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A Review: The Modification Methods of Concrete Recycled Coarse Aggregates

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Abstract: ***In recent years, the rapid development of the construction industry has led to the abandonment or demolition of numerous buildings, resulting in an increasingly prominent issue of waste concrete accumulation. However, the recycling rate of construction waste remains low. Recycled coarse aggregates are coated with a significant amount of old cement mortar, which increases their water absorption and introduces numerous weak interfacial transition zones (ITZs) in recycled concrete. These weak ITZs significantly impair the mechanical properties of recycled concrete. This paper reviews methods for removing old cement mortar from recycled coarse aggregates and enhancing the weak interfaces in recycled concrete, analyzing their advantages, disadvantages, applicability, and environmental-economic benefits.***

Keywords: Construction waste, Recycled coarse aggregates, Modification methods, Resource utilization, Old mortar.

1. Introduction

With the rapid development of industries, towns and other sectors in our country, a large number of existing buildings have been demolished and rebuilt, generating a huge amount of construction waste. In recent years, the output of construction waste in large and medium-sized cities in China has exceeded 2 billion tons, accounting for about 40% of the country's solid waste. According to the industry research report released by the CRI Industry Research Institute in 2022, the utilization rate of construction waste in some developed countries is over 90%, while the resource utilization rate of construction waste in China is around 5%. The utilization rate of construction waste resources in our country is relatively low. The "14th Five-Year Plan" attaches great importance to the resource utilization of construction waste[1].

Although significant progress has been made in the treatment of construction waste in China in recent years, landfill and random piling and discharging remain the primary methods. By summarizing the modification methods of recycled aggregates at home and abroad, analyzing the basic properties of recycled aggregates and the modification effects of modification methods on recycled aggregates, classifying and discussing according to the modification methods, exploring their advantages and disadvantages as well as existing problems, providing directions for the research and development of recycled aggregates, and offering references for subsequent research.

2. Physical Enhancement

2.1 Mechanical Grinding

Mechanical grinding is a process where recycled aggregates provided by external equipment collide with each other, causing friction between the materials or contact and impact between the recycled aggregates and the outside world, in order to remove the cement mortar adhering to their surfaces. Li[2, 3] found that when mechanical grinding was used to strengthen the recycled coarse aggregates, the old mortar on the surface of the recycled coarse aggregates could fall off after mutual collision. Some high-quality recycled coarse aggregates had the same performance as natural aggregates, and at the same time, the physical properties of the recycled fine aggregates were also improved to a certain extent. Quattrone[4] removed the adhering mortar layer on the surface of the recycled coarse aggregate by using mechanical grinding and ball milling techniques, resulting in a significant reduction in the water absorption rate of the recycled coarse aggregate and a significant improvement in the mechanical properties of the modified recycled concrete.

2.2 Heat Treatment

Peng[5] subjected the recycled coarse aggregates to heat treatment at different high temperatures. The test results showed that when the temperature was 350℃ and combined with mechanical treatment, the physical properties of the modified recycled coarse aggregates were improved in all aspects, among which the water absorption rate decreased by approximately 27%. However, if the temperature is too high (500℃ and 750℃), it will have an adverse effect on the recycled coarse aggregates. Yoon[6] demonstrated that by first calcining the recycled aggregates at 600°C for 1 hour and then grinding them for 1 to 12 hours, the adhered mortar on the surface of the recycled aggregates can be effectively removed. Moreover, calcination can also remove impurities and clay minerals, etc. The treated recycled aggregates are purer. This modification method can significantly reduce the water absorption rate of the recycled aggregates. A large number of research results show that the higher the heating temperature is, the easier the mortar is to be removed. When the heating temperature exceeds 750℃, the residual cement mortar can be almost completely removed[7].

2.3 Acid Solution Soaking Method

The main components of cement include calcium oxide (CaO), silicon dioxide (SiO_2), aluminum oxide (Al_2O_3), and iron oxide (Fe_2O_3), etc. Most of them can react with acid solutions, causing the cement mortar to lose its bonding performance with aggregates, and thus achieving the peeling of the cement mortar from the aggregates[8]. Foreign scholar Saravanakumar[9] respectively studied the effects of pre-soaking three acid solutions, namely HCL solution, H_2SO_4 solution and HNO_3 solution, at room temperature of

27-30℃ for 24 hours on recycled aggregates. The results showed that the percentage of mass loss of recycled aggregates was 1.52%, 5.63% and 2.50% respectively. The changes of bulk density and water absorption rate are both recorded. Tanta[10] treated the recycled aggregates with a 0.8mol/L HCL solution. The compressive and tensile strengths of the recycled concrete prepared from the treated aggregates were 25.3% and 22.5% higher than those of the untreated recycled aggregate concrete, respectively. Kim[11]'s research results also indicate that HCL solution can effectively remove old cement mortar. The performance summary of the recycled aggregates before and after pre-soaking treatment is shown in Table1

Table 1: The properties of recycled aggregates before and after pre-soaking treatment

Performance of recycled aggregates	Particle size/mm	Before pre-soaking treatment	After pre-soaking treatment		
			HCL	H_2SO_4	H_3PO_4
Water absorption rate/%	20	1.65	1.45	1.48	1.53
	10	2.63	2.31	2.37	2.41
Chloride ion content/%	20	0.0016	0.0025	0.0001	0.0001
	10	0.0012	0.0056	0.0001	0.0001
Sulfate content/%	20	0.0025	0.0076	0.1090	0.0110
	10	0.0025	0.0082	0.1040	0.0109
pH	20	10.46	9.07	8.95	8.55
	10	11.63	9.34	9.35	9.33

2.4 Ultrasonic Cleaning

Put the recycled aggregates into the ultrasonic bath for 10 minutes of cleaning, then continue to clean them with clean water for another 10 minutes. Repeat this process several times until the water used to clean the aggregates becomes clear. Through ultrasonic cleaning technology, the loose particles on the surface of the recycled aggregates can be removed, and the bonding strength between the new cement slurry and the recycled aggregates can be improved. The compressive strength of the recycled coarse aggregates prepared from the recycled concrete after being treated by ultrasonic cleaning technology has increased by 7%[12].Xiao, Zhang[13, 14] successfully raised the surface temperature of the recycled aggregates to 300 degrees Celsius by adopting a microwave heating cycle, while maintaining a relatively low internal temperature of the aggregates to effectively remove the cement mortar adhering to the surface of the recycled aggregates.

3. Strengthen the Interfacial Strength of Recycled Concrete

3.1 Carbonization Treatment

Carbonization is the process in which CO_2 gas from the surrounding environment diffuses into the interior of concrete through its pores and dissolves in the pore water. The CO_2 dissolved in the pore water reacts with the alkaline substances in the concrete.

Carbonization treatment can be classified into solution pre-immersion carbonization treatment[15, 16], CO_2 carbonization treatment[17], and microbial carbonization treatment[18]. Xiao[19, 20] demonstrated that carbonization of recycled aggregates can enhance the strength of the transition zone at the interface between recycled aggregates and cement mortar, as well as the peak load of compressive strength of recycled concrete, and reduce the peak displacement of compressive strength. And as the water-cement ratio increases, this effect becomes more and more obvious. Therefore, many scholars use carbonization treatment methods to modify recycled aggregates. Carbonization can not only enhance the performance of recycled aggregates and recycled concrete, but also improve the durability of recycled concrete[21]. Carbonization treatment does not introduce new ions or new components. However, it should be noted that the pH value and the ability to combine chloride ions of the aggregates after carbonization will both decrease. The degree of carbonization should be controlled to avoid excessive residual calcium hydroxide and increase the risk of alkali-aggregate reaction[22].

3.2 Chemical Solution Immersion

Chemical solution soaking is mainly aimed at addressing the defects of high porosity and high water absorption rate of the residual old mortar on the surface of recycled aggregates. The main reason for the low strength of recycled concrete is the poor adhesion between the old cement mortar and the new cement mortar remaining on the recycled aggregate[23], which is prone to form a weak interface. Sodium silicate solution[24] and sodium silicate (mainly composed of SiO_2 and Na_2O) can trigger a chemical reaction with the old cement mortar to produce C-S-H gel. This chemical substance has a bonding effect. It can enhance the adhesion between new and old cement mortars and increase the interfacial strength of concrete. Relevant studies have shown that the recycled aggregates modified with sodium silicate can improve the mechanical properties of recycled concrete by more than 10%[25]. Wang[26] treated recycled coarse aggregates jointly with 5% sodium silicate solution and 10% silane solution by mass. The water absorption rate of the modified recycled coarse aggregates decreased by 57.1%, and the strength of recycled concrete increased by 35.8%. The summary of water absorption rate and crushing indicators of recycled aggregates under different strengthening mechanisms is shown in Table 2

Table 2: Water absorption rate and crushing index of recycled aggregates under different strengthening mechanisms

	Type	Concentration	Strengthen time	Water absorption rate/%	Strengthening percentage/%	Grinding value%
Initial value				6.7		16.5
Strengthening mechanism	Nano-SiO_2	2%	48	4.7	29.6	11.6
	$NaSiO_3$	7%	5	5.6	16.4	13.8
	HCL	3%	2	5.3	20.9	13.5

3.3 Microbial Modification

In recent years, relevant scholars have also begun to pay attention to the influence of microbial-induced calcium carbonate precipitation (MICP) technology on the modification effect of recycled coarse aggregates. The main mechanism is that microorganisms can produce calcium carbonate ions through relevant reactions. The calcium

carbonate ion products can fill the pores and microcracks in the old mortar on the surface of the recycled coarse aggregates, thereby increasing the density of the recycled coarse aggregates and achieving the purpose of strengthening. During the metabolic process of urease microorganisms, a urease is produced. Urease can make urea generate carbonate ions. These carbonate ions can chemically react with calcium ions in the surrounding medium to produce calcium carbonate, which fills the pores of the old mortar on the surface of the recycled coarse aggregate, thereby strengthening the recycled coarse aggregate[27]. Fu[28]'s research indicates that after the recycled fine aggregates are modified by MICP technology, the water absorption rate and crushing index of the aggregates will decrease. Meanwhile, when $CaCl_2$ is used as the calcium source of the microbial cementing fluid, the modification effect of the aggregates will be better. Hao[29] modified the recycled aggregates by using microbial mineralization technology, and both the quality and apparent density of the modified aggregates were improved. Zhang [27] conducted experimental comparisons. When MICP treated the aggregates for 7 days, the crushing indicators of recycled coarse aggregates and recycled brick aggregates decreased by approximately 24.4% and 13.3% respectively, and their water absorption rates decreased by approximately 14.8% and 4.6% respectively. It is also recommended that the optimal processing time be within 3 to 7 days.

The summary of the technical methods of interfacial strengthening of recycled concrete is shown in the following Table 3.

Table 3: Summary of technical methods for strengthening the interfacial strength of recycled concrete

Method	Advantages	Disadvantages	Application analysis
Carbonization	Strengthen the strength of the interface transition zone; Reduce the water absorption rate of recycled aggregates; Enhance durability	Reduce the PH and the chloride ion binding ability Alkali-aggregate reaction risk	Mass production Immature carbonization rate and equipment
Solution soaking	Strengthen the performance of the interface transition zone; Reduce the water absorption rate of recycled aggregates	Introduce harmful substances; Environmental pollution	Small-scale processing
Microbial modification	Strengthen the performance of the interface transition zone; Reduce the water absorption rate of recycled aggregates; Pollution-free and environmentally friendly	Flora species is limited, difficult to cultivate, high cost	Small-scale processing

4. Conclusion and Outlook

1) The methods for removing old cement mortar include mechanical grinding, heat treatment, soaking in acid solution and ultrasonic cleaning, etc. Among them, the organic combination of heat treatment and mechanical grinding is a highly potential development direction for removing old cement mortar. This method requires exploring the optimal heating temperature and a more reasonable grinding method to ensure the removal effect while minimizing the damage to the structure of the recycled aggregates themselves.

2) Methods to enhance the interfacial strength of recycled concrete include carbonization treatment, chemical solution immersion, and microbial modification, etc. Among them, carbonization treatment is an effective way to enhance the interfacial strength of recycled aggregates. However, a large number of experimental studies are still needed on how to accelerate the carbonization reaction rate and how to effectively control the degree of carbonization.

3) In addition to the method of treating recycled aggregates to enhance the interfacial strength of recycled concrete, polymer emulsions can also be added during the mixing process of recycled concrete to improve its mechanical and durability properties. Currently, styrene/acrylate polymer latex and polyvinyl alcohol have been studied more extensively.

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