nano-SiO_2 and nano-$CaCO_3$ was 2 %, which significantly affected the slip value of steel bars. Shen [25] pointed out that nano-SiO_2 can accelerate the hydration process of cement, effectively improve the compressive strength of concrete, and thus improve the bonding performance between steel bars and concrete. Ismael [26] investigated the influence of nano-Al_2O_3 and nano-SiO_2 on the bond performance between steel bars and concrete. The results showed that the addition of nanoparticles can improve the bond performance of reinforced concrete, especially nano-Al_2O_3, which can effectively enhance the crack resistance of concrete. Li [27] found that nanomaterials can improve the Ultimate Bond Strength (UBS) between steel bars and concrete, making the descending section of the bond slip curve smoother. The reason is that nanomaterials not only have a filling effect on concrete, but also promote the reaction of cement. Hawren [28] pointed out that carbon nanotubes have a bridging effect, which can effectively improve the bonding performance between steel bars and concrete, and delay the development of cracks. Alhawat [29] studied the bonding properties of uncorroded/corroded steel bars in RAC and revealed that the effect of RAC on the bonding strength of uncorroded samples was not significant. However, owing to the high porosity and high water absorption of RA, the corrosion rate of rebar increases with increasing RA replacement level, resulting in much faster bond degradation between RAC and corroded rebar than between RAC and corroded ordinary concrete. Yang [30] reported that the addition of nano-SiO_2 and nano-TiO_2 improved the bonding performance of reinforced concrete, mainly reflected in the improvement of bond strength and slip value. This conclusion has also been confirmed by the research of Wang [31] and Baghzad [32].

However, the current research on the bonding performance between nanomaterial-reinforced RAC and rebar was not systematic enough, and this topic had not been comprehensively analyzed from recycled materials to recycled concrete. In this work, the properties of nanomaterial-reinforced RA, the properties of nanomaterial-reinforced RAC and the bonding properties of nanomaterial-reinforced RAC and rebar are comprehensively analyzed. The relationships among the aggregate properties, concrete mechanical properties and bonding performance between nanomaterial-reinforced RAC and rebar are established.

2. EXPERIMENTAL STUDY

2.1. Experimental materials

PO 42.5 cement produced by Weifang Shanshui Cement Co., Ltd. was used. The basic properties of the cement are shown in Table 1 [33]. The RA was broken from the waste concrete from a construction site in Shouguang city, and the Ordinary Coarse Aggregate (OA) was the gravel produced by Shouguang Company. The basic properties of the coarse aggregates are shown in Table 2 [34]. Fine aggregates were made of ordinary machine-made sand with a fineness modulus of 2.8. The nanomaterials used were nano-SiO_2 and nano-Al_2O_3, which were produced by a company in Shanghai, and their properties are shown in Table 3. The rebar of the pull-out specimens is HRB400 deformed rebar with a diameter of 20 mm, and the stirrups are HPB300 plain rebar with a diameter of 8 mm (the yield strength of HRB400 rebar is 520 MPa, and the yield strength of HPB300 rebar is 398 MPa).

Table 1. Properties of cement

Specific surface area, m^2 kg^{-1}	3-day compressive strength, MPa	3 -day flexural strength, MPa	28-day compressive strength, MPa	28-day flexural strength, MPa
327	5.3	27.8	47.8	9.2

Table 2. Properties of the coarse aggregates

Type	Size, mm	24 h/3d water absorption, %	Crushing index, %
RA	4.75 – 22.5	9.8/10.1	15.9
OA	4.75 – 22.5	2.7/2.8	9.8

Table 3. Properties of nano-SiO_2 and nano-Al_2O_3

Type	Grain size, nm	Content, %	Specific surface area, m^2/g
Nano-SiO_2	20	99.0	230
Nano-Al_2O_3	20	99.0	110

Air-dried RA was immersed in nanomaterial solutions with concentrations of 0 %, 1 %, 2 %, 3 %, and 4 %.

2.2. Concrete mix and specimen design

The concrete mix design is shown in Table 4 [35]. The cube specimen with a size of 100 mm × 100 mm × 100 mm was designed to test the mechanical performance of concrete (including compressive strength and splitting tensile strength). Prism pull-out specimens with a size of 100 mm × 100 mm × 180 mm were designed to test the bonding performance nanomaterial-reinforced recycled concrete and rebar.

2.3. Test method

The mechanical performance test of the concrete was tested on a hydraulic servo pressure testing machine (Fig. 1); the bonding performance test was tested on a hydraulic servo pull-out tester, as shown in Fig. 2 [36].

3. RESULTS ANALYSIS

3.1. Nanomaterial-reinforced RA performance

The properties of RAs after nanomaterial reinforcement are shown in Fig. 3 and Fig. 4. The compressive and water absorption properties of the nanomaterial-RAs were greater than those of the unreinforced RAs. This is consistent with Wang's conclusion [37]. This is because RA contains old cement mortar, which makes its performance being inferior to that of OA.

Table 4. Concrete mix design, kg/m^3

	Cement	Tap water	Fine aggregate	RA	OA	Nanomaterial-reinforced RA
OC	395	195	598	0	1085	0
RC	395	195	598	1085	0	0
RC-S-1	395	195	598	0	542.5	542.5
RC-S-2	395	195	598	0	542.5	542.5
RC-S-3	395	195	598	0	542.5	542.5
RC-S-4	395	195	598	0	542.5	542.5
RC-A-1	395	195	598	0	542.5	542.5
RC-A-2	395	195	598	0	542.5	542.5
RC-A-3	395	195	598	0	542.5	542.5
RC-A-4	395	195	598	0	542.5	542.5

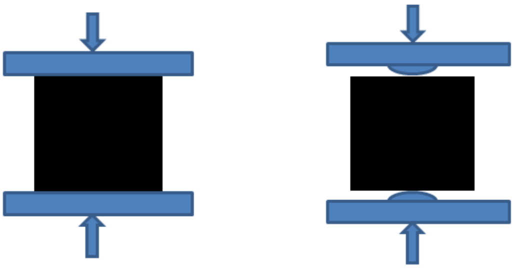

Fig. 1. Mechanical performance loading diagram: a – compressive strength test; b – splitting tensile test

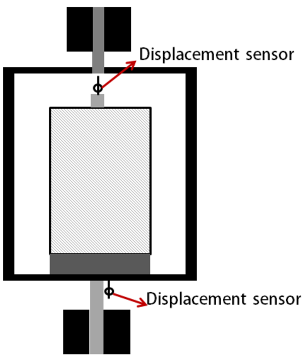

Fig. 2. Bond performance loading diagram

After the reinforcement of the nanomaterials, the compressive and water absorption properties tended to decrease. The reason is that the nanomaterials fill the initial imperfection of the RA, thereby improving the performance of aggregate.

In addition, when the concentration of the nanomaterial solution was below 3 %, the crushing index and the water absorption properties of the RA increased; when the concentration of the nanomaterial solution was 4 %, the crushing index and water absorption of the RA showed a certain degree of decrease. When the concentration of the nano-SiO_2 solution was 3 %, the crushing index and the water absorption properties of the RA decreased by 25.5 % and 14.5 %, respectively. When the concentration of the nano-Al_2O_3 solution was 3 %, the crushing index and water absorption properties of the RA decreased by 20.4 % and 12.6 %, respectively. When the concentration of the nano-SiO_2 solution was 4 %, the crushing index and water absorption properties of the RA decreased by 20.4 % and 13.8 %, respectively. When the concentration of the nano-Al_2O_3 solution was 4 %, the crushing index and water absorption properties of the RA decreased by 17.3 % and 8.8 %, respectively. Wang [37] analyzed the reasons for this phenomenon, and when the concentration of the nanomaterial solution is too high, the nanomaterial agglomerates, which hinders the nanomaterial from entering the RA, resulting in a decrease in the improvement effect on the RA.

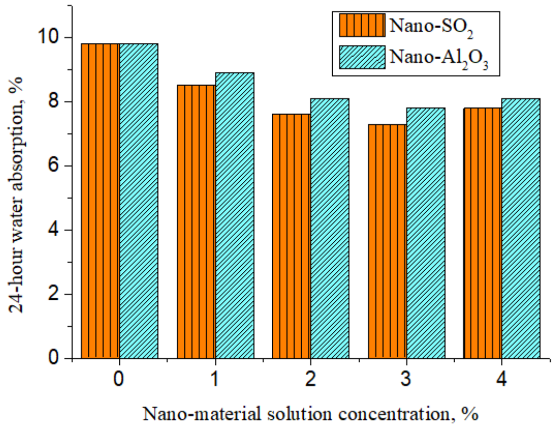

Fig. 3. Water absorption of aggregate

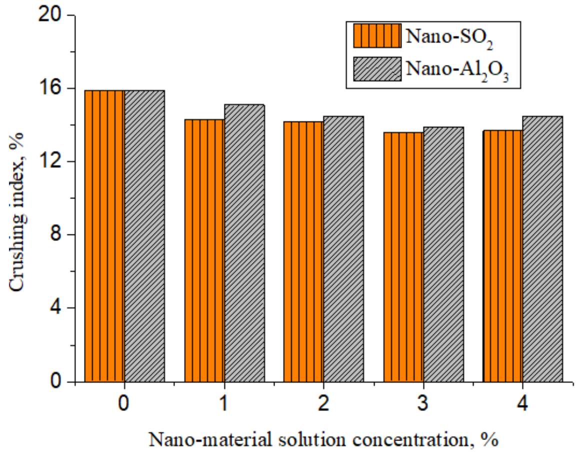

Fig. 4. Crushing index of aggregate

3.2. Mechanical performance of nanomaterial-reinforced RAC

The mechanical performance of nanomaterial-reinforced RAC is shown in Fig. 5 and Fig. 6. The compressive and splitting tensile properties (compressive strength was 35.0 MPa; splitting tensile strength was 3.25 MPa) of RAC are lower than those of Ordinary Coarse

Aggregate Concrete (OAC) (compressive strength was 42.5 MPa; splitting tensile strength was 3.87 MPa). The reason is that the ability of RA to resist loads is not as good as that of OA, and RAC has three interface transition zones that are weak areas of concrete. After the strengthening treatment of nanomaterials, the mechanical performance of nanomaterial-reinforced RAC improved. The reason is that nanomaterials not only improve the basic properties of RAs, but also promote the hydration reaction of cement to a certain extent, thereby enhancing the strength of RAC.

In addition, with increasing nanomaterial concentration, the mechanical performance of nanomaterial-reinforced RAC first increased but then decreased. This phenomenon has also been discovered in Cui's research [38]. When the concentration of nano-SiO_2 solution and nano-Al_2O_3 solution was 3 %, the compressive performance increased by 9.4 % and 7.1 %; the splitting tensile performance increased by 13.2 %, and 9.8 %. When the concentration of nano-SiO_2 solution and nano-Al_2O_3 solution was 4 %, the compressive performance increased by 5.4 % and 7.4 %; the splitting tensile performance increased by 4.9 %, and 4.6 %. This may be because when the concentration of nanomaterial solution is too high, the aggregation of nanomaterials hinders the contact between RA and cement mortar, resulting in a certain weak zone [39].

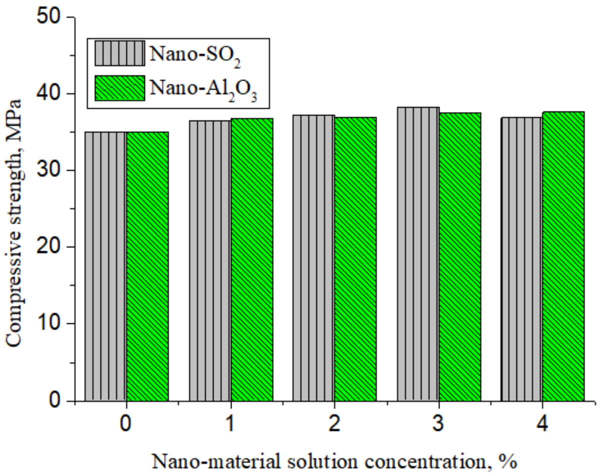

Fig. 5. Compressive performance

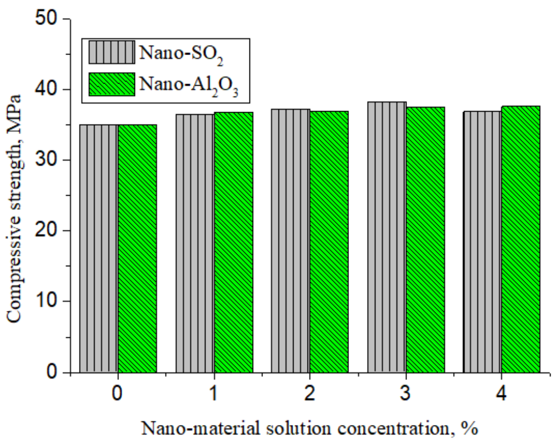

Fig. 6. Split tensile performance

3.3. Bonding performance of rebar in nanomaterial-reinforced RAC

The bond strength of the rebar in the nanomaterial-reinforced RAC is shown in Fig. 7. After the reinforcing treatment of the nanomaterials, the bond strength of rebar in RAC improved. This is similar to the conclusion drawn by Qi [24] and Shen [25]. This is because nanomaterials improve the concrete strength, and the bonding force of RAC to rebar is improved, which increases the mechanical bite force of RAC to rebar, thus improving the bonding performance of rebar in RAC.

In addition, with increasing nanomaterial concentration, the UBS of rebar in RAC first increased but then decreased. When the concentration of nano-SiO_2 solution and nano-Al_2O_3 solution was 3 %, the UBS of RAC and rebar increased by 12.8 % and 11.2 %, respectively; when the concentrations of nano-SiO_2 solution and nano-Al_2O_3 solution were 4 %, the UBS of RAC and rebar increased by 11.2 % and 7.2 %, respectively, which is due to the RAC strength being the best when the concentration of the nanomaterial solution is 3 %, and mechanical bite force of RAC to rebar is the highest, so its bonding performance is the best. This is slightly different from the results obtained by Qi [24], who believes that the best effect is achieved when the yield is 2 %.

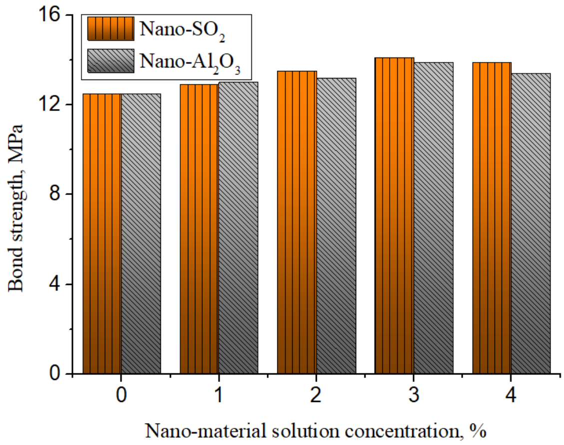

Fig. 7. Effect of nanomaterials on bond strength of RAC specimens

The slip of the rebar corresponding to the UBS of the RAC and rebar is shown in Fig. 8. After the reinforcing treatment of nanomaterials, the slip value of rebar is reduced. The reason for this phenomenon is that the concrete strength is improved after the reinforcement of nanomaterials, and its ability to constrain rebar is improved, thus reducing the slip value of rebar.

In addition, with increasing nanomaterial concentration, the slip value of rebar first decreased but then increased.

When the concentration of nano-SiO_2 solution and nano-Al_2O_3 solution was 3 %, the slip values rebar decreased by 30.9 % and 29.5 %, respectively; When the concentrations of nano-SiO_2 solution and nano-Al_2O_3 solution were 4 %, the slip values of decreased by 12.3 % and 17.6 %, respectively. This is because when the concentration of the nanomaterial concentration is 3%, the mechanical properties of the RAC are the best, and its restraint ability to the rebar is the strongest, so the slip value of the rebar is the smallest.

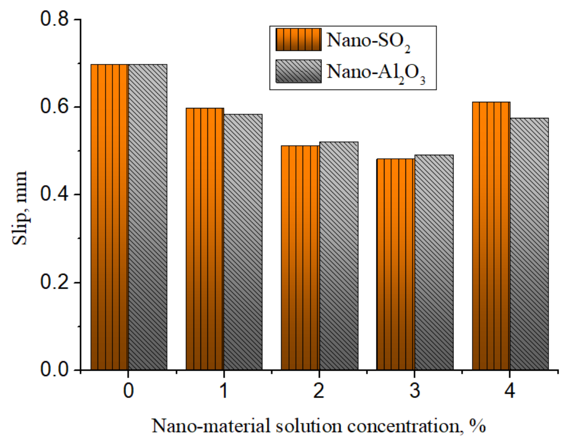

Fig. 8. Effect of nanomaterials on slip of RAC specimens

3.4. Analysis of the reinforcing mechanism of nanomaterials

During the crushing process of the waste concrete, secondary damage is caused to the recycled aggregate, which causes some micro cracks in the RA. In addition, the cement mortar attached to the surface of RA is difficult to completely remove. These cement mortars have high porosity and low strength, resulting in relatively low strength of RA. This is also one of the main reasons for the poor concrete strength, which will inevitably affect its bonding with rebars, resulting in a serious deterioration of the bonding performance.

On the one hand, nanomaterial particles are small and can enter the cracks of the aggregate during the soaking process and play a filling role (as shown in Fig. 9), improving the comprehensive performance of RA; on the other hand, nanomaterial particles have a nucleation effect, which can provide the nucleation sites required for the production of hydration products, thus promoting the hydration reaction of cement to same extent.

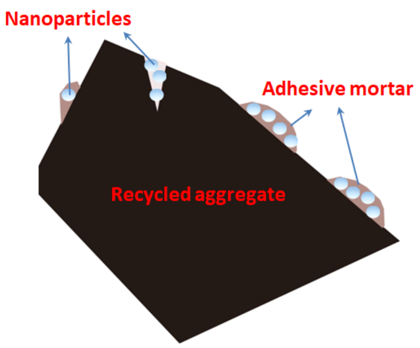

Fig. 9. Schematic diagram of nanomaterials reinforcing recycled aggregates

The hydration reaction products of cement can also fill the initial imperfection in RAs [39] and improve the interface transition zone between RAs and cement mortar, increasing the density of RAC structures (as shown in Fig. 10), which will inevitably enhance RAC strength [12].

3.5. Calculation model

Intermediate variables λ and μ are established as follows:

$$\lambda=(c+1)/\delta_a; \quad (1)$$

$$\mu=f_c/f_{ts} \quad (2)$$

where c is the nanomaterial solution concentration; δ_a is the recycled coarse aggregate crushing index; f_{ts} is the splitting tensile strength of cube RAC specimens; and f_c is the compressive strength of cube RAC specimens.

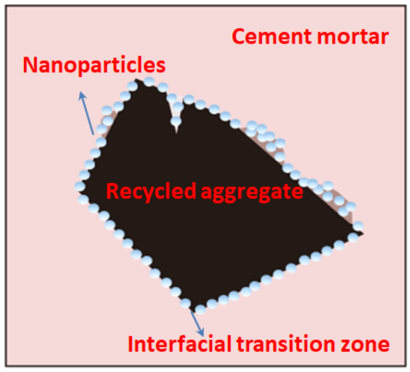

Fig. 10. Schematic diagram of nanomaterials reinforcing recycled aggregate concrete

The relationship model between the aggregate properties, concrete mechanical properties and bonding strength between the nanomaterial-reinforced RAC and rebar is shown in Fig. 11.

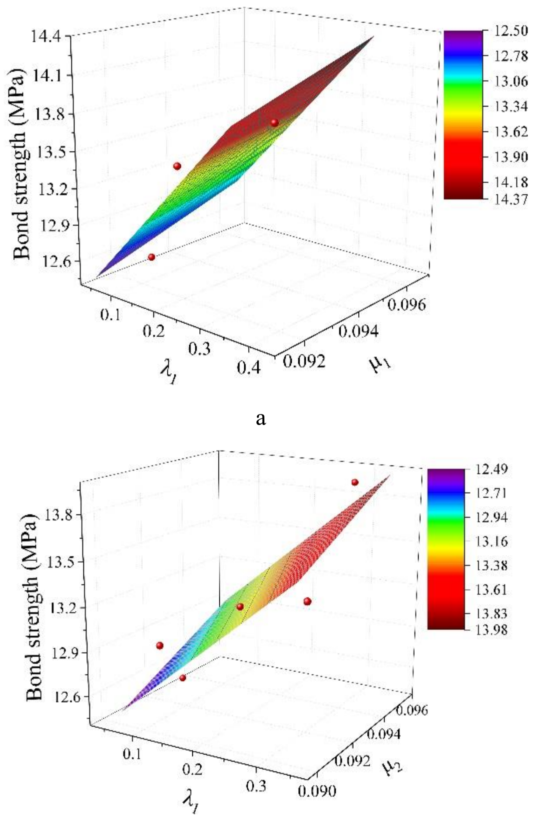

Fig. 11. Mechanical performance relationship model: a – nano-SiO_2; b – nano-Al_2O_3

The relational model equation between the aggregate properties, concrete mechanical properties and bonding strength (τ) between the nanomaterial-reinforced recycled

RAC and rebar is as follows:

Nano-SiO_2:

$$\tau_1=4.96072+4.82788\lambda_1+79.56289\mu_1; \quad (3)$$

$$\tau_1=4.96072+4.82788(c_1+1)/\delta_{a1}+79.56289f_{c1}/f_{ts1}. \quad (4)$$

Nano-Al_2O_3:

$$\tau_2=4.83164+3.74245\lambda_2+82.53042\mu_2; \quad (5)$$

$$\tau_2=4.83164+3.74245(c_2+1)/\delta_{a2}+82.53042f_{c1}/f_{ts2}. \quad (6)$$

4. CONCLUSIONS

1. After being reinforced with nanomaterials, the performance of RAs improved, crushing index and water absorption properties of the RA decreased by 25.5 % and 14.5 %.
2. The mechanical strength of nanomaterial-reinforced RAC was greater than those of unreinforced RAC, compressive performance and splitting tensile performance increased 9.4 % and 13.2 %.
3. With increasing nanomaterial concentration, the degree of improvement in RAC mechanical strength first tended to increase but then decrease, the optimal concentration of nanomaterials is 3 %.
4. The bonding performance between nanomaterial-reinforced RAC and rebar was better than that between unreinforced RAC and rebar, UBS of RAC and rebar increased by 12.8 % and 11.2 %, the slip values rebar decreased by 30.9 % and 29.5 %, respectively.
5. Nanomaterials could fill the initial imperfection of aggregates, thereby improving the performance of RAs. In addition, nanomaterials could promote the hydration reaction and make the concrete structure more compact, thus improving the RAC mechanical strength.
6. A relationship model between the aggregate properties, concrete mechanical properties and bonding performance of the RAC and rebar was established.

Acknowledgments

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