Research on the Influencing Factors and Measurements of Freeze-thawing Resistance of Recycled Concrete

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Abstract. With the introduction of green building, solid waste utilization has become a key research focus in civil engineering. Recycled concrete technology plays a crucial role in the sustainable development of the concrete industry. However, its durability in cold regions remains a pressing challenge for engineers. This paper reviews domestic and international studies to summarize the performance and degradation mechanisms of recycled concrete under freeze-thaw cycles, focusing on four factors: recycled aggregate proportion, freeze-thaw cycle conditions, water-to-cement ratio, and admixtures. Evaluation systems for frost resistance of recycled concrete are also summarized. Finally, improvement measures for enhancing the frost resistance of recycled concrete are proposed, providing a theoretical basis for further research and engineering applications in this field.

Keywords: Recycled concrete; freeze-thawing; factors; measurements.

1. Introduction

With rapid urbanization in China, there has been a significant increase in the production of waste concrete. Currently, the predominant disposal methods involve landfilling and stacking, leading to serious environmental pollution[1]. The technology of recycled concrete primarily involves crushing waste concrete into coarse aggregates and partially or entirely replacing natural aggregates, aiming to effectively utilize solid waste and conserve resources[2]. In line with the introduction of “Dual Carbon” plan, the government is actively promoting eco-friendly waste recycling measures. Considering the recycled concrete it embodies a green concept and holds significant research significance and value., it is gradually gaining momentum in the construction of new structures.

China experiences significant variations in climate conditions, particularly in the regions of the middle and upper reaches of the Yangtze River. These areas are characterized by substantial temperature fluctuations between day and night. As a result, concrete in these regions is susceptible to deterioration due to the effects of freeze-thaw cycles[3]. Although extensive research has been conducted on the impact of freeze-thaw cycles on conventional concrete[4], studies on the freeze-thawing resistance of recycled concrete are still in their early stages. Therefore, continuous and in-depth research is necessary to explore methods for improving the frost resistance of recycled concrete. This study aims to summarizing current research findings on the factors influencing the freeze-thaw resistance of recycled concrete, and it proposes technical measures to enhance frost resistance in practical engineering applications. The findings of this study are expected to provide valuable insights and serve as a reference for promoting the widespread utilization of recycled concrete.

2. Organization of the Text

2.1 Recycled aggregate

Generally speaking, frost resistance of recycled concrete is inferior to that of natural concrete [5]. Extensive freeze-thaw experiments revealed that the freeze-thaw resistance of nearly 100% recycled concrete specimens is lower than that of specimens made with natural aggregates. For instance, at water-cement ratios of 0.45 and 0.55, the durability index decreased by 6% and 10% respectively. However, the recycled concrete specimens still can meet the minimum criteria[6]. Some researches has shown that the primary factors contributing to the decline of freeze-thawing resistance are the pores in the attached substances on recycled aggregate surfaces, damages incurred during the preparation process, and the presence of microcracks[7]. Compared to natural aggregate concrete, the presence of attached substances on the surface of recycled aggregates, as well as the accumulated damages during the crushing process of the original concrete, contribute to higher porosity and water absorption rates, the formation of microcracks, and reduced strength. Ultimately, these flaws in the aggregate impair the frost resistance performance of recycled concrete under similar conditions when compared to conventional concrete.

2.2 Number of freeze-thaw cycles

With freeze-thaw cycles and the substitution rate of recycled aggregates increasing, there is a general upward trend in the overall rate of quality deterioration in recycled concrete (Figure 1)[8]. Similarly, the relative loss rates of dynamic modulus also increased. However, before reaching a certain threshold of freeze-thaw cycles, the quality of recycled concrete shows improvement firstly, as depicted in Figure 3[9]. This can be attributed to the structural integrity of the recycled concrete and the adherence of aggregates, which remain undamaged at lower freeze-thaw cycle counts. However, during this initial phase, the absorption of water by recycled concrete leads to an increase in quality.

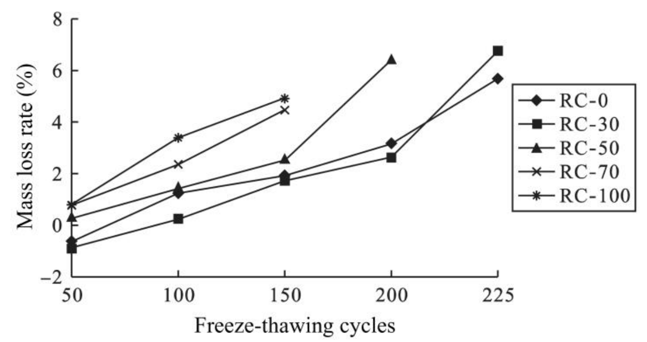

Fig. 1 Mass loss rate under different cycles

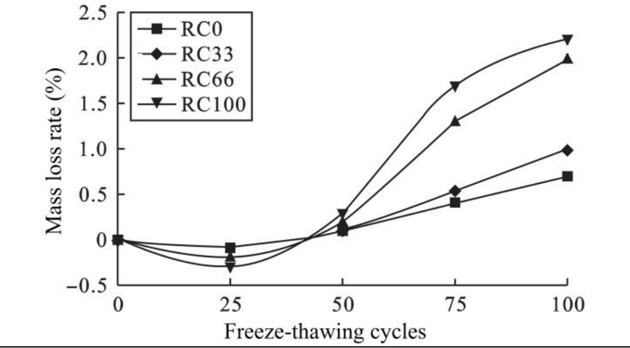

Fig. 2 Mass loss rate less than 100 cycles

2.3 Water-cement ratio

Numerous scholars have studied the effect of water-to-cement ratio on the freeze-thawing resistance of recycled concrete[10]. Results demonstrates the same findings, as depicted in Figures 4 and 5[11]. A lower water-to-cement ratio leads to higher relative dynamic modulus, lower rates of quality loss, and stronger frost resistance. This can be attributed to the increased number and average diameter of pores in recycled concrete with higher water-to-cement ratios, resulting in enhanced water absorption capacity. Consequently, after undergoing freeze-thaw cycles, the internal structure of the recycled concrete becomes less dense, leading to reduced load-bearing capacity.

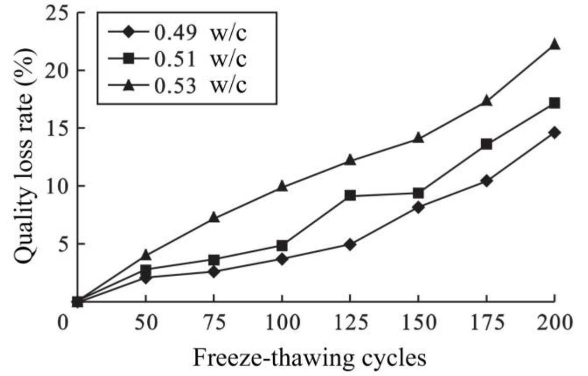

Figure. 3 Quality loss rate under different Water–cement ratio

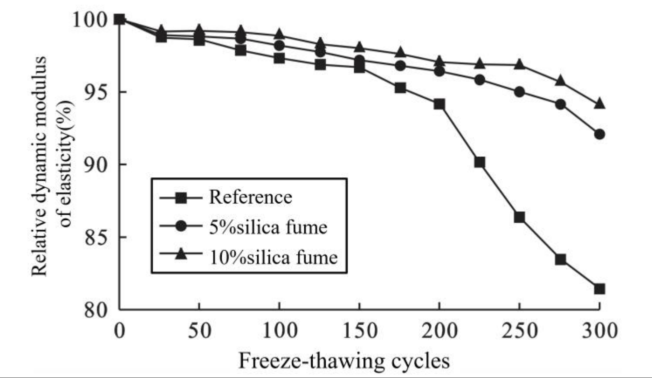

Figure. 4 Relative dynamic modulus of elasticity under different Water–cement ratio

2.4 Admixtures

Generally, the addition of suitable mineral admixtures improves the durability of concrete. For example, adding silica fume to mortar enhances its frost resistance[12]. The strong pozzolanic activity of silica fume reacts with the $Ca(OH)_2$ produced during cement hydration, forming C-S-H gel. This reduces the overall volume of cement pores, improves the interface structure and bonding strength, and refines the microstructure of concrete, thus enhancing its frost resistance. Appropriate amounts of lime powder and fly ash significantly enhance the frost resistance of recycled concrete. Lime powder increases the calcium ions in the concrete, creating an alkaline environment that facilitates the continuous secondary hydration of fly ash. This process generates more C-S-H gel, increasing the concrete density and improving its freeze-thaw resistance. However, it’s important to note that the mechanism by which fly ash improves frost resistance in recycled concrete is not well understood, and further investigation is required to explore the effects of dual admixture techniques on the frost resistance of recycled concrete.

3. Evaluation criteria for frost Resistance of recycled concrete

When studying and evaluating the frost resistance of recycled concrete, researchers often rely on the freeze-thawing resistance evaluation criteria designed for conventional concrete. However, it has been discovered that the mass loss rate fails to effectively and accurately reflect the internal damage inflicted by freeze-thaw cycles in recycled concrete.

After extensive comparative experiments, it has been found that the mass loss and relative dynamic modulus reduction in recycled concrete are lower than that of ordinary concrete, while its compressive strength reduction is greater. As a result, some scholars propose evaluating the concrete based on compressive strength loss, while others suggest incorporating compressive strength loss to assess its frost durability performance. However, compressive strength testing, being a destructive method, is less accurate in the early stages of concrete damage and is generally employed in the later stages of degradation. Moreover, some researchers recommend moving away from using metrics such as mass loss rate and strength loss, and instead propose parameters like length variation, relative dynamic modulus, and durability index for evaluating the frost resistance of recycled concrete. For example, Ref.[13] used the change in relative elastic modulus as the damage variable, establish a damage parabolic model for recycled concrete, shown in Formulas below,

$$D(n) = 1 - \frac{1}{1 - \frac{a + bexp(n/c)}{s_0}\log\left(1 - \frac{n}{N}\right)}$$

$$N^2 = \frac{2U_d^2(1 - E_i/E_0)}{e_g}$$

The assessment indicators for frost resistance in recycled concrete are currently varied and no consensus has been reached, posing challenges in comparing and analyzing research findings. Thus, it is crucial to establish an evaluation indicator system tailored to the specific characteristics of recycled concrete when assessing its frost resistance performance.

4. Summary

Based on the integration of influencing factors and performance evaluation mechanisms, recycled concrete exhibits inferior freeze-thaw resistance compared to ordinary concrete due to increased porosity, micro-cracks, reduced density, and an increased quantity of interface transition zones resulting from the use of recycled aggregates. However, various approaches such as aggregate shaping, physical-chemical enhancement, optimization of mix proportion and preparation process, incorporation of supplementary cementitious materials, nano materials, and fibers have been found effective in reducing micro-cracks and internal pore size, refining pore structure, and enhancing the mechanical properties of the interface transition zone in recycled concrete. These measures ultimately lead to improved freeze-thaw resistance. After analyzing and summarizing the current researches, the following improvement measures are proposed:

(1) Despite the existence of standards, regulations, and engineering applications for the freeze-thaw resistance of recycled concrete, a consensus standard is still lacking, requiring the establishment of a scientific application and monitoring system for the commercial use of recycled concrete.

(2) Quantitative research on the micro-mechanisms of recycled concrete is necessary, along with further analysis of factors influencing the micro-products and morphology of recycled concrete in different environments. Targeted measures should be implemented to strengthen the matrix and enhance the durability of recycled concrete.

(3) Recycled aggregates should be prepared in accordance with established standards and in qualified production and processing factories.

(4) Current research on the freeze-thaw durability of recycled concrete in complex environments is insufficient, as it mainly considers a single coupling factor. Therefore, further investigation is required.

(5) The exact mechanism of freeze-thaw failure in recycled concrete remains unclear. Conducting research through numerical simulation and theoretical analysis is recommended to provide support and reference for the long-term performance of recycled concrete structures.

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