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Influence of Titanium Dioxide Nanoparticles on the Performance Characteristics of Cement-Based Mortar

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ABSTRACT

This study investigates the influence of nano titanium dioxide (TiO_2) on the mechanical, durability, and photocatalytic properties of fly ash-based cement mortar. Mortar mixes were prepared by partially replacing cement with 25% and 30% fly ash (F25 and F30) and incorporating varying contents of nano-TiO_2 (1%, 3%, and 5% by weight of binder). The compressive and flexural strengths were evaluated at 7 and 28 days, while water absorption and photocatalytic degradation of methylene blue were tested at 28 days. Results showed that while fly ash replacement alone slightly reduced strength and did not contribute to photocatalytic activity, the addition of nano-TiO_2 substantially enhanced performance. The mix containing 1% TiO_2 (T01) demonstrated the highest compressive (49.48 MPa) and flexural (5.12 MPa) strength at 28 days, attributed to improved hydration kinetics and refined pore structure. Moreover, mixes with higher TiO_2 content (T03, T05) exhibited significantly lower water absorption and superior photocatalytic degradation, reaching up to 47.5%. These findings confirm that incorporating nano-TiO_2 is an effective strategy to improve both the mechanical integrity and environmental functionality of fly ash mortars.

1. Introduction

Over the past few decades, the building industry has evolved to create multifunctional cement products that can withstand structural loads and provide environmental sustainability. In addition to other nanomaterials, titanium dioxide (TiO_2) nanoparticles have been shown to be one of the most promising nanomaterials as additives owing to their twofold properties: enhancement of mechanical properties and addition of photocatalytic self-cleaning behavior [1].

The incorporation of TiO_2 into cement mortar leads to microstructure refinement, predominantly by filling microvoids and acting as nucleation sites for hydration products, resulting in greater compressive and flexural strengths [2]. Simultaneously, its photocatalytic behavior when subjected to ultraviolet (UV) or visible light illumination enables it to degrade environmental pollutants such as nitrogen oxides and volatile organic compounds (VOCs), and consequently, its utilization in environmentally friendly applications such as air-purifying surfaces and self-cleaning concrete [3].

Fly ash is also a material that has been widely used to aid in cementitious system sustainability and performance. Fly ash is a pozzolanic byproduct of coal combustion that, when reacting with calcium hydroxide from cement paste, forms additional calcium silicate hydrate (C-S-H), which increases the long-term strength and impermeability of the mortar [4]. However, its reduced reactivity at younger ages could reduce the initial strength, which can be compensated by incorporating fly ash with nano-additives such as TiO_2 [5].

This study investigates the influence of TiO_2 nanoparticles on the flexural and compressive mechanical strength, water absorption, and

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photocatalytic ability of cement mortar, whose photocatalytic ability was determined by methylene blue (MB) degradation. It also investigates the potential synergistic effect when combined with fly ash.

2. Literature Review

2.1. Fly Ash in Mortar

Fly ash is a popular supplementary cementitious material (SCM) with proven capability to enhance the workability, long-term strength, and durability of mortar and concrete. Owing to its pozzolanic properties, it can react with calcium hydroxide (CH) formed during cement hydration and produce more C-S-H gel, contributing to the densification of the matrix and long-term strength gain [4].

The addition of fly ash reduces water demand and improves sulfate attack resistance, alkali-silica reaction resistance, and permeability [6]. However, its lower hydration kinetics generally result in reduced early age strength. Researchers have attempted to blend fly ash with nanomaterials to improve pozzolanic reactivity and compensate for this reduction in early age strength [5].

2.2. TiO_2 Nanoparticles in Mortar

Titanium dioxide nanoparticles have drawn significant interest for use in cementitious materials because of their nanometric particle size, high surface area, and photocatalytic activity. When used in cement mortar in the appropriate amount (typically 1–3% of cement weight), TiO_2 can enhance the compressive and bending strengths owing to enhanced particle packing and hydration reactions [2][7].

Regarding durability, TiO_2 nanoparticles reduce water permeability and increase resistance to aggressive agents by minimizing matrix porosity [8]. The single most remarkable benefit, however, is the photocatalytic function of TiO_2 to degrade organic and inorganic pollutants upon exposure to light, which is quantified by the degradation of methylene blue (MB) dye as a reference test. Photocatalysis involves the generation of reactive oxygen species (ROS), which decompose organic molecules into harmless byproducts [3][9].

The incorporation of titanium dioxide (TiO_2) nanoparticles into cementitious mortars has been shown to significantly enhance the microstructural properties of the matrix. TiO_2 nanoparticles act as nanofillers, effectively filling micro voids and refining the pore structure, which leads to a denser and more homogeneous matrix. This densification reduces the total porosity and improves the interfacial transition zone (ITZ) between the cement paste and aggregate particles. Moreover, the high surface area and photocatalytic activity of TiO_2 can accelerate the hydration process by serving as nucleation sites for calcium silicate hydrate (C–S–H) formation, contributing to a more compact microstructure and enhanced durability performance [21][27].

Recent studies have also identified the synergistic use of TiO_2 and fly ash in mortar mixtures. Nanofillers compensate for the early-stage reactivity deficiency of fly ash, whereas fly ash enhances long-term pozzolanic activity and reduces cement production environmental loading [5][10].

3. Materials and Methods

Figure 1. a) OPC, b) FA, c) Ottawa Sand, d) Nano TiO2, e) Viscocrete (HRWR)

The chemicals (figure 1) used in this study were Ordinary Portland Cement (OPC) ASTM C150 [11], fly ash, Class F (Eurobuild Flyash) ASTM C618 [12], and titanium dioxide nanoparticles (anatase phase) with a particle size range of 5-10 nm were purchased from Shanghai Macklin Biochemical Technology Co., Ltd. through Al-Mansour Scientific Bureau in Baghdad (Tables 3 and 4). Nano TiO2 was incorporated into the mixing water in advance to prevent agglomeration. Ottawa sand (Table 1) with a fineness modulus of 2.775, meeting ASTM C778 [13], was used as the fine aggregate, and drinking water with a pH of 7 was used as the mixing water. To achieve workability, Sika® ViscoCrete®-180 GS, a high-range water-reducing superplasticizer (Table 5) meeting the specification of ASTM C494 [14], was applied to the mixes. Table 2 shows the chemical compositions of OPC and FA.

Table 1: Sieving test results

Sieve Size (mm)	Percentage Passing (%)
4.75	100
2.36	95
1.18	75
0.6	37.5
0.3	12.5
0.15	2.5
0.075	0

Table 2: Chemical content of the OPC and the FA

Component	OPC	FA
Silicon Dioxide (SiO_2)	19.7	48.2
Aluminium Oxide (Al_2O_3)	6.3	25.4
Iron Oxide (Fe_2O_3)	4.3	10.7
Calcium Oxide (CaO)	62.2	8.3
Magnesium Oxide (MgO)	1.8	2
Sulphur Trioxide (SO_3)	2	1.9
Loss on Ignition (LOI)	1.1	1.2
Alkalis ($Na_2O + K_2O$)	2	1.6
Other Oxides	0.6	0.7

Table 3: Properties of Nano TiO_2

Property	Value
Name	Titanium Oxide
Appearance	white to off-white powder
Phase	anatase
Purity	99.8% Metal Bases
Average Nano Particle Size	5-10 nm
Chemical Formula	TiO_2
Molecular Weight	79.87

Table 4: Chemical Properties of Nano TiO_2

Test	Specifications	
	Min	Max
Assay (TiO_2)	99%	100%
Barium (Ba)	0 ppm	5 ppm
Arsenic (As)	0%	0.005%
Heavy Metals (AS PB)	0%	0.002%
Iron (Fe)	0%	0.005%

Table 5: Super plasticizing admixture

Property	Description
Composition	Aqueous solution of modified polycarboxylates
Appearance / Colour	Light brownish liquid
pH-Value	4 - 6
Specific gravity	1.070 ± (0.005) g/cm3

4. Test Procedures

Compressive Strength and According to ASTM C109 [15], the compressive strength was tested on the 7th and 28th days using 50 × 50 × 50 mm cube specimens under a calibrated 2000 kN compression test machine. The failure load was recorded, and the strength was calculated as the maximum load over the cross-sectional area. Flexural Strength, as defined in ASTM C348 [16], was determined on 40 × 40 × 160 mm 28-day cured prisms by three-point bending with a 100 mm span; the fracture load was measured to determine the flexural strength. For Water Absorption, ASTM C642 [17] was used with test specimens 50 × 50 × 50 mm: specimens cured for 28 days were oven-dried at 105 °C for 24 h, cooled, weighed, and then immersed in water for 24 h to obtain the saturated mass. For Methylene Blue Degradation, following the procedure of Chen et al. (2011) [18], mortar was crushed to a particle size below 150 μm after curing for 28 days. A 10 mg/L methylene blue (MB) solution was agitated in the dark for 30 min (adsorption stage), blended with 1 g of mortar, and then irradiated using UV light (365 nm) under constant agitation. Aliquots were collected after 4 h, and the measurements were performed using UV-Vis spectroscopy at 664 nm. Table 6 illustrates the mix design, which was conducted at a ratio of 1:2.75:0.3. HRWR was 1.2% for all mixes. Three specimens were used for each test.

Table 6: Mix design

Mix	Cement gm	Sand gm	Water ml	FA gm	Nano TiO_2 gm
Ref	1000	2750	300	0	0
F25	750	2750	300	250	0
F30	700	2750	300	300	0
T01	700	2750	300	300	10
T03	700	2750	300	300	30
T05	700	2750	300	300	50

5. Results and Discussions

5.1. Compressive Strength

The compressive strength results at both 7 and 28 days are presented in Figure 2. The incorporation of fly ash alone (F25 and F30) resulted in a minor reduction in early and late strength compared to the reference mix. This observation is consistent with previous findings, as the reduction is attributed to the slower pozzolanic reaction rate of fly ash at early ages [19].

Compared to the fly ash-only mixes, the addition of nano-TiO_2 (T01, T03, and T05) to the fly ash-based mortars led to a noticeable improvement in compressive strength, particularly in mix T01, which recorded the highest strength values of 36.72 MPa at 7 days and 49.48 MPa at 28 days. Such improvements can be attributed to several factors. First, nano-TiO_2 acts as a nucleation site for calcium-silicate-hydrate (C–S–H) gel formation, which accelerates hydration [20]. Second, its filler effect refines the pore structure, reducing the number of micro voids and enhancing the matrix density [21]. However, although the TiO_2 dosage increased, the strength did not improve beyond the optimal level, likely due to the agglomeration of nanoparticles at higher dosages, which can impair homogeneity and reduce the effective surface area [22].

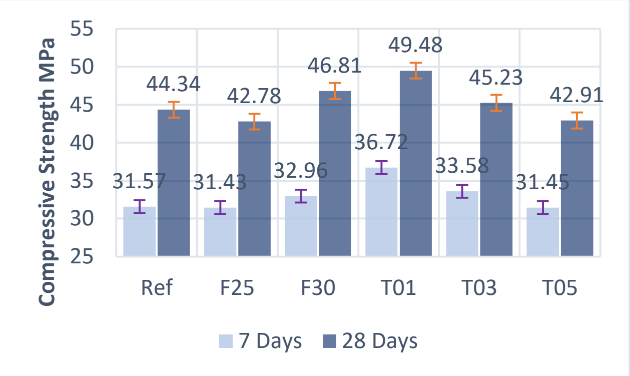

Figure 2. Compressive strength test results

5.2. Water Absorption

The water absorption results at 28 days are shown in Figure 3. The reference mix (Ref) exhibited the highest water absorption at 4.56%, whereas the modified mixes with TiO_2 showed progressively lower values, reaching 3.38% for T03 and 3.51% for T05.

Compared to the reference, the inclusion of fly ash (F25 and F30) slightly reduced water absorption compared to the reference, likely due to the secondary C–S–H formation from pozzolanic reactions that block pores over time [19]. Nonetheless, the most significant reduction occurred with the incorporation of nano-TiO_2, particularly in T03. This finding suggests that the densification of the microstructure by nanosized particles filling voids between cement grains and blocking capillary pores is the primary reason for the reduced absorption [23].

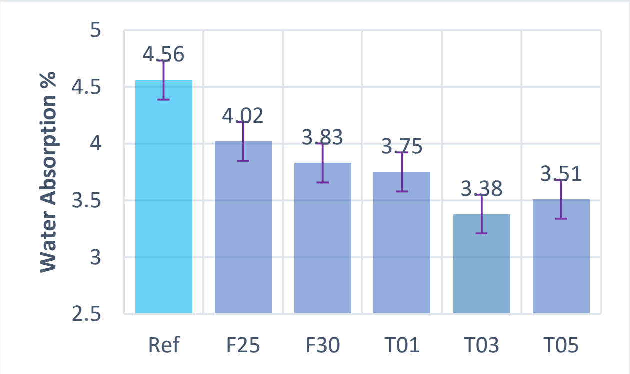

Figure 3. Water absorption test results

5.3. Flexural Strength

Figure 4 shows the flexural strengths of all mortar mixes at 28 d. The reference mix exhibited a flexural strength of 4.34 MPa, whereas the F30 mix recorded the lowest at 3.83 MPa, reinforcing earlier observations that high-volume fly ash tends to reduce flexural performance owing to reduced early hydration bonding [19].

In contrast, mix T01 exhibited a significant improvement, reaching 5.12 MPa, which was the highest among all mixes. Such enhancements can be attributed to the enhanced interfacial bonding and crack bridging effect induced by nano-TiO_2, which can increase the tensile resistance [21][24]. Furthermore, TiO_2 can form a denser hydration shell around the aggregate particles, enhancing the matrix–aggregate interaction under flexural stress. Interestingly, although T03 and T05 surpassed the reference in terms of strength, they did not outperform T01.

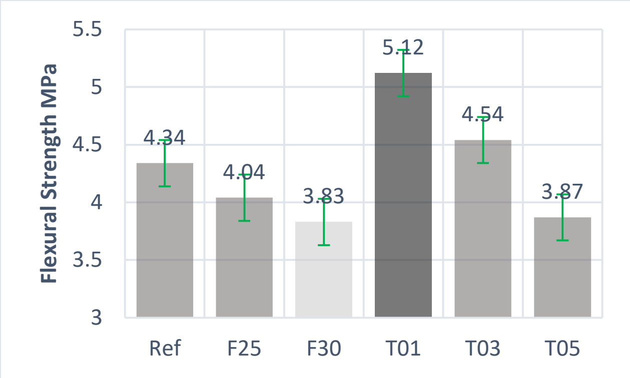

Figure 4. Flexural strength test results

5.4. Methylene Blue Degradation

The test results revealed a strong correlation between the nano TiO_2 content and the photocatalytic degradation performance of the samples. As illustrated in figure 5, the reference and fly ash-only mixes (Ref, F25, and F30) showed minimal degradation (approximately 3%), indicating negligible photocatalytic behaviour. As expected, this occurred because these mixtures lacked photocatalytic components. On the other hand, the mixes containing nano TiO_2 (T01, T03, T05) exhibited significantly higher degradation rates, with values of 18.6%, 35.2%, and 47.5%, respectively. This trend confirms the effectiveness of TiO_2 in catalysing the breakdown of organic dyes under UV light, attributed to the generation of reactive oxygen species (ROS) that oxidize dye molecules [25][26].

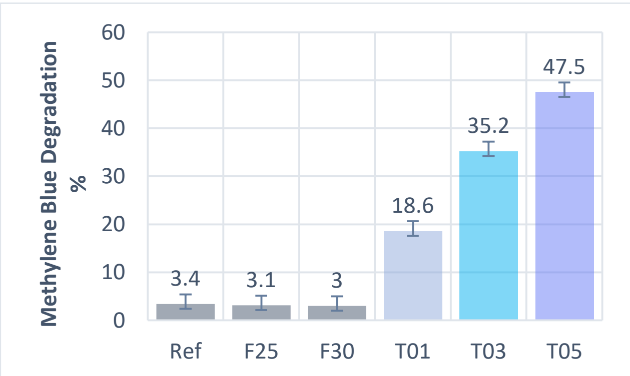

Figure 5. Methylene Blue Degradation percentage

6. Conclusions

The experimental results clearly indicate the multi-functionality of nano-TiO_2 as an admixture for multi-functional fly ash cement mortars. Although early and late mechanical strengths were reduced to some extent through fly ash application, when combined with nano-TiO_2, both flexural and compressive strengths significantly increased, primarily at a 1% addition. This enhancement was primarily attributed to the nucleation effect and microstructural densification provided by the TiO_2 nanoparticles. In addition, the addition of TiO_2 helped to significantly reduce the marked reduction in water uptake owing to its filler effect and pore-blocking property. The photocatalytic degradation experiments also confirmed the environmental benefit of TiO_2 addition, and the degradation efficiency increased proportionally with the amount of TiO_2. However, excessive amounts of TiO_2 (more than 1%) did not enhance the mechanical strength, presumably due to nanoparticle agglomeration. In general, the findings strongly support the incorporation of nano-TiO_2 as a multifunctional additive, enhancing the mechanical and environmental performance of fly ash cement mortars, especially under optimal dosing conditions, to produce high-performance, durable, and self-cleaning cementitious composites that ensure mechanical reliability and environmental sustainability. These characteristics make the developed mortars particularly suitable for real-world applications such as self-cleaning building facades, urban pavements, and air-purifying surfaces in polluted environments, where both durability and environmental responsiveness are critical.

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