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Utilization of Nanosilica in M50-grade Concrete: Mechanical and Microstructural Performance for Sustainable Construction

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ABSTRACT

The growing demand for green building materials has spurred the development of strategies to partially replace cement with nanoengineered additives, thereby minimizing the ecological footprint. This study evaluates the properties of M50-grade high-strength concrete with nanosilica (NS) as a partial replacement for cement, which can also assist in the reduction of CO_2 emissions into the atmosphere. Due to its high reactivity and small particle size, nanosilica was used as a partial replacement for cement at 0%, 5%, 10%, and 15% by weight. Mechanical properties, including compressive strength, split tensile strength, and flexural strength, were evaluated at various curing ages to identify the optimal replacement level. For microstructural characterization, separate experiments were carried out using Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) techniques to examine the formation of calcium silicate hydrate (C–S–H) gel and the refinement of the pore structure. The test results show that the addition of nanosilica improves the strength properties of the mix up to an optimum replacement level of 15%. At 28 days, the mix with 15% NS exhibited superior properties compared with all other mixes. The mix with 15% NS replacement exhibited a compressive strength of 58.21 N/mm², a split tensile strength of 8.83 N/mm², and a flexural strength of 5.34 N/mm². Thus, a 15% NS replacement level is optimal for producing high-strength M50-grade concrete suitable for environmentally friendly construction. The study further demonstrates that nanosilica is effective in developing sustainable concrete mixes through its use as a supplementary cementitious material.

Keywords: Environmentally friendly material; Microstructural analysis; Mechanical properties; Nanosilica; Sustainable concrete.

1. INTRODUCTION

The growing demand for high-performance and sustainable concrete has driven research into nanomaterials, particularly nanosilica (NS), as a partial replacement for cement (Tanimola and Steve, 2024). Due to its ultra-fine particle size, high surface area, and pozzolanic reactivity, NS enhances cement hydration, promotes additional calcium-silicate-hydrate (C–S–H) formation, refines the interfacial transition zone (ITZ), and densifies the concrete matrix. These effects collectively improve compressive, split tensile, and flexural strengths, reduce porosity, and enhance durability against aggressive environments (Al-hagri and Mahmud, 2022; Shafi *et al.* 2016). High-strength concretes, such as M50 grade, require optimized microstructural integrity, making the incorporation of NS particularly effective for strength development and long-term performance. Optimal NS dosages are generally reported between 1–4% by weight of cement. Dosages up to ~3% typically yield significant mechanical and durability improvements, while higher contents can lead to particle agglomeration, reduced workability, and performance plateauing (Khan *et al.* 2022). NS also serves as nucleation sites for C–S–H growth, lowers calcium hydroxide content, refines capillary pores, and enhances ITZ bonding, thereby improving both mechanical behavior and durability (Al-saffar *et al.* 2023). In high-strength and self-compacting concretes, NS has been shown to increase early-age and 28-day compressive strength substantially, improve tensile and flexural performance, and contribute to acid and chloride resistance (Rakesha *et al.* 2024; Patil *et al.* 2024; Gopinath *et al.* 2012).

Partial replacement of cement with NS appears to be a promising approach for reducing the amount of clinker content and the resulting CO_2 emissions, while also enhancing the properties of the resulting concrete mix. Though nanosilica has been the focus of considerable attention in conventional concrete mixtures, very little has been done on the optimized content and integrated properties, in both macro- and micro-levels, for high-strength concretes. In particular, the relationship