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Research Progress on Mechanical Properties and Frost Resistance of Rubber Recycled Concrete

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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Review Article

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ABSTRACT

The use of recycled waste tires and construction and demolition wastes as aggregates in concrete after treatment as required not only contributes to environmental sustainability, but also alleviates the growing demand for natural aggregates in concrete production. This paper focuses on the mechanical properties and frost resistance of rubberized recycled concrete, including the effects of rubber and recycled aggregates on the mechanical properties and frost resistance of concrete, as well as measures to improve the mechanical properties and frost resistance of rubberized recycled concrete. Existing studies show that the mechanical properties of concrete gradually decrease with the increase of rubber and recycled aggregate admixture. Due to the high number of defects in recycled aggregate, it has a negative effect on the frost resistance of concrete. Rubber particles have air-entraining properties and can be incorporated into concrete to enhance the frost resistance of concrete. The frost resistance of rubber recycled concrete can be improved by mixing appropriate amount of fiber, rubber or rubber modification treatment.

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1. INTRODUCTION

Accelerated modernization and industrialization are increasing the demand for transportation facilities, and there is an urgent need to dispose of wastes that have a direct and harmful impact on the global environment. Worldwide, nearly 1 billion used tires are generated annually, and it is expected that the number will reach 1.2 billion by 2030 [1], which will further increase the amount of scrap tires generated. On the other hand, a large amount of construction waste is generated during the demolition and remodeling of old buildings and the construction of new buildings, causing serious damage to the ecological environment [2]. It is one of the effective methods of resource utilization of waste tires and construction wastes that waste tires and construction demolition wastes are processed as necessary and used to prepare rubber recycled concrete according to the specified particle size and form [2a-2c]. Therefore, the research and utilization of rubber recycled concrete is of great significance for China to take the road of sustainable development.

With the popularization of the concept of sustainable development and the enhancement of environmental awareness, the research and application prospects of rubber recycled concrete will continue to expand. Studies have shown that the old mortar content, particle size and shape of recycled aggregate will affect the physical and mechanical properties of concrete [3,4]. Therefore, with the increase of recycled aggregate content, the mechanical properties of concrete will gradually decrease. Rubber is characterized by high elasticity, low strength and hydrophobicity, and its incorporation into concrete will reduce the brittleness of concrete and enhance its ductility and toughness [5,6]. At present, rubber recycled concrete is more used in roads, and some relevant research results have been accumulated in the strength theory and engineering experience of rubber recycled concrete.

In northern China, due to external temperature fluctuations and other factors, concrete exhibits significant freeze-thaw damage, resulting in shorter service life and increased maintenance and repair costs. Therefore, the durability of construction projects should not be neglected. The frost protection performance of concrete is mainly affected by its pore structure, water content and antifreeze dosage. Compared with conventional concrete, a large amount of cement matrix is attached to the surface of recycled aggregates, forming a weak interfacial transition zone between the old cement matrix and the surrounding concrete matrix [7,8]. The frost protection properties of recycled concrete deteriorate rapidly with the increase of recycled coarse aggregate admixture. In addition, rubber has significant air-entraining ability, which effectively enhances the pore structure of concrete; appropriate amount and particle size of rubber material can improve the frost resistance.

The reuse of waste concrete and rubber can reduce the impact of “waste” on the environment, alleviate the pressure on the supply and demand of natural aggregate resources, and improve the quality of life in society. In order to promote the application of recycled rubber concrete, to solve the problem of improving the mechanical properties of recycled rubber concrete and the safety of buildings in cold regions in the freeze-thaw cycle, it is necessary to further study the mechanical properties and frost resistance of recycled rubber concrete. In this paper, the effects of rubber and recycled aggregate on the mechanical properties and frost resistance of concrete and improvement measures are summarized and described.

2. STUDY ON MECHANICAL PROPERTIES OF RUBBER RECYCLED CONCRETE

Mechanical properties are the most basic properties of concrete and are one of the prerequisites for the application of concrete in engineering. When rubber and recycled aggregates are incorporated in concrete, the mechanical properties of concrete decrease significantly with the increase in the amount of rubber and recycled aggregates incorporated. Waste rubber and recycled aggregates have different particle sizes, shapes and pretreatment methods in concrete formulation. Significant differences in the strength of concrete existed due to different rubber and recycled aggregate admixture, particle size and pretreatment methods [9,10]. The 28-day compressive strength of rubberized concrete with different rubber admixtures at 100% replacement of recycled aggregates is shown in Fig. 1 [11-13].

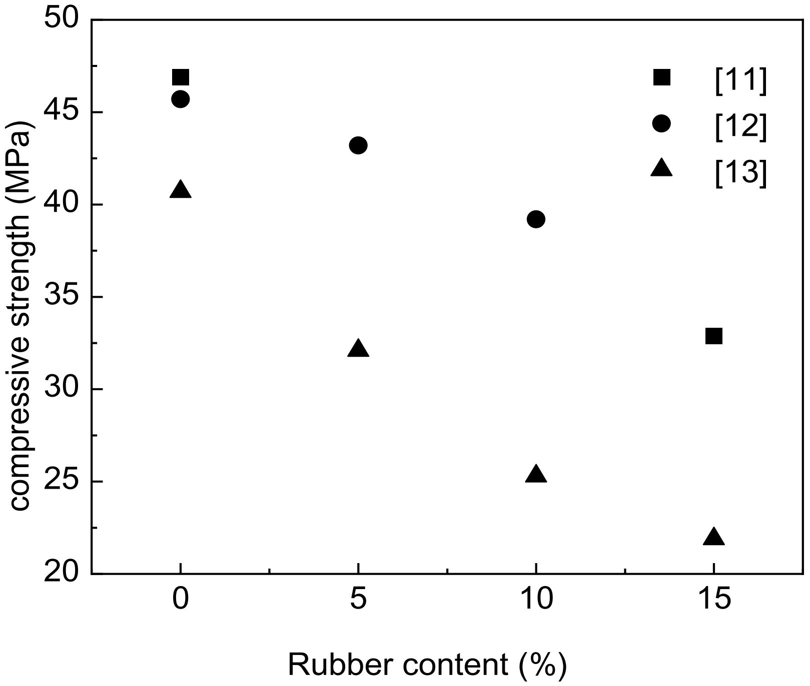

Fig. 1. Compressive strength of rubberized concrete with 100% replacement of recycled aggregates

2.1 Rubberized Aggregate Impact

A considerable body of relevant literature has demonstrated that the mechanical properties of rubber recycled concrete are influenced by varying rubber content, particle size, and methods for incorporating recycled aggregate. Wang Wenrui et al. [11] investigated the effect of rubber powder and admixture on the properties of recycled concrete. The test results showed that the rubber admixture reduced the compressive strength and flexural strength of recycled concrete within a certain range, and the strength of recycled concrete increased with the increase of rubber powder mesh, and the effect on the flexural strength of concrete was not obvious. Zhang Xia [14] investigated the influence of rubber content on the axial compressive strength and elastic modulus of recycled concrete. The findings indicate that the incorporation of rubber powder leads to a reduction in both axial compressive strength and elastic modulus. Notably, when the rubber powder content reaches 7%, a significant decrease in axial compressive strength is observed. However, by controlling the rubber powder content within a certain range (5%), the strength of rubber recycled concrete becomes comparable to that of conventional concrete, albeit with a substantial reduction in elastic modulus. Wang Liankun et al. [12] investigated the workability and mechanical properties of self-compacting concrete with recycled aggregates and rubber particles at different substitution rates. The results showed that the working and mechanical properties of self-compacting concrete decreased to different degrees with the increase of recycled aggregate and rubber particles admixture, and the cubic compressive strength decreased by 20.2%, 24.6% and 31.4% compared with that of ordinary concrete when the aggregate substitution rate was 100% and the rubber admixture was 0%, 5% and 10%, respectively. Ataria and Wang [13] primarily investigated the workability, mechanical properties, and durability of concrete incorporating 100% recycled aggregate and rubber crumb at varying replacement rates (5%, 10%, 15%, and 20%). The findings revealed that the addition of rubber particles to recycled aggregate concrete resulted in a reduction in compressive strength, with a more pronounced decrease observed as the content of rubber particles increased. Specifically, the 28-day compressive strength of rubber-reclaimed aggregate concrete with a concentration of 5% rubber particles was found to be lower by approximately 21.1% and 32.8% compared to reclaimed aggregate concrete and control concrete, respectively.

2.2 Recycled Aggregate Impact

From the beginning of application up to now, researchers from all over the world have a certain common understanding of the mechanical properties of recycled concrete: the mechanical properties of recycled concrete are slightly worse than ordinary concrete. There are hardened mortar and a lot of interfacial structures on the surface of coarse aggregate of recycled concrete, so its compressive strength is lower than that of ordinary concrete, and the compressive failure is more complicated [15]. Amiri et al. [16] conducted experimental research on the influence of waste rubber powder replacing cement and recycled concrete aggregate substituting coarse aggregate simultaneously on the mechanical properties and durability of concrete. The results show that increasing the replacement rate of recycled materials can reduce the mechanical properties of concrete, and because waste rubber powder and recycled aggregate have negative effects on the cement matrix and the interfacial transition zone respectively, the mechanical properties of concrete specimens are greatly reduced by two recycled materials. The test results of Xiao Jianzhuang et al. [17] show that with the increase of the replacement rate of recycled coarse aggregate, the cubic compressive strength of recycled concrete generally shows a downward trend. However, by adjusting the water-cement ratio, the compactness of recycled concrete can be enhanced and the crushing index can be reduced, so as to obtain recycled concrete that meets the design standards of compressive strength. Wang et al. [18] summarized the existing experimental research and explored the effect of adding fresh concrete waste aggregate on the mechanical properties of concrete. The results indicate that the mechanical properties of concrete decrease with an increase in the fresh concrete waste aggregate ratio. When the FCWA content is 30%, the compressive strength of concrete decreases by 35.7% to 58.7%, the elastic modulus decreases by 36% to 55%, and the shrinkage rate increases by 66% to 108%.

3. RESEARCH ON FROST RESISTANCE OF RUBBER RECYCLED CONCRETE

3.1 Rubberized Aggregate Impact

The freeze-thaw resistance of rubber recycled concrete is a crucial parameter for evaluating its durability in freezing and thawing conditions. It is closely associated with the incorporation of rubber aggregates, and an appropriate addition of rubber particles can significantly enhance the freeze-resistance properties of concrete. The presence of rubber particles effectively fills micropores within the concrete matrix, thereby reducing water penetration and mitigating freeze-thaw damage. Liu Liu [19] conducted freeze-thaw cycle tests on recycled concrete by incorporating varying amounts of nano-silica and rubber powder. The experimental results demonstrate that both the inclusion of rubber powder and nano-SiO_2 substantially improve the frost resistance performance of recycled concrete. Moreover, when maintaining a constant content level of nano-SiO_2, an increase in the amount of rubber powder leads to a decrease in quality loss rate during freeze-thaw cycles for recycled concrete specimens. This phenomenon can be attributed to an increase in surface cracks caused by higher levels of rubber powder content, which subsequently allows gradual filling with water within micro-cracks over time, ultimately resulting in reduced deterioration rates.

Rubber particles have the effect of air entraining, and their function is equivalent to that of air entraining agents [20]. Adding appropriate amount of rubber particles into hydraulic concrete can significantly improve the frost resistance of hydraulic concrete. Combined with the test results and engineering economy, it is recommended to add 5% recycled rubber particles into the preparation of hydraulic concrete [21]. Wang Tao and Chen Shengxia et al. [22,23] showed that the particle size of the added rubber particles had a significant impact on improving the frost resistance of rubber concrete, and only the rubber with a finer particle size could effectively improve the frost resistance of rubber concrete, while the coarse rubber particles with a particle size of 3-4 mm could not significantly improve the frost resistance of rubber concrete. Sun et al. [24] prepared rubber concrete by adding waste tire rubber particles with different particle sizes, dosage and pretreatment methods instead of fine aggregate, and studied the compressive strength of its freeze-thaw cycle from both macroscopic and microscopic aspects. The results show that the presence of rubber particles obviously limits the decline of concrete strength and weight during the freeze-thaw cycle, and the rubber fine aggregate with smaller particle size has a more significant effect on the freezing resistance of concrete.

3.2 Recycled Aggregate Impact

The frost resistance of rubber recycled concrete is influenced by factors such as the characteristics and dosage of recycled aggregate. Numerous studies have been conducted on freeze-thaw cycle experiments of recycled concrete, yielding valuable research findings. However, due to certain adverse factors associated with recycled aggregate, an increase in the content of recycled coarse aggregate accelerates the deterioration of frost resistance in recycled concrete. Therefore, it is recommended to control the mass content of recycled coarse aggregate within 50% [25]. Zaharieva et al. [26] performed freeze-thaw cycle tests on different dosages of recycled coarse and fine aggregate concrete under various environmental conditions, revealing that the freeze-resistance capability of recycled concrete is low and significantly affected by water saturation in its environment. Wang Chenxia et al. [27] observed a slightly lower frost resistance in recycled concrete compared to ordinary concrete, with further deterioration occurring after an increased number of freeze-thaw cycles. After 150 cycles, the dynamic elastic modulus decline in recycled concrete was found to be 9.3% higher than that in ordinary concrete, accompanied by a mass loss rate exceeding ordinary concrete by 0.6%.

At the same time, the content of recycled coarse aggregate also has a certain impact on the mass loss rate of recycled concrete in the freeze-thaw cycle, and has a certain regularity. Among them, the mass loss rate of recycled concrete with a content of 50% or less during the freeze-thaw process is similar to that of ordinary concrete specimens [25]. Cheng Liang et al. [28] used C30 recycled concrete as the test material to compare and analyze the mass loss of recycled concrete with 0, 25%, 50%, 75% and 100% recycled aggregate content in freeze-thaw cycle tests. The test results show that the maximum mass loss rates of each content are 1.90%, 1.82%, 1.63%, 3.55% and 5.47% respectively at 200 freeze-thaw cycles, and the frost durability of recycled concrete with 50% coarse aggregate content is comparable to that of ordinary concrete, which is better than that of other recycled concrete. Yang Rong [29] used recycled aggregate to replace part of the coarse aggregate in concrete, and tested the frost resistance of concrete, with the increase of the replacement rate of recycled aggregate, under the same condition of water-cement ratio, the mass loss rate of concrete is increasing, when the water-cement ratio is 0.6 and the replacement rate of recycled aggregate is 100%, the mass loss rate of concrete is as high as 5.37%.

4. IMPROVEMENT MEASURE

4.1 Mechanical Property Improvement

The untreated rubber is an organic macromolecular material with an inert surface, resulting in a relatively poor interface between rubber particles and cement mortar. Subsequently, extensive microscopic cracks appear near the rubber particles after concrete curing [9]. During the process of crushing and recovering recycled aggregate, its microstructure exhibits defects such as pores, micro-cracks, and a weak interface transition zone, which can also impair the mechanical properties of recycled aggregate concrete [30]. Therefore, enhancing the interface between rubber and recycled aggregate as well as cement mortar can be achieved by adjusting the content of rubber and recycled aggregate, incorporating modifiers or fiber materials, and optimizing the mix ratio. Furthermore, heat treatment of rubber-recycled concrete has been found to enhance its strength and stability while improving its mechanical properties. These methods can be employed individually or in combination based on specific engineering requirements and desired concrete performance to effectively enhance the mechanical properties of rubber-recycled concrete.

Wang Huanyu [31] prepared modified rubber recycled concrete by using rubber sodium hydroxide modification and urea oxide modification methods to study the change rule of mechanical properties and durability of concrete. At the same time, polypropylene fiber was added to further improve the mechanical properties of rubber recycled concrete and improve the durability of rubber recycled concrete under the premise of meeting the strength conditions. The results show that after modification, the compressive strength of 60-mesh rubber recycled concrete is increased by 6.3%, the folding strength is increased by 4.7%, the splitting tensile strength is increased by 6.9%, and the axial compressive strength is increased by 5.2%. When the content of rubber powder is 5%, the compressive strength, folding strength and splitting tensile strength of 60-mesh modified rubber polypropylene fiber recycled concrete are increased by 3.4%, 14.3% and 31% respectively.

Tu Yanping et al. [32] used the mass substitution method to study the effect of single and compound mixing of nano-SiO_2 (replacing cement) and rubber powder (replacing natural river sand) on the compressive strength of recycled concrete. The experimental results show that with the increase of rubber powder substitution rate, the compressive strength of reclaimed concrete after 7 days curing is lower than that of ordinary concrete. When the rubber powder substitution rate is lower than 5%, the compressive strength of reclaimed concrete after 28 days curing is increased. With the increase of the substitution rate, the compressive strength of the recycled concrete after 7 days of curing increases. When the two are mixed, they can not only make up for the reduction of the strength of rubber powder incorporation, but also restrain the slump deterioration after the incorporation of nano-SiO_2, so as to make up for each other.

4.2 Frost resistance Improvement

Rubber aggregate in concrete can be approximated as “air-entraining agent”, due to the rough surface of the rubber, the introduction of a large number of closed micro-bubbles, which can buffer the freezing and expansion stress and effectively inhibit the emergence and development of cracks. Rubber powder has a larger surface area than rubber particles, which can entrap more air and improve the frost resistance of concrete [33]. However, the bond between rubber particles and the surrounding cement matrix is weak, and this bond defect is unfavorable to the anti-freezing durability of cement-based composite materials. By improving the bond performance of rubber-cement interface and reducing the bond defect, it is expected to further improve the frost resistance of rubber concrete.

Alsaif et al. [34] evaluated the freeze-thaw performance of steel fiber reinforced rubber concrete, and the test results showed that all specimens underwent 56 freeze-thaw cycles without significant damage. Si Zheng et al. [35] investigated the frost resistance of recycled concrete with different volume admixture of basalt fiber and polyvinyl alcohol fiber in single admixture and mixed admixture. The test results show that external fiber mixing can improve the frost resistance of recycled concrete, while the effect of mixed fiber mixing is better than single fiber mixing, and the frost resistance of recycled concrete is optimal when the volume mixing amount of polyvinyl alcohol fiber and basalt fiber is 0.170% and 0.246%, respectively. Zhang Ke et al. [36] used two different types of modifiers, Span-40 and sodium dodecyl benzene sulfonate (surfactant), to modify waste tire rubber powder, and studied the effects of rubber content and rubber powder particle size on the antifreeze performance of recycled concrete. The test results show that the dynamic elastic modulus of concrete decreases uniformly during the whole freeze-thaw cycle, which indicates that the incorporation of rubber can improve the freeze-resistance of concrete, and the rubber content and rubber powder particle size have significant effects on the freeze-resistance of recycled concrete.

Various measures have been studied to improve the frost resistance of recycled concrete. Existing studies have shown that the incorporation of quantitative rubber particles and fibers can improve the frost resistance of recycled concrete, and the greater the amount of rubber particles and the smaller the particle size, the more the frost resistance of recycled concrete will be improved [37-39]. The experimental research results of Kardos et al. [38] validated the above conclusion and concluded that the optimal rubber content for improving the frost resistance of recycled concrete is 10%. Gao et al. [39] studied the frost resistance durability of recycled concrete with a volume content of steel fiber of 0-2%, and the test results showed that the frost resistance of recycled concrete was significantly improved after the addition of steel fiber, and the frost resistance of recycled concrete was the best when the steel fiber content was 1%. Yin Di et al. [40] studied the influence of the coupling effect of freeze-thaw and sulfate on the performance of recycled concrete, analyzed the mechanism leading to the deterioration of concrete, and proposed measures to improve the anti-deterioration performance of concrete, providing a reference for further improving the durability of concrete in cold environments.

5. CONCLUSION AND OUTLOOK

5.1 Conclusion

The incorporation of both rubber and recycled aggregate reduces the mechanical properties of concrete, appropriate rubber admixture and rubber particle size improve the frost resistance of recycled concrete, and recycled aggregate characteristics and admixture also affect the frost resistance of concrete. Physical or chemical treatment of rubber aggregate can improve the bond between rubber aggregate and cement matrix, thus improving the mechanical properties and frost resistance of concrete. According to the actual requirements, suitable rubber and recycled aggregate improvement measures should be selected to improve the mechanical properties and frost resistance of rubberized concrete.

5.2 Outlook

(1) At present, most of the strength grade of waste rubber recycled concrete is below C50, and the individual reaches C70. in order to obtain high strength waste rubber recycled concrete, the selection of raw materials, mixing ratio design and curing conditions need to be studied in depth.

(2) Carbonation resistance is an important indicator of the durability of concrete in engineering structures, therefore, the study of waste rubber recycled concrete carbonation resistance, to promote its application is of great significance, but the rubber substitution rate of waste rubber recycled concrete carbonation resistance less research.

(3) Before the practical application of concrete containing recycled materials, it is necessary to carry out strength and life prediction, respectively, for rubber concrete and recycled concrete more research, but less research on the recycled concrete after mixing rubber particles, especially in the different dosage of recycled coarse aggregate and rubber particles to replace the natural aggregates, the strength of the concrete and the prediction of the life of the comprehensive research is less.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author hereby declare that no generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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