

Performance Evaluation on the Strength of Nano-Enhanced Ultra-High-Performance Concrete under different Curing Regimes

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Abstract.

Ultra-High-Performance Concrete (UHPC) is characterized by its exceptional mechanical strength and dense microstructure; however, its performance is strongly influenced by curing conditions and the incorporation of advanced nano-scale materials. In this research the impact of nano-titanium dioxide (Nano-TiO₂) on the mechanical performance of UHPC under various curing regimes is investigated experimentally. UHPC mixture of M120 grade was prepared by incorporating Nano-TiO₂ at dosages of 1%, 2%, and 3% by weight of the cement binder. The prepared specimens were subjected to normal water curing, oven curing and accelerated thermal curing conditions, and their compressive strength was evaluated at different curing ages. The results reveal that the strength development of UHPC is considerably modified by the addition of nanomaterial, with the level of improvement varying according to the type of nanomaterial and the curing regimes. Due to improved particle packing, dispersion effects, and cementitious matrix modification, a 2% nano-material content often produced the best mechanical performance among the studied dosages. Nano-TiO₂ exhibited a positive influence on the strength development of M120 UHPC, with its effect becoming more evident at later curing ages. Overall, the results show that maximizing strength development, improving the UHPC matrix, and attaining superior mechanical performance all depend on the synergistic optimization of nano-material dosage and curing regime. This provides an effective method for the production of high-strength and high-performance UHPC.

Keywords: Cementitious material, curing regimes, Nano material, ultra high-performance concrete

1. Introductions

Ultra-High-Performance Concrete (UHPC) is an advanced cementitious composite characterized by very high strength, durability, and dense microstructure. Its performance is achieved through optimized particle packing, a low water-to-powder ratio, silica fume, fine powders, and high-range water-reducing admixtures. UHPC typically consists of cement, supplementary cementitious materials, fine sand, and fibers, with the absence of coarse aggregate promoting a low-porosity matrix. Silica fume enhances strength through pozzolanic and pore-filling effects, while fibers improve tensile, flexural, and post-cracking performance. Reactive Powder Concrete (RPC) is a closely related material using very fine powders, quartz powder, silica fume, and fibers. The strength development of UHPC/RPC is

significantly affected by curing conditions; therefore, conventional and heat-curing regimes are commonly investigated to improve its performance. [1–3]

Adding nanoparticles to Ultrahigh Performance Concrete (UHPC) has proven to be a successful strategy for improving the material's durability and mechanical performance. Nanomaterials can increase particle packing, fill nanoscale spaces, speed up cement hydration, and encourage the creation of more calcium silicate hydrate (C–S–H) gel because of their incredibly tiny particle size and high specific surface area. These processes help to improve the strength and longevity of UHPC by densifying the cementitious matrix and refining the pore structure. Numerous nanomaterials, such as carbon nanotubes, graphene-based materials, nano-SiO₂, nano-CaCO₃, nano-TiO₂, and nano-MgO, have been studied for possible uses in UHPC.[4]

Using a filler, nucleation, and pore-refinement actions, nano-TiO₂ improves UHPC performance and produces a denser and more compact cementitious matrix. Mechanical strength, impermeability, and resistance to frost action, carbonation, and chloride penetration can all be enhanced by its addition. On the other hand, too much nano-TiO₂ may lead to diminished workability, increased water demand, and particle agglomeration. For this reason, obtaining the most advantages requires a uniform dispersion and an ideal dosage. [4]

In order to create a novel ultra-high-performance concrete (UHPC), the current study uses powdered nano TiO₂ in combination with additional cementitious material.

The aim of the present study is to investigate how various curing regimes affect the mechanical performance of UHPC that incorporates nanoparticles. The impact of curing conditions on the strength development of nano-modified UHPC at various ages is specifically examined. The study evaluates and compares different curing regimes to identify the most effective condition for enhancing the hydration, and overall performance of UHPC containing Nano-TiO₂

2. Materials and Experimental Methods.

2.1 Raw Materials

The main binder for developing a UHPC with nano materials is an Ordinary Portland Cement of 53 grade that complied with IS 12269:2013 [5]. Fly ash, ultrafine ground granulated blast-furnace slag, micro silica are utilized. The UGGBS and micro silica, were incorporated to enhance the packing density and reduce the porosity of the cementitious matrix. Ultra-High-Performance Concrete (UHPC) mixtures were prepared using distinct aggregate combinations: natural river sand and 10 mm crushed stone for the UHPC grade, Aggregate characterization complied with IS 2386 (Part 1) [6] and satisfied the standard specifications of IS 383:2016 [7], a polycarboxylate-ether (PCE)-based high-range water-reducing admixture, was used in the UHPC grade to achieve the required workability and flowability at a low water-to-binder ratio.

Nano-TiO₂ possesses excellent chemical stability, relatively low cost, and significant photocatalytic activity, making it a promising nanomaterial for incorporation into ultra-high-performance concrete (UHPC). Its nanoscale particle size and high specific surface area can promote the nucleation of

hydration products and contribute to particle packing and microstructural refinement, potentially enhancing the mechanical performance of the UHPC matrix. [4]

In the present study, Nano-TiO₂ was incorporated into UHPC to investigate its influence on strength development under different curing regimes. The comparative assessment was aimed at evaluating the extent to which curing conditions affect the performance of Nano-modified UHPC and identifying the curing regime that provides more effective strength development.

2.2 Mix Design and Proportions

The UHPC mixtures were designed to achieve high compressive strength, and adequate workability while maintaining a low water-to-binder (w/b) ratio. The mixtures comprised cement, UGGBS, micro silica, river sand, coarse aggregate with a nominal maximum size of 10 mm, Nano-TiO₂ was incorporated as nano modifying material to investigate their influence on the strength development of UHPC under different curing regimes. A polycarboxylate-ether (PCE)-based high-range water-reducing admixture was used.

2.3 Specimen Preparation and Curing Regimes

A regulated mixing process was used to create the UHPC combinations in order to ensure that all of the component ingredients and nanoparticles were uniformly dispersed. Cement, UGGBS, Micro silica, fly ash, fine aggregate and coarse aggregate were among the dry ingredients that were first combined to create a uniform mixture.[9][10] Then, the predefined amount of Nano-TiO₂ was added and well mixed to ensure even dispersion throughout the cementitious matrix. After that, water and the necessary amount of PCE-based superplasticizer were added gradually while the mixture was being mixed until it was homogenous and completely workable.

The freshly mixed UHPC was immediately cast into the designated moulds for the respective mechanical tests. The moulds were adequately vibrated to minimize entrapped air and ensure effective densification of the concrete matrix. After casting, the moulds were carefully covered to minimize moisture evaporation and prevent premature drying. After 24 h, the specimens were demoulded and subsequently subjected to the designated curing regimes.

Three curing regimes—standard water curing, accelerated curing, and oven curing—were adopted to evaluate their effects on the compressive strength development of control and nano-modified M120 UHPC. The specimens were cured under the respective conditions for prescribed durations and tested at designated ages to comparatively assess the influence of curing regime and nanomaterial incorporation on strength development.

For standard water curing, specimens were demoulded after 24 h and immersed in clean water at $27 \pm 2^\circ\text{C}$ until the designated testing ages. Accelerated curing was performed as per IS 9013:1978 (Reaffirmed 2018) [8], involving initial curing at $27 \pm 2^\circ\text{C}$ for 23 ± 0.25 h, followed by immersion in boiling water at approximately 100°C for 3.5 ± 0.08 h and subsequent cooling in water at $27 \pm 2^\circ\text{C}$ for at least 2 h. For oven curing, specimens were cured at 100°C for 24, 48, and 72 h, followed by cooling to room temperature before compressive-strength testing.

2.4 Experimental Results and Discussion

The experimental results obtained for the UHPC specimens subjected to standard water curing, accelerated curing, and oven curing were systematically analysed and compared. The compressive strength results at the respective testing ages were evaluated to examine the influence of curing conditions and curing duration on the strength development of M120 UHPC.

The variations in compressive strength were evaluated with respect to the curing regime and exposure duration. Standard water curing was used as the baseline, and strength was measured at designated ages. The effect of Nano-TiO₂ on strength development was assessed by comparing the reference and nano-modified M120 UHPC mixtures.

The improvement of mechanical performance was examined using the measured strength values at consecutive curing ages. Additionally, baseline data for comparison with the accelerated curing test (ACT) and steam curing regimes was provided by the standard water-curing results.

2.4.1. Compressive Strength under Standard Water Curing

The compressive strength development of M120 UHPC incorporating different dosages of Nano-TiO₂ under standard water curing was evaluated at 7, 28, 90, and 365 days. The results indicate that nano-material incorporation enhanced the strength development relative to the reference mixture.

Nano-TiO₂ incorporation enhanced the compressive strength of M120 UHPC compared with the control mixture, with the improvement varying with dosage and curing age. At 7, 28, 90, and 365 days, the strength increases for 1%, 2%, and 3% Nano-TiO₂ were 3.79%, 9.65%, and 2.26%; 4.27%, 6.62%, and 3.69%; 5.68%, 6.58%, and 2.83%; and 5.59%, 6.31%, and 2.77%, respectively. Overall, 2% Nano-TiO₂ exhibited the highest strength enhancement and was identified as the optimum dosage within the investigated range.

The higher strength enhancement associated with the 2% dosage can be attributed to the effective utilization of nanoparticles for matrix densification, pore refinement, and modification of the cementitious microstructure. In contrast, the reduction in strength enhancement at 3% dosage suggests that excessive nanoparticle content may promote particle agglomeration and reduce dispersion efficiency, thereby limiting the beneficial contribution of the nanoparticles to matrix refinement.

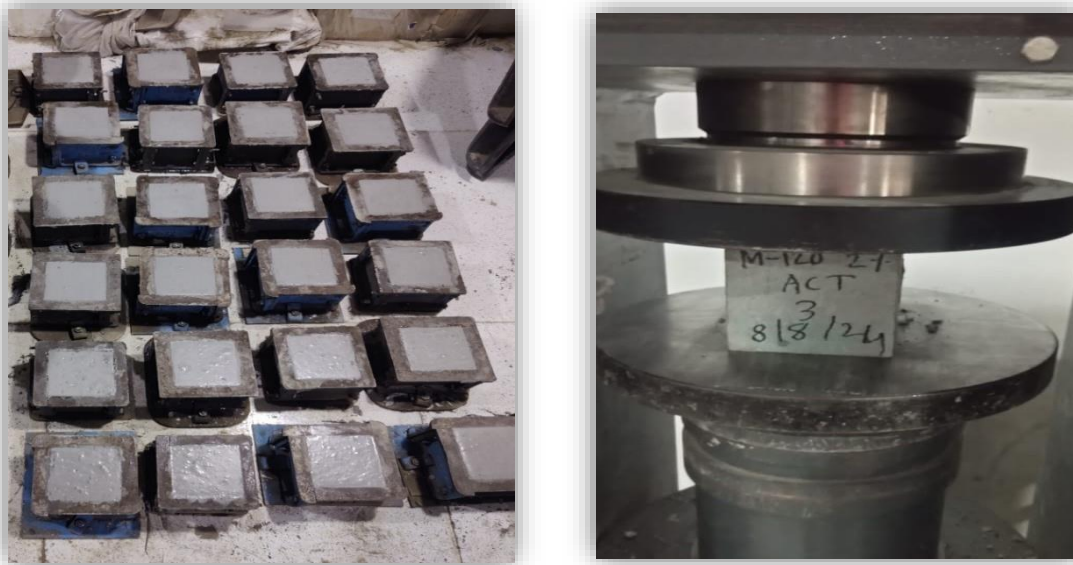


Figure-1 (a) Casting of specimens (b) Compressive Strength Testing for accelerated curing.

Nano-TiO₂ exhibited a positive effect on the compressive strength of M120 UHPC across the investigated dosages and curing ages. The highest strength enhancement was observed at the 2% dosage, with the improvement maintained throughout the curing period, indicating a sustained beneficial effect under prolonged standard water curing.

2.4.2. Compressive Strength under Oven Curing

The compressive strength development of M120 UHPC subjected to oven curing for 24, 48, and 72 h was evaluated for Nano-TiO₂ dosages of 1%, 2%, and 3%. The results indicate that oven curing promoted progressive strength development with increasing curing duration for all mixtures. The percentage changes were calculated relative to the corresponding 0% nano-material mixture at each curing duration.

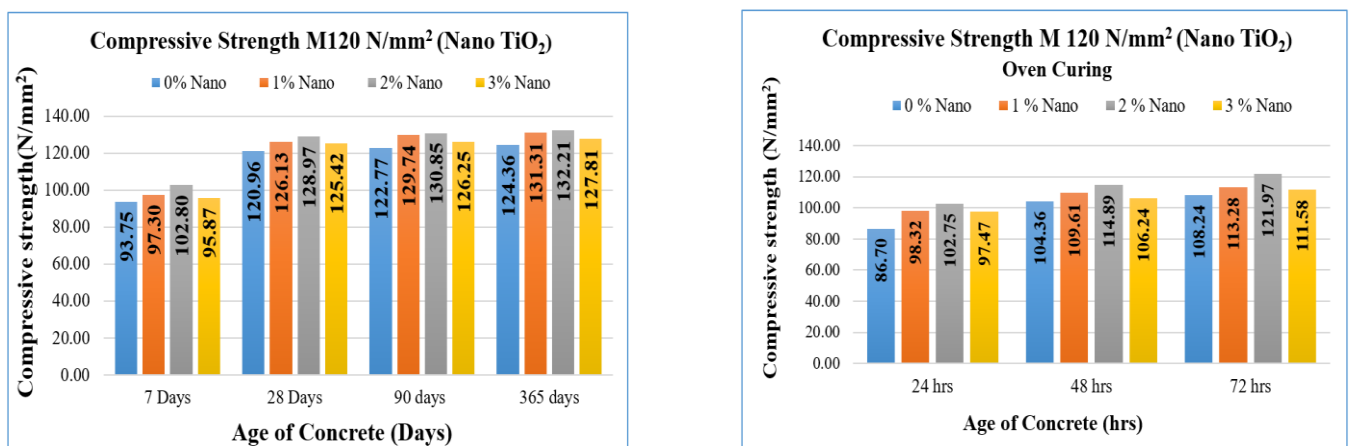


Figure- 2 Compressive strength (M120 N/mm²) Vs age of concrete (days) using Nano TiO₂ under (a) standard normal curing and (b) oven curing

For Nano-TiO₂, the strength enhancements at 24 h were 13.37%, 18.51%, and 12.42% for 1%, 2%, and 3% dosages, respectively. At 48 h, the corresponding improvements were 5.03%, 10.08%, and 1.80%, while at 72 h, they were 4.66%, 12.68%, and 3.09%, respectively.

Inclusive, the 2% Nano-TiO₂ dosage exhibited the highest strength enhancement. In nano-modified systems, the 2% dosage consistently exhibited the highest strength enhancement, indicating an optimum nano-material content within the investigated range. The enhanced early-age performance under oven curing can be associated with accelerated hydration and faster development of the cementitious matrix under elevated-temperature conditions, while the nanoparticles can additionally contribute to matrix densification through their filling and pore-refinement effects.

For Nano-TiO₂, the optimum 2% dosage resulted in compressive-strength enhancements of 18.51%, 10.08%, and 12.68% at 24, 48, and 72 h, respectively. These results indicate that 2% Nano-TiO₂ provided the most favorable strength improvement among the investigated dosages.

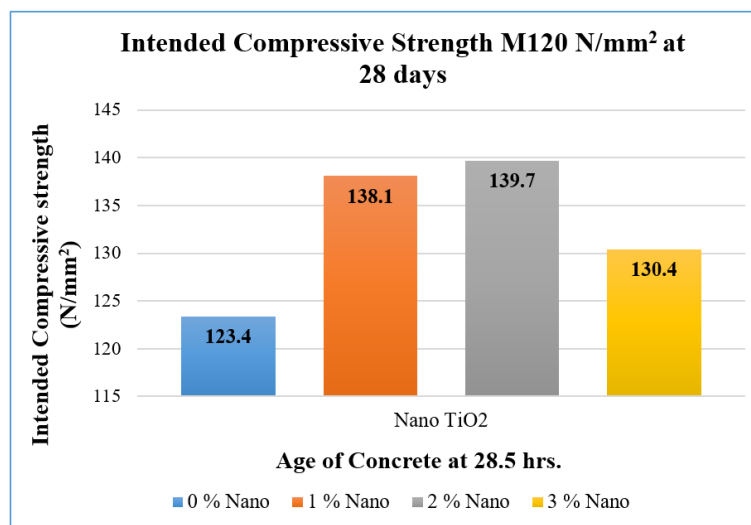


Figure- 3 Compressive strength (M120 N/mm²) Vs age of concrete (Hours) using Nano TiO₂ under Accelerated Curing

2.4.3. Compressive Strength under Accelerated curing

The accelerated curing results for M120 UHPC indicate a clear influence of nano-material incorporation on the intended 28-day compressive strength, as illustrated by the compressive strength testing shown in Figure 1(b). [8]

When compared to the reference combination, the 1%, 2%, and 3% dosages of Nano-TiO₂ produced the desired 28-day compressive-strength increases of 11.91%, 13.21%, and 5.67%, respectively. The 2% Nano-TiO₂ dosage showed the best reaction under accelerated curing, with a maximum enhancement of 13.21%.

The enhanced compressive strength under accelerated curing can be attributed to the combined effects of elevated temperature and nano-material incorporation, which accelerate hydration and promote matrix densification through improved particle packing and pore refinement. The 2% dosage provided the most effective nanoparticle dispersion and matrix refinement. At 3% dosage, reduced improvement may be associated with increased nanoparticle interaction and agglomeration, limiting their effective contribution to strength development.

3. Conclusion:

Based on the results of the present experimental investigation, the following conclusions are established.

1. The experimental results indicate that dosages of nanomaterial and the curing regime have a major impact on the development of M120 UHPC's compressive strength. When compared to the corresponding reference mixture, the strength response was significantly improved by the addition of nanomaterials.
2. Across all three curing regimes—standard water curing, oven curing, and accelerated curing—the 2% nano-material dosage demonstrated the most favorable compressive-strength performance. Increasing the dosage to 3% did not provide further improvement, confirming the importance of optimizing nano-material content rather than simply increasing its dosage.
3. Nano-TiO₂ demonstrated a positive influence on the strength development of UHPC under the investigated curing regimes. The 2% dosage exhibited the most favorable strength enhancement, indicating its effective contribution to modifying and densifying the UHPC cementitious matrix.
4. Oven and accelerated curing helped achieve higher compressive strength in a shorter curing period compared with conventional curing. Therefore, these curing methods can be useful when early strength development is required, provided that the curing temperature and duration are properly controlled.
5. The optimum compressive-strength performance of M120 UHPC was observed with the incorporation of 2% Nano-TiO₂ under the investigated curing regime. The results indicate that the nano-material dosage and curing regime significantly influence the strength development of M120 UHPC.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this research paper.

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