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Repair of existing concrete using high-ductility alkali-activated slag composite material

Benrui Chen [1]
*[*1] School of Environment and Architecture, University of Shanghai for Science and Technology, 516 Jungong Road, Shanghai 200093, China*
Corresponding Author: Benrui Chen

Abstract
This study investigates the bonding performance of high-ductility alkali-activated slag composite material for repairing existing concrete, including its resistance to splitting and shear forces, as well as the interface failure morphology. The research reveals that the choice of interface treatment significantly influences the failure morphology and bonding performance of the specimens. As the roughness of the interface treatment increases, the severity of damage at the bonding interface worsens, but the bonding performance improves. The IV-type specimens (groove cutting treatment) exhibit the most severe failure but demonstrate the best bonding performance, with a shear strength 215.2% higher than that of the I-type specimens. High-ductility alkali-activated slag composite material displays distinct advantages as a repair material for existing concrete.
Keywords: *High-ductility alkali-activated slag composite material, Repair of existing concrete, Bonding performance, Interface treatment, Resistance to splitting and shear forces.*

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I. INTRODUCTION

With the increasing service life of concrete structures, issues such as spalling, aging, degradation of load-bearing capacity, and reduced durability have gradually emerged, shortening the lifespan of structures. Therefore, repairing and strengthening existing building structures has become an urgent need in the industry. However, this task requires not only scientific design but also the search for economically, environmentally friendly, and high-performance repair and reinforcement materials.

Currently, commonly used repair materials include cement mortar, fiber-reinforced polymers (FRP) sheets, and epoxy resins, each with their own advantages but also significant limitations. For example, cement mortar has good performance but limited durability; FRP sheets provide the best repair effect, but the interfacial bond strength is susceptible to high temperatures; epoxy resins exhibit superior strength and durability but can deteriorate under high temperatures.

In recent years, alkali-activated materials have gained significant attention due to their low energy consumption, environmental friendliness, excellent performance, high-temperature resistance, and corrosion resistance. Among them, alkali-activated slag-based materials can achieve high strength under normal temperature curing and show great potential for repair and reinforcement[1-2]. However, research on their bonding performance and long-term durability is still insufficient.

Therefore, this study focuses on the study of the bond performance of high-ductility alkali-activated slag composites for repairing existing concrete. Through in-depth analysis of their resistance to splitting, shear performance, and interface failure mode, the repair effectiveness is comprehensively evaluated. Additionally, considering their advantages in rapid repairs in areas such as road maintenance and sewer pipelines, this research aims to provide valuable references for the application of alkali-activated slag materials in the field of repair and reinforcement. Through continuous exploration and optimization, we expect that high-ductility alkali-activated slag composites will play a greater role in the repair and reinforcement of future building structures.

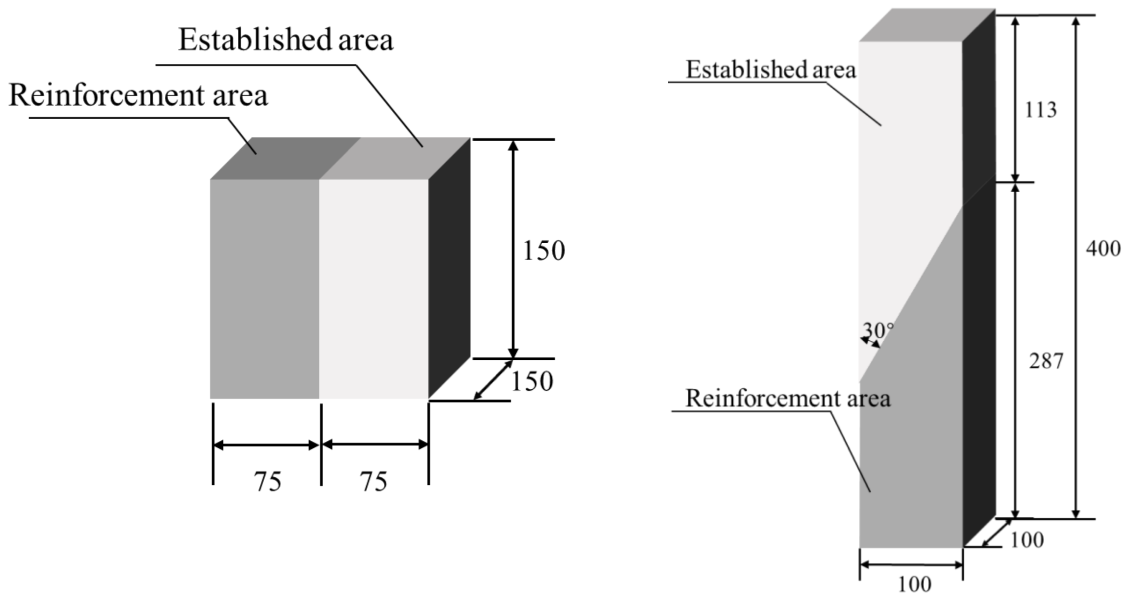
1.1.1 Specimen handling

This test uses C30 concrete provided by Shanghai Tongshun Concrete Co., Ltd. of Liping Road Branch, with a flow degree of 180 ± 20mm, as shown in Table 1.

Table 1 C30 concrete mixing ratio.

Cement	Slag	Fly ash	Stone	Coarse sand	Medium sand	Water	Admixture
221	112	66	925	693	208	121	8.78

Based on the literature and specifications related to the tensile splitting test and shear test of composite components for repairing existing concrete, in order to simulate the actual stress conditions of repairing existing concrete structures with high-ductility alkali-activated slag, and to ensure uniform stress distribution at the bonding interface, this study conducted shear performance research using 30° inclined shear specimens and tensile splitting performance research using cubic specimens with a side length of 150mm. The specific specimen dimensions are shown in Fig. 1.



(a) Split tensile specimen size (b) Shear specimen size

Figure 1: Dimensional drawing of AAFRC repair test specimen

The specimen preparation steps are as follows:

(1) Firstly, a cubic mold with a side length of 150mm is lined with adhesive paper after measuring the height to 75mm from the bottom. A custom-made foam is used to fill a prism mold measuring 100×100×400mm, and the mold is then coated with oil.

(2) Concrete is poured into the prepared molds and compacted by vibration. After 24 hours of curing, the molds are removed, and the specimens are transferred to a standard curing room for further curing until the age of 28 days.

(3) Upon reaching the specified age, the specimen interfaces are treated and marked. The interface treatment methods are illustrated in Figure 2 and the specific procedures are as follows: Type I surface: Dust on the concrete bonding interface is brushed off and rinsed with water, resulting in a roughness of approximately 0mm. Type II surface: Artificially remove some aggregates and mortar from the concrete bonding surface by chiseling, followed by brushing off the dust and rinsing with clean water. This creates a slightly uneven surface with roughness in the range of 0.5-0.7mm. Type III surface: The treatment method is the same as for Type II surface, but with a roughness in the range of 1.1-1.2mm. Type IV surface: The concrete bonding surface is treated by cutting with a cutting machine, creating grooves with a width of 10mm and a depth of 5mm, resulting in a roughness in the range of 1.4-1.5mm. Five specimens are prepared for each surface type.

(4) After the interface treatment is completed, the specimens are placed back into their respective molds. Then, high-ductility alkali-activated slag composite material is poured into the molds. After 24 hours of curing, the molds are removed, and the specimens are further cured at room temperature until the age of 28 days for the subsequent testing of tensile splitting performance and shear performance.

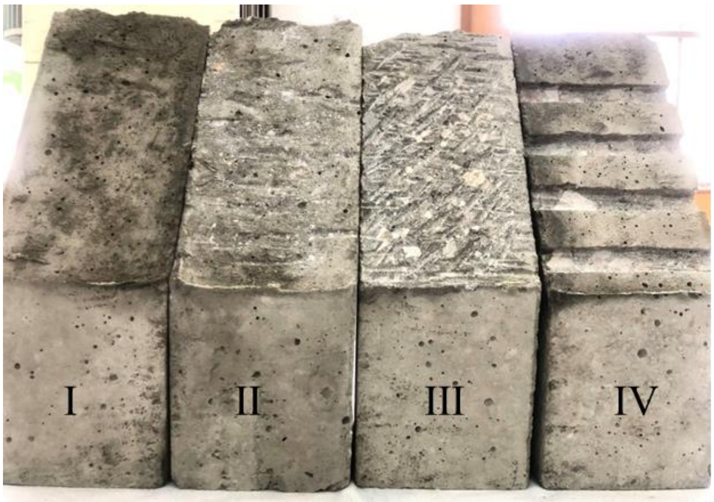


Figure 2: Concrete bonding interface treatment

II. RESULT AND DISCUSSION

The results obtained are as discussed below

2.1.1 Splitting tensile strength

The tensile splitting strength of high-ductility alkali-activated slag repair material applied to existing concrete is presented in Table 2, and Figure 3 provides a comparative graph of the tensile splitting strength. It can be observed that different interface treatment methods have a significant influence on the tensile splitting strength at the interface between the high-ductility alkali-activated slag and the existing concrete. As the roughness of the interface treatment increases, the repaired tensile splitting strength gradually improves. Compared to the Type I specimens, the Type II, III, and IV specimens all exhibit good bonding performance.

Among them, the Type I specimens with a roughness of 0 achieved a maximum load of 56.63 kN, resulting in a tensile splitting strength of 2.52 MPa. When the bonding interface roughness was increased to 0.5-0.7 mm through chiseling, the tensile splitting strength of the specimens improved by 16%. Further increasing the bonding interface roughness to 1.1-1.2 mm using the same method resulted in a maximum load of 82.47 kN and a tensile splitting strength of 3.67 MPa, representing an improvement of approximately 46% compared to Type I specimens. When the bonding interface was treated by cutting grooves with a roughness of 1.4-1.5 mm, the specimens exhibited the best bonding performance with a maximum load of 124.47 kN and a tensile splitting strength of 5.53 MPa, showing an improvement of approximately 120%. Regarding the research findings of other scholars, Fan et al. [3] used slag and fly ash as the main components to prepare alkali-activated materials for repairing C50 concrete, resulting in a tensile splitting strength of less than 3 MPa. Wang Junjie et al. [4] used UHPC to repair C50 concrete, achieving a maximum tensile splitting strength of around 4 MPa. It can be concluded that high-ductility alkali-activated slag has significant advantages for repairing existing concrete.

The results indicate that the cutting treatment method provides the best bonding performance, which is also confirmed by the fracture morphology of the specimens. Additionally, increasing the interface roughness can enhance the bonding performance. The improved bonding performance of high-ductility alkali-activated slag repair material applied to existing concrete can be attributed to the reaction between the activated SiO_2 (with a slag content exceeding 30% and a silica fume content exceeding 90%) in the alkali-activated material and the hydration product $Ca(OH)_2$ of the concrete, resulting in the formation of hydrated calcium silicate (C-S-H) gel products. This densifies the bonding interface and improves the bonding strength while reducing the accumulation of $Ca(OH)_2$ in the concrete. Since the strength of C-S-H gel is higher than that of $Ca(OH)_2$, this becomes a crucial condition for alkali-activated materials to be used for concrete repair. Furthermore, there are also some unreacted slag and silica fume particles in the alkali-activated material, which fill the hydration products and interweave with them, reducing the porosity and refining the pore size, ultimately leading to an increase in bonding strength [5].

Table 2 Tensile strength of splitting after repair of high-tensile alkali slag

The specimen number	Ultimate load (kN)	Cleavage Tensile Strength (MPa)	Harshness (mm)
Type I	56.63±2.94	2.52±0.13	0
Type Ⅱ	66.00±0.87	2.93±0.04	0.5~0.7
Type Ⅲ	82.47±2.39	3.67±0.11	1.1~1.2
Type Ⅳ	124.47±5.53	5.53±0.25	1.4~1.5

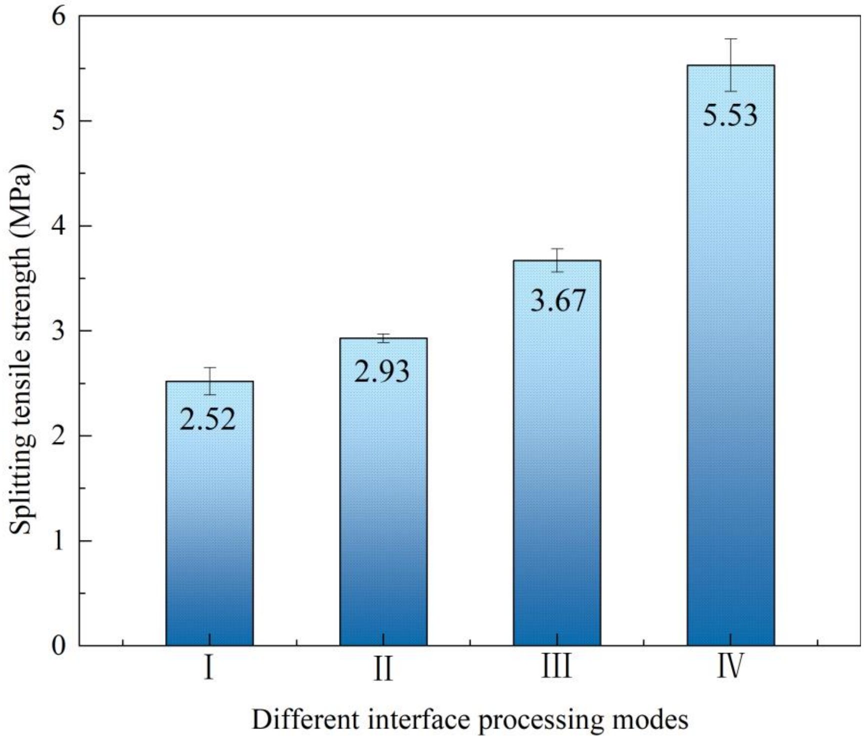


Figure 3: Split tensile strength after repair of high-tensile alkali slag

2.1.2 Shear strength

The shear strength of the existing concrete is shown in Table 2, and the shear strength is compared in Figure 4. It can be seen that different interface treatment methods have a great impact on the repair of concrete and shear strength of high ductility alkali slag. As the roughness of the interface processing increases, the shear strength after repair gradually increases. Compared with type I specimens, type II, III and IV specimens all showed good bonding performance. The roughness of the type I specimen is 0, the ultimate load is about 112 kN, and the shear strength is 5.6MPa. When the roughness of the bonding interface is 0.5~0.7mm, the shear bearing capacity of the specimen is significantly improved. Compared with the type I specimen, the ultimate load of the type II specimen is increased by 119.3%, and the corresponding shear strength reaches 12.28MPa. With the increase of the interface processing roughness, the shear bearing capacity of the specimen gradually increases. When the bonding interface is treated to roughness is 1.1~1.2mm, the limit load of the specimen reaches 284.3kN and the shear strength is 14.22MPa, which is 153.9% higher compared with type I. When the bonding interface is treated with groove, the roughness is 1.4~1.5mm, the bonding effect of the specimen is the best, the limit load is about 353 kN, and the shear strength reaches 17.65MPa, which increases by 215.2%. In addition, as can be seen from the destruction pattern of the bonding interface after cutting the specimen (Figure 3), the bonding interface with cutting groove treatment (type IV) is the most seriously damaged, and the corresponding shear bearing capacity is the highest.

The results show that increasing the roughness of the interface treatment can improve the shear strength of the slag (type IV) test.3.2 The shear bearing capacity of the interface is mainly composed of two parts, one part is provided by the mechanical bite force, van der Waals force and friction force at the bonding interface between high tile alkali slag and concrete, and the other part is the shear bearing capacity provided by the groove at the bonding interface. The combined action of the two leads to its good shear strength. At the same time, the reason for its good bonding strength as a repair material can be explained from the microscopic perspective, see 6. Considering that there may be a large area of repair in the actual engineering, it is more convenient to treat the bonding interface construction, and it is easier to obtain accurate roughness.

Table 2 Tensile strength of splitting after repair of high-tensile alkali slag

The specimen number	Ultimate load (kN)	Shear strength (MPa)	Harshness (mm)
Type I	111.98±4.29	5.60±0.21	0
Type Ⅱ	245.62±1.85	12.28±0.09	0.5~0.7
Type Ⅲ	284.30±0.72	14.22±0.04	1.1~1.2
Type Ⅳ	352.96±2.46	17.65±0.12	1.4~1.5

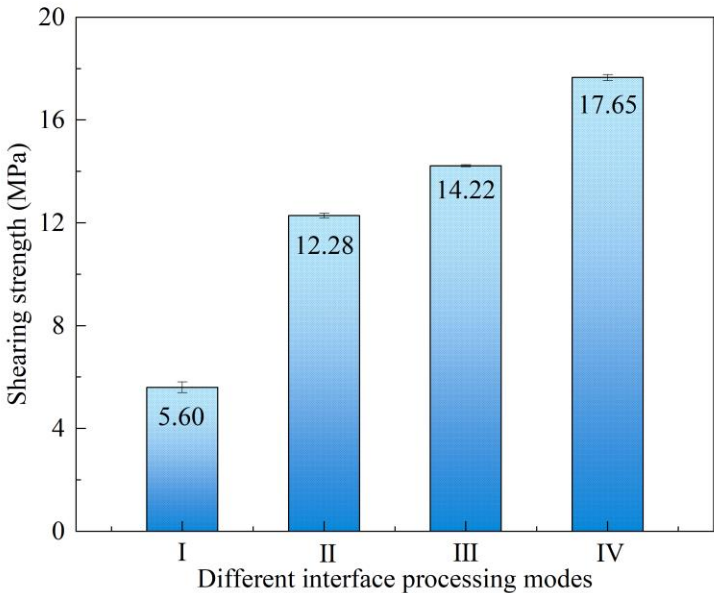


Figure 4: Shear strength after repair of high-tensile alkali slag

III. CONCLUSION

This study mainly investigates the bonding performance of high-ductility alkali-activated slag composite material used for repairing existing concrete. The main aspects include the tensile splitting performance and interface failure analysis after repairing the concrete, as well as the shear performance and interface failure analysis after the repair. Therefore, a comprehensive evaluation of the performance of using high-ductility alkali-activated slag composite material for repairing existing concrete was conducted, leading to the following conclusions:

(1) Different interface treatment methods result in varied forms of tensile splitting failure after the specimens are subjected to splitting forces. With an increase in interface roughness, the severity of the damage at the bonding interface between the high-ductility alkali-activated slag and the existing concrete becomes more pronounced. The tensile splitting failure in all four interface treatment methods occurs at the bonding interface, with the IV-type specimens (groove cutting treatment) experiencing the most severe failure and exhibiting the best bonding performance.

(2) With an increase in interface roughness, the bonding performance of high-ductility alkali-activated slag for repairing existing concrete shows improvement. The tensile splitting strengths of the four interface treatment specimens are 2.52 MPa, 2.93 MPa, 3.67 MPa, and 5.53 MPa, respectively.

(3) The influence of different interface treatment methods on the shear performance of high-ductility alkali-activated slag for repairing existing concrete follows a similar pattern as the tensile splitting performance. Among them, the wire brush treatment (Type I) and chiseling treatment (Type II and III) specimens exhibit shear failure at the bonding interface, while the groove cutting treatment (Type IV) specimens experience shear failure on the concrete side. The IV-type specimens show the most severe failure.

(4) Increasing the interface roughness significantly improves the shear bearing capacity of high-ductility alkali-activated slag for repairing existing concrete. The shear strengths of the four interface treatment specimens are 5.6 MPa, 12.28 MPa, 14.22 MPa, and 17.65 MPa, respectively. The shear strength of the IV-type

specimens is 215.2% higher than that of the I-type specimens. It can be concluded that high-ductility alkali-activated slag exhibits excellent bonding performance and has significant advantages as a repair material for existing concrete.

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