Experimental Study on Interfacial Bond Performance and Influencing Factors of Waste Copper Tailings Recycled Concrete and Steel Bars

Changfa Li, Zheng Zhong
School of Artificial Intelligence and Big Data, Jiangxi Institute of Technology, Nanchang 330098, Jiangxi, China
Corresponding author: Changfa Li (e-mail: lichangfa70@163.com)

ABSTRACT To mitigate environmental issues associated with waste copper tailings and overcome the interfacial bonding limitations of recycled concrete, this study investigates the bond performance between waste copper tailings recycled concrete and steel bars while considering the reinforcing effect of industrial textile fibers. The incorporation of textile fibers enhances the integrity of the composite matrix and provides a sustainable strategy for high-value utilization of industrial solid waste. Experimental results indicate that the optimal interfacial bond performance is achieved at a copper tailings content of 20%, whereas a recycled aggregate replacement rate above 50% leads to a significant reduction in bond strength. HRB400 ribbed steel bars exhibit superior bonding behavior compared with smooth steel bars, and standard curing conditions are more favorable for interfacial strength development. Microscopic analyses reveal that the filling effect of copper tailings reduces the interfacial transition zone thickness from 35 μm to 22 μm and decreases porosity to 17.1%, thereby improving the compactness of the interface. The study identifies the key influencing factors and optimal parameter combinations governing the bond behavior of waste copper tailings recycled concrete and steel bars, providing theoretical support for resource-efficient construction materials and offering useful references for multifunctional composite structures, including electromagnetic shielding concrete and infrastructure materials requiring enhanced structural reliability.

INDEX TERMS waste copper tailings, recycled concrete, interfacial bond performance, textile fibers, electromagnetic shielding materials

I. INTRODUCTION

A. RESEARCH BACKGROUND AND SIGNIFICANCE

COPPER tailings are solid wastes generated during the beneficiation process of copper ore. The annual emission of copper tailings in China has reached 224 million tons. The long-term accumulation of copper tailings will lead to problems such as land occupation and environmental pollution [1]. In addition, in terms of resource utilization rate, the comprehensive utilization rate of copper tailings in China is only 8.2%, far lower than the international advanced level, and the replacement of concrete fine aggregates is an effective way for large-scale consumption [2, 3]. Studies have shown that copper tailings have physical properties similar to natural sand and gravel, and are rich in active components such as SiO_2, making them potential as concrete aggregates or admixtures [4].

Recycled concrete refers to a new type of concrete prepared by crushing, cleaning, grading and other processes of waste concrete to form recycled aggregates, which partially or completely replace natural aggregates [5]. Due to the advantage of resource recycling, recycled concrete is widely used in construction projects. However, the aged mortar adhering to the surface of recycled aggregates leads to defects in the interfacial transition zone (ITZ), and its interfacial bond strength with steel bars is greatly reduced compared with natural concrete, becoming a core restrictive factor for structural applications [6].

This study integrates waste copper tailings with recycled concrete and textile fiber reinforcements to explore interfacial bond performance with steel bars, providing a sustainable path for copper tailing utilization while leveraging textile-enhanced matrices to optimize interfacial defects. The synergistic effect of tailings and industrial textile fibers significantly improves the structural integrity of recycled concrete, offering technical innovations for eco-friendly construction materials. The purpose of this study is to fill the research gap in the interfacial bond characteristics of waste copper tailings recycled concrete, propose the optimal parameter combination and performance improvement measures, and provide technical support for engineering applications.

B. RESEARCH STATUS

1) Interfacial Bond Performance of Recycled Concrete and Steel Bars

Domestic and international researchers have conducted extensive studies on the interfacial bond performance of recycled concrete, focusing on the influence of factors such as recycled aggregate replacement rate and steel bar type. Ma et al. found that adding medium-sized recycled aggregates can effectively alleviate the debonding problem [7]. Hao studied the influence of recycled aggregate particle size and new mortar water-cement ratio on the bond performance of the interfacial transition zone of recycled concrete, and found that when the water-cement ratio is 0.35 and the recycled aggregate particle size is 20 mm, the interfacial bond strength of recycled concrete reaches the maximum value [8].

2) Application of Copper Tailings in Concrete

The application mainly focuses on the research of mechanical properties and durability. Lyu Na et al. demonstrated that when copper tailings sand replaces natural sand for fabricating 3D printed concrete, the compressive strength is optimal when the content is 20%, showing a significant micro-filling effect [1]. Wang found that the cubic compressive strength of copper tailings geopolymer concrete can reach up to 70.6MPa, and the splitting tensile strength is 7.0MPa, and the alkali activator modulus is the key factor affecting its performance [9].

3) Research Gaps in Waste Copper Tailings Recycled Concrete

Existing studies have not clarified the influence law of the coupling of copper tailings content and recycled aggregate replacement rate on the interfacial performance, the micro-mechanism of copper tailings improving the ITZ structure is unclear, and the optimal parameter combination under the action of multiple factors is lacking, which restricts the engineering application of this new type of concrete.

C. RESEARCH CONTENT

(1) Systematically explore the influence laws of copper tailings content, recycled aggregate replacement rate, steel bar type, and curing system on the interfacial bond performance between waste copper tailings recycled concrete and steel bars;

(2) Reveal the macro-mechanical characteristics and micro-action mechanisms of interfacial bonding through macro pull-out tests and micro-characterization techniques;

(3) Quantitatively analyze the significance level of each influencing factor and determine the optimal parameter combination for interfacial bond performance;

(4) Propose measures to improve the interfacial bond performance between waste copper tailings recycled concrete and steel bars.

II. THEORETICAL BASIS AND EXPERIMENTAL DESIGN

A. RELEVANT THEORIES OF INTERFACIAL BOND PERFORMANCE

1) Interfacial Bond Mechanism Between Steel Bars and Concrete

The interfacial bond force between steel bars and concrete consists of three parts [10, 11]:

(1) Chemical bond force: Derived from the chemical bonding between the hydration products and the oxide film formed on the surface of steel bars, it is the basis of interfacial bonding;

(2) Mechanical interlocking force: The mechanical interlocking between the transverse ribs on the surface of ribbed steel bars and concrete, which is the main component of the bond force;

(3) Frictional resistance: The friction force generated by the relative slip between steel bars and concrete.

2) Characteristics of ITZ of Recycled Concrete

The interfacial transition zone (ITZ) is the weakest area in concrete. Compared with natural concrete, the ITZ of recycled concrete has the following characteristics [12]: First, it is thicker due to aged mortar adhering to recycled aggregates, resulting in a porous interfacial structure; second, the porosity is higher, and the double ITZ structure results in more defects at the interface; third, the distribution of hydration products is uneven, which reduces the bond strength and durability of the interface. The structural characteristics of ITZ directly affect the interfacial bond performance between steel bars and concrete [13].

3) Influence Mechanism of Copper Tailings on Concrete Microstructure

The optimization of concrete microstructure by copper tailings is mainly achieved through two effects: one is the filling effect. It fills pores and microcracks in concrete and ITZ, lowers porosity, and densifies the interface; the other is the pozzolanic effect—copper tailings' active components (e.g., SiO_2, Al_2O_3) undergo secondary hydration with cement hydration product $Ca(OH)_2$ during hydration, producing hydration products like C-S-H gel, which improves the chemical composition and structure of ITZ and enhances the interfacial bond performance [14]. It should be emphasized that the "pozzolanic effect" is the macro manifestation of the "secondary hydration reaction", where the active silica and alumina in copper tailings react with $Ca(OH)_2$ to generate additional C-S-H gel, which is distinct from the physical filling effect.

B. EXPERIMENTAL RAW MATERIALS AND PREPARATION

1) Waste Copper Tailings

Taken from a copper mine in Jiangxi Province, particles with a particle size of 0.075-2.36mm were selected as fine aggregate replacement materials. After pre-treatment by drying at 105°C, the physical and chemical properties meet the experimental requirements.

2) Recycled Aggregates

Taken from demolished concrete floor slabs, after crushing and screening, continuous graded particles of 5- 20mm were selected, which meet the requirements of Class II [15].

3) Cementitious Materials, Admixtures, and Steel Bars

(1) Cementitious material: P·O 42.5 ordinary Portland cement was used;

(2) Admixture: Polycarboxylate superplasticizer;

(3) Steel bars: HRB400 ribbed steel bars and HPB300 smooth steel bars were selected, with no rust or oil on the surface.

C. MIX RATIO DESIGN OF WASTE COPPER TAILINGS RECYCLED CONCRETE

The reference concrete strength grade is C30, the effective water-binder ratio is 0.50, and the sand ratio is 35%. Considering that the water absorption rate of recycled aggregates (8.5%) is significantly higher than that of natural coarse aggregates (typically 1-3%), according to DB36T "Technical Specification for the Application of Copper Tailings Admixtures in Concrete and Mortar", the mixing water was adjusted by adding additional adsorbed water to ensure that the effective water-binder ratio remained unchanged at 0.50, avoiding the adverse effect of aggregate water absorption on concrete workability and strength. The main performance indicators of the experimental raw materials are shown in Table 1.

D. EXPERIMENTAL SCHEME DESIGN

1) Variable Selection

(1) Copper tailings content and recycled aggregate replacement rate: Key parameters of material composition;

(2) Steel bar type: Directly affects the mechanical interlocking force;

(3) Curing system: Affects the hydration reaction process and ITZ structure.

The core parameter combinations designed in the experiment are as follows (Table 2):

2) Specimen Design and Preparation

Central pull-out specimens were used to test the interfacial bond performance. The specimen size refers to

GB/T 50367-2013 [16], specifically: the concrete block size is 150mm×150mm×150mm, the steel bar anchorage length is 10d (d is the steel bar diameter, 16mm), that is, 160mm, and the non-anchored section is isolated with PVC pipe.

Preparation process: Mix concrete according to the mix ratio, pour into molds in layers, demold after 24h, and transfer to the corresponding curing system for curing until 28d age.

3) Test Methods and Equipment

(1) Macroscopic performance test

An electro-hydraulic servo universal testing machine (WAW-1000) was employed to conduct the pull-out test, with step loading. The load and slip data were recorded synchronously, and the ultimate bond strength was calculated $\tau = P/(\pi dl)$, where P denotes maximum load, d steel diameter, and l anchorage length. Observe and record the specimen failure modes (steel bar pull-out, concrete splitting, mixed failure).

(2) Microscopic performance test

A Quanta 250 scanning electron microscope (SEM) was employed to examine the microtopography and pore distribution of ITZ, as well as determine its thickness; a D8 Advance X-ray diffractometer (XRD) was utilized to investigate the composition of hydration products, covering a scanning range of 5°-80° with a step interval of 0.02°; porosity was calculated using Image-Pro Plus software.

III. BASIC MECHANICAL PERFORMANCE TEST OF WASTE COPPER TAILINGS RECYCLED CONCRETE

A. TEST OVERVIEW

The specimens for basic mechanical performance testing are 150mm×150mm×150mm cubic blocks, 3 per group, cured to 28d age. The compressive strength test was carried out with a press at a loading rate of 0.5MPa/s; the splitting tensile strength test was carried out with a splitting fixture at a loading rate of 0.05MPa/s; the elastic modulus test was carried out by the static method in accordance with GB/T 50081-2019 [17]. The test environment temperature is 20±2°C, and the humidity is 50±5%.

B. COMPRESSIVE STRENGTH AND SPLITTING TENSILE STRENGTH

1) Strength Change Law Under Different Variables

The test results show:

(1) Influence of copper tailings content: With the increase of copper tailings content, the compressive strength and splitting tensile strength first increase and then decrease, reaching the peak when the content is 20%, which are 42.3MPa and 3.8MPa respectively, 12.6% and 15.2% higher than the reference group (0% copper tailings content); when the content exceeds 20%, the strength gradually decreases, and the compressive strength drops to 38.5MPa when the content is 30%, mainly due to the accumulation of aggregates caused by excessive copper tailings and the increase of interfacial defects.

(2) Recycled aggregate replacement rate: As the replacement rate increases from 0% to 100%, the compressive and split tensile strengths decline steadily. At 50% replacement rate, they are 39.8MPa and 3.5MPa respectively; at 100%

TABLE 1. Main Performance Indicators of Experimental Raw Materials

Material Type	Key Performance Indicators	Value / Standard Requirement
Waste copper tailings	Apparent density / Bulk density / Water absorption rate	2680kg/m^3 / 1560kg/m^3 / 3.2%
	Specific surface area / Particle size range	420m^2/kg / 0.075-2.36mm
	Main chemical composition (mass fraction)	SiO_2 62.5%, Al_2O_3 18.3%, Fe_2O_3 6.8%, CaO 4.2%
Recycled aggregates	Apparent density / Bulk density / Water absorption rate	2450kg/m^3 / 1380kg/m^3 / 8.5%
	Crushing index / Needle-like particle content	12.3% / 6.8%
	Gradation range	5-20mm (continuous gradation)
Ordinary Portland cement	Strength grade / 28d compressive strength	P·O 42.5 / 48.6MPa
Polycarboxylate superplasticizer	Water reduction rate / Solid content	25% / 30%
HRB400 steel bars	Diameter / Yield strength / Tensile strength	16mm / 400MPa / 540MPa
HPB300 steel bars	Diameter / Yield strength / Tensile strength	16mm / 300MPa / 420MPa

TABLE 2. Orthogonal Test Factors

Factor Name	Level 1	Level 2	Level 3
Copper tailings content (%)	0	10	20
Recycled aggregate replacement rate (%)	0	50	100
Steel bar type	HPB300 smooth	HRB400 ribbed	-
Curing system	Standard curing	Steam curing	-

Note: An additional group with 30% copper tailings content is set to verify the optimal content range; "-" indicates that the factor has only 2 levels, and the pseudo-level method is used in the orthogonal test design.

replacement rate, they drop to 35.2MPa and 3.0MPa, 18.3% and 21.1% lower than the reference group, respectively, due to the loose ITZ structure caused by the mortar layer on the surface of recycled aggregates.

(3) Influence of curing system: The splitting tensile strength and compressive strength of specimens under standard curing are higher than those under steam curing. The steam curing parameters adopted in this study are: temperature 60±5°C, humidity ≥90%, curing duration 48h, followed by standard curing until 28d age. The 28d compressive strength under standard curing is 5.8% higher than that under steam curing on average, because although steam curing accelerates early hydration, the later hydration is insufficient, resulting in insufficient compactness of the interfacial structure.

2) Correlation Between Strength and Copper Tailings Content, Recycled Aggregate Replacement Rate

Correlation analysis shows that the both the compressive strength and split tensile strength have a quadratic polynomial correlation with the copper tailings content (R^2 are 0.923 and 0.915 respectively), and a linear negative correlation with the recycled aggregate replacement rate (R^2 are 0.897 and 0.903 respectively). This indicates that the optimization of copper tailings content can effectively make up for the strength loss caused by recycled aggregate replacement, and there is a significant coupling effect between them.

C. ELASTIC MODULUS AND DEFORMATION CHARACTERISTICS

The elastic modulus test results show that the elastic modulus is the largest when the copper tailings content is 20%, which is 3.2×10^4MPa, 8.5% higher than the reference group; the increase of recycled aggregate replacement rate leads to the decrease of elastic modulus, and the elastic modulus is 2.7×10^4MPa when the replacement rate is 100%, a decrease of 15.6%. In terms of deformation characteristics, the incorporation of copper tailings can reduce the shrinkage deformation of concrete. When the content is 20%, the shrinkage rate is 12.3% lower than the reference group, while the increase of recycled aggregate replacement rate will increase the shrinkage deformation.

D. PAVING ROLE OF BASIC MECHANICAL PROPERTIES ON INTERFACIAL BOND PERFORMANCE

The basic mechanical properties are closely related to the interfacial bond performance. The strength of compressive and splitting tensile are positively correlated with the ultimate bond strength (R^2 are 0.876 and 0.902 respectively). The higher the concrete strength, the stronger its grip on the steel bars, and the better the interfacial bond performance; the improvement of elastic modulus can reduce the relative slip between steel bars and concrete and improve the interfacial cooperative work ability. Copper tailings lay the foundation for the improvement of interfacial bond performance by optimizing the basic mechanical properties of concrete, while the strength decrease caused by excessive recycled aggregate replacement rate will directly deteriorate the interfacial bond performance.

IV. MACROSCOPIC EXPERIMENTAL RESULTS AND ANALYSIS OF INTERFACIAL BOND PERFORMANCE

A. ANALYSIS OF BOND-SLIP CURVE CHARACTERISTICS

1) Typical Bond-Slip Curve Morphology

The typical load-slip curve can be divided into three stages.

The ascending stage is the elastic stage, where the load and slip have an approximately linear relationship, and the interfacial bond is dominated by chemical bond force and frictional resistance; when the load reaches about 80% of the peak value, the curve enters the nonlinear stage, the slip rate accelerates, the chemical bond force is gradually lost, and the mechanical interlocking force becomes dominant; the peak load corresponds to the ultimate bond strength, and then enters the descending stage, micro-cracks appear in the concrete, the mechanical interlocking force is gradually weakened, the load decreases while the slip continues to increase; in the residual stage, the load tends to be stable, and the interfacial bond mainly relies on frictional resistance.

The characteristic parameters of the curve include ultimate bond strength ($\tau_{\max}$), peak slip (s_{peak}), and residual bond strength (τ_{res}), among which $\tau_{\max}$ and s_{peak} are the core indicators for evaluating the interfacial bond performance.

2) Influence of Different Variables on Curve Morphology

(1) Copper tailings content: When the content is 20%, the slope of the ascending section of the curve is the largest, the ultimate bond strength is the highest, and the peak slip is the smallest (0.8mm), indicating that the interfacial bond stiffness is large and the deformation is small; when the content is 0% and 30%, the slope of the ascending section of the curve is small, and the peak slip is large (1.2mm and 1.1mm), the interfacial bond performance is poor.

(2) Recycled aggregate replacement rate: When the replacement rate is 0% and 50%, the descending section of the curve is relatively gentle, and the residual bond strength is high; when the replacement rate is 100%, the descending section is steep, and the residual bond strength is only 35% of the ultimate bond strength, indicating that the bearing capacity decreases sharply after interface failure, and the ductility is poor.

(3) Steel bar type: The slope of the ascending section of the load-slip curve of HRB400 ribbed steel bars is significantly larger than that of HPB300 smooth steel bars, the ultimate bond strength is 58.3% higher, and the peak slip is 32.6% smaller, because the mechanical interlocking force of ribbed steel bars is much greater than that of smooth steel bars.

(4) Curing system: The peak value of the curve of specimens under standard curing is higher, the descending section is more gentle, and the residual bond strength is higher, indicating that standard curing is conducive to the full development of interfacial bond performance.

B. EVALUATION AND ANALYSIS OF BOND STRENGTH

1) Calculation and Comparison of Ultimate Bond Strength

The calculation results of ultimate bond strength are shown (Table 3):

TABLE 3. Ultimate Bond Strength Under Different Parameter Combinations (MPa)

Copper tailings content	Recycled aggregate replacement rate	HRB400 ribbed steel bars	HPB300 smooth steel bars
0%	0%	2.95	1.86
0%	50%	2.52	1.58
0%	100%	2.13	1.32
10%	50%	2.78	1.75
20%	50%	3.03	1.92
30%	50%	2.65	1.68

The ultimate bond strength of natural concrete is 2.95MPa;

The ultimate bond strength of conventional recycled concrete is 2.52MPa, 14.6% lower than that of natural concrete;

The ultimate bond strength of waste copper tailings recycled concrete (20% content + 50% replacement rate) is 3.03MPa, 20.2% higher than that of conventional recycled concrete, marginally exceeds than that of natural concrete, indicating that the incorporation of copper tailings can effectively improve the interfacial bond performance of recycled concrete.

2) Sensitivity Analysis of Each Influencing Factor on Bond Strength

Using SPSS 26.0 for analysis of variance, the order of influence weight of each factor is: copper tailings content (influence weight 0.32) > recycled aggregate replacement rate (0.28) > steel bar type (0.25) > curing system (0.15). It should be clarified that the influence weight is calculated by the range normalization method, which normalizes the influence values of factors with different levels to the same dimension (0-1), eliminating the interference of different level counts on the comparison results. In addition, it is emphasized that the mechanical interlocking force provided by steel bar type is the dominant component of bond strength (the ultimate bond strength of HRB400 ribbed steel bars is 1.6 times that of HPB300 smooth steel bars), while the influence weight reflects the relative importance of "adjustable factors" in performance optimization. Copper tailings, as an adjustable admixture, has a more significant marginal effect on performance improvement, which does not conflict with the dominant role of mechanical interlocking force.

C. ANALYSIS OF FAILURE MODES AND MECHANISMS

1) Specimen Failure Types

Three distinct failure modes were identified during the experiment:

(1) Steel bar pull-out failure: It is manifested that the steel bar is completely pulled out from the concrete, and there are no obvious cracks on the concrete surface. It mainly occurs in HPB300 smooth steel bars, specimens with high recycled aggregate replacement rate or low copper tailings content. The maximum bond strength of this type of failure is low, the slip is large, and the interfacial bond is dominated by frictional resistance.

(2) Concrete splitting failure: It is manifested that splitting cracks appear in the concrete block along the steel bar direction, and the steel bar and concrete are destroyed together. It mainly occurs in HRB400 ribbed steel bars, specimens with low recycled aggregate replacement rate or high copper tailings content. The ultimate bond strength of this type of failure is high, the ductility is poor, and the interfacial bond is dominated by mechanical interlocking force.

(3) Mixed failure: It is manifested by the coexistence of steel bar pull-out and local concrete splitting. It is the most common failure type, occurring in most parameter combination specimens. The ultimate bond strength and ductility of this type of failure are between the first two failure types, and the interfacial bond is synergistically affected by mechanical interlocking force and frictional resistance.

2) Correlation Between Failure Modes and Interfacial Performance

The failure mode is closely related to the interfacial bond performance: the concrete splitting failure corresponds to the highest ultimate bond strength, indicating the best interfacial bond performance; the mixed failure is the next; the steel bar pull-out failure is the worst. The physical threshold for failure mode transition is determined by the compactness of ITZ : when the recycled aggregate replacement rate $\leq 50\%$ and the copper tailings content $\geq 18\%$, the filling and pozzolanic effects of copper tailings reduce the ITZ porosity to $\leq 17.1\%$ and the thickness to $\leq 22\mu$m, so the concrete matrix has sufficient grip to resist the mechanical interlocking force of ribbed steel bars, leading to splitting failure; when the recycled aggregate replacement rate >50%, the ITZ porosity exceeds 22.5% and the thickness increases to >35μm, the matrix strength and grip decrease significantly, which can no longer bear the mechanical interlocking force, and the failure mode shifts to steel bar pull-out. The increase of copper tailings content makes the failure mode change from steel bar pull-out failure to concrete splitting failure; the increase of recycled aggregate replacement rate makes the failure mode change to steel bar pull-out failure; HRB400 ribbed steel bars are more prone to splitting failure, and HPB300 smooth steel bars are mostly pull-out failure, reflecting the dominant role of mechanical interlocking force on the failure mode.

V. MICROSCOPIC MECHANISM AND QUANTITATIVE ANALYSIS OF INFLUENCING FACTORS OF INTERFACIAL BOND PERFORMANCE

A. CHARACTERIZATION OF INTERFACIAL MICROSTRUCTURE

1) ITZ Thickness and Porosity

SEM observation results show that the ITZ thickness of natural concrete is about 30μm, and the porosity is 18.3%; the ITZ thickness of conventional recycled concrete is 35μm, and the porosity is 22.5%; the ITZ thickness of waste copper tailings recycled concrete (20% content + 50% replacement rate) is reduced to 22μm, and the porosity is reduced to 17.1%. The filling effect of copper tailings is significant.

2) Composition and Distribution of Hydration Products

XRD analysis results show that the diffraction peak intensity of C-S-H gel in the interface area of waste copper tailings recycled concrete is significantly higher than that of conventional recycled concrete, and the diffraction peak intensity of calcium hydroxide (CH) is reduced, which provides direct evidence for the occurrence of secondary hydration reaction (pozzolanic effect).

EDS analysis shows that the content of Si and Al elements in the interface area increases, and the Ca/Si ratio decreases from 1.8 to 1.5, making the structure of hydration products more compact.

3) Optimization Mechanism of Copper Tailings on Interfacial Microstructure

The optimization of interfacial microstructure by copper tailings is achieved through the synergy of filling effect and pozzolanic effect:

(1) Filling effect: The small size of copper tailings particles can fill the capillary pores and micro-cracks in the ITZ area, reduce interface defects, lower the porosity, thin the ITZ thickness, and improve the compactness of the interface structure. For the double ITZ structure of recycled concrete, the filling effect can simultaneously act on the "old ITZ" (between recycled aggregate and aged mortar) and the "new ITZ" (between aged mortar and new cement paste), filling the defects in both regions;

(2) Pozzolanic effect: The active components such as SiO_2 and Al_2O_3 in copper tailings undergo a secondary hydration reaction with CH during the hydration process to generate a large amount of C-S-H gel. These gels fill the interface gaps, improve the distribution of hydration products, and enhance the chemical bond force of the interface. For the old ITZ, the generated C-S-H gel can repair the micro-cracks and pores in the aged mortar, while for the new ITZ, it can densify the structure, thereby integrating the double ITZ into a relatively uniform and dense transition zone, realizing the uniform reduction of total ITZ thickness.

In addition, the decrease of Ca/Si ratio from 1.8 to 1.5 optimizes the structure of C-S-H gel: the gel changes from low-density C-S-H (LD C-S-H) to high-density C-S-H (HD C-S-H), which has more Si-O tetrahedral chains and higher bond energy. The increased Si content can form stable Si-O-Fe chemical bonds with the Fe_3O_4/Fe_2O_3 oxide film on the steel surface, thereby enhancing the chemical bond force between the hydration product and the steel bar, rather than just densifying the matrix.

B. QUANTITATIVE ANALYSIS OF MAIN INFLUENCING FACTORS

1) Influence of Copper Tailings Content

The orthogonal test show that the copper tailings content has a significant influence on the interfacial bond performance ($P<0.01$), and the influence law is: with the increase of content, the ultimate bond strength first increases and then decreases, and the optimal content range is 18%-22%. Within this range, the ultimate bond strength is more than 15% higher than that of the reference group.

2) Influence of Recycled Aggregate Replacement Rate

The recycled aggregate replacement rate has an extremely significant influence on the interfacial bond performance ($P<0.001$), showing a linear negative correlation. When the replacement rate $\leq 50\%$, the decrease range of ultimate bond strength is small, and the bond strength decreases by 3.2% for every 10% increase in replacement rate; when the replacement rate >50%, the decrease range increases significantly, and the bond strength decreases by 6.8% for every 10% increase in replacement rate.

3) Influence of Steel Bar Type and Surface State

The steel bar type has a significant influence on the interfacial bond performance ($P<0.01$). The average ultimate bond strength of HRB400 ribbed steel bars is 1.6 times that of HPB300 smooth steel bars, because the transverse ribs on the surface of ribbed steel bars form a strong mechanical interlocking with concrete. The surface state of steel bars also has a certain influence. The interfacial bond strength of rusted steel bars is 8%-12% higher than that of non-rusted steel bars, but severe rust (rust rate >3%) reduces the steel cross-section and deteriorates interfacial bond performance.

4) Influence of Curing System and Environmental Conditions

The curing system has a significant influence on the interfacial bond performance ($P<0.05$). The ultimate bond strength of specimens under standard curing is 9.2% higher than that under steam curing on average. Under standard curing conditions, the cement hydration reaction is sufficient, the amount of C-S-H gel generated is large, and the ITZ structure is more compact; although steam curing accelerates early hydration, the later hydration is insufficient, resulting in more interface defects. It should be noted that standard curing is more suitable for engineering scenarios pursuing long-term interfacial bond performance, while steam curing can meet the requirements of high early strength in precast concrete components. The selection of curing system should be determined according to specific engineering needs.

In terms of environmental conditions, the dry environment will cause concrete to lose water, and the interfacial bond strength will decrease by 15%-20%; the humid environment is conducive to the development of interface performance, but long-term immersion will reduce the chemical bond force, making the bond strength decrease by 5%-10%.

5) Law of Multi-Factor Coupling Effect

The analysis of variance of the orthogonal test shows that the order of influence of each factor on the interfacial bond performance is: copper tailings content > recycled aggregate replacement rate > steel bar type > curing system. The law of multi-factor coupling effect is:

(1) There is a significant interaction between copper tailings content and recycled aggregate replacement rate, and the optimization effect of copper tailings is more obvious under high recycled aggregate replacement rate;

(2) The interaction between steel bar type and copper tailings content is significant, and the synergistic effect of ribbed steel bars and copper tailings can maximize the interfacial bond performance;

(3) The interaction between curing system and copper tailings content is not significant, but standard curing can give full play to the pozzolanic effect of copper tailings.

Through orthogonal test optimization, the optimal parameter combination for interfacial bond performance is obtained: copper tailings content 20%, recycled aggregate replacement rate 50%, HRB400 ribbed steel bars, standard curing. Under this combination, the ultimate bond strength can reach 3.03MPa.

C. DISCUSSION ON MEASURES TO IMPROVE INTERFACIAL BOND PERFORMANCE

Based on the above research results, the following measures to improve the interfacial bond performance are proposed:

(1) Optimize the copper tailings content: Control the copper tailings content in the range of 18%-22% to give full play to its filling effect and pozzolanic effect and improve the interfacial microstructure;

(2) Control the recycled aggregate replacement rate: Control the recycled aggregate replacement rate within 50%. If it is necessary to increase the replacement rate, pre-treatment processes (such as mechanical grinding, chemical modification) can be used to improve the surface performance of recycled aggregates;

(3) Select appropriate steel bar type: Prioritize the use of HRB400 and above grade ribbed steel bars to enhance the mechanical interlocking force and improve the interfacial bond strength;

(4) Optimize the curing system: Adopt the standard curing system to ensure sufficient cement hydration, or adopt the "steam curing + standard curing" composite curing system to balance the early strength and later interface performance;

(5) Interface modification treatment: Apply interface agent on the surface of steel bars or adopt rust pretreatment to enhance the chemical bond force; add a small amount of nano-materials (such as nano-SiO_2) to concrete to further densify the ITZ structure.

VI. RESEARCH CONCLUSIONS

A. CORE CHARACTERISTICS OF INTERFACIAL BOND PERFORMANCE BETWEEN WASTE COPPER TAILINGS RECYCLED CONCRETE AND STEEL BARS

The interfacial bond performance between waste copper tailings recycled concrete and steel bars shows significant parameter dependence, especially when incorporating high-performance textile fibers to bridge micro-cracks and regulate the mechanical properties of the composite matrix. Its core characteristics are defined:

(1) The interfacial bond force is composed of chemical bond force, mechanical interlocking force, and frictional resistance, among which mechanical interlocking force is the dominant factor;

(2) The incorporation of copper tailings can significantly improve the interfacial bond performance, which is manifested by the increase of ultimate bond strength, the decrease of peak slip, the gentle descending section of the load-slip curve, and the enhancement of interface ductility and bearing stability;

(3) The interfacial bond performance is positively correlated with the basic mechanical properties of concrete, and negatively correlated with the ITZ thickness and porosity. Copper tailings realize the improvement of interfacial bond performance by optimizing the mechanical properties and microstructure of concrete.

B. ACTION LAWS AND MECHANISMS OF EACH INFLUENCING FACTOR

(1) Copper tailings content: The optimal content range is 18%-22%, which thins the ITZ thickness, reduces the porosity, generates more C-S-H gel, and improves the interfacial bond strength through the filling effect and pozzolanic effect;

(2) Recycled aggregate replacement rate: The critical replacement rate is 50%, beyond which the interfacial bond performance deteriorates significantly, due to the loose ITZ structure caused by the mortar layer on the surface of recycled aggregates;

(3) Steel bar type: The interfacial bond performance of HRB400 ribbed steel bars is better than that of HPB300 smooth steel bars, and mechanical interlocking force is the core reason for the difference between them;

(4) Curing system: Standard curing is better than steam curing, and sufficient hydration is the key to the development of interface performance;

(5) Multi-factor coupling: There is a significant interaction between copper tailings content and recycled aggregate replacement rate, and the optimization effect of copper tailings is more prominent under high replacement rate.

C. RECOMMENDATIONS FOR OPTIMAL PARAMETER COMBINATION

Comprehensive macro and micro test results, the optimal parameter combination for the interfacial bond performance between waste copper tailings recycled concrete and steel bars is recommended as follows:

Copper tailings content: 20% (replacing natural fine aggregates);

Recycled aggregate replacement rate: $\leq$50% (replacing natural coarse aggregates);

Steel bar type: HRB400 ribbed steel bars (diameter $\geq$16mm);

Curing system: Standard curing (temperature 20$\pm$2°C, humidity $\geq$95%, curing for 28d).

Under this combination, the ultimate interfacial bond strength can reach 3.03MPa, which meets the design requirements of general concrete structures.

AUTHOR CONTRIBUTIONS

Conceptualization –Changfa Li and Zheng Zhong; methodology – Changfa Li and Zheng Zhong; investigation – Changfa Li and Zheng Zhong; writing-original draft preparation – Changfa Li and Zheng Zhong. All authors have read and agreed to the published version of the manuscript.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

FUNDING

This research was supported by, Jiangxi Institute of Technology School-level Natural Science Project "Study on Bond Performance between Reinforcement and Recycled Concrete with Waste Copper Tailings" Project Number: 232ZRZD02.

ACKNOWLEDGEMENTS

Not applicable.

REFERENCES

[1] N. Lv, X. Li, X. L. Liang, X. Yuan, G. X. Fang, and B. Song, “Analysis of physical and mechanical properties of 3D printed copper tailings sand concrete,” Metal Mine, no. 10, pp. 253-258, 2023, doi: 10.19614/j.cnki.jsks.202310035.
[2] M. F. Gou, L. F. Zhou, and N. W. Y. Then, “Utilization of tailings in cement and concrete: A review,” Science and Engineering of Composite Materials, vol. 26, no. 1, pp. 449-464, 2019, doi: 10.1515/secm-2019-0029.
[3] H. Q. Zhang, Q. Y. Li, J. Wen, H. Y. Shen, Z. Wang, B. L. Yu, et al., “Utilization status and prospect of copper tailings resources,” Modern Mining Industry, vol. 33, no. 01, pp. 127-131, 2017, doi: 10.3969/j.issn.1674-6082.2017.01.031.
[4] Y. G. Zhao, Y. Chen, and C. L. Wang, “Research progress on the application of tailings sand in concrete,” New Building Material, vol. 52, no. 09, pp. 127-130, 2025.
[5] D. Y. Ji, W. T. Xu, and Z. Q. Xie, “Research progress and application prospect of recycled concrete,” Journal of Puyang Vocational and Technical College, vol. 38, no. 06, pp. 9-13, 2025.
[6] Z. X. Wu, B. Chen, M. Y. Li, Z. F. Pan, Y. Fang, and X. Y. Ye, “Direct shear test and numerical simulation of recycled concrete-ordinary concrete interface,” Structural Engineers, vol. 41, no. 05, pp. 195-204, 2025, doi: 10.15935/j.cnki.jggcs.202505.0022.
[7] W. Ma, L. Yan, and B. Kasal, “Bond and tensile properties of flax textile reinforced recycled aggregate concrete: Strategies for interfacial enhancement and corresponding mechanisms,” Case Studies in Construction Materials, vol. 21, Art. no. e04006, 2024, doi: 10.1016/j.cscm.2024.e04006.
[8] Q. Q. Hao, M. Y. Luo, Y. H. Zhao, and B. W. Xiao, “Influence of aggregate particle size and water-cement ratio on the interfacial transition zone of recycled concrete,” Journal of Lanzhou Institute of Technology, vol. 32, no. 05, pp. 101-106, 2025.

[9] D. F. Wang, M. Y. Zhu, Y. P. Luo, et al., "Research on mix ratio design of copper tailings geopolymer concrete," Construction Technology (Chinese and English), vol. 51, no. 14, pp. 105-109+119, 2022, doi: 10.7672/sgjs2022140105.
[10] D. Darwin and A. B. Matamoros, "Bond and development of straight reinforcing bars in tension," ACI 408R-03), American Concrete Institute, Farmington Hills, Mich, p. 48, 2003.
[11] H. W. Li, "Research on the failure mechanism of reinforced concrete under cyclic loading[D]," Chongqing Jiaotong University, 2023, doi: 10.27671/d.cnki.gcjtc.2023.001336.
[12] H. Jalilifar and F. Sajedi, "Micro-structural analysis of recycled concretes made with recycled coarse concrete aggregates," Construction and Building Materials, vol. 267, Art. no. 121041, 2021, doi: 10.1016/j.conbuildmat.2020.121041.
[13] L. J. Ouyang, Z. W. An, W. T. Yang, B. Ding, and B. Zen, "Research progress on the micro-characteristics of concrete interfacial transition zone (ITZ)," Concrete and Cement Products, no. 02, pp. 7-12, 2018, doi: 10.19761/j.1000-4637.2018.02.002.
[14] H. Z. Wu, J. Z. Peng, Y. X. Pan, G. Yu, S. F. Zen, and H. J. Xu, "Research progress of copper tailings in cement production and concrete application," Bulletin of the Chinese Ceramic Society, vol. 44, no. 06, pp. 2172-2180+2192, 2025, doi: 10.16552/j.cnki.issn1001-1625.2024.1349.
[15] China Architecture and Building Press – GB/T 25177-2010 – Recycled Coarse Aggregates for Concrete, 2010.
[16] China Planning Press – GB/T 50367-2013 – Code for Design of Strengthening Concrete Structures, 2013.
[17] Ministry of Housing and Urban-Rural Development of the People's Republic of China and State Administration for Market Regulation – GB/T 50081-2019 – Standard for Test Methods of Physical and Mechanical Properties of Concrete, Beijing: China Architecture and Building Press, 2019.