Investigating the Effects of Recycled Micropowder and Aggregate on the Properties of Cement Stabilization of Crushed Aggregate (CSCA)

Miaoyi Deng,1 Xiangbing Xie,1 Kaiwei Wang,1 Mingwei Wang,1 Jinggan Shao,2 Zi Yun Li,3 and Hui Wang4

1School of Civil Engineering and Architecture, Zhengzhou University of Aeronautics, Zhengzhou, Henan 450046, China
2Henan College of Transportation Engineering Technology Group Co., Ltd., Green High-Performance Material Application Technology Transportation Industry R&D Center, Zhengzhou 450018, Henan, China
3Zhengzhou Lutong Highway Construction Co., Ltd., Zhengzhou, China
4Zhengzhou Road & Bridge Construction Investment Group Co., Ltd., Zhengzhou 450007, China

Correspondence should be addressed to Xiangbing Xie; xiexiangbing.good@163.com

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The recycled powder produced in the process of crushing concrete and brick waste (C&BW) into recycled aggregate will cause environmental pollution. To realize the green full recycling of concrete and brick waste, the cement stabilization of crushed aggregate (CSCA) containing recycled brick-concrete composite micropowder (RBCP) and recycled brick-concrete composite aggregate (RBCA) is proposed. In this paper, RBCP, recycled brick-concrete composite fine aggregate (RBCCA), and recycled brick-concrete composite coarse aggregate (RBCCA) were the recycled materials from C&BW. The orthogonal test table was used to analyze the effects of the three recycled materials on the compaction characteristics, mechanical properties, and shrinkage behavior of CSCA at different dosages. The effects of RBCP, RBCCA, and RBCCA on the properties of CSCA are studied by variance analysis methods. On this basis, the micromorphology and the interface transition zone (ITZ) were studied for CSCA and the cement stabilization of crushed aggregate with RBCP, RBCCA, and RBCCA through scanning electron microscopy with energy dispersive spectroscopy (SEM/EDS), and the mechanism was revealed. The results indicate that the addition of RBCCA and RBCCA can increase the optimal water content while decreasing the optimal dry density of CSCA, and the influence of RBCCA on the optimal water content is greater than that of RBCCA. Three optimal composite replacement systems for CSCA, including 20% RBCP/20%RBCCA/40%RBCCA, are proposed and have the best mechanical and antishrinkage performance through the range analysis. Furthermore, the variance analysis test results show that RBCCA and RBCCA have the most significant effect on the compressive strength and shrinkage strain properties, while RBCCA has the most significant effect on the bending tensile strength. It is found that RBCCA played a filling effect and pozzolanic activity in the strength formation of CSCA. The SEM/EDS test shows that the CSCA with recycled materials produced the Ca/Si ratio in the interfacial zone between the cement paste and aggregate lower than the CSCA without recycled materials, the largest decline 52.83%. The research results of this paper can provide the potential application of RBCP and RBCCA.

1. Introduction

Since 2014, the total amount of construction and demolition waste (C&DW) produced in China has been estimated to be about 1.55~2.4 billion tons. Concrete and brick waste possesses one of the highest shares and accounts for about 85% of the total of C&DW [1]. Seeking the “recycling of (C&DW)” has become the most effective environmental protection method. The semirigid base is used as a structural bearing stratum in the road with an
inorganic binder, compared with the flexible road that adopts the granular material as road construction layer, with the advantage of high strength, carrying capacity, good wholeness, and rigidity, accounting for more than 85% of the road base engineering in China [2]. Fly ash, as a by-product of coal-fired power stations, causes significant economic and environmental problems. However, adding some fly ash into CSCA can effectively promote hydration and improve interface adhesion and later strength to realize the first leap of turning industrial solid wastes into treasures [3]. Furthermore, the addition of recycled brick-concrete composite micropowder (RBCP) and recycled brick-concrete composite aggregate (RBCA) in CSCA is used to replace a part of cement and natural aggregate, respectively, which not only makes the effective use of concrete and brick waste (C&BW) but also meets the requirements of green development strategy. Take a second-class highway with a thickness of 20 cm for road base as an example. 1728 m$^3$/km recycled aggregate can be used for cement-stabilized materials (CSCA). Therefore, it is of great theoretical and engineering significance to carry out the research on CSCA containing RBCP and RBCA.

C&BW can be crushed into RBCA, which is then applied in road engineering based on its mechanical and physical-chemical properties. During the recycling process, a large amount of waste powder (WP), as a by-product, is produced [3]. The effective use of WP as a partial substitute for Portland cement can significantly reduce the number of C&DW particles that eventually enter the landfill, reduce the upstream impact of concrete, including its carbon footprint, and reduce the need for exploiting the natural resources required for cement production. However, the particle size of WP is more significant than that of cement and fly ash. Furthermore, the standard Chinese GB1596 (2015) specifies a minimum cumulative content of 88% for particles sized less than 45 μm in class I powders. Compared with fly ash and cement, the application of WP produced by current technology is limited. The main reason is that its performance is poor, and its particle size is large. Therefore, many researchers began to study the preparation of more delicate recycled powder[4–6]. In recent years, with the increasing engineering demand, the method of developing auxiliary cementitious materials has been widely concerned. Standard methods include the thermal process, physical form, chemical method, etc [6, 7]. Because of its fineness and potential reactivity, a lot of pure and application-oriented fundamental research was conducted to scientifically and technologically support RBCP to replace partial Portland cement as a road base in recent years [4, 7, 8]. In an investigation by Xiao et al. [9], after recycled concrete micropowder replaces the part of Portland cement, it could promote hydration reaction. The mechanical property test shows that the optimal proportion of recycled micropowder instead of Portland cement is 15%–30%. Similar to recycled concrete micropowder, the recycled brick powder is also used as a supplement in road bases because of its pozzolanic effect [6]. In recent research [10], different types of clay bricks from European countries were collected and then ground into powder to replace the cement. It is found that the recycled brick powder can effectively improve cement paste’s sulfate resistance, refine cement paste’s structure, reduce permeability, and improve the characteristics of calcium silicate gel [11–13]. Therefore, an environment-friendly way is to use RBCP the same as fly ash to replace cement-based materials and be widely used in road engineering.

After the removal of plastic and organic materials, (C&DW) is mainly composed of concrete and clay brick, which are prepared into a recycled aggregate by the jaw crusher mechanism, and then, it is reused in the building according to its mechanical and chemical properties [14]. Recycled aggregate mainly includes recycled coarse aggregate and recycled fine aggregate. Many scholars have conducted a lot of research on a recycled coarse aggregate and the effect of the properties of concrete. Krizek and Krizek [15] and Akentuna [16] adopted the physical reinforcement technology to improve the properties of recycled aggregate. They analyzed the fatigue performance of recycled aggregate replaced part of natural aggregate in CSCA under repeated load. The results confirmed the feasibility of the recycled aggregate replacing a part of the natural aggregate [15]. Moreover, it is also found that recycled concrete aggregate can be used as granular base materials in road engineering [16]. De Brito and De Brito [17] and Fan et al. [18] studied the effect of the replacement rate of recycled fine aggregate (concrete and brick) on the mechanical properties of recycled concrete. When the replacement rate of brick reclaimed fine total does not exceed 25%, the compressive strength decreases by only 4%, and the tensile strength and elastic modulus decrease significantly. Bui et al. [19] and Thomas et al. [20] found that with the increase in the replacement rate of recycled coarse aggregate, the compressive strength of recycled concrete decreases, and the changing trend of the elastic modulus is similar to the compressive strength, while the splitting tensile strength is the most sensitive to the change of the replacement rate. Combined with the mechanical property test results, it is recommended that the replacement rate of the recycled coarse aggregate should not exceed 30%. Sri Ravindrarajah et al. [21] obtained from the test that the shrinkage deformation of recycled coarse and fine aggregate double replacement concrete is significantly greater than that of ordinary concrete and increases with the replacement rate. The decrease in the durability of recycled coarse and fine aggregate dual replacement concrete is mainly because of more cracks in recycled aggregate production and the increase in interface transition zone caused by old mortar, which eventually leads to an increase in concrete porosity and a decrease in durability. Wang et al. [22–24] proposed that 7% to 25% of the total drying shrinkage and all (or most of) the autogenous shrinkage can be compensated by adding 5% to 10% MgO in face slab concrete. In a word, the mechanical properties and durability of recycled coarse aggregate concrete and recycled fine aggregate concrete decrease with the increase in recycled aggregate replacement rate. However, there are few research results on the influence of recycled brick-concrete coarse aggregate (RBBCA) and recycled brick-
concrete fine aggregate (RBCFA) on the performance of cement stabilization of the crushed aggregate (CSRA) mixture.

As the transition material between asphalt pavement and soil subgrade, CSCA has lower requirements on aggregate performance than structural concrete, especially the pavement base. Du et al. [25] used coarse brick aggregate to replace the natural aggregate to prepare concrete. The results show that when the replacement rate is less than 20%, the mechanical properties of brick aggregate concrete have no apparent downward trend. In comparison, when the replacement rate is 50% or more, the mechanical properties of brick aggregate concrete significantly decrease. If the application of recycled brick aggregate in CSCA can be realized, the resource utilization of recycled brick aggregate will be substantially expanded. Therefore, if the proportion of the recycled clay brick aggregate in the cement stabilization of the recycled aggregate mixture is well-controlled, the performance of the road base is not significantly compromised. Many scholars have conducted a lot of research on the performance of brick-concrete recycled coarse aggregate, especially the impact of the content of clay brick on the performance of recycled materials. Xu et al. [26] showed that the essential performance of brick-concrete recycled aggregate presents a deterioration trend with the increase of the proportion of clay brick. Xia et al. [27] studied the road performance of the cement stabilization of brick-concrete recycled aggregate base. They analyzed the interface transition zones (ITZs) of clay brick, concrete, and natural aggregate, respectively, by SEM and industrial CT. The feasibility of brick-concrete recycled aggregate as a semirigid base material is proved. Yuan et al. and Zhang et al. [28, 29] studied the influence of recycled brick aggregate on the properties of brick-concrete recycled aggregate. The results show that with the increase of recycled brick aggregate content, the crushing value index and water absorption of the mixed recycled aggregate gradually increase, and the apparent density gradually decreases. The research of Zhang et al. [30] shows that the recycled concrete prepared with 30% brick-concrete recycled coarse aggregate has the best mechanical properties. Liu et al. [31] used brick recycled aggregate to prepare sublightweight concrete, in which the strength of recycled aggregate is the critical factor affecting mechanical properties. Cai et al. [32] showed that the recycled coarse aggregate could be used for the highway base, and the optimal water content of the cement-stabilized recycled crushed stone mixture is high. Wu et al. [33] studied the mechanical properties of the asphalt pavement with a cement-stabilized recycled brick-concrete base. With the increase of recycled aggregate content, the road surface deflection decreases first and then increases, and the tensile stress at the bottom of the ground rises first and then decreases. Zou et al. [34] studied the road performance of cement-stabilized recycled aggregate mixture and proposed that the maximum content of recycled coarse aggregate in cement fly ash stabilized recycled base can reach 80%.

Therefore, the recycled concrete powder, brick powder, and recycled aggregate can be used in road engineering bases. At the same time, RBCP and RBCA are less-studied on road bases, and the strength of cement stabilization recycled aggregate (CSRA) is the critical factor affecting its road performance. The compressive strength and flexural tensile strength at different ages are the key indexes to evaluate the road performance, and the dry shrinkage performance is the crucial factor affecting the durability of the cement stabilization of the recycled aggregate base. In the present work, the influence of the content of RBCP and RBCA on the mechanical properties and shrinkage properties of CSRA is studied using an orthogonal test. Furthermore, scanning electronic microscopy with energy dispersive spectroscopy (SEM/EDS) was used to interpret further the mechanism underlying the observed improvement. It is expected to promote the recycling of RBCP and RBCA in road engineering.

2. Materials and Experimental Details

2.1. Materials. C&BW used to prepare RBCP and RBCA was collected from the demolition of the 50-year-old factory districts located in Er-qi town in Zhengzhou, Henan Province. This waste consisted of clay brick, concrete, ceramics, and so on. Ordinary Portland cement 42.5 was prepared according to the standard Chinese GB175-2007, and tap water (temperature∼20°C) was used in the experiments. Recycled brick and concrete powder (RBCP) is produced by processing the original waste clay brick and concrete through a three-stage process. In the first stage, a crusher is used to reduce the size of waste brick and concrete to fine particles that are below 10 mm, which obtain particles with different particle sizes through a vibrating screen and can be categorized as RBCCA. In the second stage, the output of stage one is then fed into a ball grinding mill with a circular cavity to produce fine aggregates with a maximum size of 2.36 mm, which can be categorized as RBCFA. The output of stage two is then fed into an electromagnetic sample pulverizer to produce fine powders with a maximum size of 45μm, which can be categorized as RBCP. Figure 1 describes the preparation method of RBCP and RBCA through the deep processing of C&BW. The total processing time includes crushing and sieving, and the grinding duration is about 6–8 minutes. The notable characteristic of RBCP is its higher fineness and more active pozzolanic material, whose particle size is usually less than 45μm [5].

2.2. Experimental Design. To investigate the evolution law of these different particles’ sizes and content with recycled materials on the mechanical and dry shrinkage properties of CSCA with recycled materials, RBPC, RBPCA (2.36–4.75 mm), and RBCCA (4.75–9.5) are selected as three factors while ensuring that the amount of aggregate with other particle sizes remains unchanged. To maximize the use of brick aggregate, the mixed recycled coarse aggregate and mixed recycled fine aggregate are prepared, and the mass ratio of the recycled brick to the concrete is 3:2, according to the previous research results [4, 7, 35]. The mixed recycled micropowder is composed of brick powder, concrete
powder, and fly ash with a mass ratio of 3:2:5 and added 3% activator Na$_2$SO$_4$ [8, 35]. According to the current research results [28–31], RBCP content is selected as 20%, 40%, and 60%, and the RBCA content is 20%, 40%, and 60% for the orthogonal test. The sample without recycled materials is named as a reference specimen, which is denoted as JZ. This experimental scheme is shown in Table 1. RBCP, RBCFA, and RBCCA are shown in Figure 2. Particle size distributions and cumulative quantity curves for RBCP and cement are demonstrated in Figure 3. Compared with cement, RBCP particles are coarse and evenly distributed. The median particle size, surface area average particle size, and volume average particle size of brick powder are 12.639 $\mu$m, 3.900 $\mu$m, and 20.600 $\mu$m, respectively. Based on the characteristics of various structural types of semirigid base materials (dense suspension type, skeleton void type, and dense skeleton) and combined with the characteristics of the recycled aggregate of construction waste, to ensure the performance requirements, such as the structural strength of the base, the cement-stabilized macadam base for the test adopts the dense skeleton structure.

2.3. Test Method. According to the optimum water content determined through the compaction test, the cement-stabilized recycled gravel specimen was formed by the static-pressure method. The 7d unconfined compressive strength and 90d flexural tensile strength of the analyzed cement-stabilized recycled gravel samples were measured according to JTG/E51-2009 [36], respectively. Uniaxial compressive and flexural tensile loads were applied at a displacement rate of 1 mm/min and 50 mm/min separately until the specimens failed. At least a dozen specimens were tested for each scenario for a specific curing age, and the averages over these three replicates were calculated. In addition, the size of the prism specimen was (100 $\times$ 100 $\times$ 400 mm$^3$), and the size of the cylinder specimen was 80 mm $\times$ 100 mm.

In this study, the dry-shrinkage experiment was carried out according to the Chinese standard JTG E51-2009 using 100 $\times$ 100 $\times$ 400 mm$^3$ prism, and the dry-shrinkage strain ($\xi_i$) value was calculated by equations (1) and (2). All the samples were subjected to a specific testing environment specified by the code, following a constant temperature of around 20°C ± 1°C and a constant relative humidity (RH) of 60% ± 5%. After being kept in this test environment for 28d, the dry-shrinkage characteristics specified by the code were measured using a dial gauge.

$$\delta_i = \frac{\sum_{j=1}^{4} x_{27,j} - \sum_{j=1}^{4} x_{28,j}}{2}$$  

$$\xi_i = \frac{\delta_i}{l}$$

where $l$ is the original length of the sample, $x_{28,j}$ represents the data of the j dial gauge at the 28th test, and $\delta_i$ is the value of dry shrinkage at the 28th observation.

To ensure the accuracy and reliability of the test results, the number of specimens in each group of unconfined compressive strength test is 9, the number of samples in each group of flexural tensile strength test is 12, and the number of specimens in each group of dry shrinkage test is 6.

2.4. Micromorhology Characterization. Scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were used to study the micromorphology and interface transition zone (ITZ) structure of RBCP with
cement-stabilized RBCA. The SEM sample preparation and observation process are as follows: take out about three cubes (1 cm × 1 cm × 1 cm) from the center of the cement stabilization of crushed aggregate (CSCA) sample and the cement stabilization of crushed aggregate containing recycled materials (CSRA) sample, CSCA sample, and CSRA samples after the 90d flexural tensile strength test. These cubes were put in anhydrous ethanol to stop hydration and dried in an electric heating blast drying oven at 60°C. After cooling, the above samples are gold-coated through the particular machine, and then imaging from the section of these samples is performed by SEM.

3. Results and Discussion

3.1. Compaction Characteristics Analysis. According to the dates of the compaction experiment, the relationship of all samples among the optimum water content and maximum dry density can be obtained. The relationship curve of all samples between water content and dry density is shown in Figure 4. The results in Figure 4 reveal that the dry density of CSCA contained with RBCP and RBCA is less than that of the JZ sample (without recycled materials), and the optimal water content range of these samples gradually increases with the addition of recycled materials, especially the change range of the BZ3 selection (RBCP-20%, RBCFA-100%, and RBCCA-100%) is the most significant.

The best water content and maximum dry density of all samples are shown in Table 2. Compared with the JZ sample, the optimum water content of the cement-stabilized macadam mixture increases after mixing RBCP and RBCA, mainly because recycled materials have specific water absorption, and the recycled aggregate is greater than that of natural aggregate. However, the maximum dry density decreases. In addition, the best water content of BZ3 samples is 10.58%, which is the minimum value of all experimental groups, and its dry density is 2.199, which is the minimum value of all test samples. Furthermore, compared with the BZ3 samples, the optimum water content of the BZ9 sample is reduced by 29.82% when the replacement amount of RBCP for cement is increased from 20% to 60%. The replacement amount of RBCA is reduced from 100% to 40%. The corresponding optimal water content is reduced by 41.63%. Compared with BZ3 and BZ5, the contribution of each gram of binders (RBCFA + RBCP) to water content is 0.0775. Compared with BZ3 and BZ9, the gift of each gram of coarse aggregate to water content is 0.01133. The results of the experiments indicated that the influence of binders

Figure 2: Recycled products with RBCP, RBCFA, and RBCCA.

Figure 3: Particle size distribution and cumulative volume of fine powder.
The water content of the cement-stabilized recycled macadam mixture is more significant than that of RBCFA.

3.2. Unconfined Compressive Strength. The unconfined compressive strength results of all samples are shown in Table 3. In general, a larger $R_j$ indicates a more significant factor level [37]. As presented in Table 3, the relationship of the effects of the three recycled materials on the compressive strength is $\text{RBCCA} > \text{RBCFA} > \text{RBCP}$. It is mainly because the cement-stabilized macadam mixture is a framework closed structure. The coarse aggregate plays a specific "skeleton" role in the compacted mixture, and RBCFA and RBCP are used as binders to fill the skeleton formed by RBCCA. Recycled aggregate needs to have sufficient strength and firmness in highway engineering. Crushing value and firmness index are common technical indexes to evaluate aggregate strength. Compared with the JZ specimen, the compressive strength decreases 20.88% when the RBCCA and RBCFA completely replace the natural aggregate with the same particle size. While the content of RBCP instead of cement is 60%, and the replacement content of RBCA and RBCFA is 20% and 40%. The compressive strength is 8.16 MPa, with a decrease of 10.32%. The results of the experiments show that RBCP has the role of filling and improving the composition and gradation of recycled materials.

3.3. Bending Tensile Strength. Table 4 presents the properties of bending tensile on cement-stabilized aggregate containing RBCP and RBCF after 90d curing. The bending tensile strength of all samples is lower than that of the JZ samples, with a minimum decrease of 25.26% and a maximum decrease of 59.79%. However, all samples meet the requirements of cement-stabilized aggregate. Among the three (RBCFA + RBCP) on the water content of the cement-stabilized recycled macadam mixture is more significant than that of RBCFA.
factors, the extremum difference of RBCP(A) is the largest, followed by RBCFA (B) and RBCCA (C), and the extremum difference of blank column (D) is the smallest. The greater the extremum difference, the more significant the impact of factor level change on the test results [38]. The relationship of the effects of three factors on the bending tensile properties is A > C > B. The greater the flexural tensile strength of the base course required by the specification, the better its properties [39]. To resist the flexural tensile stress under vehicle load, the optimal scheme of cement-stabilized recycled materials is A2B1C1.

3.4. Dry Shrinkage Behavior. It can be seen from Table 5 that among the dry shrinkage strain values of all samples, the values of BZ1 and BZ4 are less than those of the JZ sample, with a maximum decrease of 27.82%. In addition, the dry shrinkage strain value of BZ4 is less than BZ1. However, other samples’ dry shrinkage strain values are higher than the JZ sample, with a maximum increase of 69.75%. The dry shrinkage strain of the BZ3 sample reaches $192.425 \times 10^{-6}$. The dry shrinkage strain of the BZ1 sample is $46.989 \times 10^{-6}$, which is 75.58% less than the dry shrinkage strain of the BZ3 sample. The results indicate that RBCCA and RBCFA have a

| Table 4: Test results and calculation analysis. |
|-----------------------------------------------|
| Test number | Factor | Test results |
|--------------|--------|--------------|
| A (%) | B (%) | C (%) | D (%) | Bending tensile strength (MPa) |
| 1 | 20 | 20 | 20 | 1 | $y_1 = 2.38$ |
| 2 | 20 | 40 | 40 | 2 | $y_2 = 2.32$ |
| 3 | 20 | 100 | 100 | 3 | $y_3 = 1.91$ |
| 4 | 40 | 20 | 20 | 3 | $y_4 = 3.55$ |
| 5 | 40 | 40 | 100 | 1 | $y_5 = 3.21$ |
| 6 | 40 | 100 | 20 | 2 | $y_6 = 3.33$ |
| 7 | 60 | 20 | 100 | 2 | $y_7 = 2.06$ |
| 8 | 60 | 40 | 20 | 3 | $y_8 = 2.22$ |
| 9 | 60 | 100 | 40 | 1 | $y_9 = 2.15$ |
| $K_{ij}$ | 6.54 | 7.96 | 7.93 | 7.74 | $T = 23.13$ |
| $K_{ij}$ | 10.06 | 7.68 | 7.89 | 7.71 | $\gamma = 2.57$ |
| $K_{ij}$ | 6.40 | 7.36 | 7.18 | 7.68 | $\bar{K} = 1001.714$ |
| $K_{ij}$ | 2.203 | 2.663 | 2.643 | 2.580 |
| $K_{ij}$ | 3.636 | 2.583 | 2.673 | 2.570 |
| $K_{ij}$ | 2.143 | 2.463 | 2.393 | 2.560 |
| $R_i$ | 1.220 | 0.200 | 0.280 | 0.020 |

Relationship factor $A > C > B$

Optimized scheme $A_2C_2B_1$

| Table 5: Test results and calculation analysis. |
|-----------------------------------------------|
| Test number | Factor | Test results |
|--------------|--------|--------------|
| A (%) | B (%) | C (%) | D (%) | Shrinkage strain ($\times 10^{-6}$) |
| 1 | 20 | 20 | 20 | 1 | $y_1 = 46.989$ |
| 2 | 20 | 40 | 40 | 2 | $y_2 = 69.849$ |
| 3 | 20 | 100 | 100 | 3 | $y_3 = 192.425$ |
| 4 | 40 | 20 | 20 | 3 | $y_4 = 42.024$ |
| 5 | 40 | 40 | 100 | 1 | $y_5 = 168.895$ |
| 6 | 40 | 100 | 20 | 2 | $y_6 = 136.893$ |
| 7 | 60 | 20 | 100 | 2 | $y_7 = 119.851$ |
| 8 | 60 | 40 | 20 | 3 | $y_8 = 94.912$ |
| 9 | 60 | 100 | 40 | 1 | $y_9 = 129.876$ |
| $K_{ij}$ | 309.264 | 208.863 | 278.793 | 345.759 |
| $K_{ij}$ | 347.811 | 333.657 | 241.749 | 326.592 |
| $K_{ij}$ | 344.64 | 459.195 | 481.170 | 329.361 |
| $K_{ij}$ | 103.088 | 69.621 | 92.931 | 115.253 |
| $K_{ij}$ | 115.937 | 111.219 | 80.583 | 108.864 |
| $K_{ij}$ | 114.880 | 153.065 | 160.390 | 109.787 |
| $R_i$ | 12.849 | 83.444 | 79.807 | 6.389 |

Relationship factor $B > C > A$

Optimized scheme $B_1C_2A_2$

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| Source   | Square | df | Mean square | F   | $F_{1-0.01(2, 2)}$ | Significance |
|----------|--------|----|-------------|-----|------------------|--------------|
| **Compressive strength (MPa)** |        |    |             |     |                  |              |
| RBCP     | 0.091  | 2  | 0.0455      | 45.50| $F_{1-0.01(2, 2)} = 99.00$ | *            |
| RBCFA    | 0.221  | 2  | 0.1105      | 110.50| **               |              |
| RBCCA    | 0.854  | 2  | 0.427       | 427.00| **               |              |
| Error    | 0.002  | 2  | 0.001       |      |                  |              |
| **Bending tensile strength (MPa)** |        |    |             |     |                  |              |
| RBCP     | 5.676  | 2  | 19.905      | 189.571| **              |              |
| RBCFA    | 0.122  | 2  | 0.205       | 1.952 |                  |              |
| RBCCA    | 0.284  | 2  | 2.370       | 22.571|                  |              |
| Error    | 0.0006 | 2  | 0.105       |      |                  |              |
| **Shrinkage strain ($\times 10^{-6}$)** |        |    |             |     |                  |              |
| RBCP     | 4610.568 | 2  | 2305.284   | 32.219| *              |              |
| RBCFA    | 22888.432| 2  | 11444.216  | 159.947| **          |              |
| RBCCA    | 22144.816| 2  | 11072.408  | 154.478| **          |              |
| Error    | 143.100 | 2  | 71.55       |      |                  |              |

$F_{1-0.01(2, 2)}$ indicates the significance level of the variance analysis.

![Figure 5: SEM images of distribution of hydration products.](image)
pronounced coupling effect in the shrinkage process of the mixture sample. Furthermore, the dry shrinkage strain of the BZ5 sample is $168.895 \times 10^{-6}$, which is 12.23% lower than the BZ3 sample. The results of the experiments indicated that reducing the content of RBCFA can improve the dry shrinkage strain of cement-stabilized recycled macadam mixture.

3.5. Analysis of Variance (ANOVA). In the analysis of the variance table, if $F > F_{1-0.01}(2, 2) = 99.00$ > $F = F_{1-0.05}(2, 2) = 19.00$, the influence of factor A is significant and is recorded as “∗∗.” As presented in Table 6, the factor RBCP is highly significant for the effect of bending the tensile strength, and the factors RBCFA and RBCCA are highly influential in the influence of compressive strength and shrinkage strain. According to the relevant research results [40], the cement paste composed of RBCP and RBCFA can effectively fill the gap formed by the coarse aggregate. Therefore, the combined effect of the cement paste and RBCCA is the main reason for the drying shrinkage of the cement-stabilized macadam mixture.

Figure 6: SEM images of ITZ.
The optimal level of selection factors is related to the required indicators. The larger the indicator, the better and the largest level should be selected, namely, the most significant level in each column, $K_{1j}, K_{2j},$ and $K_{3j}$. Otherwise, the more minor the indicators, the better, and the lowest level should be selected [37]. Therefore, the optimal scheme of RBCP, RBCCA, and RBCFA in the cement-stabilized recycled aggregate is A2B1C2.

3.6. SEM Analysis

3.6.1. Micromorphology of Cement Stabilized Macadam. Micromorphology images of the studied CSCA and cement-stabilized of recycled aggregate (CSRA) are shown in Figure 5. C–S–H gel and AFm are observed in the cement-stabilized materials. The cement-stabilized aggregate has some loose and void morphology, and the interlaced connection between AFm and C–S–H gel is not sufficiently tight at 90 days, as can be seen in Figures 5(a) and 5(c). Compared with the cement-stabilized macadam, the paste with RBCP always presented a denser structure, as seen in Figure 5(b). Obviously, a layer of reticulated C–S–H gel layer is coated on the surface of the fly ash, of which the gel layer develops toward the inner surface, increasing the gel layer’s thickness with the development of hydration. In addition, because of the pozzolanic activity of RBCP, the CH content of cement pastes decreased in the later stage of cement hydration, indicating that mechanical activation could efficiently stimulate the pozzolanic activity of RBCP (see Figures 5(e) and 5(f)).

3.6.2. Microstructure/EDS of ITZ. The microstructure characterization of the interface transition zone (ITZ) is mainly microcracks and the volume of pores, which significantly affect the strength or elastic modulus of cement-stabilized materials [38, 41]. In the two-phase composite material system, the ITZ is the link between the cement mortar and coarse aggregate particles, which has an essential impact on the material’s durability. In the SEM image, the smooth and dense part is the aggregate, and the gray region is the hydration product of the cement paste, as shown in Figure 6.

It can be seen that there are some microcracks in the two samples, off which the number and width in the ITZ of the cement fly ash-stabilized macadam sample are more than those of the BZ4 sample. Obviously, there is interlocking between C–S–H gel and AFm in the microstructure of all samples, and the C–S–H gel layer is attached to the surface of the fly ash. In addition, the thickness of the surface of the fly ash is thicker, the amount of AFm is more enormous, and the CH content of the ITZ decreases because of the pozzolanic activity of RPB, as can be seen in Figure 6(b).

It can be shown from Table 7 that the ratio of Ca/Si decreases by 52.83% after adding RBCP. According to the current research results, the lower the Ca/Si ratio, the better the durability of the mixture samples, which is consistent with the mechanical properties of BZ4 samples [41, 42]. The experiments’ results indicated that the ITZ microstructure shows that the pozzolanic effect occurs between the RBCP and the cement hydration products, which improves the compactness of the interface transition zone.

4. Conclusion

The results of a comprehensive experimental study reported in this paper highlighted the viability of the entire green recycling product of concrete and brick waste for the partial replacement of Portland cement and aggregate. The mechanical and shrinkage properties of CSCA were investigated by varying the replacement percentage of RBCP, RBCCA, and RBCFA. Based on the findings of this study, the following conclusions are drawn.

(1) The optimal water content of CSCA increases, and the optimal dry density decreases with an increase in the composite of concrete and brick waste (C&BW). The mechanical properties of CSCA are found to decrease with growth in the RBCP, RBCCA, and RBCFA replacement percentage. Furthermore, RBCP and RBCCA have the most significant influence on the mechanical properties of CSCA. In addition, the impact of RBCP on 90d flexural tensile strength is much more effective than that of RBCCA.

(2) The dry-shrinkage test shows that reducing the content of RBCCA and increasing the range of RBCP could improve the dry-shrinkage strain of CSCA. The RBCCA and RBCCA had a noticeable coupling effect in the shrinkage process of the mixture sample. The appropriate addition of RBCCA could effectively improve the dry shrinkage performance of CSCA.

(3) SEM-EDS analysis was used to analyze the microstructure of CSCA containing RBCP and RBCA. The SEM-EDS test results show that RBCP could play a filling effect, gradation effect, and pozzolanic activity, which increased the interfacial transition zone density and reduced the interfacial transition zone Ca/Si ratio.

(4) The RBCP, RBCCA, and RBCFA investigated in this paper are produced using the C&BW collected in China, which commonly contains the fired brick. Considering the changes in the composition of C&BW in different regions, the effects of RBCP, RBCCA, and RBCFA replacement percentages are needed to investigate these properties of CSCA.

| Element | The paste of cement and aggregate | The paste of cement and RBCP-aggregate |
|---------|----------------------------------|---------------------------------------|
|         | Wt%  | At%   | Wt%  | At%   |
| C       | 11.40 | 18.38 | 1.18 | 2.77  |
| O       | 52.72 | 63.80 | 24.75 | 43.63 |
| Si      | 1.33  | 0.92  | 5.61 | 4.88  |
| Al      | 0.93  | 0.67  | 1.65 | 7.20  |
| Ca      | 33.61 | 16.24 | 66.88 | 47.06 |

Table 7: EDS test results of the cement-stabilized materials.
Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare they have no conflicts of interest.

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