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Influence of Titanium Dioxide (TiO_2) Nanoparticles on Durability Properties of Lightweight Foamed Concrete

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ABSTRACT

The worldwide construction industry has realized the need for lightweight building materials that are flexible, high-performance, and ecologically benign. Considering the need, it has been found that lightweight foamed concrete (LFC), a new revolutionary material, can be used to lower the overall weight of conventional concrete. In concrete, nanoparticles are used due to their beneficial effects, such as their tiny size of particles and high reactivity to improve concrete's strength. Furthermore, LFC is quite porous due to which it becomes less effective. The LFC matrix can be made effective by including many nanoparticles to improve its strength. In the current body of information, the impact of nano titanium dioxide in LFC has not yet been studied. As a result, there is considerable confusion regarding the method by which the nano TiO_2 might influence the LFC's durability properties. Therefore, the application of nano TiO_2 in the LFC matrix is the main emphasis of this work. The goal was to determine how various nano TiO_2 weight fractions (1%, 2%, 3%, 4%, and 5%) affect the durability characteristics of LFC, including setting time, drying shrinkage, porosity, and water absorption. The findings suggested that excellent water absorption, porosity, and drying shrinkage of LFC are made possible by the presence of a 3% weight fraction of nano TiO_2 in LFC. The microstructural of LFC is changed by the addition of nano TiO_2.

1. Introduction

Lightweight foamed concrete (LFC) has gained popularity over the past 40 years as a crucial building and civil engineering material for use in the construction sector [1-7]. The quantity of FC used and the variety of applications for which it has been used have both increased dramatically [8-12]. In comparison with other conventional construction materials for various applications, LFC can provide economic as well as performance advantages [13]. A type of lightweight concrete called LFC can be made of mortar or cement paste and in which stable bubbles are retained within the mortar's matrix using a foaming agent that is either protein- or synthetic-based [14-19]. Lightweight foamed concrete (LFC) can be used for a variety of purposes, including floor construction, culvert or bridge

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approaches, void filling, trench reinstatement, roofing insulation, bridge strengthening, and many more. Its densities range from 300 kg/m^3 to 1800 kg/m^3 [20-27]. Due to its numerous advantages, which include excellent acoustic and thermal absorption properties and its relatively low density, several research has lately concentrated on the characteristics of various forms of LFC [28-37]. Due to its excellent thermal insulation, low self-weight, low aggregate consumption, good flow-ability, and regulated low strength, LFC has been receiving a lot of attention [38-44]. LFC is also regarded as an environmentally beneficial material since it uses less aggregate and has a great potential for incorporating waste [45].

LFC is viewed as an affordable alternative in the production process of large-scale lightweight construction components, such as road embankment infills, wall panels, structural elements, and filling grades, due to its simple manufacturing process, which involves all stages from the beginning of the manufacturing plants to the final position [46-48]. LFC is typically manufactured with a density of 500–1600 kg/m^3. The low concentration of cement paste and an excessive amount of foam make it unstable at densities below 500 kg/m^3, thus limiting its uses [49]. It is typically referred to as ultra-lightweight foamed concrete (ULFC) at such low densities and needs additional care compared to the normal concrete while choosing its ingredients and throughout the mixing process to improve its physical properties, such as durability and stability [50].

The building sector might undergo a revolution if nanoparticles are included into concrete. These minute additions result in concrete that is stronger, more flexible, workable, resistant to chemicals, and environmentally sustainable. Utilizing the structure at the nanoscale, nanotechnology has led to the development of multifunctional, bespoke cementitious composites with exceptional mechanical and durability characteristics. High ductility, the capacity to regulate fracture development, self-healing, low electrical resistance, self-detection, and self-cleaning are some of these materials' potential special qualities. Those with at least one dimension less than 100 nm are considered nanoparticles [51]. By lowering the alignment degree and extent of $Ca(OH)_2$, increasing compactness, and enhancing pores and microcracks, nano TiO_2 can progress the concrete’s strength of reactive powder after certain later periods. At different phases of hydration, cement's strength may be increased with the right quantity of TiO_2 [52,53]. The inclusion of the CSH gel and TiO_2 barrier improved the mechanical performance and durability of concrete that had been sprayed with TiO_2. After impregnation, the sprayed-on TiO_2 maintained high elimination efficiency for acetaldehyde and methyl orange [54]. Concrete's long-term chloride resistance Is enhanced by Nano-TiO_2 Coatings, hence increasing the durability of the concrete [55]. In addition, CH carbonation is encouraged by TiO_2. The outcomes indicate that TiO_2 has additional effects that can help increase strength in addition to promoting hydration. Data from three-dimensional X-Ray imaging show that TiO_2 reduces the size, homogeneity, and sphericity of pores at room temperature. This might be a potential method by which these nanoparticles increase strength [56]. In addition, TiO_2 promotes CH carbonation. The results indicate that TiO_2 has additional effects that can help increase strength in addition to promoting hydration. According to 3D X-Ray microscopy data, at 20 °C, TiO_2 makes holes smaller, more homogenous, and spherical. This might be a potential method by which these nanoparticles increase strength [57].

LFC becomes more durable and resistant to fracture propagation because of nano-TiO_2[6]. The material's capacity to endure structural stresses and deformation is boosted by its increased toughness, which also increases durability [58]. The permeability of LFC is decreased by the inclusion of nano TiO_2, making it less permeable to chemicals and water. By preventing moisture intrusion, this quality enhances the concrete's durability over time. and chemical breakdown [59]. The photocatalytic properties of TiO_2 may destroy organic pollutants when exposed to ultraviolet rays.

LFC with nano TiO_2 may provide self-cleaning capabilities in outdoor applications, preventing the accumulation of dirt and pollutants on its surface [60].

The majority of the currently conducted research on concrete focuses on high-performance concrete and emphasizes the stringent performance requirements, such as durability, mechanical, and thermal characteristics. The durability characteristics of LFC, including its relatively low ductility, slight brittleness, and limited susceptibility to breaking, have not received much attention from research investigations. Internally generated fractures are another feature of LFC, and when they spread, they create brittle fractions with low tensile strength. Due of the significant drying shrinkage and other factors, structural fractures in LFC start to form even before the material is loaded. Following the application of the load, internal fractures have a tendency to spread and deepen under stress, leading to the development of new cracks [61]. As these cracks deepen, LFC begins to distort in an inelastic manner. When the loading is smaller than the critical dynamic stress, the hysteretic curve is flat and thin, demonstrating that the LFC's viscosity is tiny and that both its damping effectiveness and loss of energy are insignificant. The LFC primarily induces deformation of elastic material when the loading force is applied, and the repeating distortion transition from an elastic state requires almost little energy. When the loading strength is larger than the critical dynamic stress, the hysteretic curve tends to have a larger form [62].

According to the review above, using nano TiO_2 in cement-based materials like LFC has enormous promise. In order to determine the possible dose of nano TiO_2 in LFC, this research effort was undertaken. Although numerous studies have been conducted on LFC's mechanical characteristics and durability of concretes containing various nanoparticles, findings relating to the effects of nano-sized TiO_2 particles on LFC's durability are comparatively uncommon. To establish the ideal nano TiO_2 content, how different nano TiO_2 dosages affect the setting time, water absorption, porosity, and drying shrinkage were examined in this work.

2. Methodology

This section covers the mix ratios, laboratory test protocols, and the ingredients needed to manufacture LFC. Here is a detailed explanation of material preparation. The experimental set up, mix ratios, and mixing techniques for the LFC samples reinforced with nano TiO_2 were established. This study examined the effects of TNP at six various weight fractions, focusing on 0% (control), 1%, 2%, 3%, 4%, and 5%, on the durability qualities of LFC. The result was a dry density LFC of 980 kg/m^3. LFC with a medium density were taken into account in this study since they are employed as semi-structural components in the construction of structures and can profit from nano TiO_2 reinforcement. Four durability factors have been studied: bulk density, water absorption, porosity, and drying shrinkage test. The relationship between porosity and water absorption was also estimated to determine how closely these characteristics are connected to one another.

2.1 Constituent Materials

The manufacturing and testing of lightweight LFC with various nano TiO_2 weight fractions ranging from 0% to 5% are the primary goals of this work. A control LFC was also produced as a point of comparison. Ordinary Portland Cement (OPC) (CEM1 52.5 R) was utilized as the cementitious component in the production of LFC. The cement utilized in the study to make the LFC mix was OPC CEM-I, which is offered for sale under the trade name Blue Lion. From one of the greatest quarries, 2.59 specific gravity fine river sand was commercially acquired. The sand met ASTM C33-03 specifications [63]. This experiment used clean drinking water straight from the tap in compliance with BS-3148 [64]. TiO_2 is the material of choice for the LFC in this experiment. When employed as a nanoparticle in cement-based products, TiO_2 provides a number of benefits. When applied to cement-based goods, TiO_2, a unique photocatalytic substance, confers biocidal, self-cleaning, and smog-abating qualities. The microstructure of LFC may benefit from the addition of TiO_2 nanoparticles. It could result in a finer, denser microstructure, increasing toughness and resistance to deterioration from the environment. TiO_2's photocatalytic characteristics can help LFC's surface degrade toxic chemicals and organic contaminants, strengthening the concrete's defence against chemical assault. LFC can be more permeable due to its porosity, which increases its susceptibility to moisture infiltration and subsequent ageing. This might affect how long it lasts, particularly under difficult environmental circumstances. TiO_2 has photocatalytic characteristics that may help LFC absorb water less readily. By limiting the entry of moisture and possibly dangerous elements, this decreased water absorption contributes to improving the concrete's longevity. The commercial made of protein foaming substance Noraite PA 1 may create a density of 68 ± 15 kg/m^3 when diluted with water by 1:30. The nano TiO_2 used in this study contained grains between 55 and 75 nm and was purer than 99.5%. Six different weight fractions of TiO_2 were used: 0% (control), 1%, 2%, 3%, 4%, and 5%. The nano TiO_2 sample used in the investigation is shown in Figure 1.

Fig. 1. Titanium dioxide (TiO_2) nanoparticles employed in this study

2.2 Mix Design

The desired dry density used in this investigation was 980 kg/m^3. Cement to sand ratio of 1:1.5 and water-cement ratio of 0.5 was employed. Six distinct LFC mixes were created. The LFC mix percentage is shown in Table 1.

Table 1
LFC mix proportion

Mix reference	Target density (kg/m^3)	Weight fraction of TD (%)	TD (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Foam (kg/m^3)
TD0	980	0	0.0	361.3	542.0	180.7	31.3
TD1	980	1	11.2	361.3	542.0	180.7	31.3
TD2	980	2	22.3	361.3	542.0	180.7	31.3
TD3	980	3	33.5	361.3	542.0	180.7	31.3
TD4	980	4	44.6	361.3	542.0	180.7	31.3
TD5	980	5	55.8	361.3	542.0	180.7	31.3

2.3 Experimental Setup

The durability characteristics of LFC with nano TiO_2 addition were investigated in this study. The variables examined included bulk density, water absorption, porosity and drying shrinkage.

2.3.1 Setting time

To find out how long it takes for cement to stiffen or set after coming into contact with water, the setting time test of cement is performed. The first setting period is the interval after putting water in the paste before the cement stops being malleable. The final setting time is the amount of time that passes after adding water to cement before the paste completely loses its ductility. Vickat equipment is used to ascertain the time of the initial setup. Cement paste was used to fill the vicar's mould, and the time it took for the needle to pierce the block 5 ± 0.5 mm from the bottom was recorded. the needle was replaced in the Vickat apparatus with a circular attachment to find the final setting time. The time taken for the circular connection to lose its impact is noted in accordance with BS EN 196-3 [65].

2.3.2 Water absorption

A concrete sample's ability to absorb water is measured by the water absorption test. When only one side of the specimen is exposed to water, this test measures the increase in mass of concrete samples due to water absorption. A specimen's absorption of water is determined by multiplying its weight increase by its original mass. Percentages are often used to express this absorption rate. As per BS1881-122, the water absorption test used a cylinder with a diameter of 75 mm and a height of 100 mm [66]. The day before the curing procedure, the cylinder specimen was removed, cleaned, and weighed to estimate the dry weight. In order to ensure that the item was completely dry before testing, it was baked at 105 degrees Celsius for 72 hours. The procedure aids engineers and scientists in determining the calibre of concrete and its resistance to exposure to moisture, such as groundwater or precipitation. It is frequently used in building projects to choose the best concrete mixes and guarantee the longevity and performance of concrete structures. The water absorption was calculated using Eq. (1):

$$\text{Water absorption ratio} = \left(\frac{w_a - w_b}{w_b^*}\right)100 \tag{1}$$

where,
W_a = saturated weight of LFC surface
W_b = weight of the sample in water
W_b^* = oven dried weight of the specimen

2.3.3 Porosity

The word porosity describes the existence of voids or pores inside the matrix of concrete, which may affect how well the concrete can absorb liquids or other things. This test is essential for determining how long-lasting and high-quality concrete is since too many voids can cause a number of problems, including decreased strength and an increased risk of freeze-thaw damage. The porosity value was computed using the Vacuum Saturation Apparatus. The cylindrical specimen used possess diameter as 50mm and height as 100mm. For three days, the dried samples were kept in a vacuum-sealed desiccator. Afterwards, distilled and de-aired water was added to the desiccator. The samples were kept in a vented oven set at 105 °C for three days in order to determine the oven-dry mass. The specimens were taken out of the oven and set aside to cool at ambient temperature. Finding the specimens' oven-dry mass and getting them ready for suction absorption are the goals of weight measurement. The pressurized air is going to circulate and last for three consecutive days when the vacuum line connection is connected to a gauge of pressure. Eq. (2) can be used to calculate the porosity of LFC:

$$\mathrm{P}_r = \frac{w_s - w_d}{w_s - w_w} \times 100 \tag{2}$$

where,
P_r = Porosity
W_s = saturated surface dry weight of LFC
W_d = Oven dried weight of the specimen
W_w = weight of the sample in water

2.3.4 Shrinkage

Concrete's volume reduction or contraction as a result of the loss of capillary moisture is referred to as drying shrinkage. Concrete goes through a drying process during which water vapor escapes from its surface as it sets and cures. The cement matrix's mesopore structure develops capillary tension as a result of this water loss, which causes the concrete to shrink or contract. The drying shrinkage, stated as a percentage of dry length, is the difference between the rectangular molded sample's initial wet and dry measurements. ASTM C878 was followed when conducting this test [67]. The prism that was used was 75mm long and, with the rod and cap nuts, had a 290mm calculated overall length. A bare minimum of 3 samples were collected. for each test in order to get the average result. A length analyzer with a 250m invar bar and 0.001mm of resolution was used to determine the original length. The length of the comparator was compared for each specimen to a predetermined invar. Eq. (3) is used to compute the drying shrinkage:

$$L = \frac{L_w - L_d}{G} \times 100 \tag{3}$$

where,
L = Change in length
Lw = variation between the comparator reading at age
Li = Initial dry length of the specimen
G = Gauge length

3. Results

3.1 Setting Time

Because of their large specific surface area, TiO_2 nanoparticles offer more active sites for the formation and expansion hydration of cement products. The outcome is, TiO_2 causes the early phases of hydration of cement to proceed more quickly, resulting in quicker setting time. Early strength development of LFC may benefit from the TiO_2's accelerated rate of hydration's heat. The toughness properties of the LFC will be impacted by the setting time. TiO_2 can adsorb and lower the free water content in a mixture when it is added to LFC. Cement hydrates and sets more quickly when the percentage of water to cement is lower. When the weight fraction of TiO_2 is optimised to preserve the necessary workability of the LFC, this impact is particularly obvious. As the weight fraction of TiO_2 is raised, as illustrated in Figure 2, the setting time continues to decrease.

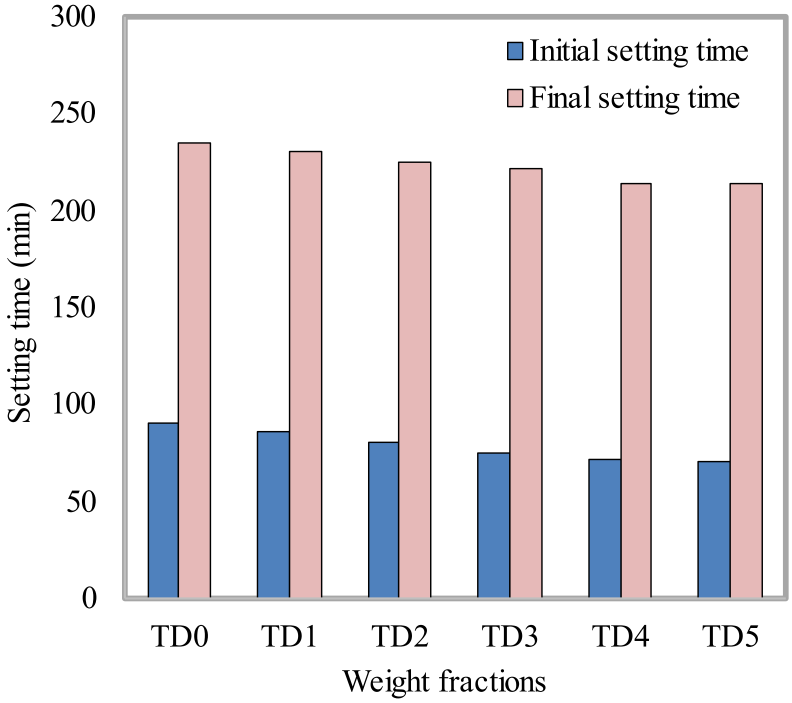


Fig. 2. Initial and final setting times of LFC with different weight fractions of nano TiO_2

3.2 Porosity

To determine the quantity and distribution of pores or voids inside the concrete matrix, a porosity test is used. Porosity describes the existence of empty spaces or gaps in the concrete, which can have a big impact on its performance and durability. The rate at which moisture penetrates concrete in the presence of a pressure gradient is known as permeability. Concrete has cracks that let moisture pass through. The movement of moisture can be slowed by a small pore in the concrete. The porosity and pore structure will have an effect on the LFC's durability characteristics. Therefore, lowering the porosity % will make LFC stronger. Figure 3 shows different TiO_2 ratios coupled with the percentage of LFC porosity. In addition to the rise in TiO_2 in the LFC, the percentage of porosity is also falling. In accordance with the findings, the TiO_2 concentration varied from 5% in the LFC with the lowest porosity percentage (53.53%) to 1% in the LFC with the greatest porosity percentage. (57.17%). Figure 3 shows that 5% and 4% of TiO_2 in LFC produce 53.53% and 54.28% of permeability, respectively. The TiO_2 addition to the LFC has an effect on the percentage of porosity. decrease in density of LFC (980 kg/m^3) will make the structure more porous. In order to get a better porosity rating, a lower density of LFC contains more foam. As a result, LFC will have a lower compressive strength when its porosity value is larger. This results from the addition of TiO_2 to a matrix or substrate, which might affect the hydration process during the production of the material. As the TiO_2 dose rises, the hydration products may gather and fill the voids, causing the porosity to decrease.

Additionally, things with a lower LFC density are prevented from attaching by the massive amount of foam [68]. But TiO_2 quickly improves the LFC's matrix and increases compressive strength [69].

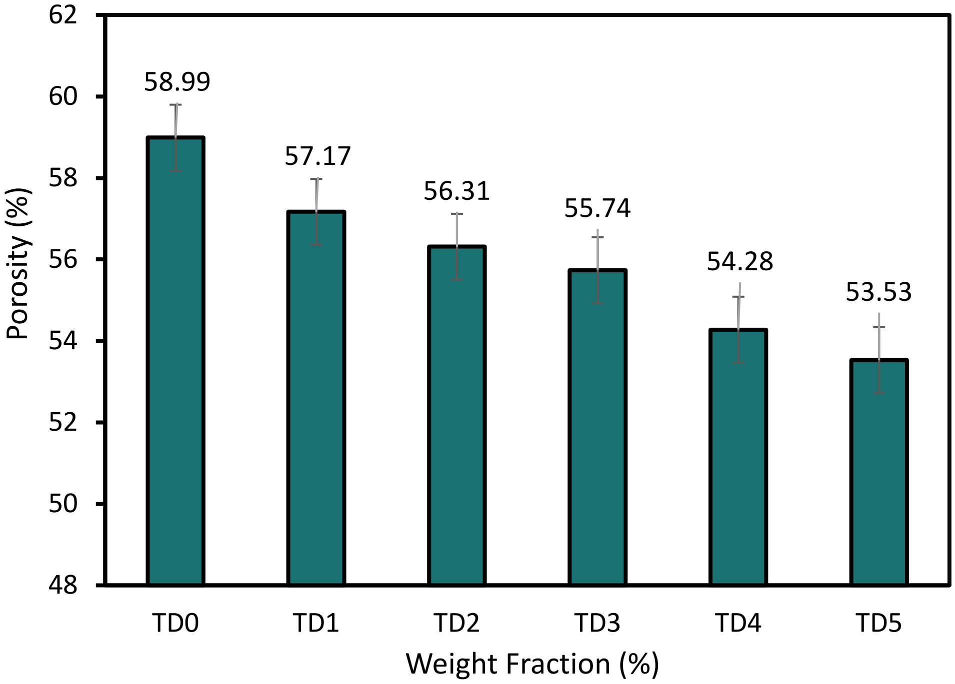


Fig. 3. Different weight percentages of nano TiO_2 influence the porosity of LFC

3.3 Water Absorption

To ascertain the water absorption in LFC, a test for water absorption is conducted. Figure 4 displays the water absorption with the addition of nano TiO_2 at various TiO_2 fractions. The TiO_2 in the LFC rose while water absorption decreased, as seen by the graph. The TiO_2 inclusion in LFC, at 5% by mix, results in the lowest water absorption, at 19.82%, when compared to the inclusion of 1% TiO_2 by mix, which results in 22.44% water absorption and also the root cause of the declining tendency. The second-lowest percentage of absorption of water is 20.16%, 4% TiO_2 in LFC was present. The third lowest was a 20.66% water absorption with 3% TiO_2 content. TiO_2 nanoparticles are very porous and have a large surface area. More water molecules can interact with the TiO_2 at more active spots because of the larger surface area [70]. Consequently, the probability of water molecules adhering to the TiO_2 surface increases, decreasing overall water absorption in the LFC. TiO_2 is also a well-known photocatalyst, which means that when exposed to light, it may accelerate chemical processes. Reactive oxygen species (ROS), which may break down organic substances, including water molecules, are produced by TiO_2 in the presence of light. More ROS are formed when the dose of TiO_2 rises, which accelerates water deterioration and decreases water absorption [71].

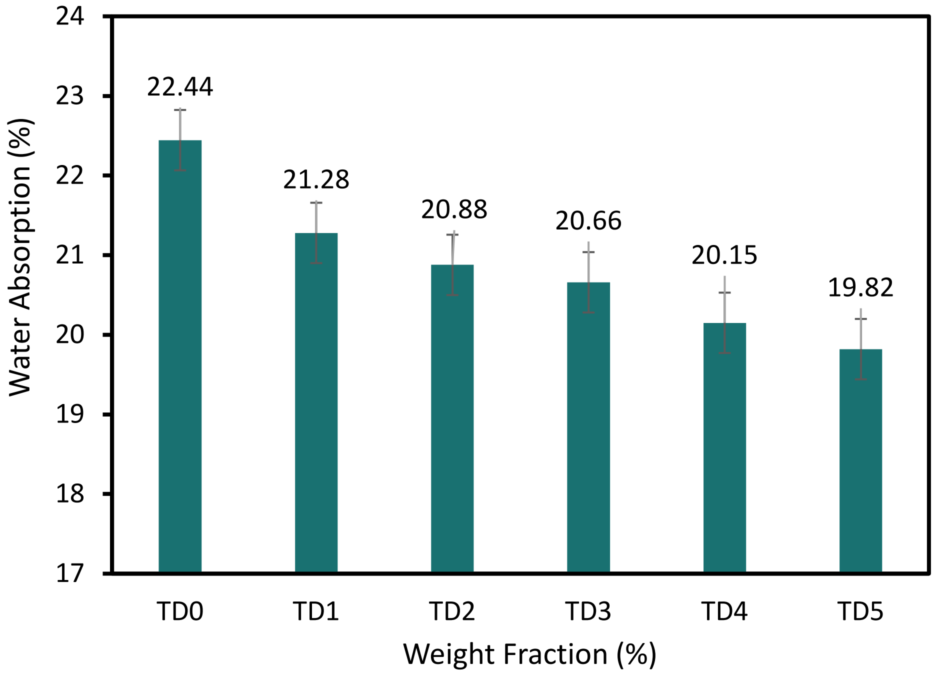
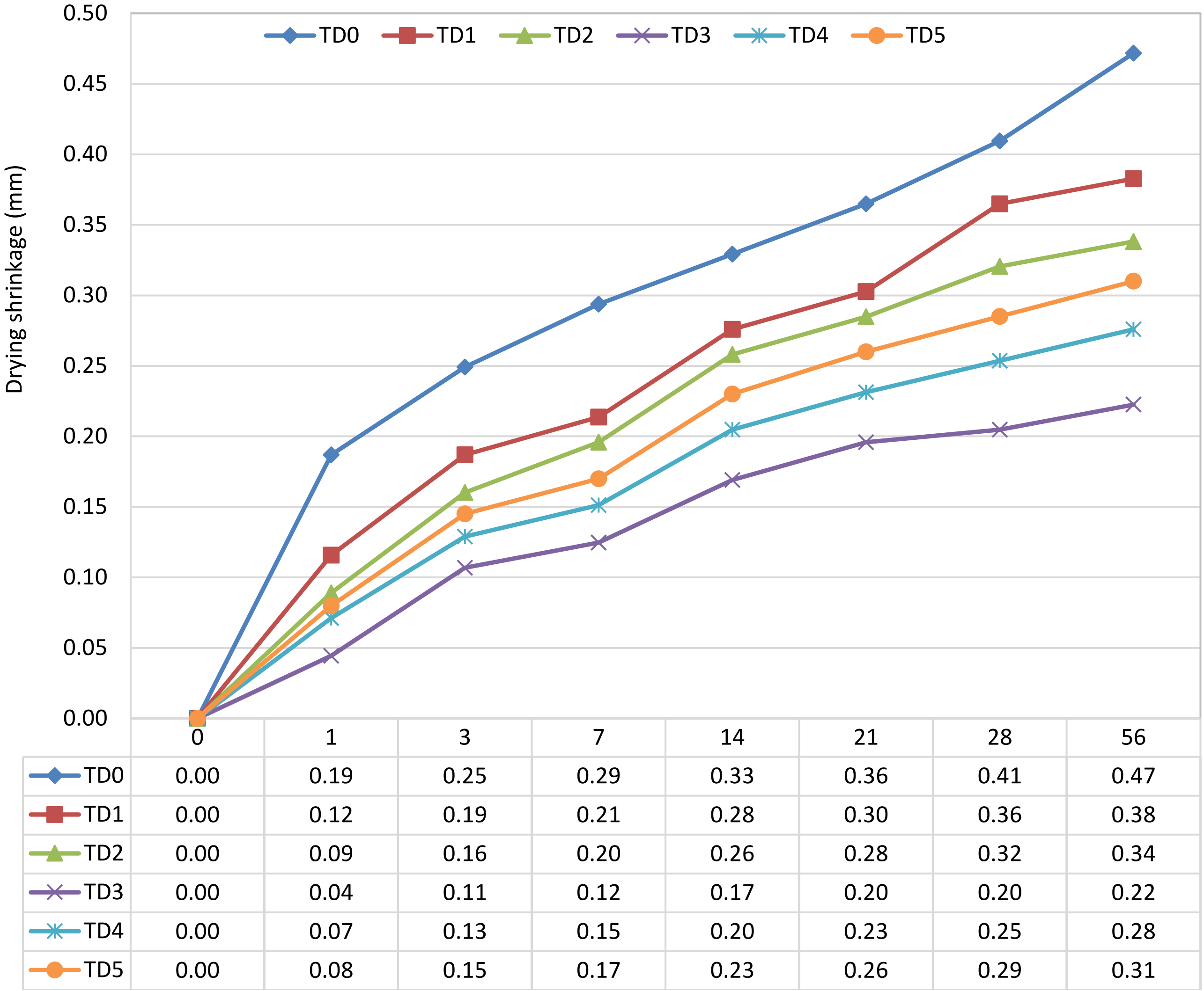


Fig. 4. Water absorption of LFC with various nano TiO_2 weight fractions

3.4 Shrinkage

Drying shrinkage is the term for shrinkage of the concrete mixture due to water loss. The researchers were able to calculate concrete's expansion using drying shrinkage experiments. When under load, this shrinkage might increase the tensile stress and result in crack. This experimental test's objective is to provide more light on TiO_2's ability to endure variations in concrete volume. Figure 5 shows that from day 1 to day 28, all samples are significantly increased, and readings begin continuously until day 60. In contrast to the specimens with, the control specimens have the highest reading TiO_2 in LFC and a density of 980 kg/m^3. TiO_2 was also present in the least drying shrinkage LFC, which had 3% of it, then 4%. 5%, 2%, and 1% as shown in Figure 5. The addition of TiO_2 to LFC reduces the concrete's shrinkage. The increased amount of foam in the concrete is what affected the shrinkage patterns. In LFC, TiO_2 nanoparticles can change the water-cement ratio. TiO_2 has the ability to absorb and lower the amount of free water in concrete at higher doses, which reduces the overall drying shrinkage. Lower shrinkage is the result of the lowered water content, which controls the total volume change throughout the drying process. This is because, as mentioned by Wu *et al.,* [72], Using more foam will reduce the need for cement paste. LFC 's strength and durability can be improved by adding TiO_2 nanoparticles. The formation of shrinkage cracks is inhibited, and total shrinkage is minimized, due to increased strength and enhanced crack resistance. Additionally, it helps to lessen fractures in the LFC [73]. It might therefore be claimed that including TiO_2 into the LFC will reduce drying shrinkage.



	0	1	3	7	14	21	28	56
TD0	0.00	0.19	0.25	0.29	0.33	0.36	0.41	0.47
TD1	0.00	0.12	0.19	0.21	0.28	0.30	0.36	0.38
TD2	0.00	0.09	0.16	0.20	0.26	0.28	0.32	0.34
TD3	0.00	0.04	0.11	0.12	0.17	0.20	0.20	0.22
TD4	0.00	0.07	0.13	0.15	0.20	0.23	0.25	0.28
TD5	0.00	0.08	0.15	0.17	0.23	0.26	0.29	0.31

Fig. 5. Shrinkage of LFC with varying weight fractions of nano TiO_2

3.5 Porosity-Water Absorption Relationship

For LFC with a density of 980 kg/m^3, Figure 6 below demonstrates the relationship between porosity and water absorption. Various amounts of TiO_2 were mixed with the LFC before being applied. The graph below displays the range of values for porosity and water absorption. The linear line illustrates the optimum trend relationship between water absorption and porosity, and the R2 value, which is nearly 1, shows the connection between the two parameters. Ibrahim *et al.,* [74] found that porosity increases water absorption. The resulting linear line on the graph demonstrated that porosity and water absorption are directly inversely related. LFC density is more water-absorbent and less resistant. The porosity and water absorption of the LFC cement paste are influenced by its pore structure.

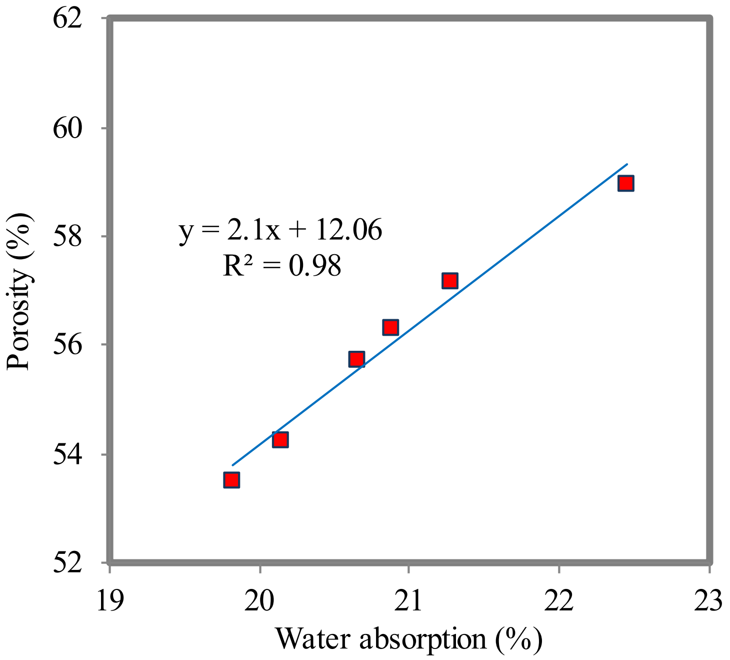


Fig. 6. Correlation between porosity and water absorption of LFC with different weight fractions of nano TiO_2

4. Conclusions

This study looked at how nano TiO_2 affected the durability of LFC composite. In light of the findings, the following conclusions can be drawn:

i. If the dosage of TiO_2 nanoparticles is kept within a particular range, the use of nano-TiO_2 particles has considerably reduced the setting time, porosity, water absorption, and drying shrinkage of LFC, enhancing the concrete's durability in the process. TiO_2 nanoparticles may begin to combined at higher concentrations and form clusters as opposed to being evenly dispersed throughout the concrete matrix. The capacity of the nanoparticles to enhance the microstructure and durability of the material may be hampered by this agglomeration's uneven distribution.

ii. The results of the tests showed that the durability properties (water absorption, porosity, and shrinkage) were ideal when TiO_2 was present in a 3% volume fraction.

iii. At a weight fraction of 3% TiO_2, maximum compaction was attained for the cementitious matrix and TiO_2, resulting in high mix regularity. TiO_2 nanoparticles can have a beneficial impact on the material's microstructure when added to LFC. It can result in a microstructure that is denser and more refined, which helps materials last longer and resist deterioration from the environment.

iv. Beyond weight fraction of 3%, TiO_2 nanoparticles may have an excessive particle size, which might have an adverse effect on photocatalytic activity and surface area. TiO_2's photocatalytic activities contribute to the breakdown of organic pollutants and the reduction of water absorption, however, too-large particles can counteract these benefits.

v. The LFC matrix may become denser after the inclusion of TiO_2 nanoparticles, especially at doses above 3%. While this could be advantageous up to a point, excessive densification might lead to pore clogging, which would limit the permeability of the concrete and lessen its durability.

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