Review Article

Research progress on mechanical propertiesand frost resistance of rubber recycled concrete

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ABSTRACT

Utilizing recycled waste tires and construction demolition waste as aggregates in concrete not only promotes environmental sustainability but also addresses the increasing demand for natural aggregates in concrete production. This paper mainly expounds the research progress of mechanical properties and frost resistance of rubber recycled concrete, including the influence of rubber and recycled aggregate on the mechanical properties and frost resistance of concrete, and the improvement measures. Previous studies indicate that as the content of rubber and recycled aggregate increases, the mechanical properties of concrete gradually decrease. While adding air-entrained rubber particles can enhance frost resistance, defects in recycled aggregate may have an adverse effect on it. The addition of an appropriate amount of fiber, rubber or modified rubber can improve the mechanical property and the frost resistance of rubber recycled concrete.

Keywords: Concrete; Rubber; recycled aggregates; mechanical properties; Frost resistance

1. INTRODUCTION

The acceleration of modernization and industrialization is driving the demand for transportation facilities and the urgent need to dispose of waste that directly harms the global environment. From a global perspective, approximately 1 billion used tires are generated annually, with an estimated increase to 1.2 billion by 2030 [1]. Consequently, the volume of scrap tires will continue to rise. Simultaneously, during the demolition and reconstruction of old buildings as well as new construction projects, a substantial amount of construction waste is produced, resulting in severe ecological damage [2]. Proper treatment of waste tires and building demolition waste is essential, and one effective approach involves preparing rubber recycled concrete according to specified particle sizes and forms. Therefore, researching and utilizing rubber recycled concrete holds significant importance for our country's pursuit 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 has the characteristics of high elasticity, low strength and hydrophobicity, and its incorporation into concrete will reduce the strength of concrete to a certain extent, but it can reduce its brittleness 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, the concrete exhibits evident freeze-thaw damage due to fluctuations in external temperature and other factors, resulting in reduced service life and increased maintenance and repair costs. Therefore, the durability of construction projects cannot be overlooked. The antifreeze performance of concrete is primarily influenced by its pore structure, water content, and the utilization of antifreeze agents. Compared to conventional concrete, a substantial amount of cement matrix adheres to the surface of recycled aggregate, creating a weak interface transition zone between the old cement matrix and surrounding concrete matrix [7,8]. The antifreeze performance of recycled concrete deteriorates more rapidly with an increase in recycled coarse aggregate content. Furthermore, rubber possesses significant air entraining capabilities that effectively enhance the pore structure of concrete; appropriate quantities and particle sizes of rubber materials can improve frost resistance.

The reuse of waste concrete and waste rubber can reduce the impact of "waste" on the environment, reduce the pressure of supply and demand of natural aggregate resources, and improve the quality of social life. In order to promote the application of recycled rubber concrete, solve the problem of improving the mechanical properties of rubber recycled concrete and the safety of buildings in the freezing and thawing cycle in the cold area, it is necessary to further study the mechanical properties and frost resistance of rubber recycled concrete. In this paper, the effects of rubber and recycled aggregate on the mechanical properties and frost resistance of concrete and the improvement measures are summarized and expounded.

2. STUDY ON MECHANICAL PROPERTIES OF RUBBER RECYCLED CONCRETE

Mechanical properties are the most basic properties of concrete, which is one of the preconditions for its application in engineering. When rubber and recycled aggregate are added to concrete, the mechanical properties of concrete decrease significantly with the increase of rubber and recycled aggregate content. Waste rubber and recycled aggregate have different particle size, shape and pretreatment methods in concrete preparation. Due to different rubber, recycled aggregate content, particle size and pretreatment methods, there are significant differences in concrete strength [9,10].

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. Tang Qingzhao [11] investigated the impact of rubber particles on the strength and carbonation resistance of recycled concrete. The test results indicate that the compressive strength of recycled concrete decreases with increasing rubber particle content but increases with age. When the rubber particle content is below 10%, there is no significant decrease in compressive strength observed in recycled concrete. However, when the rubber particle content exceeds 10%, there is a substantial reduction in compressive strength by over 20%. At a rubber particle content of 30%, the 28-day compressive strength of recycled concrete with rubber particles is reduced by up to 34% compared to the reference group.Zhang Xia [12] 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. Liang Jiongfeng et al. [13] studied the effects of different rubber and recycled aggregate content on the mechanical properties of concrete. The experimental results show that the addition of rubber particles can improve the ductility of recycled concrete, and the cubic compressive strength, prismatic compressive strength and splitting tensile strength of concrete decrease with the increase of rubber content and recycled coarse aggregate.

Ataria and Wang[14] 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.Amiri et al.[15] 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.

3. RESEARCH ON FROST RESISTANCE OF RUBBER RECYCLED CONCRETE

3.1Rubber 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 [16] 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 [17]. 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 [18]. Wang Tao and Chen Shengxia et al. [19,20] 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. [21] 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.

3.2Regenerated 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% [22]. Zaharieva et al. [23] 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. [24] 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 [22]. Cheng Liang et al. [25] 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. The Ma [26] test measured the mass loss at different freeze-thaw cycles. The results show that the mass loss increases with the increase of the number of freeze-thaw cycles. The incorporation of recycled aggregate further increased the mass loss after the same cycle, indicating that the freeze-thaw resistance decreased with the incorporation of recycled aggregate.

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 [27]. 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 [28] 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. [29] 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

The researchers believe that rubber can be used as a solid air entraining agent, thereby improving the frost resistance of concrete. 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. [30] 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. Li Xiaohui et al. [31] studied the law of influence of the change of basalt fiber content on the freeze-thaw resistance of concrete, and the results showed that the fiber incorporation of concrete could effectively reduce the degree of damage and deterioration caused by the freeze-thaw cycle of concrete, and significantly improve the freeze-thaw cycle resistance of concrete. Zhang Ke et al. [32] 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.

Many measures have been taken 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 [33-35]. The experimental research results of Adam et al. [34] validated the above conclusion and concluded that the optimal rubber content for improving the frost resistance of recycled concrete is 10%. Gao et al. [35] 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. [36] 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

Methods for improving the performance of rubber concrete and recycled concrete have been extensively studied. In general, physical or chemical treatment of rubber aggregates can improve the bond between rubber aggregates and cement matrix, thereby improving the mechanical properties and frost resistance of concrete. To improve the performance of recycled concrete, we can improve the performance of recycled aggregate itself or add mineral admixtures, fibers, admixtures and so on. According to the actual requirements, appropriate improvement measures were selected for rubber and recycled aggregate to improve the mechanical properties and frost resistance of rubber recycled concrete.

Recycling waste materials and using them in the concrete industry is a good solution to reduce natural resources and protect the environment. However, before its practical application, it is necessary to study the properties of concrete containing recycled materials. Although some research progress has been made, rubber recycled concrete still faces some challenges in engineering applications. For example, the treatment method of rubber aggregate still needs to be further optimized to improve its compatibility and bonding properties with the cement matrix. In addition, the quality and stability of recycled aggregates also require stricter control to ensure the reliability and durability of recycled concrete.

Therefore, the future research direction should focus on further improving the process technology and quality control means of rubber recycled concrete to improve its mechanical properties and frost resistance. At the same time, we should also explore the feasibility and economy of rubber recycled concrete in various engineering applications, and make greater contributions to the field of sustainable construction and environmental protection.

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