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Effect of High-Volume Substituted Nanosilica on the Hydration and Mechanical Properties of Ultra-High-Performance Concrete (UHPC)

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ABSTRACT

Ultra-high-performance concrete (UHPC) is known for its superior durability and mechanical properties in the built environment, where it is used as a cementitious material in modern application. However, highly dependent on ordinary Portland cement, UHPC production significantly contributes to greenhouse gas emissions. Partial replacement of cement with supplementary materials to reduce environmental impacts while maintaining or even enhancing the performance of UHPC has recently gained attention. Among these materials, nanosilica (NS) has been recognized as a promising additive because of its exceptional pozzolanic activity, high surface area, and the ability to enhance the microstructure of cementitious systems. The present study explores the effect of high-volume substituted nanosilica on the hydration and mechanical properties of UHPC.

INTRODUCTION

Ultra-High-Performance Concrete (UHPC) is a breakthrough in cementitious materials with outstanding mechanical properties, durability, and resistance to harsh environments. The development of UHPC has opened up new avenues for structural engineering to design slender, long-span, and lightweight structure with greater durability. However, the preparation of UHPC frequently involves high cement content, which poses environmental and economic issues.

Nanosilica was identified as a promising additive for optimizing UHPC formulations. It replaces huge portions of traditional cement with enhanced hydration, improved densification of the microstructure, and better mechanical performance. There is a need to understand the effects of nanosilica substitution on the fundamental hydration mechanisms in order to reap its full potential in sustainable and high-performance applications.

To assess the feasibility of incorporating a high volume of NS in UHPC, SF with a similar chemical composition was replaced by NS. In earlier studies, we had targeted silica flour substitution and SF substitution and the impact of replacing high volumes of NS on the bond behavior of steel fibers in UHPC. This work aimed to investigate the effect of the substitution of SF by large amounts of NS at the composite level on the behavior of UHP-FRC. SF was replaced by up to 50% NS, and the hydration characteristics were evaluated with isothermal calorimetry and thermo gravimetric (TG) analyses, shrinkage behavior analysis, and nuclear magnetic resonance (NMR) analyses. Compressive, single-fiber pullout, and direct tensile tests were performed to evaluate the mechanical properties of composites affected by NS substitution.

LITERATURE REVIEW

Ultra-High-Performance Concrete (UHPC): A Revolutionary Material
Ultra-High-Performance Concrete (UHPC) is distinguished by its ultradense microstructure, low water-to-cement ratio, and fine particles such as silica fume and superplasticizers. These factors allow UHPC to reach compressive strengths that are more than 120 MPa, tensile strength superior to the former, and high durability.

Composition and Mix Design
Cementitious Components: Portland cement, silica fume, and other pozzolanic materials.
Fine Aggregates: Sand or powdered quartz to improve packing density.

Water-Reducing Agents: Superplasticizers to maintain workability in low water-to-cement ratios.

Fiber Reinforcement: Steel or polymer fibers to enhance tensile performance.

Uses of UHPC span bridge decks and precast structural parts through architectural features, where the high strength, durability, and design flexibility are important considerations.

Microstructural Enhancements
The addition of nanosilica provides:
Pore size and volume reduction.
Improved ITZ between aggregate and cement paste.
Increased density of C-S-H gel, which means increased strength and durability.

Compressive Strength
Nanosilica enhances compressive strength by densifying the microstructure.
Substitution levels of 5-15% by weight of cement proved to be optimum in laboratory studies.

Tensile Strength and Flexural Performance
Improved ITZ, coupled with reduced porosity, improves tensile strength and flexural capacity, necessary for resisting cracking.These properties are further improved by synergistic action of fibers in combination with nanosilica.

Durability Improvements through Nanosilica
Nanosilica has been reported to improve long-term durability of UHPC.

Sulfate Attack Resistance: Low porosity and better matrix content improve resistance to chemical attack.

Shrinkage Reduction: Nanosilica addition reduces autogenous shrinkage, a major challenge in UHPC.

Dispersion Challenges: Uniform distribution of nanosilica in the mix is essential for achieving consistent performance.

Cost-Related Issues: Nanosilica is still an expensive material, which will affect the economic viability for large-scale applications.

Workability: High doses of nanosilica result in decreased workability, where high-performance super plasticizers are required.

CONCLUSION

High volume of substituted nanosilica was tested and analyzed on ultra-high-performance concrete to observe changes in its hydration and mechanical characteristics. This aims at ascertaining whether there is the potential to utilize the nanosilica in replacement with part cement, in substitution of producing cement for the concrete in question as well as maintain or even develop more significant characteristic values regarding durability and mechanics.

The experimental results showed that the addition of nanosilica has a significant effect on the hydration process and microstructure of UHPC. The pozzolanic activity of nanosilica, along with its high specific surface area, accelerates the hydration reaction and enhances the formation of additional C-S-H gel. This enhances the densification of the matrix and the bonding between cementitious phases, which is responsible for the excellent mechanical performance of UHPC. At high volumes (10% to 30% by weight of cement), replacement with nanosilica was seen to increase compressive and flexural strengths significantly at the early ages through the nucleation effect of nanosilica. Overall, the findings reveal that nanosilica has an excellent capacity for microstructural refinement and improving mechanical properties of UHPC.

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