Study of the Mechanical Properties of Alkali-Activated Solid Waste Cementitious Materials at the Interface

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ABSTRACT: The paper uses alkali-activated slag and fly ash as cementitious materials to pour and repair concrete. Their modification on the bonding surface of new and old concrete is studied. The new and old concrete composite specimens were prepared. The split tensile strength test of the new and old concrete specimens along the interface was carried out, and the test results of different alkali-stimulated slag and fly ash concrete as repair materials were compared and analyzed. The influence of activator modulus and other factors on the bond strength of new and old concrete interfaces was studied, and the law of its strength change was explored. The research results show that with the gradual increase in the amount of fly ash minerals, the splitting tensile strength presents a trend of first increasing and then decreasing. When the amount is 50%, the splitting surface partly occurs on the old concrete. It shows that the bonding effect is the best at this content; the alkali excitation modulus gradually increases, and the splitting tensile strength shows a downward trend. When the activator modulus is 1.3, more gelatinous substances can be observed in the section of the specimen. These overlap each other to form a tight material skeleton structure; a comparative analysis of the bonding strength of the new and old concrete interfaces with different interface agents and without interface agents showed that the alkali-activated solid waste cementitious material has the best repair performance and greater bonding strength when the water-to-binder ratio is 0.3.

1. INTRODUCTION

Concrete is the main building material in civil engineering. Due to the external environment such as temperature difference during use, chemical corrosion, and other factors such as its own design defects, improper maintenance, or conventional aging, the safety, stability, and durability of the structure are reduced. Therefore, it is necessary to repair and strengthen the old concrete. However, the bonding surface of the new and old concrete is the weakest link of the repaired concrete. At present, a large number of scholars are conducting research on new and old concrete repair materials. Shenghua developed two polymer mortars. Through mechanical performance tests, they found that the polymer mortar has good adhesion to old concrete and good durability. Compared with ordinary mortar, the polymer mortar has high total porosity and pores. The structure is inversely proportional to the water–binder ratio, and it has good frost resistance and impermeability. Xiaqin used different types of interface agents to conduct splitting tensile strength tests on the bonding surfaces of new and old concretes. The study showed that both cement expandable interface agents and silica fume-added interface agents can improve the tensile strength of the interface between new and old concrete. Yue et al. found that the polymer and the adhered matrix material have a good bonding effect. Also, these influence the cement hydration process to improve the cement microstructure and the mechanical properties of the mortar, and they can change the type of polymer. The bonding properties of the mortar have varying degrees of influence. Kumar et al. found that by replacing part of fly ash with slag, the two gels of C–S–H and N–A–S–H coexist under the action of alkali, which shortens the setting time to a certain extent and improves the compression resistance strength of the hydration product structure. Pacheco-Torgal et al. found that the limestone sand material and the alkali-activated cementitious material produced a gel-like aluminum silicide component in the aggregate due to the chemical action so that there was no transition zone between the aggregate and the cementitious material interface. Lee studied the chemical reaction of geopolymers on the surface of aggregates under alkaline conditions and showed that the polymerized products are tighter and stronger in the transition zone of the interface.

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Table 1. Content of Chemical Composition of Different Materials

| name    | SiO₂ | CaO  | TiO₂ | Al₂O₃ | Fe₂O₃ | MgO | K₂O | Na₂O | SO₃ | others |
|---------|------|------|------|-------|-------|-----|-----|------|-----|--------|
| fly ash | 55.25| 5.03 | 1.78 | 24.55 | 6.53  |      |     |      |     | 5.87   |
| slag    | 33.45| 36.8 | 0.34 | 14.32 | 5.39  | 8.22|    |      |     | 0.32   |
| cement  | 19.22| 64.98| 0.33 | 5.34  | 3.99  | 1.73| 0.29| 0.15 | 1.34| 3.22   |

2. TEST PLAN

2.1. Test Materials. The bonding quality of the new and old concrete interface determines the integrity and safety of the overall construction and the quality of the repair of the concrete. Therefore, many scholars believe that the meshing force is the main bonding force of the new and old concrete interface and the van der Waals force is the secondary force. As a result, many research studies focus on the method of changing the interface roughness to study the bond strength. The experiment mainly studied the bonding properties of the interface by changing the mineral content of the alkali-activated cementitious material and the modulus of the alkali-activating agent both in the presence and absence of an interface agent. The alkali activator water glass used in this experiment has a density of 1.258 g/cm³, and its modulus is adjusted by adding pure NaOH. The coarse aggregate is a crushed stone with a grain diameter of 5–20 mm. The fine aggregate is fine sand with a modulus of 2.6. Other materials are shown in Table 1.

2.2. Preparation of Test Piece. The interface between the old and the new concretes is a uniform rough surface. A cube with a sample size of 100 × 100 × 100 mm³ is selected. After curing for 14 days, the crack surface obtained by the splitting experiment is the test interface. To maintain the uniqueness of the interface between the new and the old concretes, plaster is used as an inverted mold to pour old concrete specimens with the same rough interface. After reaching a certain strength under standard curing conditions, the poured old concrete is placed in a 100 × 100 × 100 mm³ cube mold. The 0.5–1.5 mm thick interface agent is evenly spread on the interface, and then new C40 concrete, or in the old After the concrete is put into the mold, the alkali-excited concrete with different slag content and sodium silicate modulus is directly poured, and the pouring sequence is shown in Figure 1. The mixing ratio of new and old concretes is shown in Table 2. The mixing ratio of alkali-activated concrete with different slag contents, sodium silicate moduli, and interface agents is shown in Table 3. Each ratio is made of three specimens, with a total of 30 specimens. The test piece J0 means no interface agent.

This paper analyzes the influence of mineral content, sodium silicate modulus, and interface agent on the interfacial bond strength through splitting tensile strength and conducts a splitting test when the new concrete is cured to the specified age, with the splitting tensile strength of 3.128 MPa. According to the “Standard for Test Methods of Physical and Mechanical Properties of Concrete” (GB/T50081-2019), the loading speed is controlled at 0.02–0.05 MPa/s, and this test is taken as 0.04 MPa/s. Splitting tensile strength is calculated according to formula 1, and the schematic diagram of loading is shown in Figure 2.

\[
f_{ts} = \frac{2P}{\pi A} = 0.673 \frac{P}{A}
\]  

(1)

Also, \(f_{ts}\) is the split tensile strength of the specimen, \(P\) is the failure load of the specimen, and \(A\) is the area of the fracture surface. Since this test uses a nonstandard specimen of 100 × 100 × 100 mm³, it should be multiplied by a scale conversion factor of 0.85 when calculating the splitting strength.

Figure 1. Schematic diagram of the pouring sequence of the test piece.

Figure 2. Schematic diagram of the loading sequence of the test piece.
3. ANALYSIS OF TEST RESULTS

3.1. Research on the Interfacial Cohesion of Different Slag and Fly Ash Contents. Using alkali-activated solid waste cementitious materials to modify the bonding properties of the new and old concrete interfaces, and analyzing the tensile strength of the interface with different slag and fly ash contents, the results shown in Table 4 can be obtained.

Table 3. Mixture Ratio of Alkali-Activated Concrete with Different Slag and Fly Ash Contents, Sodium Silicate Moduli, and Interface Agents

| number | slag (kg/m³) | fly ash (kg/m³) | sand (kg/m³) | stone (kg/m³) | water (kg/m³) | sodium silicate 1 (kg/m³) | sodium silicate 2 (kg/m³) | water–binder ratio | modulus |
|--------|--------------|----------------|--------------|---------------|---------------|-----------------|----------------|----------------|--------|
| K1     | 350          | 150            | 500          | 1000          | 100           | 150             | 25              | 0.4            | 1.5    |
| K2     | 250          | 250            | 500          | 1000          | 100           | 150             | 25              | 0.4            | 1.5    |
| K3     | 150          | 350            | 500          | 1000          | 100           | 150             | 25              | 0.4            | 1.5    |
| S1     | 250          | 250            | 500          | 1000          | 100           | 140             | 28              | 0.4            | 1.3    |
| S2     | 250          | 250            | 500          | 1000          | 100           | 150             | 25              | 0.4            | 1.5    |
| S3     | 250          | 250            | 500          | 1000          | 100           | 160             | 20              | 0.4            | 1.7    |
| J0     |              |                |              |               |               |                 |                 |                |        |
| J1     | 250          | 250            | 500          | 100           | 150           | 25              | 0.3             | 1.5            |
| J2     | 250          | 250            | 500          | 100           | 150           | 25              | 0.4             | 1.5            |
| J3     | 250          | 250            | 500          | 100           | 150           | 25              | 0.5             | 1.5            |

Table 4. Splitting Tensile Strength under Different Slag and Fly Ash Contents

| number (content) | failure load (KN) | splitting strength, $f_{ts}$ (MPa) | mean (MPa) |
|------------------|-------------------|-----------------------------------|------------|
| K1 (70%)         | 33.23             | 1.796                             | 1.851      |
|                  | 36.51             | 1.922                             |            |
|                  | 34.44             | 1.834                             |            |
| K2 (50%)         | 42.84             | 2.325                             | 2.4        |
|                  | 44.38             | 2.387                             |            |
|                  | 46.75             | 2.489                             |            |
| K3 (30%)         | 25.46             | 1.388                             | 1.439      |
|                  | 28.89             | 1.635                             |            |
|                  | 24.72             | 1.294                             |            |

The splitting strength under different slag and fly ash contents is plotted and its changing trend with the gradual decrease in the content is analyzed, as shown in Figure 3. When the slag and fly ash content is 50%, the bonding strength of the new and old concretes reaches the highest value of 2.4 MPa. The average strength can reach 76.7% of the split tensile strength of the complete specimen C40 concrete, and an interface bonding strength is also present. With the increase in the slag and fly ash content, the trend first increases and then decreases, indicating that the alkali-activated slag and fly ash cementitious material has a significant effect on the interfacial cohesiveness of the repaired concrete under a certain proportion of the content. The bonding effect of the new and old concrete interface can basically be reflected in two aspects: one is the bonding between the new concrete mortar and the coarse aggregate of the old concrete; the other is the bonding between the new concrete mortar and the cement stone in the old concrete. As the old concrete is washed before the concrete is repaired, the bond between the mortar in the new concrete and the coarse aggregate...
of the old concrete is similar to the bond between the mortar and the coarse aggregate in the new concrete. Therefore, the key point is the bonding force between the cement stone of the old concrete and the mortar in the new concrete. The fractured form of the bonding surface between the new and the old concretes reflects the bonding condition of the bonding surface. The fracture surface morphology after splitting is shown in Figure 4.

From the image of the fracture surface, it can be seen that the color of the fracture surface is not the same when the new concrete uses alkali-activated slag fly ash (50%) concrete (K2), showing part of the dark green (this is the slag hydrated normal color) and part the color of old concrete. Therefore, it can be inferred that one part of the fracture occurs in the cement stone part of the old concrete and the coarse aggregate part and another part of the fracture occurs along the fracture surface of the old concrete, indicating that the bonding effect between the mortar in the new concrete and the cement stone in the old concrete is sufficient. The damage occurs on the cement stone of the old concrete, not on the joint surface of the cement stone and the new concrete mortar. When alkali-activated slag fly ash (30, 70%) concrete (K1 and K3) is used to repair old concrete, the fracture surface of the new and old concrete basically breaks along the surface of the old concrete, and the fracture of the old concrete cement stone does not occur.

3.2. Research on the Modulus of Alkali Activator on the Interfacial Adhesion. Water glass is a common alkaline activator for preparing geopolymers. The higher the modulus of the activator, the greater the density and viscosity. When used as an activator, the hardening speed is faster, and the adhesive force and durability of the gel system after hardening are also higher. However, when the modulus of water glass is too high, the viscosity is too high and it is not conducive to construction. Therefore, it is quite necessary to choose a suitable modulus of water glass. The cleavage tensile strength under different alkali activator moduli is shown in Table 5.

Taking the average value of the splitting strength of each test piece, the trend of the splitting strength under different modulus of the alkali activator can be obtained, as shown in Figure 5. With the gradual increase in the alkali excitation modulus, the splitting strength shows a gradually decreasing trend, indicating that the larger the alkali activator modulus, the lower the cohesive force of the cementitious material, which is not conducive to the pasting and repairing of new and old concretes. Studies have shown that when the modulus of water glass in the alkali activator is lower, the higher its pH value, the more it can promote the performance of the mechanical properties of the cementitious material, generate more C−S−H and C−A−S−H gels, and thereby increase the strength of the cementitious material.

The crack surface of the specimen was magnified 2000 times and observed under a microscope. It can be seen from Figure 6 that when the modulus of the stimulant is 1.3, more gelatinous substances can be observed on the section of the specimen. Also, they overlap each other to form a compact material. The skeleton structure and a small amount of unreacted gray particles embedded in the gaps of the gel can be observed; when the modulus of the activator is 1.5, a small amount of gel-like hydration product is produced. The unreacted fly ash particles are wrapped to form the basic skeleton of the reaction system; when the modulus of the activator is 1.7, the microscopic view of the structure shows that tiny particles of the cementitious material are loosely packed together and some needles connecting these tiny particles form a complete part.

3.3. Analysis of Adhesive Force under Different Interface Agents. To compare the bonding effect of the interface agent, the experiment was conducted on three different water-to-binder ratios of 0.3, 0.4, and 0.5. To determine the increasing effect of the interface agent, a group of J0 specimens without an interface was used for comparison. The cleavage strength under different interface agents in the analysis is shown in Table 6.
According to Table 6, with the gradual increase in the water-to-binder ratio in the alkali-activated cementitious material, the cleavage strength first increases and then decreases. Also, the increasing percentage also shows the same trend. When the water-to-binder ratio is 0.3, the ratio of the splitting strength of the test interface agent increases by 25.1%. It is possible that alkali stimulates the secondary hydration reaction of fly ash in the cementitious material. After the cemented layer on the surface of fly ash dissolves, the active silica in it interacts with the old concrete. The hydration product Ca(OH)$_2$ reacts to form a C−S−H gel, which makes the structure of the interface more dense and solid and alleviates the phenomenon of Ca(OH)$_2$ enrichment and directional arrangement, reducing the possibility of interfacial moisture accumulation and improving interfacial adhesion.

### 4. CONCLUSIONS AND DISCUSSION

This article mainly discusses the influence of three factors of different slag and fly ash contents, interface agents, and alkali activator moduli on the bonding performance of the new and old concrete interface. Cementitious materials are used to repair new and old concrete with waste alkali, and the interface splitting tensile strength after repairing, the interface failure is formed and the microstructure diagram of the crack surface is analyzed, leading to the following conclusions:

1. As the contents of slag and fly ash gradually increase, the bonding strength shows a trend of first increasing and then decreasing. When the content is 50%, the bonding strength reaches the highest, which is mainly due to the incorporation of slag and fly ash. Under the action of an alkali activator, the hydration products are mutually transformed under the condition of mutual influence, and the secondary reaction of fly ash and the hydration product C−S−H of the old concrete causes its bonding strength to reach the highest.

2. Through the gradual increase in the modulus of water glass in the cementing material by alkali, the splitting tensile strength of the new and old concrete interface is gradually reduced. The observation of the microstructure shows that the modulus of water glass is lower. At this time, the amount of the reaction products C−S−H and C−A−S−H is large. However, as the modulus of the water glass increases, a large amount of air causes the compactness of the interface structure to decrease.

3. A comparative analysis of the bond strength of the new and old concrete interfaces with different interface agents and without the interface agent was performed. The cracking strength is compared, and the increasing rate of the bonding strength under the alkali-activated cementitious material is analyzed, which shows that the alkali-activated cementitious material has a significant influence on improving the bonding strength of new and old concretes.

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