

Research Article

Performance Evaluation of Strengthening Recycled Coarse Aggregate in Cement Stabilized Mixture Base Layer of Pavement

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Received 18 August 2020; Revised 9 December 2020; Accepted 15 December 2020; Published 28 December 2020

Academic Editor: Linglin Li

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This paper attempts to study the effect of different strengthening methods on recycled coarse aggregate (RCA) reprocessed from construction and demolition (C&D) waste. And it aims to obtain the optimal RCA content in cement stabilized recycled mixture (CSRМ) applied in the base layer of pavement. Firstly, three strengthening methods were used to strengthen the RCA. It was revealed that the sodium silicate solution is the best method in a strengthening concentration of 8% and strengthening for five hours. Then, the mechanical experiments under two cement dosages, including unconfined compressive strength, splitting strength, and compressive rebound modulus tests, were carried out. In each cement dosage, five different RCA contents (0%, 25%, 50%, 75%, and 100%) were considered. It was found that, at 5% of cement dosage, the strength of CSRМ satisfied the requirements of the base layer of the expressway under heavy traffic load. In the case of 4% of cement dosage, the strength of CSRМ which was beyond 50% of RCA content was failed to meet specification requirements. For the failed cases, by strengthening RCA in the best method obtained before, 7 d unconfined strength and crushing value of the CSRМ with 50% RCA content could meet the requirements of the subbase of expressways and first-class highways in China; the 75% of the mixture meets the requirements of the second-class highways and below.

1. Introduction

The rapid development of China's urbanization has resulted in massive generation of C&D waste, and it represents more than 30% of the world's municipal solid waste, 2 billion tons in 2019 [1]. After separating, screening, and removal of impurities, converting C&D waste into RCA and then applying it into road engineering have become a hot issue at present. Many research studies show that C&D waste has been widely utilized as materials of pavement base [2, 3] and subgrade fillers [4, 5]. In addition, by the end of 2030, 47,000 kilometers of highways and 100,000 kilometers of national highways will be built in China [6]. The increasing demands of construction in highway will lead to significant increasing depletion of natural aggregate sources. Due to the strict restrictions on exploitation of natural aggregates, there is a growing gap between the demand and supply capacity of road sources materials. Utilization of RCA into the

pavement construction industry contributes to improving the efficiency and sustainability by conservation of raw materials and reduction of the landfilled C&D waste amount and greenhouse gas emission [7–10].

Characterization studies of RCA have been conducted in recent years. Compared with natural coarse aggregate, RCA has higher crushing index, larger water absorption rate, and lower apparent density [11, 12]. Microexperiments were carried out to analyze the reasons for these differences [13, 14]. Some studies also have shown that the cement kilns, fly ash, etc. considerably help to improve its performance [15, 16]. At the same time, in order to make better use of RCA, various enhancement methods have been proposed to improve the performance of RCA, including mechanical device [17], nanosilica and bacteria [18], waste basalt powder [19], and microbial carbonate precipitation treatment [20]. However, there were no experiments carried out to establish the relationship between the above strengthening methods

and the mechanical properties of CSRMs under the condition of different RCA contents and cement dosages.

At present, many scholars have carried out researches on the strength, stiffness, crack resistance, and shrinkage properties of CSRMs by utilizing RCA as materials in the base layer of highway [21–23]. Researchers have found that, with the increase of RCA content, the mechanical properties will deteriorate [24–26]. Under the same cement dosage, after mixing with RCA, the compressive strength of CSRMs will be reduced by 12% to 25% [27, 28]. Butler [29] even concluded that it will be reduced by 30%. At the same time, the RCA will also have a certain impact on the flexural strength and unit wear loss of CSRMs [11]. Therefore, the natural coarse aggregate can be only partially replaced by RCA to meet the requirements of the pavement base. Mills-Beale suggested that the RCA content should not exceed 75% [30]. Under a single cement dosage, Poon and Chan [31] and Azam and Cameron [32] have carried out researches on the performance of RCA as a base or subbase layer of granular materials. Resilient modulus is also a mechanical performance index that can be studied [33, 34]. Li et al. [35] concluded that the RCA content should not exceed 75% from the perspective of freeze-thaw splitting tensile strength, elastic modulus, and dynamic modulus.

In this paper, 3 different strengthening methods were compared to evaluate their effect on RCA. By comparing the changes in the water absorption rate and crushing value, the optimal strengthening method was selected. Then, under different cement dosages (3%, 4%), the mechanical properties of CSRMs with different RCA contents (0%, 25%, 50%, 75%, and 100%) were studied. At cement dosage of 5%, the 7 d unconfined compressive strength satisfies the requirements of the base layer of the expressway under heavy traffic load. For these RCA contents at 4% of cement dosage that does not meet the requirements of the specification, the optimal strengthening method was applied to improve the mechanical performance of CSRMs. Finally, by comprehensive evaluation, the recommended RCA content was proposed corresponding to different-class highways. The outcomes of this study are expected to provide a useful reference for pavement analysis and design, thus promoting the consumption of C&D waste.

2. Materials and Research Content

2.1. Cement. The cement used in this experiment was P.C32.5. Its basic performance indicators were measured, and the results are shown in Table 1. The standard value is obtained from China specification “*General Portland Cement*” [36].

2.2. Aggregate. This study mainly focused on coarse aggregates with particle size of 4.75–26.5 mm. Due to a large number of impurities on the surface of the RCA reprocessed from C&D waste, it needs to be washed and dried before testing. RCA mainly includes recycled concrete aggregate and recycled brick. There are huge

differences between them in flexural strength, permeability, and other properties [37, 38]. Therefore, the natural coarse aggregate and these two main ingredients of RCA were separated manually, as shown in Figure 1. According to the method of Chinese standard “*Highway Engineering Aggregate Test Regulations*” [39], the basic properties of the RCA with 3 different particle sizes were studied. And the test of water absorption rate was conducted by Volumetric flask method in this standard. The results are shown in Table 2.

According to Table 2, the water absorption rate of the recycled brick aggregate is higher than those of the natural aggregate and recycled concrete aggregate. With the increasing in brick aggregate particle size, its water absorption rate slowly decreases. The crushing values of these two main ingredients of RCA can meet the requirements of the base and subbase of China’s standard “*Technical Rules for Construction of Road Pavement Base Courses*” [40]. But the values of the concrete aggregate and brick aggregate are 25.47% and 39.62% greater than those of natural aggregates, respectively. The difference between these two main ingredients and natural aggregates is mainly because of the differences in their surface state. There are some mortars attached on the surface of recycled concrete aggregates and recycled brick aggregates, which results in more pores on the surface of the RCA. Compared with recycled concrete aggregates, there are more mortars attached to recycled brick aggregates. Thus, the water absorption rate and crushing value of recycled brick aggregates are larger than those of recycled concrete aggregates [41, 42].

The indexes of fine aggregate are shown in Table 3.

As can be seen from Table 3, the apparent density and water absorption rate of recycled fine aggregate are, respectively, smaller and higher than those of natural fine aggregate. The water absorption rate of recycled fine aggregate is 75.65% greater than that of natural fine aggregate. This is mainly because the recycled fine aggregate is composed of some stones in the crushing process and unhydrated mortar or brick aggregate.

2.3. Grading Design. The grading of the mixture adopted the median value of the skeleton dense grading range specified in China’s standard [40], as shown in Figure 2.

In order to determine the optimal moisture content (OMC) and maximum dry density (MDD) of the CSRMs, the compaction test was carried out. Since the recycled brick aggregate accounted for 10% in RCA, the influence of the recycled brick aggregate on the properties of CSRMs could not be ignored. The ratio between recycled concrete and recycled brick aggregate was approximately 9 : 1. Then, the natural coarse aggregate was replaced by RCA in this ratio to carry out the compaction experiment. The RCA replacement rates are 0%, 25%, 50%, 75%, and 100%. In addition, two different cement dosages (4%, 5%) were considered. The results are shown in Figure 3.

The following information can be obtained through Figure 3:

TABLE 1: Cement quality index test results.

| Detection index | Setting time (min) | | Stability (mm) | Flexural strength (MPa) | | Compressive strength (MPa) | |
|-----------------|----------------------|--------------------|----------------|-------------------------|------|----------------------------|-------|
| | Initial setting time | Final setting time | | 3d | 28 d | 3 d | 28 d |
| Detection value | 248 | 385 | 1.0 | 3.3 | 7.1 | 18.5 | 36.2 |
| Standard value | ≥180 | ≥360 | ≤5 | ≥2.5 | ≥5.5 | ≥10.0 | ≥32.5 |

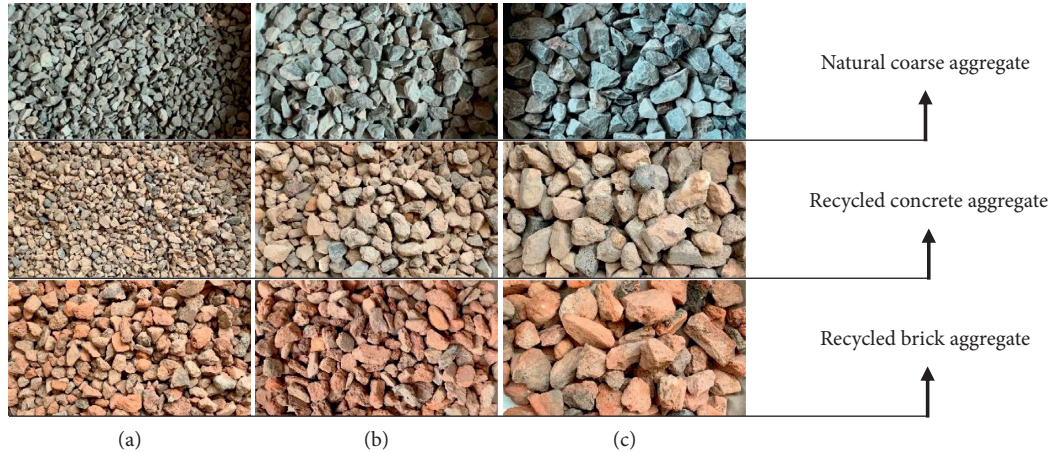


FIGURE 1: Natural coarse aggregate and RCA source materials. (a) 4.75–9.5 mm. (b) 9.5–19 mm. (c) 19–26.5 mm.

TABLE 2: Prosperities of coarse aggregate.

| Test detection index | Natural aggregate | | | Recycled concrete aggregate | | | Recycled brick aggregate | | |
|---|-------------------|--------|---------|-----------------------------|--------|---------|--------------------------|--------|---------|
| | 4.75–9.5 | 9.5–19 | 19–26.5 | 9.5–19 | 9.5–19 | 19–26.5 | 4.75–9.5 | 9.5–19 | 19–26.5 |
| Apparent density (kg/m^3) | 2.77 | 2.76 | 2.76 | 2.50 | 2.54 | 2.56 | 2.31 | 2.27 | 2.29 |
| Water absorption rate (%) | 0.67 | 0.53 | 0.41 | 5.71 | 5.44 | 5.23 | 17.08 | 16.55 | 14.61 |
| Needle particles (%) | 8.3 | 7.8 | 4.5 | 7.6 | 6.9 | 5.7 | 8.9 | 7.3 | 5.2 |
| Crushing value (%) | | 21.2 | | | 26.6 | | | 29.3 | |

TABLE 3: Prosperities of fine aggregate.

| Detection index | Natural fine aggregate | Recycled fine aggregate |
|---|------------------------|-------------------------|
| Apparent density (kg/m^3) | 2.68 | 2.35 |
| Water absorption rate (%) | 4.23 | 7.43 |
| Liquid limit (%) | 22.6 | 28.2 |
| Plastic limit (%) | 14.9 | 22.3 |

- (1) As the content of RCA increases, the MDD of the CSRMs decreases and its OMC increases, regardless of the cement dosage. Taking the cement dosage of 4% as an example, when the content of RCA increases from 0% to 100%, the MDD decreases from $2.32 \text{ g}/\text{cm}^3$ to $1.90 \text{ g}/\text{cm}^3$. The OMC increases from 4.11% to 10.52%.
- (2) The MDD and the OMC of the CSRMs, respectively, increase and decrease with the increase of cement dosage regardless of the RCA contents. This is mainly because more water is needed to hydrate the CSRMs with the increase of cement dosage. During the compaction, hydrated products will gradually fill the voids of the CSRMs, which contributes to the increase of the MDD.

2.4. Research Content. This article mainly studies different strengthening methods for strengthening the RCA and mechanical properties of CSRMs with different cement dosages. In each cement dosage (4%, 5%), five different RCA contents (0%, 25%, 50%, 75%, and 100%) were considered. The research contents are as follows:

- (1) Basic material performance tests were conducted to compare the performance of RCA and natural aggregates. The main performance indicators were apparent density, water absorption, crushing value, etc.
- (2) Three different strengthening methods were adopted to strengthen the RCA. Different working conditions were set in each method. For the Los Angeles (LA)

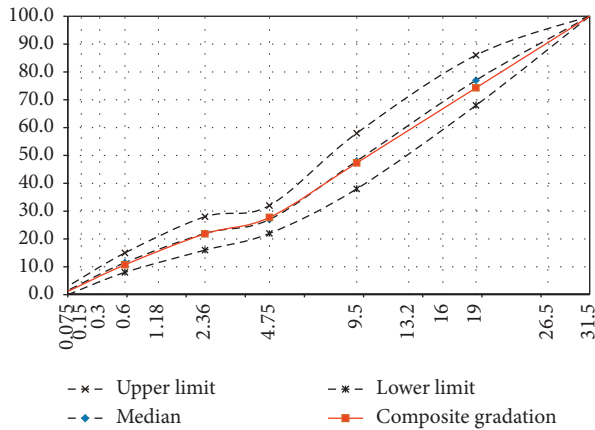


FIGURE 2: Design diagram of the gradation curve of framework dense structure.

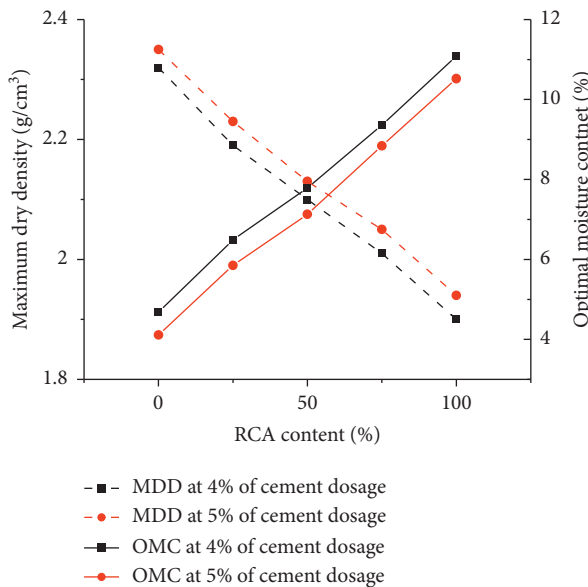


FIGURE 3: Results of the compaction test under different RCA content and cement dosages.

abrasion test, three different revolutions and steel balls were considered. For chemical strengthening tests, solution concentration and soaking time were two variables considered for experiments. Water absorption rate and crushing value were used as evaluation indexes to get the best strengthening method.

- (3) The diagram of the gradation curve was made to meet the grading range given by the specification. Then, the compaction experiments were conducted to research the OMC and the MDD under different contents of RCA and cement dosage.
- (4) According to the results in compaction tests, the mechanical properties experiments were conducted. These experiments included unconfined compressive strength, splitting strength, and compressive rebound modulus tests. By analyzing the influence of

cement dosage and the RCA content on the performance of CSRM, a recommended range of RCA was obtained in road engineering.

- (5) For the content of RCA that does not meet the requirements of the specification, the best strengthening method obtained in the previous tests was utilized to strengthen the RCA. By comparing three mechanical properties before and after strengthening, the recommended content of RCA after strengthening was obtained.

3. Aggregates Treatment

3.1. LA Abrasion Test. LA abrasion test is a physical strengthening method, designed to make RCA collide with steel balls. After friction, the surface of the mortar was shedding, thus obtaining reinforced aggregates. Turns of the LA abrasion test (200, 400, and 800) and steel balls (4, 8, and 12) were used as two variables in this experiment. To carry out this experiment, 5 kg each of recycled concrete aggregate and recycled brick aggregate was utilized. The water absorption rate and crushing value of the RCA after strengthening are shown in Figure 4.

It can be seen from Figure 4 that the water absorption rate and crushing value take the minimum value at 400r. From 0 to 400r, the water absorption rate and crushing value of the RCA decrease. The water absorption rates of recycled concrete aggregate and recycled brick aggregate decrease by 1.21%, and 0.72%, respectively. The crushing values related to these materials decrease by 3.7% and 4.36%, respectively. When the cycles increase from 400 to 600r, they show an upward trend. For recycled concrete aggregate, the water absorption rate and crushing value averagely increase by 0.07% and 0.4%, respectively. For recycled brick aggregate, they sharply increase by 0.31% and 0.86%, respectively. This fact is because microcracks on the surface of RCA arise as the number of turns increases, and this phenomenon increases its water absorption and crushing values. But for recycled brick aggregate, it causes cracks and even damage. As shown in Figure 4(b), by colliding with 12 steel balls, the water absorption rate and crushing value increase from 400 to 600r. The greater the number of steel balls, the greater the damage to the recycled brick aggregate. That is the reason why the greater the number of steel balls for recycled brick aggregate, the greater the increase in water absorption rate. It can be easily concluded that the 12 steel balls and 800r are the most proper condition.

3.2. Sodium Silicate Solution. The colloidal particle structure in the sodium silicate solution can be expressed by Figure 5, and the hydrolysis reaction can be briefly summarized as (1). Sodium silicate solution can react with calcium hydroxide to form C-S-H gel as shown in (2):

After mixing the sodium silicate solution and RCA, the surface of aggregate is coated with a thin layer of sodium silicate film, that is, the adhesive film [43]. Adjacent aggregates are connected by an adhesive film to

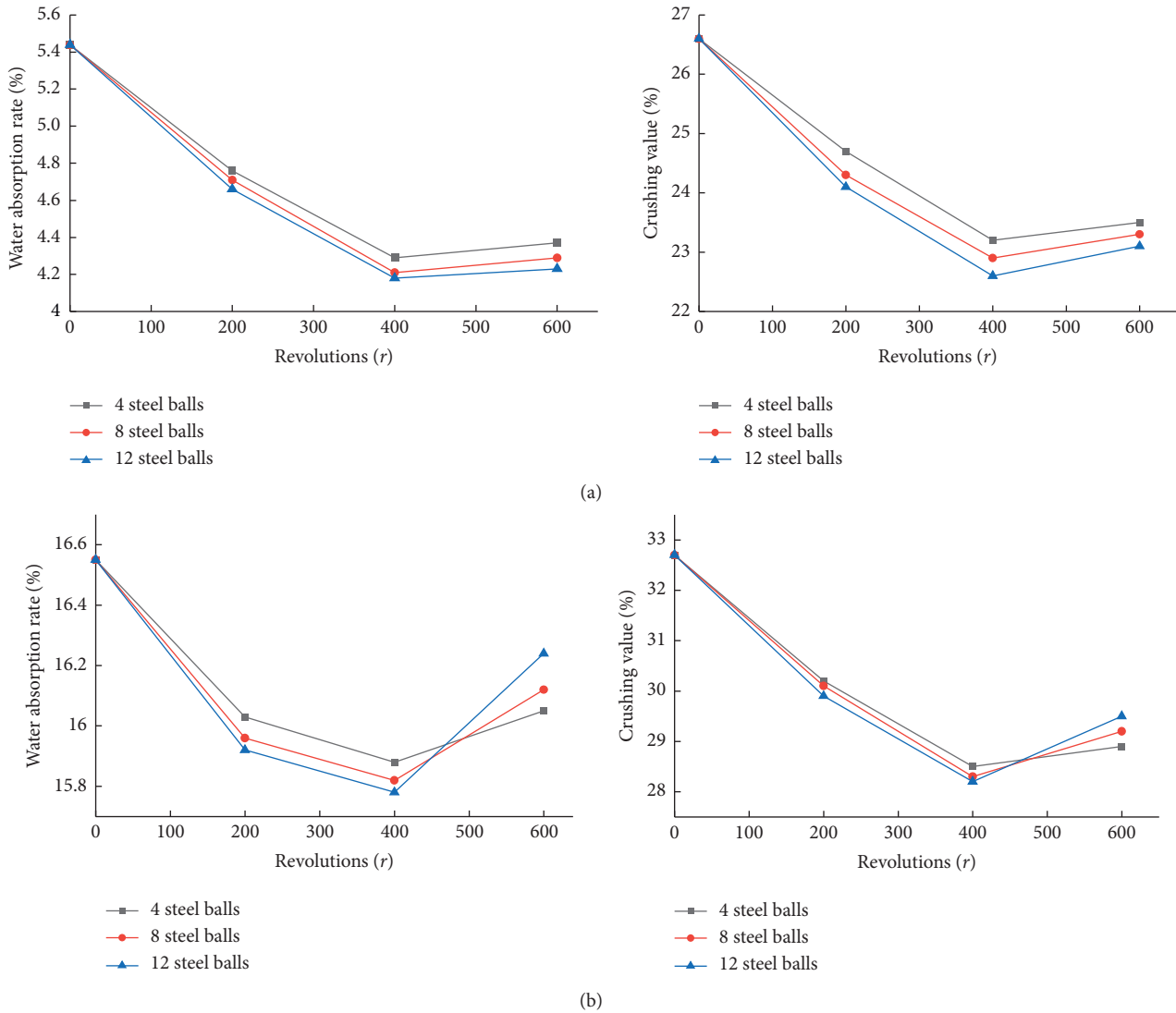


FIGURE 4: Results of the LA abrasion test. (a) Recycled concrete aggregate. (b) Recycled brick aggregate.

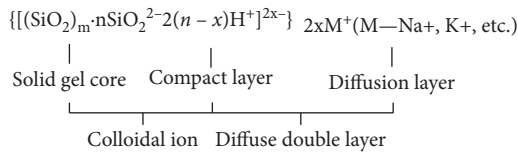
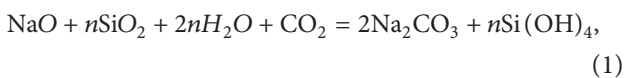


FIGURE 5: Colloidal particle structure in sodium silicate solution.

form an adhesive bridge (Figure 6). Then, the adhesive strength is established through the gelation process of sodium silicate.



The basic indicators of sodium silicate solution are shown in Table 4.

The mass percentage of the sodium silicate solution was 41.64%. By adding water, it was prepared at 5%. To ensure that the solution can fully submerge the aggregate, the sorted recycled concrete aggregate and recycled brick aggregate were poured into the sodium silicate solution and stirred evenly. At the soaking time of 2h, 5h, and 10h, the recycled concrete aggregate and the brick aggregate were taken out and filtered out. Then, they were spread on the enamel tray to naturally dry in the room. The water absorption rate and crushing value of the dried aggregates are measured. The above operation was repeated with 8% and 12% sodium silicate solution. The results are shown in Figure 7.

It can be seen from Figure 7 that as the strengthening time increases, the water absorption rate of two main compositions of RCA decreases at a concentration of 5%. As the substances in the sodium silicate solution react with the old mortar on the surface of the RCA, the hydrated silica colloid fills the pores and cracks on the surface of the aggregate. The change in crushing value also meets this law.

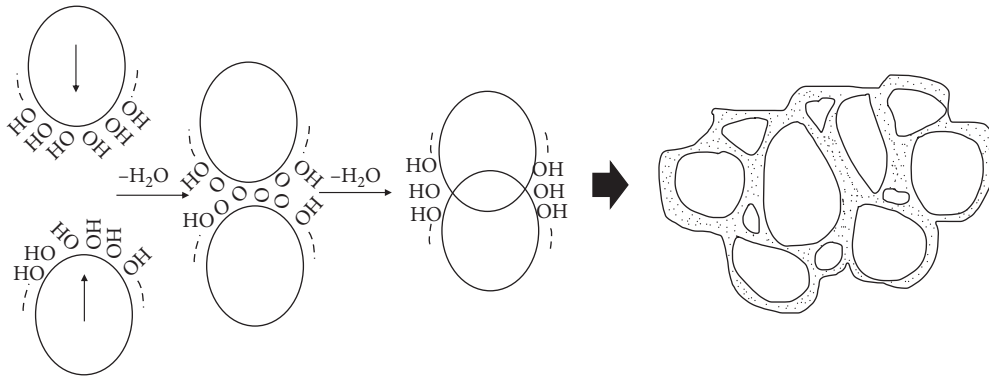


FIGURE 6: Adhesive strength forming process.

TABLE 4: The basic indicators of sodium silicate solution.

| Baume degree (°Bé) | Na ₂ O (%) | SiO ₂ (%) | Modulus (<i>M</i>) |
|--------------------|-----------------------|----------------------|----------------------|
| 39 | 8.2 | 26 | 3.1 |

For recycled concrete aggregate, its water absorption rate and crushing value, respectively, decrease 1.21% and 1.5% when soaking from 0 to 10 h; for recycled brick aggregate, these two indexes decrease 3.99% and 4.6%. When the concentration is 8% and 12%, the higher the concentration of the sodium silicate solution, the more intense the reaction with the mortar on the surface of the RA, and more C-S-H gel will also be produced. Therefore, the water absorption rate and crushing value reach the maximum in the 5 h of strengthening time. As strengthening time increases, the sodium silicate solution will form a coating on the surface of the RCA and the layer thickness gradually increases, which in turn causes the decrease of its strength [44]. In terms of water absorption rate, it is when the concentration is 8% and strengthening is five hours that the value reaches the minimum. The crushing value associated with 12% sodium silicate solution is slightly lower than that of 8%. But at 12%, the crushing value is more sensitive. With the increase of strengthening time, its value decreases.

3.3. Titanate Coupling Agent. The titanate coupling agent used in this experiment was TM-200S. The mechanism of titanate coupling agent has always been an issue to research. There are many coupling theories about the coupling agent [45–47]. The principle of chemical bond is the most traditional and classical theory in the theory of coupling between the titanate coupling agent and inorganic filler [48]. It was proposed that titanium-derived coupling agents react with free protons at the inorganic interface to form organic monomolecular layers on the inorganic surface. The compatibilization of the inorganic/organic phase resulted in new composite property, catalysis, adhesion, and rheology performance. Its structural composition and action mechanism are shown in Figures 8 and 9.

In this figure, $1 \leq M \leq 4$, $M + N \leq 6$; R is short chain alkane group; R' is long chain alkane group; X is C, N, P, S, etc.; Y is group of hydroxy, amino, epoxy, double bond, etc.

To carry out the experiments, 2 kg of 10 mm and 20 mm recycled brick aggregate and recycled concrete aggregate was poured into titanate coupling agent solution (1%, 2%, and 3%). The soaking time was 1 h, 2 h, 3 h, 4 h, and 5 h. After reaching the specific strengthening time, they were taken out and dried indoors. Finally, the water absorption rate and crushing value were measured according to the method in the specification. The results are shown in Figure 10.

It can be seen from Figure 10 that as the strengthening time increases, the water absorption rate and crushing value of the RCA also gradually decrease. The water absorption rate and crushing value rapidly decrease within 1–3 h of strengthening time. After 3 h, the water content and crush value tend to be stable. As the concentration of the titanate coupling agent increases from 1% to 2%, a hydrophobic layer can be formed on the surface of the RCA after the hydrolysis of the coupling agent. The number of pores on the surface of the aggregate decreases, thus strengthening RCA. By chemical reaction with the inorganic filler, the surface of the filler is coupled and cross-linked with the polymer matrix to combine two substances with different properties. It can form a monomolecular covering film on the surface of the filler, which contributes to improving its inherent hydrophilic properties and preventing moisture from entering into the aggregate. Lu et al. [49] also applied this principle to the surface modification of microfibrillated cellulose. The optimal concentration of the titanate coupling agent is determined by the RCA particle size and conditions of the surface functional group. The finer the filler particle size and the larger the surface area, the greater the amount of coupling agent used. When the strengthening time is 4 h and the concentration of titanate coupling agent is 2%, the effect of enhancement is the best.

By comprehensive comparison, the best working conditions of each strengthening methods are listed as follows:

- (1) Method 1: colliding with 12 steel balls and spinning 100r in the LA abrasion tester
- (2) Method 2: strengthening by 8% sodium silicate solution for 5 h
- (3) Method 3: strengthening with a 2% titanate coupling agent solution for 4 h

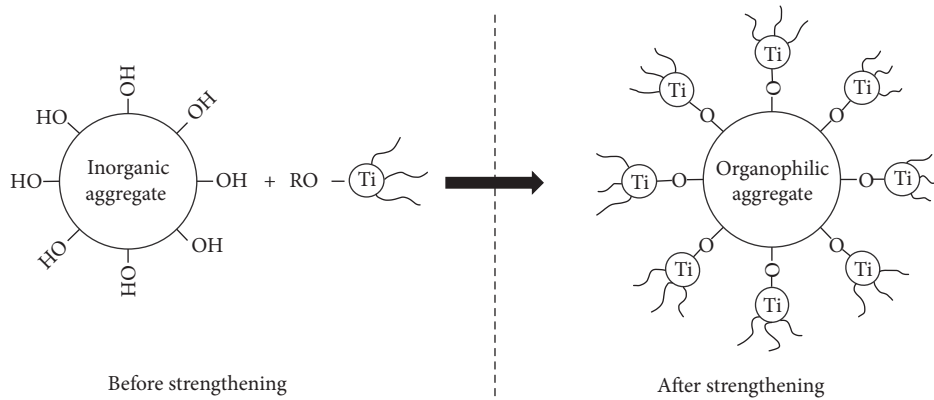


FIGURE 9: Mechanism of titanate coupling agent.

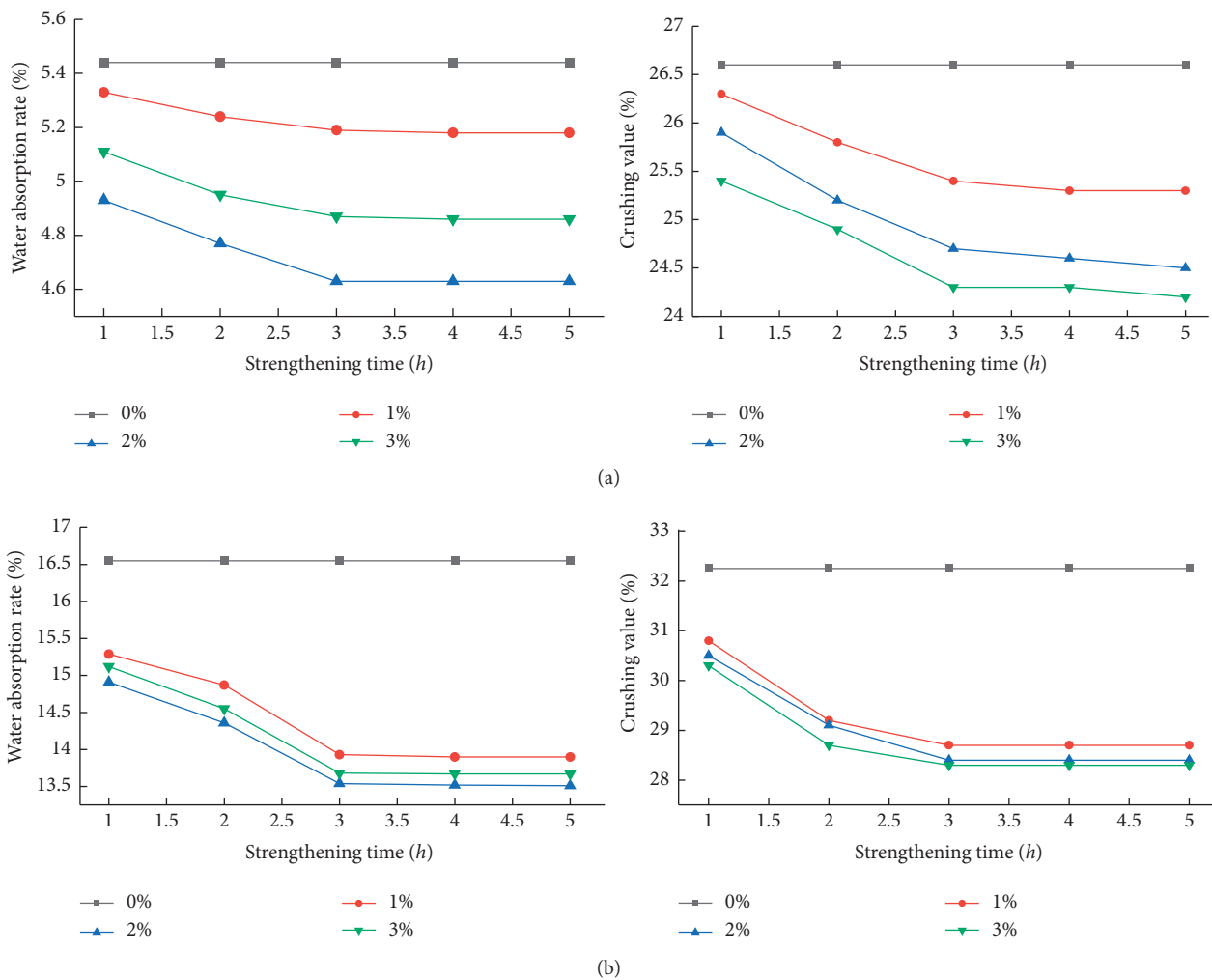


FIGURE 10: Results of titanate coupling agent. (a) Recycled concrete aggregate. (b) Recycled brick aggregate.

Moreover, when the cement dosage is 4% and the age is 7 d, the unconfined compressive strength corresponding to the 25% RCA content is the maximum, 4.16 MPa. Compared with the 90 d unconfined compressive strength of cement stabilized natural mixture, that parameter related to CSR increases by 5.33% in the

25% of RCA content, while it decreases by 10.22%, 14.89%, and 19.33% under the condition of 50%, 75%, and 100% RCA content, respectively. Studies have shown that old mortar is contained in a suitable content of RCA. And its rough surface makes benefits to the binding of aggregates and cement. For the cement dosage of 4%,

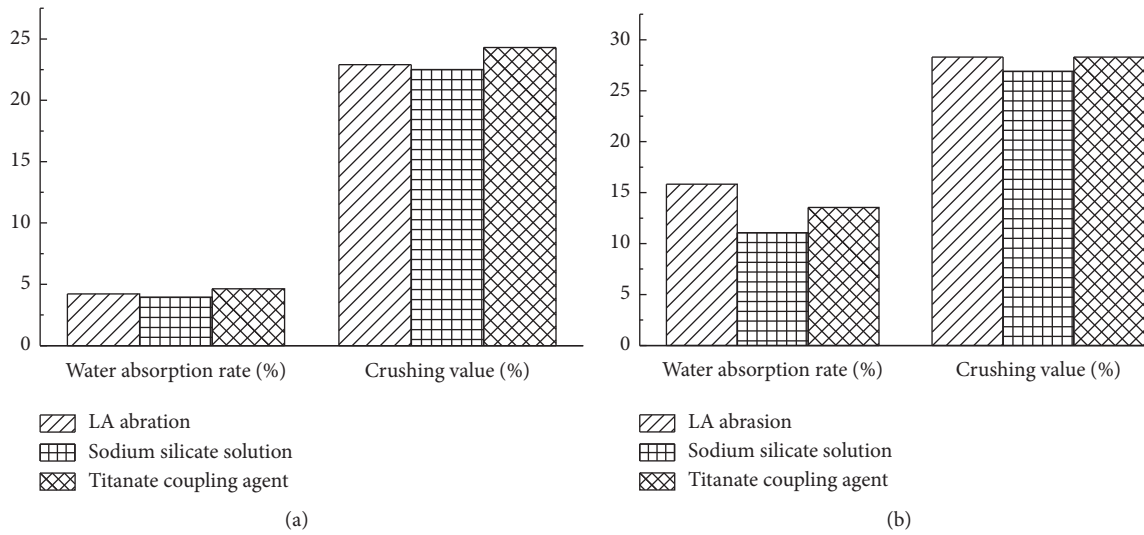


FIGURE 11: Comparison of three strengthening methods. (a) Recycled concrete aggregate. (b) Recycled brick aggregate.

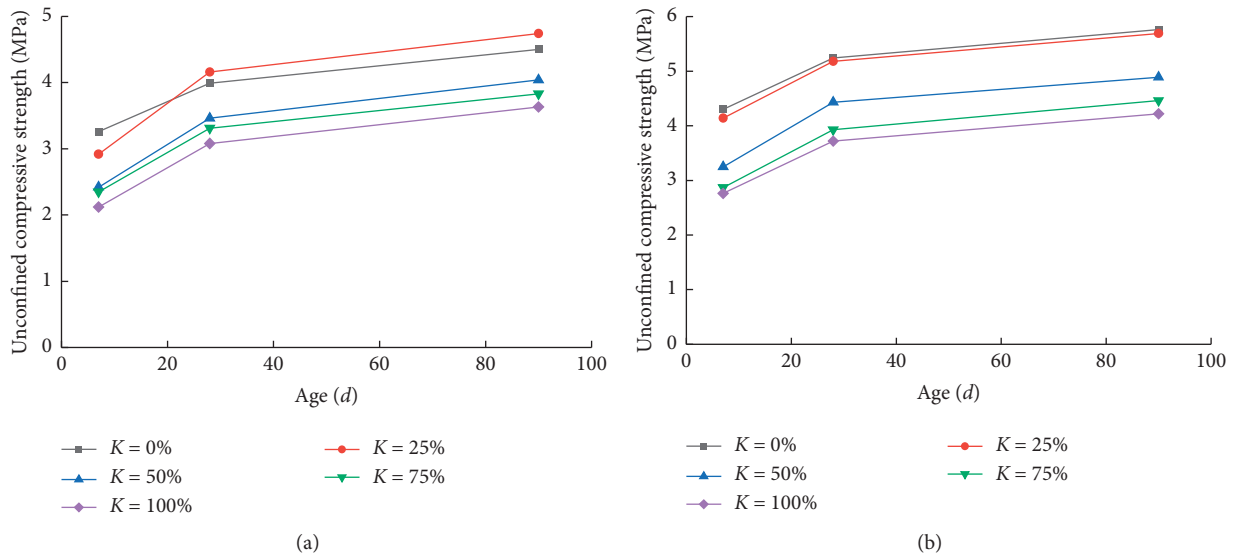


FIGURE 12: Unconfined compressive strength of CSRMs at different cement dosages. (a) 4% and (b) 5%.

when the curing age is 28 d and 90 d, the unconfined compressive strength of the CSRMs firstly increases and then decreases with the increase of the RCA content. As the curing age grows, there is some unreleased bound water in the RCA. The water is released to promote the progress of hydration. When the content of RCA exceeds a certain limit, the mechanical properties of CSRMs deteriorate. Some studies also obtained the same conclusion from the perspective of microanalysis and macro-performance [42, 51]. Unlike the trend of unconfined compressive strength in cement dosage of 4%, the strength of the mixture decreases with the cement dosage of 5% when the RCA content increases. As the cement dosage increases, the disadvantage of low strength with RCA becomes more and more obvious, which makes the overall strength of the CSRMs decrease.

4.2. *Splitting Strength.* The results of the splitting tests are shown in Figure 13.

It can be seen from Figure 13 that the changing trend of the splitting strength of CSRMs is roughly the same as that of unconfined compressive strength. This fact is because the splitting strength under the same material has a certain correlation with the unconfined compressive strength. At a cement dosage of 4%, the splitting strength increases firstly and then decreases with the increase of RCA content. The maximum splitting strength appears at 25% of the RCA content in all ages. At a certain content of RCA, the characteristics of the old mortar attached to the RCA and its rough surface play a greater advantage than the shortcomings of its strength. When exceeding this ratio, as the RCA content increases, the splitting strength decreases. Compared with the 90 d splitting strength of cement stabilized natural mixture, its value decreases by 5.36%, 16.07%, and 26.79% under

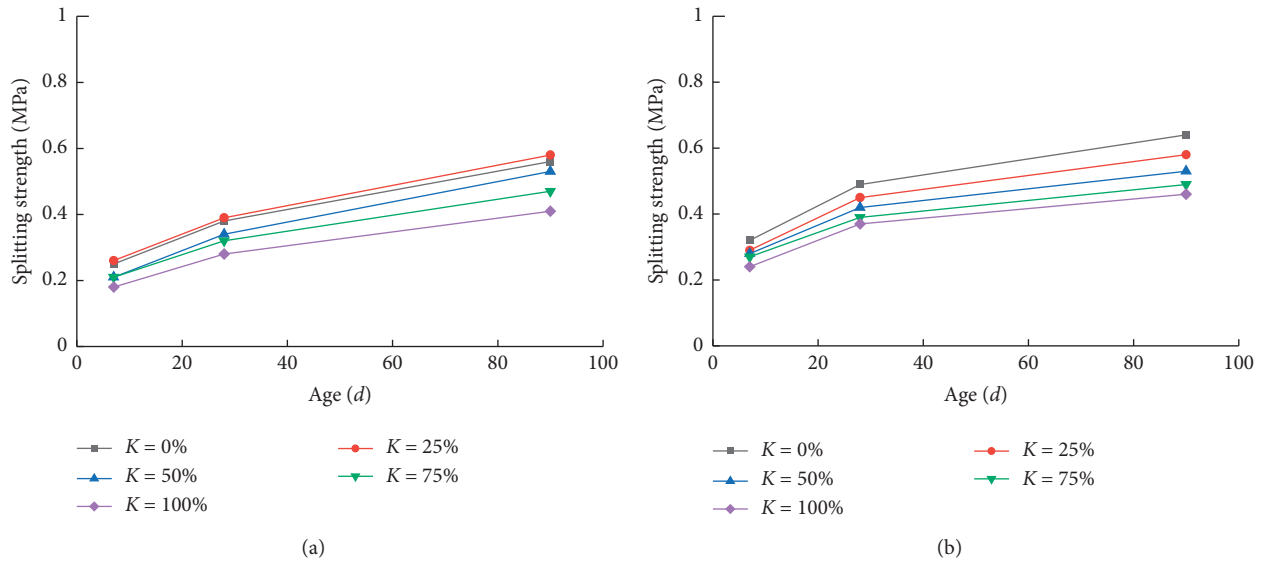


FIGURE 13: Splitting strength of CSRMs at different cement dosage. (a) 4% and (b) 5%.

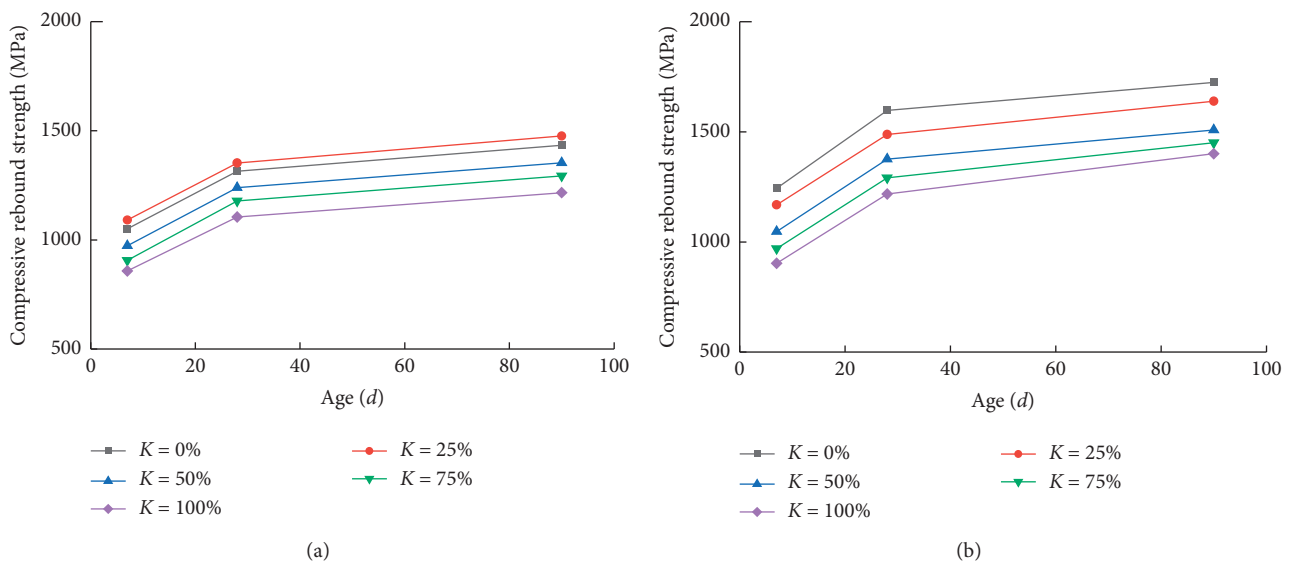


FIGURE 14: Compressive rebound strength of CSRMs at different cement dosage. (a) 4% and (b) 5%.

the condition of 50%, 75%, and 100% of RCA content. When the cement dosage is 5%, as the RCA content increases, the strength of the mixture gradually decreases, which is caused by the defects of its strength. The 90 d average strength of CSRMs with a 5% cement dosage is 0.622 MPa, which is 0.112 MPa higher than that of 4% cement dosage, while the 7 d average strength with 5% cement dosage is only 0.06 MPa larger than that of 4%. As the curing age increases, the advantage in the strength of the high cement dosage is gradually revealed.

4.3. *Compressive Rebound Modulus.* The results of the compressive rebound modulus tests are shown in Figure 14.

It can be noticed from Figure 14 that the change law of the compressive rebound modulus is the same as the two

mechanical properties measured before. Compared with the 5% cement dosage, the strength is lower at the 4% cement dosage. Taking the cement stabilized natural mixture as an example, the 90 d compressive rebound strength of 5% cement dosage is 291.67 MPa greater than that of 4%. At 5% cement dosage, the 7 d unconfined compressive strength satisfies the requirements of the expressway base layer under heavy traffic load. Except for the 0% and 25% of RCA content, the value of splitting strength and compressive rebound modulus of 4% of cement dosage fail to meet the requirements of China standard “*Highway Asphalt Pavement Design Criterion*” [52] in the other content. In the existing research, there is no scientific basis to support the use of RCA to replace 100% of natural aggregates in the pavement base layer.

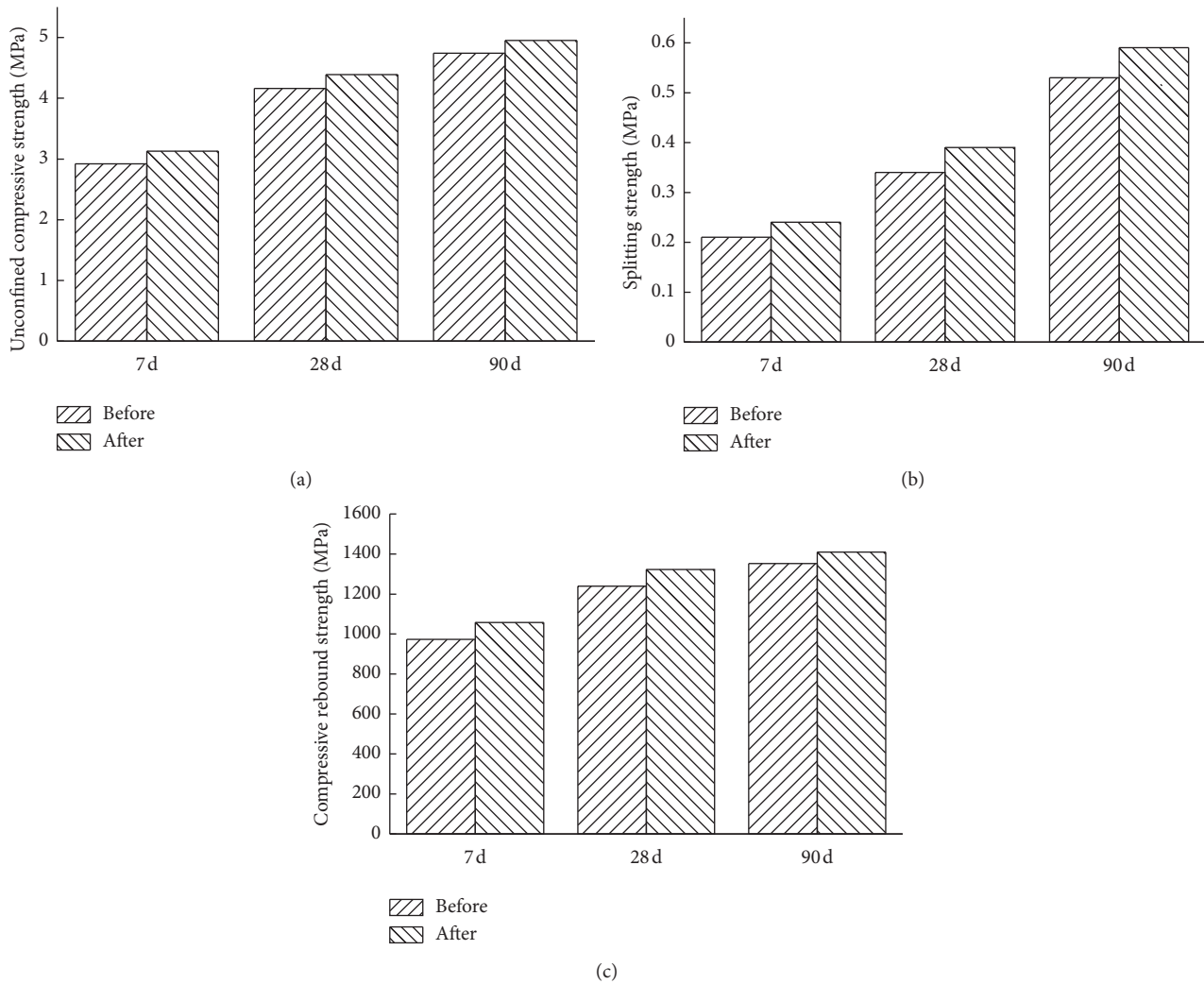


FIGURE 15: Mechanical performance results under 50% of RCA content. (a) Unconfined compressive strength. (b) Splitting strength. (c) Compressive rebound modulus.

Therefore, in this paper, the CSRMs with two different RCA contents (50%, 75%) at 4% cement dosage were strengthened.

4.4. Comprehensive Evaluation. As can be seen from the strengthening method section in this study, 8% sodium silicate solution and strengthening for 5 h are the best strengthening method. Firstly, by strengthening the RCA and then comparing the mechanical properties of CSRMs with 50% and 75% RCA contents, the range of the RCA content strengthening with sodium silicate solution was recommended. The unconfined compressive strength, splitting strength, and compressive rebound modulus were measured at 50% RCA content before and after strengthening. The results are shown in Figure 15.

It can be seen from Figure 15 that the unconfined compressive strength of 7 d after strengthening increases from 2.92 MPa to 3.13 MPa, which represents an increase of 7.19%. The splitting strength of 7 d increases from 0.21 MPa

to 0.24 MPa. It means an increase of 14.29%. The compressive rebound modulus of 7 d increases from 973.06 MPa to 1058.39 MPa. In this case, the parameter increases by 8.77%. According to the standard [52], the strength of CSRMs with 50% RCA content after strengthening can meet the requirements of the subbase for expressways and first-class highways.

The results of the mechanical performance of CSRMs at 75% content of RA are shown in Figure 16.

It can be seen from Figure 16 that the 7 d unconfined compressive strength after strengthening increases from 2.12 MPa to 2.69 MPa, which represents an increase of 26.89%. The splitting strength of 7 d increases from 0.18 MPa to 0.22 MPa. It means an increase of 22.22%. The compressive rebound modulus of 7 d increases from 857.31 MPa to 947.32 MPa. In this case, it increased by 10.5%. The reason for its strength improvement is that the sodium silicate solution fills some pores on the surface of the RCA. It can be clearly seen that the mechanical properties of the CSRMs in 100% RCA content have been greatly improved, especially reflected in the

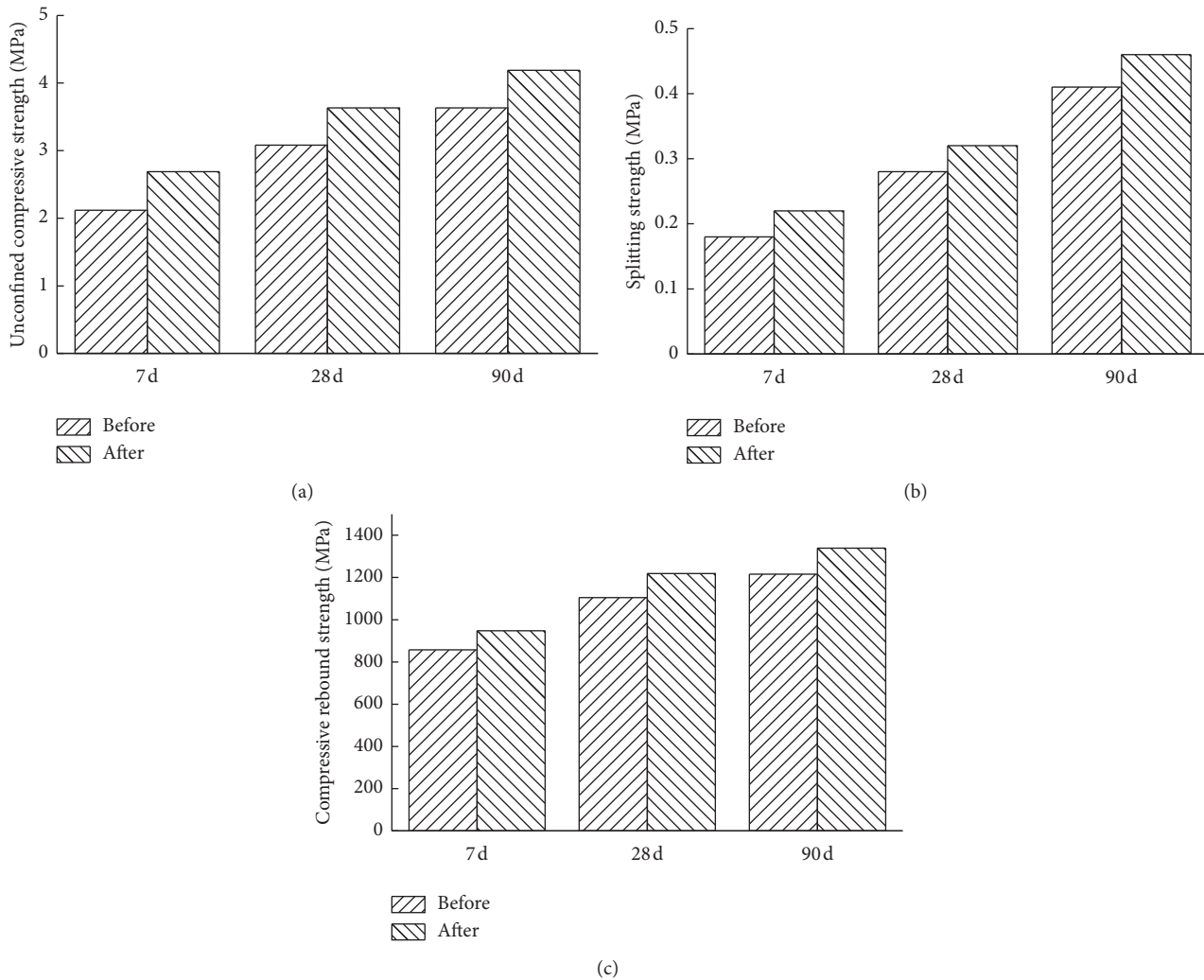


FIGURE 16: Mechanical performance results under 75% of RCA content. (a) Unconfined compressive strength. (b) Splitting strength. (c) Compressive rebound modulus.

unconfined compressive strength and splitting strength. These two mechanical performance indexes increase by more than 20%. The 7 d unconfined strength has also met the requirements of the subbase for second-class highway subjected to heavy traffic in China specification “*Highway Asphalt Pavement Design Criterion*” [52].

5. Conclusions

As a promising material in the pavement base, RCA play an increasingly significant role in the consumption of C&D waste and promoting sustainability of the construction industry. In this study, laboratory experiments were carried out to study the effect of different strengthening methods on RCA and mechanical properties of CSRMs. The following conclusions can be summarized from the previous findings and observation:

- (1) Compared with natural aggregates, the RCA has a higher water absorption rate, a smaller apparent

density, and a larger crushing value. Especially for recycled brick aggregate, its water absorption rate is dozens of times of natural aggregate.

- (2) Comparing the water absorption rate and crushing value before and after strengthening, the best strengthening way is obtained among different working conditions of the three strengthening methods. The sodium silicate solution is the best method in a strengthening concentration of 8% and strengthening duration of five hours.
- (3) When the cement dosage is 4%, with the increase of the RCA content, the unconfined compressive strength, splitting strength, and compressive rebound modulus of the CSRMs firstly increase and then decrease. When the RCA content is 25%, the mechanical properties of CSRMs are the best. It can meet the strength requirements of the base and subbase layer of highway and first-class expressway. When the cement dosage is 5%, all these mechanical

properties all show a decreasing trend when the RCA content increases.

- (4) Strengthening treatment was carried out for CSRMs at 4% of the cement dosage. When it comes to 50% and 75% RCA content, the mixture does not meet the requirements of the specifications. By comparing the value of the three mechanical properties before and after strengthening, it was found that the strength growth rate of the 75% CSRMs after strengthening is significantly higher than that of 50%. After strengthening treatment, the strength of CSRMs with 50% RCA content has met the strength requirements of the base and subbase layer of highway and first-class expressway. The 75% of RCA content can meet the strength requirements of the subbase of second-class highways or inferior highways.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

The authors gratefully acknowledge the National Natural Science Foundation of China (51878078, 51911530215, and 51478054), the Training Program for High-level Technical Personnel in Transportation Industry (2018-025), the Excellent Youth Foundation of Natural Science Foundation of Hunan Province (2018JJ1026), and the Key Project of Education Department of Hunan Province (17A008). This work was also supported by the Key Project of Open Research Fund of National Engineering Laboratory of Highway Maintenance Technology (kfj150103) and the Graduate Research Innovation Project of Hunan Province (CX20190644).

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