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A critical assessment on the effect of nano-titanium dioxide on the properties of concrete

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Research Paper

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A critical assessment on the effect of nano-titanium dioxide on the properties of concrete

Recent advances in nanotechnology in various fields demonstrate tremendous promise for resolving a wide variety of problems. Nanotechnology has been shown to improve the efficiency of conventional building materials such as concrete. Numerous types of nanoparticles, such as nano-titanium dioxide, are being used to significantly improve the efficiency, longevity, and sustainability of concrete. This paper summarises prior research on the effect of nano-titanium dioxide on a variety of properties, including heat of hydration, workability, setting time, chemical shrinkage, mechanical strength, abrasion resistance, fire resistance, and freeze/thaw resistance. Water absorption, chloride penetration, and permeability are all low in conventional plain or blended cement systems. Additionally, the matrix containing nano-titanium dioxide is compared in this study to a matrix containing other nanoparticles. Civil engineers can use this paper as a quick reference.

Key words:
nanomaterials, concrete durability, nano-titanium dioxide, nanotechnology, permeability

Prethodno priopćenje

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Kritička procjena učinka nanotitanijeva dioksida na svojstva betona

Nedavni napredak nanotehnologije u raznim područjima izuzetno je obećavajuće za rješavanje širokog spektra problema. U istraživanjima i izumima se pokazalo da nanotehnologija poboljšava učinkovitost konvencionalnih građevnih materijala kao što je beton. Brojne vrste nanočestica, kao što je nano titanijev dioksid, koriste se za značajno poboljšanje učinkovitosti, dugotrajnosti i održivosti betona. Ovaj rad sažima prethodna istraživanja o učinku nanotitanijeva dioksida na različita svojstva, uključujući toplinu hidratacije, obradivost, vrijeme vezivanja, kemijsko skupljanje, mehaničku čvrstoću, otpornost na abraziju, vatrootpornost i otpornost na smrzavanje/odmrzavanje. Vrijednosti upijanje vode, penetracija klorida i propusnosti su male u konvencionalnim sustavima običnog ili mješovitog cementa. Osim toga, u ovom istraživanju matrica koja sadrži nanotitanijev dioksid uspoređuje se s matricom koja sadrži druge nanočestice. Građevinski inženjeri mogu koristiti ovaj opis kao izvor podataka.

Ključne riječi:
nanomaterijali, trajnost betona, nanotitanijev dioksid, nanotehnologija, propusnost

1. Introduction

High-quality concrete is low cost and easy to fabricate. Moreover, it exhibits a superior performance and has general applicability. However, the limitations of concrete, such as its low strength, cracking susceptibility, and sudden failure due to its brittle nature, increase its rate of deterioration and repair costs. The majority of degradation occurs in the marine environment, where the presence of chloride and sulfate ions impairs the durability of concrete structures. Numerous factors, including chloride ion concentration, type of cement, alkalinity, and temperature, all affect the corrosion rate of embedded reinforcement. According to Salman et al. [1], the behavior of concrete is influenced by its durability, porous nature, and resistance to harmful agents, such as sulfate and chloride ions. The performance of these agents is reduced caused by the localised breakdown of the passive layer and corrosion of embedded steel rebars.

According to Nazari et al. [2], capillary pores form an interconnected network that facilitates the penetration of impurities into concrete. Air-trapped, air-entrained, gel, and capillary pores all contribute to the transport of impurities via diffusion, permeation, and migration. Hence, there is a need for more durable infrastructure with low repair costs. The development of new-generation cement-based materials through the incorporation of auxiliary cementitious materials, such as pozzolans and nanomaterials, to mitigate structure degradation is ongoing. Recent years have seen a surge in scientific interest in nanomaterials, owing to the potential benefits of molecules in the nanometer range (10^{-9} m). This could be because nanoparticles can alter the properties of molecules with predictable particle sizes and the same chemical composition. According to Nazari et al. [3], the incorporation of nanomaterials into concrete specimens has received global attention for its potential to improve the durability, mechanical properties, pore structure, and microstructure of cement-based materials. Wang et al. [4] enhanced the effect of nano-titanium dioxide using a variety of techniques, including filler material, cement hydration, and parallel packing to form a high-density C-S-H structure.

Iyappan et al. [5] demonstrated the ability of nano-titanium dioxide to improve the resistance of concrete to physical and chemical deterioration, as well as its beneficial effects on the technical properties of concrete. According to Joshaghani et al. [6], nano-titanium dioxide has attracted widespread interest due to its high catalytic activity, chemical stability, and low cost. Nano-titanium dioxide contributes to the improvement of cement-based materials' mechanical, rheological, and durability properties.

2. Theory and discussion

2.1. Workability and setting time

Salemi et al. [7] found that adding 2 % nano-titanium dioxide to concrete reduces its workability. In comparison, the slump for the test mixture was 60 mm, whereas it was 120 mm for the control mixture. Nazari et al. [8] investigated the workability of concrete with nano-titanium dioxide at 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight replacement of cement. There was a decrease in workability observed as the percentage of added nano-titaniumdioxide increased. Li et al. [9] also reported a decrease in the workability of concrete mixtures as a result of partial replacement of concrete with 0 %, 1 %, and 3 % by weight of nano-titanium dioxide. Li et al. [10] and Li [11] measured the slump values of concrete modified with 0 %, 1 %, 3 %, and 5 % by weight of nano-titanium dioxide. The results indicated a 54.54 % reduction in slump values with the addition of 1 % or 3 % nano-titanium dioxide and a 72.75 % reduction with the addition of 5 % nano-titanium dioxide. Table 1 presents the slump value obtained by various authors when nano TiO_2.

Table 1. Slump of nano-titanium dioxide blended concrete

Autori	Slump [cm]		
	0 % TiO_2	1 % TiO_2	2 % TiO_2
Nazari et al. [1]	8.52	6	2.98
Nazari et al. [2]	8	5.3	2.2
Sorathiya et al. [3]	7.2	4.25	2.6

Jalal et al. [13] found that adding nano-titanium dioxide to self-compacting concrete mixtures in proportions of 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % by weight reduces the slump flow. Jalal et al. [14] also attempted to determine the properties of high-strength self-compacting concrete mixed with nano-titanium dioxide at concentrations of 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % by weight. The result indicated a decrease in workability due to the addition of nano-titanium dioxide to the mixture. Additionally, slump diameter reductions of 1.25 %, 2.5 %, 5 %, 7.5 %, and 8.75 % were reported.

Senff et al. [15] analysed the rheological and flow properties of mortar mixtures containing nano-titanium dioxide at concentrations of 0 %, 1.30 %, 2.60 %, and 5.20 % by weight and found an increase in torque values and yield stress. These values increased proportionately as the nano content increased. Chen et al. [17] considered two types of nano-titanium dioxide: P25 (75 % anatase, 25 % rutile) and anatase (99 % anatase). They investigated the initial and final setting times of concrete containing nano-titanium dioxide at concentrations of 0 %, 5 %, and 10 % by weight. The results indicated that pastes containing higher nano-titanium dioxide content set faster. Lee [18] measured the initial and final setting times of concrete mixtures with nano-titanium dioxide at 0 %, 5 %, and 10 % by weight and discovered a significant reduction in initial and final setting times. Nazari et al. [2] reported the same result for nano-titanium dioxide replacement at 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight. Essawy and Abd Elhaleem [19] reported that adding 5 %, 7 %, or 10 % nano-titanium dioxide to sulfate-resistant cement reduces the setting time. Tables 2 and 3 present the initial and final setting times of concrete with nano mix.

Table 2. Initial setting time of nano-titanium dioxide-blended concrete

Autori	Initial setting time [min]				
	0 % TiO_2	0.5 % TiO_2	1 % TiO_2	1.5 % TiO_2	2 % TiO_2
Nazari et al. [1]	225.36	171.53	145.98	119.52	104.92
Nazari et al. [4]	225.1	170.12	145.22	119.29	105.8
Khataee et al. [5]	160	152	141	134	120

Table 3. Final setting time of nano-titanium dioxide blended concrete

Autori	Final setting time [min]				
	0 % TiO_2	0.5 % TiO_2	1 % TiO_2	1.5 % TiO_2	2 % TiO_2
Nazari et al. [1]	335.74	261.85	252.77	221.66	207.4
Nazari et al. [4]	335.65	262.5	251.02	220.9	206.5
Khataee et al. [5]	270	268	257	249	240

Based on the foregoing analysis of the literature, it is concluded that the workability of a concrete mixture decreases with the addition of nano-titanium dioxide. This could be explained by the fact that more water is required to wet the cement particles owing to the increased surface area of nano-titanium dioxide particles [8]. The reduced workability of concrete is one of the disadvantages of nano-titanium dioxide addition that may limit its widespread use by engineers. The addition of nano-titanium dioxide particles resulted in a decrease in the mixture's initial setting time. This is because the incorporation of nano-titanium dioxide particles results in rapid consumption of free water, which accelerates the gap bridging process. As a result of this increase in viscosity, solidification occurs earlier [17]. Additionally, the shorter setting time is due to the large surface area of nano-titanium dioxide, which increases the availability of nucleation sites, resulting in a faster hydration rate [18]. The reduction in setting time caused by nano-titanium dioxide is application-dependent.

2.2. Water absorption

Salemi et al. [7] found that nano-titanium dioxide at a concentration of 2 % by weight of cement reduces water absorption in 28-day concrete by approximately 22 %. Nazari [20] investigated concrete modified using nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight of cement at ages of 7, 28, and 90 days. The result indicated that the addition of nano-titanium dioxide reduced water absorption, the rate of water absorption, and the coefficient of water absorption. For samples with nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight of cement, water absorption decreased by 59.1 %, 54.1 %, 51.1 %, and 47.5 %, respectively, for samples cured in water, and by 73.73 %, 71.45 %, 68.65 %, and 65.85 %, respectively, for samples cured in saturated limewater. However, it was determined that the optimal replacement proportion was 0.5 %. The limewater-cured samples had significantly lower water absorption values and a lower water absorption rate than the water-cured samples.

Soleymani [21] investigated the %age of water absorbed by concretes containing nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight of cement. At 7 days, the %age of water absorbed increased with the addition of nano-titanium dioxide, whereas at 28 and 90 days, the %age of water absorbed decreased under all curing conditions. The specimens cured in saturated lime water absorbed less water than those cured in water. At 28 days, for specimens with nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight of cement, the reduction was 59.11 %, 54.11 %, 51.1 %, and 47.5 %, respectively, for specimens cured in water, and 73.73 %, 71.45 %, 68.65 %, and 65.85 %, respectively, for specimens cured in saturated limewater. The specimen with a nano-titanium dioxide concentration of 0.5 % achieved the lowest %age of water absorption. Table 4 presents the %age of water absorbed by blended concrete.

Table 4. Percentage of water absorption of concrete containing nano-titanium dioxide

Autori	Percentage of water absorption		
	0 % TiO_2	1 % TiO_2	2 % TiO_2
Nazari et al. [8]	9.14	6.59	6.14
Nazari et al. [1]	5.6	2.57	2.94
Nazari [9]	4.8	1.12	1.63
Jalal [10]	5.12	4.93	4.68

Jalal [13] investigated the water absorption and capillary absorption of self-compacting concretes incorporating nano-titanium dioxide at concentrations of 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % by weight of cement after 14 days. The results indicated that nano-titanium dioxide reduced capillary absorption and water absorption. The optimal nano-titanium dioxide concentration exhibiting the lowest water absorption or capillary absorption value was 4 %. Jalal et al. [14] investigated the %age of water absorption and capillary water absorption in high strength self-compacting concretes modified with nano-titanium dioxide at concentrations of 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % by weight of cement after 90 days. The results indicated that both the rate of water absorption and capillary water absorption was decreased. For concentrations of nano-titanium dioxide greater than 4 %, the lowest %age of water absorption and capillary water absorption were observed.

Nazari and Riahi [22-24] investigated the %age of water absorbed by self-compacting concretes modified with nano-titanium dioxide at 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % by weight of cement at ages of 2, 7, and 28 days. At 7 and 28 days, the %age of water absorbed decreased. The lowest %age of water absorption was observed when 4 % nano-titanium dioxide was added. Meanwhile, with nano-titanium dioxide, the %age of water absorbed increased after 3 days. Jalal [25] investigated the %age of water absorbed by concretes containing 45 % slag by weight at ages of 7, 28, and 90 days. The binder materials were incorporated with nano-titanium dioxide at concentrations of 0 %, 1 %, 2 %, 3 %, and 4 % by weight. The results indicated that nano-titanium dioxide significantly reduced the %age of water absorbed at all ages. At 28 days, the %age of water absorbed decreased by 38.42

%, 41.35 %, 45.75 %, and 43.4 %, respectively. The nano-titanium dioxide concentration that resulted in the lowest %age of water absorption was 3 %. Shekari and Razzaghi [26] investigated the %age of water absorbed by concretes containing 15 % metakaolin modified with nano-titanium dioxide after 28 days. Nano-titanium dioxide was used at a concentration of 1.5 % in the cement, resulting in a 75.74 % reduction in water absorption.

From the summary of the literature above, nano-titanium dioxide significantly reduces the %age of water absorption in the majority of cases. Nonetheless, it occasionally accelerates the rate of water absorption in concrete. The decrease in water absorption %age could be attributed to the pozzolanic and filler effects of nano-titanium dioxide particles [20]. According to some studies [20, 22], the lowest water absorption %age is 0.5 % nano-titanium dioxide, while others [13, 14, 25, 27] report a value of 4 %. With 5 % silica fume, the optimal nano-titanium dioxide content is 2 % [28]. Thus, the optimal range of nano-titanium dioxide varies according to the curing condition, the hydration age, the nano-titanium dioxide particle size and type, the w/b ratio, and the amount of pozzolan used in place of cement.

2.3. Porosity

Behfarnia et al. [29] found that replacing cement with 1 %, 2 %, 3 %, 4 %, and 5 % nano-titanium dioxide reduces the permeability of concrete. The lowest permeability was observed following the addition of 4 % nano-titanium dioxide. Chen et al. [17] examined the porosity of pastes modified with nano-titanium dioxide at concentrations of 0 %, 5 %, and 10 % by weight of cement at 3, 7, and 28 days. There was a clear reduction in porosity at all ages following the addition of nano-titanium dioxide. The porosity of specimens containing 5 % and 10 % P25 decreased by 11.68 % and 14.65 %, respectively, over 28 days, whereas that of samples containing 5 % and 10 % anatase decreased by 21.36 % and 21.65 %, respectively. However, it appeared as though the nanoparticles acted as effective fillers. As the conglomerations containing the nanoparticles expanded, the void space around them gradually filled up. Due to the presence of these "nuclei," the rate of hydration was significantly accelerated. Consequently, reduced porosity caused by accumulated hydration rapidly expanded outward into water-filled pores. Essawy and Abd Elhaleem [19] found that sulfate-resistant cement blended with micro silica modified with 5 % nano-titanium dioxide resulted in decreased porosity, whereas that modified with 7 % and 10 % nano-titanium dioxide did not. Mohammadi et al. [30] discovered that adding 2.5 %, 5 %, or 10 % nano-titanium dioxide to calcium phosphate cement reduced the total porosity. Table 5 presents the effect on the porosity of various authors' suggested cement replacements.

Nazari and Riahi [22, 24] examined the porosity of concretes with varying amounts of slag after 90 days. The binder materials were partially replaced with nano-titanium dioxide at concentrations of 0 %, 1 %, 2 %, 3 %, and 4 % by weight. The results indicated that the addition of nano-titanium dioxide reduced the specimens' porosity. The lowest porosity was observed at a nano-titanium dioxide concentration of 3 %. With the addition of 1 %, 2 %, 3 %, and 4 % nano-titanium dioxide, the porosity decreased by 1.64 %, 4.3 %, 5.67 %, and 5.07 %, respectively.

Table 5. Percentage porosity of nano-titanium dioxide blended concrete

Authors	Porosity [%]	
	0 % TiO_2	5 % TiO_2
Chen et al. [11]	22.92	21.63
Lee [12]	47.41	41.12
Nazari et al. [8]	45.7	32.95
Teixeira et al. [13]	35.09	36.64
Nazari [9]	49.95	43.5
Li et al. [14]	15.6	13.3

2.4. Mechanical properties

According to Li et al. [34], adding 1 % nano-titanium dioxide to the cement weight increased the compressive strength of the concrete mixture by approximately 36 %. Nazari [22] and Soleymani [21] investigated the flexural strength of concrete modified with nano-titanium dioxide at ages of 7, 28, and 90 days. Cement was replaced with nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight. Certain specimens were cured in water, while others were cured in limewater. The results indicated that the addition of nano-titanium dioxide increased flexural strength at all ages (i.e., Figure 1). For specimens with nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight of cement, the increase in 28-day flexural strength was 13.64 %, 20.45 %, 15.91 %, and 11.36 %, respectively, for the specimens cured in water, and 36.58 %, 48.78 %, 56.1 %, and 65.85 %, respectively, for the specimens cured in limewater.

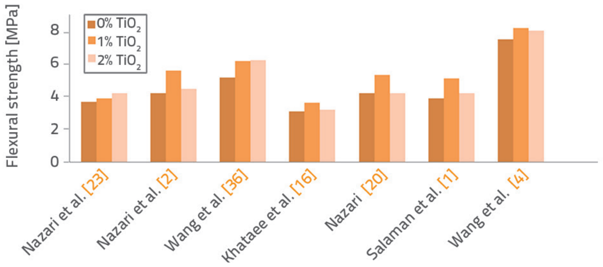

Figure 1. Effect of nano-titanium dioxide on the flexural strength of plain and blended concrete for 7-day samples

Flexural strength was greater in the samples cured in saturated limewater than in the samples cured in water. The addition of 1 % nano-titanium dioxide resulted in the highest flexural strength for the samples cured in water, and the addition of 2 % nano-titanium dioxide resulted in the highest flexural strength for the samples cured in limewater. Soleymani [21] investigated the compressive strength of concrete at ages of 7, 28, and 90 days that had been modified with nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight. The result indicated that nano-titanium dioxide increased compressive strength under all curing conditions. For samples containing nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight of cement, the increase in compressive strength after 28 days was

13.86 %, 17.93 %, 15.49 %, and 6.79 %, respectively [36] and 21.47 %, 29.1 %, 35.88 %, and 40.96 %, respectively, for the samples cured in limewater. The compressive strength was greater in samples cured in limewater than in the samples cured in water. The addition of 1 % nano-titanium dioxide resulted in the highest compressive strength for the specimens cured in water. However, the addition of 2 % nano-titanium dioxide resulted in the highest compressive strength for the specimens cured in limewater. Soleymani [21] observed similar splitting tensile strength results. Nazari et al. [22] examined the splitting tensile and flexural strengths of concrete samples containing nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight that had been aged for 7, 28, and 90 days. At all ages, the results indicated that the addition of nano-titanium dioxide increased both the splitting tensile and flexural strengths. The increase in the 28-day flexural strength was 15.91 %, 25 %, 22.73 %, and 15.91 %, respectively, whereas the increase in 28-day splitting tensile strength was 44.44 %, 66.6 %, 50 %, and 5.55 %, respectively, for the samples containing nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight. Nazari et al. [8] also investigated the compressive strengths of the concrete samples. The compressive strength increased by 13.86 %, 17.93 %, 15.49 %, and 6.79 % after 28 days, respectively, for the samples containing nano-titanium dioxide at concentrations of 0 %, 0.5 %, 1 %, 1.5 %, and 2 % by weight. Salemi et al. [7] reported an increase in the compressive strength of concrete when 2 % nano-titanium dioxide was added. The compressive strength increased by 12 %, 22.71 %, and 27 % at ages of 7, 28, and 120 days, respectively. Jayapalan et al. [40]examined the flexural strength of concrete after 28 days. Cement was replaced with nano-titanium dioxide in concentrations of 0 %, 1 %, and 3 % by weight. As illustrated in Figure 2, the results reveal an increase in flexural strength when nano-titanium dioxide is used.

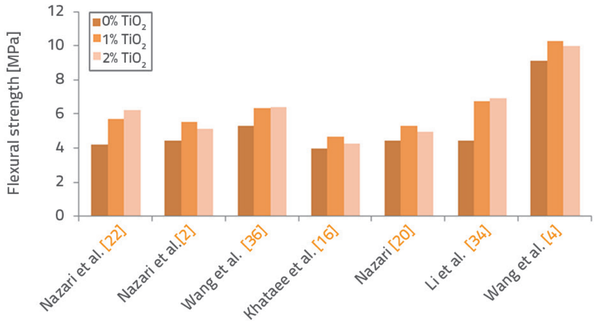

Figure 2. Effect of nano-titanium dioxide on plain and blended concrete, flexural strength after 28 days

The addition of 1 % nano-titanium dioxide resulted in greater flexural strength than the addition of 3 % nano-titanium dioxide, with an increase of 10.27 % and 2.93 %, respectively. The optimal flexural fatigue performance was achieved with a nano-titanium dioxide concentration of 1 %.

The compressive and flexural strengths of concrete after 28 days were investigated by Li et al. [10] and Zhang and Li [11]. Cement was replaced with nano-titanium dioxide in weight proportions of 0 %, 1 %, 3 %, and 5 %. The results indicated that the addition of nano-titanium dioxide increased the compressive strength of concrete. The compressive and flexural strengths were greatest when 1 % nano-titanium dioxide was added. The compressive strength was increased by 18.03 %, 12.76 %, and 1.55 % following replacement with nano-titanium dioxide in weight proportions of 0 %, 1 %, 3 %, and 5 %, respectively. The addition of 1 % and 3 % nano-titanium dioxide increased the flexural strength by 10.28 % and 3.04 %, respectively, whereas the addition of 5 % nano-titanium dioxide decreased it by 3.27 %.

Nazari and Riahi [23] investigated the compressive, splitting, and flexural strengths of self-compacting concrete admixed with nano-titanium dioxide at ages of 2, 7, and 28 days. The cement was partially replaced with 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % nano-titanium dioxide by weight. The results indicated that the addition of nano-titanium dioxide increased all the strengths. For concrete samples in which cement was partially replaced with 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % nano-titanium dioxide by weight, the compressive strength increased by 11.39 %, 21.2 %, 40.82 %, 58.54 %, and 54.1 %, respectively, after 28 days. Jalal et al. [14] investigated the splitting tensile strength and flexural strength of high strength self-compacting concrete altered with nano-titanium dioxide at ages of 7, 28, and 90 days. The cement was replaced with nano-titanium dioxide at concentrations of 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % by weight. As illustrated in Figure 3, the results indicate an increase in all strengths when nano-titanium dioxide is used.

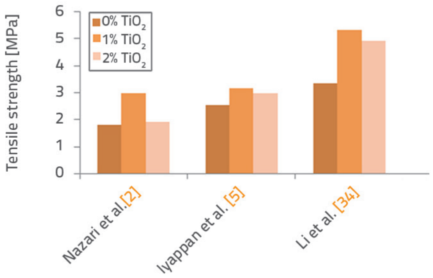

Figure 3. Effect of nano-titanium dioxide on plain and blended concrete, tensile strength after 28 days

The highest splitting tensile and flexural strengths were obtained with the addition of 4 % nano-titanium dioxide. For concrete samples in which cement was partially replaced with 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % nano-titanium dioxide by weight, the 28-day splitting tensile strengths increased by approximately 8.8 %, 18.61 %, 27.78 %, 36.67 %, and 30 %, respectively, whereas the 28-day flexural strengths increased by approximately 10.58 %, 21.75 %, 29.4 %, 44.67 %, and 36.46 %, respectively. Senff et al. [27] observed a slight increase in the compressive strength of mortar when 5 % nano-titanium dioxide was added by weight. Meanwhile, Behfarnia et al. [30] discovered that nano-titanium dioxide decreased the compressive strength of concrete. The compressive strengths of concrete samples partially replaced with 0 %, 1 %, 2 %, 3 %, 4 %, and 5 % nano-titanium dioxide by weight decreased by 20.73 %, 27.17 %, 14 %, 15.97 %, and 26.3 %, respectively.

Chen et al. [17] investigated the compressive strength of mortars modified with two types of nano-titanium dioxide, P25 (75 % anatase and 25 % rutile) and anatase (99 % anatase). Nano-titanium dioxide was added to the cement at concentrations of 0 %, 5 %, and 10 % by weight. The results indicated that the addition of nano-titanium dioxide increased the compressive strengths of all the mortars at all ages. Lee [18] investigated the compressive strength of nano-titanium dioxide-modified pastes at ages of 1, 3, 7, 14, and 28 days. Cement was admixed with nano-titanium dioxide at concentrations of 0 %, 5 %, and 10 % by weight. The results indicated that the addition of 5 % nano-titanium dioxide increased the compressive strengths of the pastes after 1, 3, and 7 days, but decreased them after 28 days. With the addition of 10 % nano-titanium dioxide, the compressive strength increased at 1 and 7 days, but then decreased at the remaining ages. Mohammadi et al. [30] found that adding 5 % and 10 % nano-titanium dioxide to calcium phosphate cement increased its compressive strength. Meng et al. [38] examined the compressive strength of mortars containing nano-titanium dioxide at the ages of 1, 3, 7, and 28 days. Cement was replaced with nano-titanium dioxide in concentrations of 0 %, 5 %, and 10 % by weight. With increasing nano-titanium dioxide content, there is an increase in early strength and a decrease in evening strength, Figure 4.

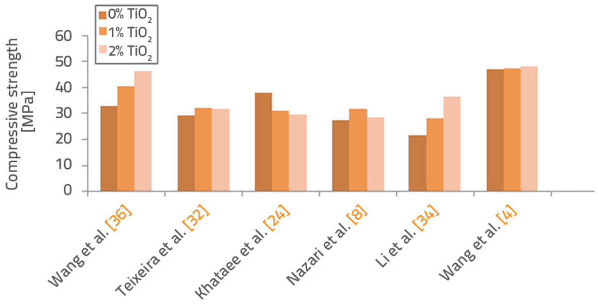

Figure 4. Effect of nano-titanium dioxide on plain and blended concrete, compressive strength after 7 days

The addition of 5 % and 10 % nano-titanium dioxide resulted in a 46 % and 47 % increase in 1-day compressive strength, respectively. Simultaneously, nano titanium nano-titanium dioxide at 5 % and 10 % reduced the 28-day compressive strength. Nazari and Riahi [22, 24] examined the flexural strength of concrete containing varying amounts of slag and partially replaced with nano-titanium dioxide at 0 %, 1 %, 2 %, 3 %, and 4 % by weight at ages of 7, 28, and 90 days. The results indicated that nano-titanium dioxide increased flexural strength after 7, 28, and 90 days. The addition of 3 % nano-titanium dioxide resulted in the highest flexural strength at all ages. At 28 days of age, the increase in flexural strength with the addition of 1 %, 2 %, 3 %, and 4 % nano-titanium dioxide was 5.56 %, 14.81 %, 27.78 %, and 16.67 %, respectively. Nazari and Riahi [24, 39] investigated the compressive strength and splitting tensile strength of the same previous mixtures containing 1 %, 2 %, 3 %, and 4 % nano-titanium dioxide. As demonstrated above, the addition of nano-titanium dioxide improved the strength of resulting concrete. The increase in strength observed with the addition of nano-titanium dioxide may be a result of the nano-titanium dioxide's high reactivity, which results in the rapid consumption of the crystalline $Ca(OH)_2$, that forms rapidly during the early stages of cement hydration. Consequently, accelerated hydration of cement and larger volumes of reaction products are observed [24].Owing to the presence of nanoparticles, the particle packing density of blended cement particles recovers, resulting in a reduction in the volume of larger pores in the cement paste and directing the formation of compact hydration products [24].

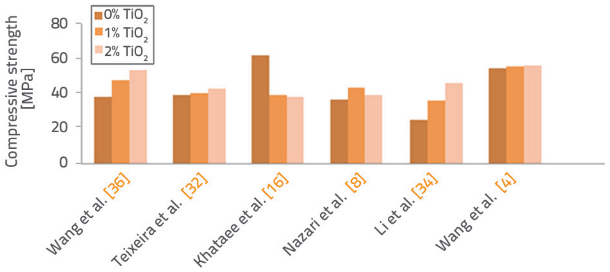

Figure 5. Effect of nano-titanium dioxide on plain and blended concrete, compressive strength after 28 days

According to some observations [17], nano-titanium dioxide enhances the mechanical strength of concrete. Nonetheless, the rate of strength gain was greater in the early ages than in the late ages for the samples partially replaced with nano-titanium dioxide. This could be because nanoparticles have a slower C_2S hydration reaction, which contributes to their longer-term properties. Nano-titanium dioxide may affect only the early stages of hydration (C_3A and C_3S), while the majority of hydrated cement pastes may be unaffected [40]. This implies that the curing conditions, curing age, w/b ratio, type, and content of the cementitious material all determine the optimal nano-titanium dioxide content of the matrix.

3. Conclusion

The current review article summarises previous research on the effect of nano-titanium dioxide on a few properties of plain or blended cement systems (workability, setting time, mechanical strengths, water absorption, and porosity). The following conclusions can be drawn:

- Increasing the nano-titanium dioxide content of a cement system reduces its workability, flowability, initial setting time, and final setting time.
- In general, the addition of nano-titanium dioxide increases the strength of concrete up to a specified limit. The optimal concentration depends on a variety of factors, including the weight/volume ratio, curing condition, curing age, pozzolana type, pozzolana content, chemical admixture, and nanoparticle size [41]. However, a concentration of 1–4 % nano-titanium dioxide in concrete appeared to be optimal, resulting in satisfactory strength [42].
- With the addition of nano-titanium dioxide to the matrix, the %age of water absorption and permeability decrease, but water absorption occasionally increases at early ages. The majority of studies found that the optimal concentration was 4 %. However, a few others found that concentrations of 0.5 %, 1 %, 2 %, and 3 % were also acceptable optimum concentrations for decreased water absorption.

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