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Research Progress on the Performance of Nano-Silica Modified Rubberized Concrete

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Abstract: Rubberized concrete, while possessing excellent toughness, ductility, crack resistance, and seismic resistance, experiences a significant decrease in mechanical properties due to the hydrophobic nature of rubber particles, resulting in distinct interfaces between the rubber particles and the surrounding mortar. Due to the ability of nanomaterials to promote cement hydration reactions, they play a filling and strengthening role in concrete, improving the performance of the interface transition zone and microstructure of the concrete. Additionally, nanomaterials can reduce the porosity of rubberized concrete and significantly enhance its compressive strength and ductility, making them of significant importance in the application of reinforced modified rubberized concrete. Based on this, a comprehensive analysis and summary were conducted on the mechanical properties, durability, and interface structure of nano-silica modified rubber concrete, discussing the modification mechanism by which nano-silica enhances its performance. This study provides theoretical and technical support for the application and promotion of nano-silica in improving the performance of rubber concrete.

1. Introduction

In recent years, with the rapid development of transportation and the automotive industry, the accumulation of waste rubber tires has been increasing. If these accumulated waste rubber tires are not recycled, it will not only waste rubber resources but also cause serious environmental pollution[1]. Therefore, grinding the waste tires into particles of different sizes and using these particles as a replacement for aggregates in concrete to develop rubberized concrete can simultaneously address the issues of environmental pollution and shortage of concrete resources, which is of significant importance[2].

Rubber concrete has excellent properties such as low elastic modulus, high toughness, strong deformation ability, high damping, shock resistance, impact resistance, strong resistance to violence, good thermal insulation performance, and noise reduction[3]. However, due to the hydrophobic nature of rubber particles, there is a distinct interface between the rubber particles and the surrounding mortar, which leads to a significant decrease in mechanical properties. To address the issue of low mechanical properties in rubber concrete, improvements can be made through the addition of fibers, chemical admixtures, or active substances. Nanomaterials, such as SiO_2, $CaCO_3$, and TiO_2, have been successfully applied in cement-based materials and have shown various positive effects due to their unique surface, size, and interface effects[4-6]. Nano-Silica (NS), as a representative example, when added to concrete, can promote the hydration reaction of cement, fill harmful pores in the cement matrix, accelerate the reaction of volcanic ash inside the concrete, slow down the dissolution rate of calcium hydroxide, reduce the gaps in the interface transition zone, and make the concrete more compact, thereby improving its strength[7-9]. Based on this, a detailed analysis and summary were conducted on the performance of rubber concrete modified by NS, elucidating the impact of NS on the mechanical properties, durability, and interface structure of rubber concrete. This study provides theoretical and technical support for the research on enhancing the performance of rubber concrete with NS, expanding the application scope of rubber concrete in the field of civil engineering.

2. Current Research Status on Nano-silica Modified Rubberized Concrete at Home and Abroad

2.1. Research Status of Mechanical Properties of Nano-Silica Modified Rubber Concrete

Since nanomaterials were recognized as a new branch in materials science and introduced to the world by the United States, scholars both domestically and internationally have conducted extensive research on nanomaterials. Significant progress has been made in enhancing the mechanical properties of rubberized concrete through the application of nanomaterials. For example, Tu Yanping et al.[10] replaced a portion of cement and natural river sand in concrete with nano-silica (NS) and rubber powder. They conducted compressive strength and slump tests on recycled concrete cured for 7 and 28 days by single and double substitutions using the mass replacement method. The study analyzed the influence of nano-silica on the mechanical properties of rubberized recycled concrete. The research findings suggest that adding rubber powder alone decreases the early compressive strength of recycled concrete, but an appropriate amount can enhance the compressive strength of recycled concrete at 28 days, while an excessive amount leads to a reduction in strength. Conversely, the sole addition of nano-silica enhances the compressive strength of recycled concrete. When both materials are combined, they complement each other by compensating for the reduction in strength caused by rubber powder and mitigating the negative impact on workability due to the addition of nano-silica, thereby achieving a synergistic effect.

Xu Yaoqun et al.[11] introduced colloidal nano-silica (CNS) as an additive directly mixed into concrete, with the rubber component replacing the fine aggregate in the concrete. Compression strength tests were conducted on ordinary concrete (PC), rubber concrete (RC), and colloidal nano-silica modified rubber concrete (NR) to explore the strengthening effect and mechanism of colloidal nano-silica modified rubber concrete. The research results indicate that the compression strength of RC and NR is generally lower than that of PC, but compared to RC, NR exhibits a significant increase in compression strength. Moreover, CNS demonstrates a more pronounced improvement in the early strength of rubber concrete.

Bashar S. et al.[12] partially replaced the cementitious material in concrete with shredded rubber and NS, and conducted compression strength tests on the concrete using single and double substitutions through the volumetric replacement method. The compression performance and impact resistance of nano-silica modified rubber concrete were analyzed. The research findings indicate that the addition of NS in rubber concrete mixtures leads to an increase in compression strength due to the physical and chemical effects of NS on improving the microstructure of the mixture. While the introduction of NS in rubber concrete may compromise its higher impact resistance, this trade-off is a desired outcome resulting from the careful design of these mixtures compared to traditional concrete.

Chen Xuyong et al.[13] conducted a study on the influence of nano-silica and rubber powder on the compressive strength, flexural strength, and splitting tensile strength of recycled concrete. Different percentages of rubber powder (0%, 1%, 3%, 5% by weight) were used to replace natural river sand, while different percentages of NS (0%, 1.5%, 3% by weight) were used to replace cement. The study also included an analysis of the experimental research and numerical simulation on the mechanical properties of nano-silica rubber powder recycled concrete. The experimental results showed that, with a constant amount of rubber powder, the compressive strength, splitting tensile strength, and flexural strength of the recycled concrete increased with the increasing NS content.

Jianbai Zhao et al.[14] used two types of nanomaterials, namely nano-silica solution and NS sol-gel, for pretreating recycled coarse aggregates (RCA) and rubber. The mechanical properties of mortar prepared with pretreated rubber were investigated. The effects of factors such as water-to-cement ratio, rubber content, rubber particle size, and aggregate treatment on the stress-strain curve, compressive strength, elastic modulus, toughness, and failure mode of recycled concrete were analyzed. The research results showed that the RCA pretreated with NS exhibited lower water absorption and better mechanical properties. In addition, the compressive and flexural strengths of NS-modified rubber mortar increased by 35% and 17% respectively.

2.2. Research Status of Durability Properties of Nano-Silica Modified Rubber Concrete

The research on incorporating nanomaterials into cement concrete can be traced back to the 1990s. The addition of nanomaterials in concrete can enhance the durability of concrete in terms of performance. For example, Jicun Shi et al.[15] replaced sand with 5%, 7.5%, and 10% of silane-modified rubber (SR) based on the mass of cement, and replaced cement with 1%, 3%, and 5% of nano-silica based on the mass of cement. The freeze-thaw resistance of concrete mixtures containing SR and NS was studied using the response surface methodology. The effects of silane-modified rubber and nano-silica on the microstructure and freeze-thaw resistance of concrete were analyzed. The experimental results showed that the combination of SR and NS exhibited a synergistic effect, resulting in a more uniform distribution of pores in the concrete. After freeze-thaw cycles, the mass loss rate and relative dynamic modulus of elasticity (RDME) damage were reduced.

Fang Jun et al.[16] incorporated nano-silica by partially replacing the powder materials (cement and fly ash) in concrete, with the addition amount given as a mass fraction. The content of rubber and silane-modified rubber particles was calculated based on the mass of cement, and they were partially replaced by volume. The microstructure, mass loss, relative dynamic modulus of elasticity, chord length distribution of pores, and specific surface area of pores in the concrete were studied through freeze-thaw tests and scanning electron microscopy (SEM). The freeze-thaw resistance and pore structure of rubber aggregate and nano-silica composite concrete were explored. The experimental results showed that the appropriate addition of rubber aggregate significantly improved the freeze-thaw resistance of the concrete, but generally lowered its mechanical strength. However, due to the synergistic effect between rubber and NS, the addition of NS could partially compensate for the strength loss.

Musa Adamu et al.[17] investigated the effect of incorporating shredded rubber and nano-silica on the durability (porosity and permeability) and skid resistance of roller compacted concrete (RCC) pavements with high volume fly ash (HVFA). The shredded rubber was used to partially replace the fine aggregate at varying percentages by volume (0%, 10%, 20%, and 30%). The addition of NS was varied from 0% to 3% by weight of the cementitious materials. The study revealed that incorporating 10% shredded rubber as a replacement for the fine aggregate, along with the addition of up to 2% by weight of nano-silica, enhanced the skid resistance of HVFA roller compacted concrete pavements.

2.3. Research Status of Interface Structure of Nano-Silica Modified Rubber Concrete

The birth of nanomaterials is widely regarded as a significant outcome of nanotechnology. Nanomaterials, characterized by their precise dimensions, physical, and chemical properties, have a significant impact on the performance of various products. Nanomaterials with sizes smaller than 100nm can fill micro-pores ranging from 20 to 150nm within the cement paste, thereby reducing the porosity of concrete and altering its pore structure. Additionally, nanoparticles exhibit a "nucleation effect" during the cement hydration process, increasing the number of gel bodies formed. The uniform dispersion of nanomaterial particles further enhances the uniformity of the hydration products at the interface transition zone within the concrete matrix. For instance, Xu Yaoqun et al.[11] incorporated colloidal nanosilica (CNS) as an admixture directly into concrete, with the rubber portion replacing the fine aggregate in the concrete mix. Microstructure tests were conducted on plain concrete (PC), rubber concrete (RC), and colloidal nanosilica-modified rubber concrete (NR) to investigate the enhancement effect and mechanism of colloidal nanosilica-modified rubber concrete. Microcrack test results show that the microcrack width of CNS-modified rubberized concrete ranges from 3 to 10 μm, while that of conventional rubberized concrete ranges from 35 to 45 μm. The quantitative analysis of element distribution in the rubber-cement interface transition zone was conducted using energy-dispersive spectroscopy grayscale value correction method. The research findings indicate that the surface effect of nano-silica and the filling effect of nano particles in the interface zone contribute to the improvement of the microstructure of the rubberized concrete interface. These effects represent the primary mechanisms through which CNS-enhanced rubberized concrete performance is achieved.

Bashar S. et al.[12] partially replaced the cementitious materials in concrete with crushed rubber and nano-silica, and conducted field emission scanning electron microscopy (FESEM) and mercury intrusion porosimetry (MIP) tests on the concrete using volume replacement method for single and double blending. The microstructure and performance of nano-silica modified rubberized concrete were analyzed. The research findings indicate that the addition of nano-silica in rubberized concrete mixtures can refine the pore system, densify the interface transition zone, and consequently improve the microstructure of rubberized concrete. The incorporation of nano silica reduces the total pore volume and porosity of rubberized concrete, enhancing its durability.

3. Conclusion and Prospects

The addition of nano-silica in rubber concrete has been found to effectively enhance its performance through its pozzolanic and filler effects. A comprehensive summary of the current research on the mechanical properties, durability, and interface structure of rubber concrete with NS was conducted, leading to the following conclusions:

1) The addition of nanoparticles can enhance the compressive strength of rubber concrete. NS can fill the microscopic pores in the concrete, increasing the compactness of the concrete matrix, thereby improving its strength.

2) The incorporation of nanoparticles can enhance the frost resistance of concrete and mitigate damage resulting from freeze-thaw cycles. NS addition improves the performance of the interfacial transition zone (ITZ) in rubber concrete, resulting in a more compact interface structure and reducing the likelihood of water penetration into the concrete. Furthermore, NS particles can fill the microscopic pores within the concrete, decreasing water permeability and minimizing the potential

for ice expansion and damage caused by freeze-thaw cycles.

3) Nanoparticles have the capability to fill the microcracks in concrete, enhancing its cohesion and toughness, thus reducing the occurrence and propagation of cracks and improving the crack resistance of concrete. Additionally, the addition of NS can also enhance the oxidative resistance and durability of rubberized concrete. NS can react with the oxides in concrete, forming a dense calcium silicate gel, which increases the compactness and hardness of the concrete, thereby enhancing its durability and resistance to aging.

4) The interface structure of rubber concrete is closely related to its macroscopic mechanical properties. By compensating for the high porosity of the interface structure, nano-silica particles accelerate the hydration process and increase the hydration products, thereby improving the transition zone structure of rubber concrete. This in turn enhances the mechanical properties of rubber concrete. However, the agglomeration of nano-silica particles in concrete is a significant issue. Addressing the dispersion problem of nano-silica particles in concrete remains one of the main directions for future research.

5) Currently, there have been relevant studies on the durability performance of nanomaterial-modified rubber concrete. However, existing research mostly focuses on the analysis of durability degradation mechanisms under single-factor and single-field conditions. There is a lack of long-term performance monitoring data, and concrete is subjected to multiple factors in actual service environments, making the mechanisms of action more complex. There is a lack of research on the durability degradation of nanomaterial-modified rubber concrete under the influence of multi-field coupling and time-dependent effects in actual service environments. Thus, there is a need for multidimensional and multi-interface performance degradation mechanism research on nanomaterial-modified rubber concrete, considering multiple factors and multi-field coupling effects such as load, salt erosion, and freeze-thaw.

Overall, the mechanical properties and durability of rubberized concrete modified with nano-silica have been significantly enhanced. The use of nano materials for modifying rubberized concrete is an effective technique to address the interface-related performance issues between rubber particles and surrounding mortar, thereby promoting the utilization of waste rubber resources. Nano-Silica modified rubberized concrete has the potential to become an important material in future engineering construction, providing strong support for the safety, durability, and sustainable development of construction projects.

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