

Study of effect of nano silica on the mechanical strength and durability performance of waste rubber aggregate mixed concrete

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Abstract - The disposal of waste tires has emerged as a major environmental challenge, necessitating sustainable recycling strategies. Rubberized concrete, which incorporates recycled tire rubber into the cementitious matrix, has gained considerable attention as an eco-friendly construction material that supports sustainable waste management. However, the practical use of rubberized concrete in structural applications is often limited by reductions in mechanical strength and stiffness. This study investigates the effectiveness of nano silica (NS) in enhancing the mechanical and durability properties of rubberized concrete. Concrete mixtures were prepared by partially replacing manufactured sand with recycled rubber aggregates at 5%, 10%, and 15%, while NS was used as a partial cement replacement at 3% and 5%. A total of ten mix combinations were evaluated. The results demonstrate that NS significantly improves strength and durability by enhancing the interfacial bonding and densifying the cement matrix, thereby mitigating the adverse effects of rubber inclusion and improving the overall performance of rubberized concrete.

Key Words: Sustainable concrete, Rubber aggregate, Mechanical strength, Durability performance

1. INTRODUCTION

Concrete has long been recognized as the most widely used construction material in the world and continues to play a fundamental role in the development of modern infrastructure. Its versatility, durability, and relatively low cost make it indispensable for a wide range of civil engineering applications, including high-rise buildings, bridges, highways, dams, and transportation networks. Rapid urbanization and industrial expansion across the globe have significantly increased the demand for concrete in recent decades. As countries continue to invest heavily in infrastructure development to support economic growth and urban population expansion, the consumption of concrete has reached unprecedented levels. This increasing demand has consequently intensified the extraction and utilization of natural resources required for concrete production [1].

According to recent reports by the Global Cement and Concrete Association, the worldwide production of concrete is estimated to be approximately 14 billion cubic meters annually, making it the most consumed manufactured material on Earth. The production of such enormous volumes of concrete requires vast quantities of natural aggregates, cement, and water. Construction aggregates, including sand and gravel, constitute nearly three-quarters of the total volume of conventional concrete. Global aggregate production reached nearly 51.7 billion metric tonnes in 2014, and this figure continues to rise steadily due to ongoing infrastructure development and urbanization. Similarly, global cement demand is projected to grow at an annual rate of around 2.5%, reaching approximately 4.7 billion metric tonnes by 2025. These projections highlight the increasing pressure on natural resources and underline the urgent need to explore sustainable alternatives and innovative construction materials capable of reducing the environmental footprint of the construction sector [2].

The accumulation of waste tires poses multiple environmental hazards. Large stockpiles of discarded tires occupy significant land area and can serve as breeding grounds for mosquitoes and other disease-carrying insects, thereby increasing the risk of vector-borne diseases such as dengue, malaria, and Zika virus infections. Furthermore, waste tire dumps are highly susceptible to accidental fires that are extremely difficult to extinguish. Tire fires can burn for extended periods and release toxic gases, including polycyclic aromatic hydrocarbons and other hazardous pollutants, which severely degrade air quality and threaten surrounding ecosystems. Consequently, the development of sustainable methods for recycling and utilizing waste tire rubber has become a pressing priority in both environmental management and materials engineering [3].

One promising approach to address this issue is the incorporation of waste tire rubber into cementitious composites to produce rubberized concrete. Rubberized concrete is developed by partially replacing conventional aggregates with recycled

rubber particles, commonly in the form of crumb rubber or shredded tire chips. The integration of rubber particles into concrete offers several environmental and functional benefits. From a sustainability perspective, the use of recycled rubber reduces the demand for natural aggregates while simultaneously providing an effective method for diverting waste tires from landfills. In addition, rubber particles impart unique mechanical characteristics to concrete, such as enhanced toughness, improved ductility, and superior energy absorption capacity. These properties make rubberized concrete particularly attractive for applications where impact resistance, vibration damping, and shock absorption are desirable, including road pavements, safety barriers, industrial flooring, and seismic-resistant structural elements [4].

Recent advances in nanotechnology have opened new opportunities for enhancing the performance of cement-based materials. Among various nano-materials investigated for concrete modification, nano silica (nano-SiO₂) has emerged as one of the most promising additives. Nano silica possesses an extremely high specific surface area and exhibits strong pozzolanic reactivity with calcium hydroxide produced during cement hydration. When incorporated into concrete in small quantities, nano silica can significantly improve the microstructure of the cementitious matrix by filling nano-scale voids and promoting the formation of additional calcium silicate hydrate (C-S-H) gel. This process results in a denser and more compact microstructure, leading to improvements in both mechanical strength and durability characteristics [5].

The incorporation of nano silica in rubberized concrete has therefore attracted growing research interest, as it offers a potential solution to mitigate the strength reduction associated with rubber inclusion. By refining the pore structure and enhancing the interfacial transition zone between aggregates and cement paste, nano silica can improve bonding and overall structural integrity. Furthermore, nano silica has been shown to enhance resistance to permeability, chloride ion penetration, and chemical attack, thereby improving the long-term durability of concrete exposed to aggressive environments. These characteristics suggest that nano-modified rubberized concrete could serve as a viable sustainable material capable of combining environmental benefits with improved mechanical performance [6].

In this context, the present study aims to develop a sustainable rubberized concrete system by incorporating waste tire crumb rubber together with supplementary cementitious materials such as fly ash and nano silica. The research focuses on evaluating the influence of nano silica on the mechanical and durability properties of rubberized concrete while promoting the utilization of waste-derived materials in construction. Through this approach, the study seeks to contribute to the development of environmentally responsible construction materials that can reduce natural resource consumption, improve waste management practices, and enhance the overall sustainability of the built environment.

2. Materials and methodology

For the experimental program, Ordinary Portland Cement (OPC) of 53 grade conforming to IS 12269:2013 was used in combination with manufactured sand (MS), coarse aggregate (CA), potable water, crumb rubber aggregate (RA), superplasticizer (SP), fly ash (FA), and nano-silica (NS).

The experimental program was designed to evaluate the mechanical strength and durability performance of rubberized concrete containing nano silica. Concrete specimens were prepared with different proportions of recycled rubber aggregates and nano silica, and the hardened properties were assessed at curing ages of 7 and 28 days. The mechanical performance of the concrete was evaluated through compressive strength, split tensile strength, and flexural strength tests, while durability was assessed through an acid attack test.

The compressive strength test was conducted to determine the load-bearing capacity of the concrete mixes. Cube specimens of size 150 × 150 × 150 mm were cast, compacted properly, and cured under controlled conditions until the testing age. The test was performed using an automated compression testing machine (CTM) with a capacity of 3000 kN. Load was applied uniformly at a controlled rate of 14 N/mm² per minute until failure occurred, following the procedure specified in IS 516:1959. The compressive strength was calculated by dividing the maximum load carried by the specimen by its cross-sectional area. Three specimens were tested for each mix, and the average value was reported.

The split tensile strength test was carried out on cylindrical specimens measuring 100 mm in diameter and 200 mm in height to evaluate the tensile behavior of the concrete. The cylinders were placed horizontally in the compression testing machine, and load was applied at a constant rate of 1.8 N/mm² per minute in accordance with IS 5816:1999. The applied compressive load generated indirect tensile stresses along the vertical diameter of the specimen, causing it to split. The split tensile strength was calculated using the standard equation

The flexural strength test was performed on beam specimens of size 100 × 100 × 500 mm to determine the bending resistance of the concrete. The specimens were tested under a two-point loading arrangement with a clear span of 400 mm between the support rollers. Load was applied at a constant rate of 180 kg/min in accordance with IS 516:1959 until failure occurred. The

modulus of rupture was calculated based on the peak load and the specimen dimensions, and the average value of three specimens was recorded.

To evaluate durability, an acid attack test was conducted following ASTM C267. Concrete cube specimens of 150 mm size were immersed in 5% sulphuric acid (H₂SO₄) solution for 7 and 28 days. The resistance of the concrete was assessed by measuring mass loss and compressive strength reduction after exposure. For each mix, three specimens were tested, and the average results were used to analyze the influence of nano-modified rubberized concrete on durability performance.

3. Results and Discussion

3.1 Compressive Strength

The compressive strength results of the different concrete mixes at curing ages of 7 and 28 days are presented in Fig.1. The control mix (S1), which contained neither rubber aggregate (RA) nor nano silica (NS), exhibited compressive strengths of 33.48 MPa at 7 days and 47.36 MPa at 28 days. These values represent the baseline mechanical performance of conventional concrete used for comparison with modified mixes. When 5% rubber aggregate was incorporated as a partial replacement, the compressive strength decreased to 31.56 MPa at 7 days and 42.89 MPa at 28 days, indicating a noticeable decline in load-bearing capacity [6-8].

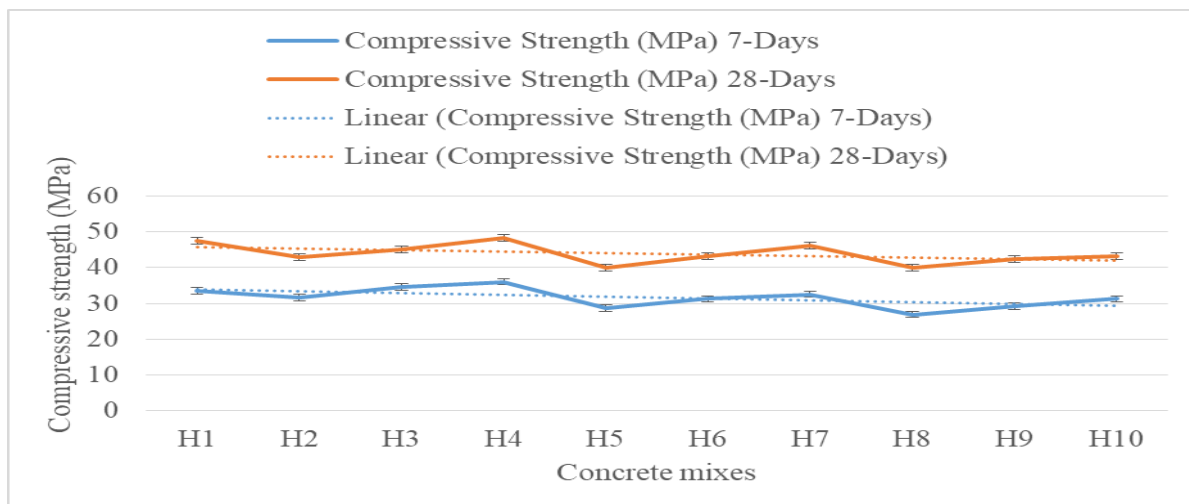


Fig. 1: Compressive strength of concrete mixes

However, the incorporation of nano silica (NS) significantly improved the compressive strength of rubberized concrete. The mixes containing NS demonstrated higher strength values compared with their corresponding rubberized mixes without NS. The 5% NS dosage was found to provide the optimum improvement in compressive strength. This enhancement can be attributed to the nano-filler effect of NS and its high pozzolanic reactivity. Due to its extremely fine particle size and large surface area, NS fills micro-voids within the cement matrix and promotes the formation of additional calcium silicate hydrate (C-S-H) gel during hydration. As a result, a denser and more compact microstructure is formed, which enhances the load-carrying capacity of the concrete composite.

3.2 Split Tensile Strength

The split tensile strength results for the various concrete mixes are illustrated in Fig.2. The control mix recorded tensile strengths of 3.65 MPa at 7 days and 5.12 MPa at 28 days. Similar to the compressive strength behavior, the inclusion of rubber aggregates resulted in a gradual reduction in tensile strength. When 5% RA was incorporated, the tensile strength decreased to 3.43 MPa at 7 days and 4.88 MPa at 28 days. Further increases in RA content to 10% and 15% resulted in additional reductions in tensile strength.

The decrease in tensile strength can primarily be attributed to the weak adhesion between rubber particles and the cementitious matrix. Rubber aggregates tend to create localized stress concentrations and discontinuities within the concrete structure. Under tensile loading, these zones become potential sites for crack initiation and propagation, which reduces the

tensile capacity of the composite material. Furthermore, the elastic nature of rubber particles limits effective stress transfer across the matrix, thereby contributing to premature failure [9-10].

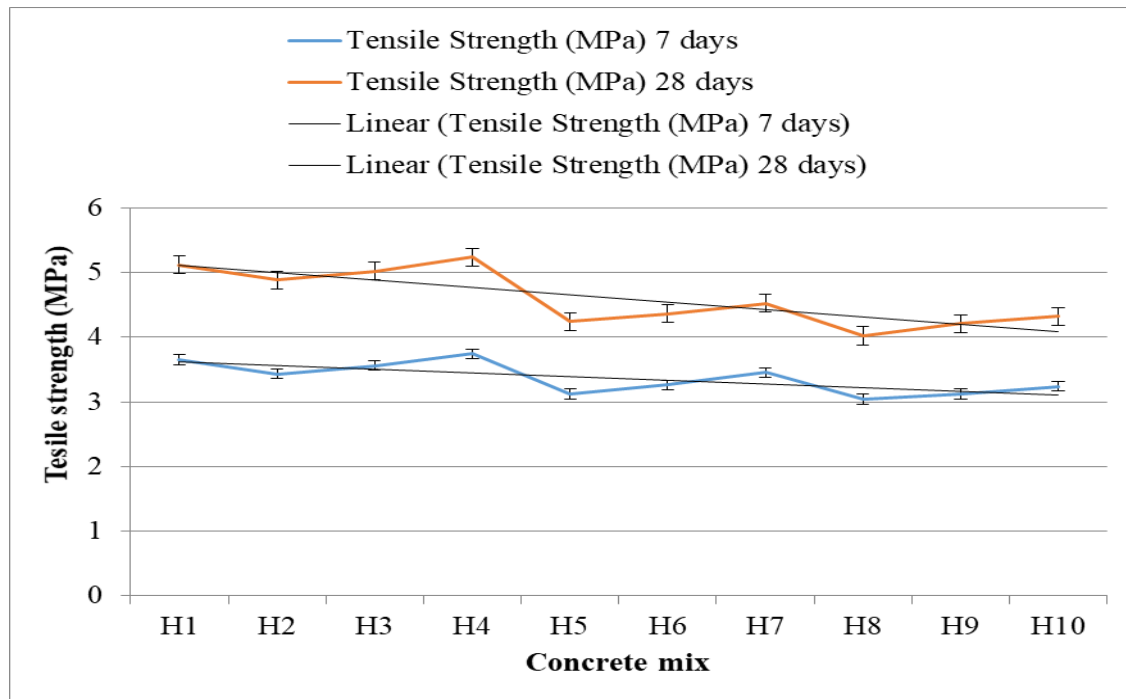


Fig. 2: Tensile strength of concrete mixes

Despite the negative influence of rubber aggregates, the incorporation of nano silica significantly enhanced the tensile strength of the concrete mixes. The addition of NS improved the interfacial bonding between cement paste and aggregates by refining the microstructure of the interfacial transition zone. The nano-sized particles act as micro-fillers that improve particle packing and reduce internal porosity. In addition, the pozzolanic reaction of NS accelerates cement hydration and promotes the formation of additional C-S-H gel, which strengthens the matrix and increases its ability to resist tensile stresses. As a result, the NS-modified rubberized concrete exhibited improved tensile performance compared with mixes containing only rubber aggregates.

3.3. Flexural Strength

The flexural strength results of the different concrete mixes are shown in Fig.3. The control mix recorded flexural strengths of 3.95 MPa at 7 days and 5.24 MPa at 28 days. The introduction of rubber aggregates at 5%, 10%, and 15% replacement levels resulted in a reduction in flexural strength across all mixes. This reduction is mainly associated with the low stiffness of rubber particles and the weak bonding between rubber and cement paste, which causes stress concentration under bending loads.

Under flexural loading, cracks tend to initiate at the tension zone of the beam specimen. The presence of poorly bonded rubber particles within this region reduces the resistance of the concrete to crack initiation and propagation. Additionally, achieving uniform dispersion of rubber particles within the concrete matrix can be challenging, which further contributes to localized weaknesses and reduced flexural capacity [11-12].

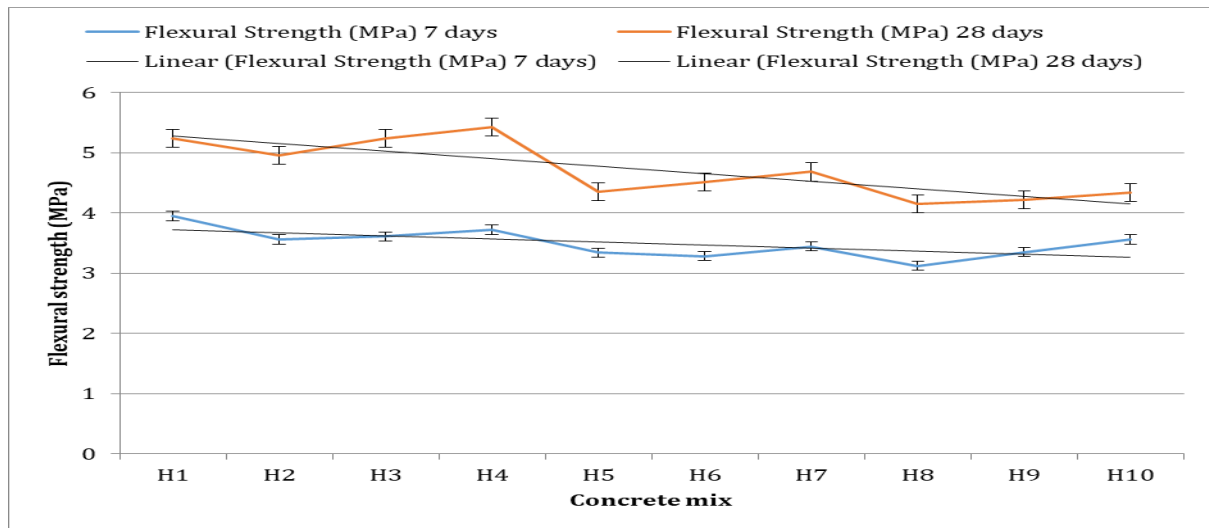


Fig. 3: Flexural strength of concrete mixes

Nevertheless, the incorporation of nano silica effectively improved the flexural performance of rubberized concrete. The improvement is attributed to the ability of NS to densify the cementitious matrix, reduce porosity, and enhance the bonding between aggregates and cement paste. The high pozzolanic activity of NS accelerates hydration reactions and contributes to the formation of a more homogeneous microstructure. Consequently, the NS-modified mixes demonstrated better resistance to bending stresses compared with mixes containing rubber aggregates alone.

3.4 Loss in Strength after Acid Exposure

The durability performance of the concrete mixes was evaluated by examining the loss in compressive strength after exposure to an acidic environment, as shown in Fig.4. The reference concrete mix, containing neither RA nor NS, exhibited the lowest reduction in compressive strength after exposure to acid at both 7 and 28 days. As the percentage of rubber aggregate increased to 5%, 10%, and 15%, the loss in strength increased progressively.

However, the inclusion of nano silica significantly reduced the loss in compressive strength after acid exposure. The improved performance is mainly due to the ability of NS to refine the pore structure and produce a denser microstructure that limits the ingress of aggressive chemicals. Moreover, the pozzolanic reaction of NS consumes calcium hydroxide and forms additional C-S-H gel, which enhances chemical resistance. Consequently, the NS-modified rubberized concrete demonstrated improved durability and better resistance to acid attack compared with conventional rubberized concrete [11 -12].

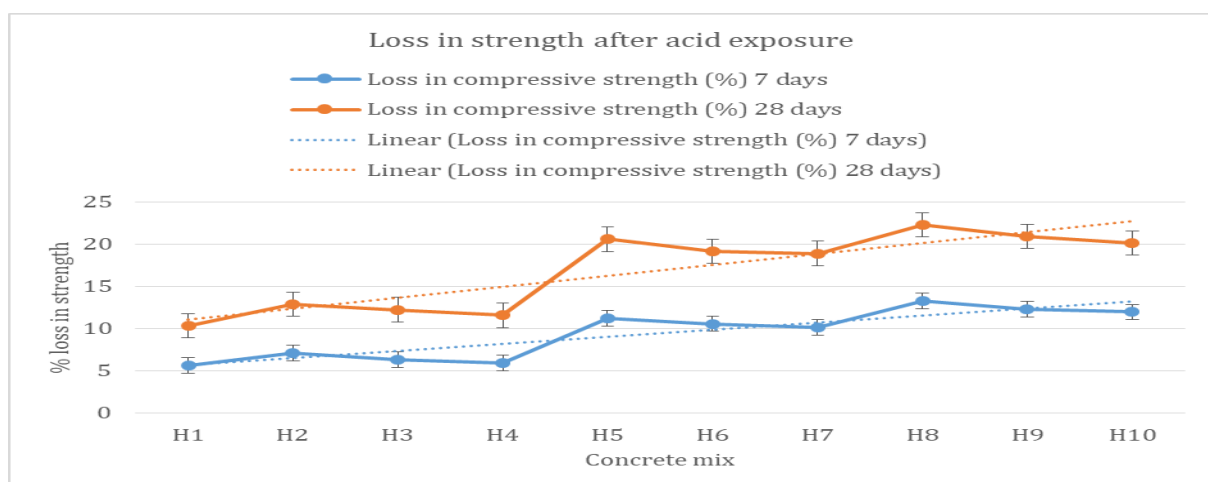


Fig. 4: Loss in strength of concrete mixes after acid exposure

4. CONCLUSIONS

The control concrete mix exhibited the highest compressive, split tensile, and flexural strengths at both 7 and 28 days, serving as a reference for comparison. The inclusion of rubber aggregate (RA) resulted in a gradual reduction in mechanical strengths due to weak bonding, low stiffness, and poor stress transfer within the concrete matrix. However, the addition of nano silica (NS) significantly improved the mechanical performance by refining particle packing and forming a denser microstructure, with optimum results at 5% replacement. NS also enhanced tensile and flexural strengths and reduced strength loss under acid exposure. Overall, NS effectively mitigates the negative effects of RA, producing more durable and sustainable rubberized concrete.

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