JEE Journal of Ecological Engineering

*Journal of Ecological Engineering* 2023, 24(12), 319–335
https://doi.org/10.12911/22998993/173210
ISSN 2299–8993, License CC-BY 4.0

Received: 2023.09.12
Accepted: 2023.10.21
Published: 2023.11.04

# Combined Effect of Silicon Dioxide and Titanium Dioxide Nanoparticles on Concrete Properties

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## ABSTRACT

Nanoconcrete is an attractive research area because of its recent practical applications in building materials technologies. This study investigates the individual and combined effects of using nanoparticles in concrete mixtures as a cement substitute. Microscopic images are also used to determine changes in the microstructure of modified concrete in the present study. Concrete's thermal and mechanical properties, including thermal conductivity ($k$), specific heat capacity ($C$), thermal diffusivity ($\alpha$), and compressive strength ($\sigma$), are the leading concrete characteristics examined. The current study used different percentages (0%, 1%, 3%, and 5%) of nano-$SiO_2$, nano-$TiO_2$ and combined nano-$SiO_2$/$TiO_2$ particles as cement substitutes for 7 and 28 days of curing to examine the characteristics of nanoconcrete compared to conventional concrete (CC). The results indicated that adding individual nanoparticles to CC could improve concrete's thermal and mechanical properties. Among the investigated nanomaterials (nano-$SiO_2$, nano-$TiO_2$ and combined nano-$SiO_2$/$TiO_2$ particles), nano-$SiO_2$ was superior in that context. The optimal thermal properties of nanoconcrete were achieved when 5% nano-$SiO_2$ (C-S5 specimen) was added. The $k$ and α coefficients of sample C-S5 compared to the CC specimen were reduced by 65.6% and 80.3%, respectively, while the $C$ coefficient was increased by 12.8%. Meanwhile, the optimal compressive strength coefficient of nanoconcrete was achieved when 3% nano-$SiO_2$ (C-S3 specimen) was added, where the compressive strength coefficient of sample C-S3 compared to sample CC was increased by 19.6%. In contrast, for the combined effect, the thermal properties of concrete were improved, but the compressive strength coefficient of concrete was reduced. Overall, the present experimental findings offer valuable information about the impact of nanotechnology on high-performance concrete to save energy in buildings.

**Keywords:** nanoconcrete, compressive strength, thermal conductivity, thermal diffusivity, specific heat capacity, nanoparticles.

## INTRODUCTION

One of the largest industries in the world is construction, which uses a vast range of materials to complete various construction works. Portland cement concrete is a common cement material used in the construction industry. Different types of supplementary materials are identified and used in concrete mixtures to enhance the thermal and mechanical properties of concrete. One of the supplementary materials used in concrete is nanoparticle materials, i.e. nano-$ZnO_2$, nano-$SiO_2$, nano-$ZrO_2$, nano-$TiO_2$, nano-$Al_2O_3$, nano-$CaCO_3$, nano-$Fe_2O_3$, nano-MgO, carbon nanotubes (CNTs), and carbon nanofibers (CNFs) (Huseien, 2023; Miyandehi et al., 2016; Selvasofia et al., 2021; Goel et al., 2022; Faraj et al., 2022; Al-Marafi, 2021; Al-Amir et al., 2023; Salman et al., 2023). The addition of suitable nanoparticles to concrete is expected to improve the concrete's thermal and mechanical properties.

A significant change in concrete properties can be found due to the effect of high surface area and small particle size for nanoparticles. This may enhance the properties and add a new function to concrete. By incorporating nanoparticles with concrete mixtures, the concrete microstructure becomes homogeneous and dense, reducing the number of harmful pores. In addition, reduced porosity in concrete results in a reduced *k* coefficient. A number of researchers (Reddy et al., 2022; Selvasofia et al., 2021; Ren et al., 2018; Jittabut, 2015; Saleh et al., 2023) have recently investigated the effect of nanoparticle materials in enhancing the thermal and mechanical properties of concrete.

According to Ren et al. (2018), nanomaterials can improve the microstructure of concrete as they can help the generation of C-S-H gel through the accelerated hydration process. Albakkar and Behfarnia (2021) revealed that the concrete mixture with 2% nano-$SiO_2$ particles contained fewer pores than the mixture without nano-$SiO_2$. In the same context, Askari Dolatabad et al. (2020) studied the effect of nano-$Al_2O_3$, nano-$SiO_2$, and nano-$TiO_2$ on the performance of concrete. They found that adding nanoparticles promoted the production of more C-S-H gel, which improved the mechanical properties of concrete by reducing calcium hydroxide crystals and nonporous.

Reddy et al. (2022) investigated the influence of ground-granulated blast furnace slag (GGBS) and nano-$SiO_2$ on the mechanical and thermal properties of concrete. The results revealed that including nano-$SiO_2$ and GGBS improved the tensile and compressive strengths of the modified concrete by 10% compared to CC. In addition, the inclusion of nano-$SiO_2$ in concrete resulted in a reduction in the rate of heat transfer. In a similar study, Jittabut (2015) studied the mechanical and thermal properties of cement mortar using different sizes and concentrations of nano-$SiO_2$ particles. The results showed that cement mortar modified by 4.0 to 5.0% nano-$SiO_2$ of 5.0 nm particle size provides a low *k* coefficient and high compressive strength coefficient. Generally, a lower *k* coefficient is required to minimize the building's cooling and heating load. As a result, heating and cooling devices that depend on fuel and electric energy will be diminishe, thus reducing environmental pollution (Al-Rbaihat et al., 2023; Alrbai et al., 2023; Alahmer et al., 2016; Al-Rbaihat et al., 2017). On the other hand, it should be noted that nanoparticles may have negative environmental impacts in some cases. The release of nanoparticles into the environment during the production, handling, or demolition of structures could have adverse ecological effects. These nanoparticles may persist in the environment and potentially impact ecosystems. Therefore, careful planning, monitoring, and adherence to environmental standards are crucial to minimize the environmental footprint associated with using nanoparticles in concrete construction.

Selvasofia et al. (2021) studied the impact of nano-clay and nano-$TiO_2$ particles on the concrete's mechanical properties. The study found that flexural, tensile, and compressive strengths were improved by 30% after substituting 3.0% nano-clay of the weight of the fine aggregate and 2% nano-$TiO_2$ of the weight of the cement. Pathak and Vesmawala (2022) investigated the mechanical strength of the modified concrete using nano-$TiO_2$ and fly ash. The results revealed that the compressive strength coefficient of concrete improved by 3.82% after the partial replacement of cement with 4% nano-$TiO_2$ and 20% fly ash. On the other hand, the flexural and split tensile strengths were not improved by using nanomaterials, as CC showed the highest flexural and split tensile strengths among all mixes. Modified concrete was shown to have a better microstructure than CC. This result was expected because the spaces in concrete will be filled with nanomaterials that enhance the density and reduce the porosity. In another work, Saleh et al. (2023) concluded that replacing cement in a concrete mixture with 0.8% polystyrene granules and 3.0% nano-$SiO_2$ enhanced the concrete's thermal and compressive strengths. The study also found that adding only nano-$SiO_2$ has provided the highest compressive strength coefficient compared to using polystyrene, which has decreased compressive strength coefficient. However, polystyrene granules were used due to their ability to enhance the *k* coefficient of concrete.

According to the literature, concrete with a higher *C* coefficient has a good insulator. This is because such material takes a long time to transfer heat. Low *k* and α coefficients accomplish high-performance concrete, which may minimize energy losses in buildings. A decrease in *k* coefficient causes a decrease in α coefficient and an increase in *C* coefficient, possibly due to the reduction in density. Furthermore, concrete with higher compressive strength coefficient is desirable construction material because it can receive extra load without leading to cracks or damage (Pathak and Vesmawala, 2022; Sastry et al., 2021;

Akkouri et al., 2022; Kiran et al., 2023; Raheem et al., 2023; Abbas et al., 2023). The *k* coefficient of CC is between 0.6 and 3.6 W/m.°C. Conductivity depends on density, temperature gradients, porosity, moisture content, composition material characteristics, cement paste percentage, and testing method (Al-Rbaihat and Awwad, 2021; Uysal et al., 2004; Demirboğa, 2003). The *C* coefficient of CC is between 840 and 1170 J/kg.°C (Neville, 1996; Howlader et al., 2012; Saleh et al., 2021). The α coefficient of CC is between 0.55 and 1.55 $\mu m^2/s$ (Neville, 1996; Howlader et al., 2012). Whereas the compressive strength coefficient of CC is between 15 and 28 MPa (Association, 2003). However, concrete's thermal and mechanical characteristics dramatically depend on the concrete composites.

Most of the nanoconcrete studies, as seen from a review of earlier research, concentrated on the impact of specific nanoparticles on modified concrete's thermal and mechanical properties. Also, only a few studies have been conducted to investigate the combined effect of using nanomaterials on concrete properties. To bridge this research gap, this study aims to assess the individual and combined impact of adding nano-$SiO_2$ and nano-$TiO_2$ on concrete's thermal and mechanical properties. For the individual effects, the nanomaterials were added at percentages of 1%, 3%, and 5% by weight of cement. Whereas for the combined effect, the nanoparticles were added in similar percentages of 0.5%, 1.5%, and 2.5% by weight of cement. This work investigates the hypothesis that combined nanoparticles may produce a more substantial influence than individual capabilities. The coefficients ($k$, $C$, $\alpha$, and $\sigma$) are the leading concrete characteristics examined. Microscopic images are also used to determine changes in the microstructure of modified concrete in the present study. A comparison of the present findings with previous studies in the literature is introduced.

## EXPERIMENTAL WORK

### Materials used

In this work, ordinary Portland cement with compressive strength coefficient of 41.9 MPa, according to ASTM C109/C109M:2021, was used for the experimental examination. The compressive strength coefficient was recorded at 28 days of curing using a 2×2 inch cube mold. Hydration is a chemical interaction that occurs when cement and water are mixed, causing heat to be produced and the concrete to become firm. Concrete features are unstable during the hardening process but become more volatile over time, depending on the degree of hydration (Sastry et al., 2021).

With a maximum possible particle size of 20 mm, crushed stone was employed as coarse aggregate. The course aggregate's specific gravity and fineness modulus were 2.65 and 6.55, respectively. River sand was used as a fine aggregate with a specific gravity and a fineness modulus of 2.59 and 6.20, respectively. In all the examined mixtures, potable water with a cement to water ratio of 0.53 was employed. Table 1 shows the specifications of mixtures in cement mortar.

Silicon dioxide ($SiO_2$) is commonly known as silica, whereas titanium dioxide ($TiO_2$) is known as Titania. They are both among the most widely used nanomaterials. Nano-$SiO_2$ and nano-$TiO_2$ particles are selected as cement substitutes in the concrete mixtures. This is because the cost of their products is often cheaper than other nanomaterials, in addition, it is comparatively simple to handle compared to other nanoparticles. Concrete mixtures were prepared with different fraction of nano-$SiO_2$ and nano-$TiO_2$. Figure 1 shows samples of nano-$SiO_2$ and nano-$TiO_2$ particles considered in this study. Table 2 provides an overview of the main features of the nanoparticles employed in the present study.

**Table 1.** Physical properties of cement material

| Test* | Specification | Results | Specification limits |
|---|---|---|---|
| Compressive strength (at 28 days) | ASTM C109 | 41.9 MPa | 22.5 to 42.5 MPa |
| Fineness (on sieve 90 μm) | ASTM C184 | 8.2% | < 10% |
| Specific gravity | ASTM C188 | 3.12 $g/cm^3$ | 3.10 to 3.16 |
| Initial setting time | ASTM C191 | 95 min | ≥ 45 min |
| Final setting time | ASTM C191 | 165 min | 90 to 375 min |
| Water content for normal consistency | ASTM C187 | 27.5% | 25-35% |

**Note:** * Tested in the laboratory of the Civil Engineering Department at Tafila Technical University, Jordan.


**Figure 1.** Samples of nano-$SiO_2$ and nano-$TiO_2$ materials with a particle size of 20–30 nm

It is important to note that the health risks associated with handling nanoparticles can vary depending on factors like particle size, concentration, and the specific properties of the nanoparticles used. Therefore, it is crucial to conduct a thorough risk assessment and follow safety guidelines and recommendations from relevant regulatory agencies in your area when working with nano-$SiO_2$, nano-$TiO_2$, or any other nanoparticles in concrete or other materials. Moreover, the application of nanoparticles in large construction projects is feasible, but it comes with challenges related to mixing uniformity, cost, and logistics. Addressing these challenges requires careful planning, advanced mixing techniques, quality control measures, and a commitment to safety.

## Mixture preparation

The preliminary mix of cement, nanoparticles, and water was first prepared. The components were then blended in the appropriate amounts using a mechanical mixing device to produce a homogeneous combination of composition and quality. The mixing device was turned on until the consistency of the mixture was homogeneous for about 5 minutes. After that, the required amount of fine and coarse aggregates was added to the preliminary mixture, and the entire composites were well-mixed to produce the nanoconcrete mixtures. The concrete mixtures were then cast in 15×15×15 cm cubes, as shown in Figure 2. To prevent the concrete mixture from adhering to the molds, the cube's surface was cleaned and lubricated.

The casting process was conducted in three stages. The concrete mix was initially poured until a third of the mold; an iron rod was immediately used to well-mix the concrete composites for about one minute. The process was repeated for each layer until the mold was filled without time interruption. This resulted in the crop air expanding, achieving the greatest density, and increasing the interaction forces between the concrete composites in a homogenous mixture. After 24 hours, the specimens were removed from their molds and cured in water inside the duration tank for curing periods of 7 and 28 days at 20 ± 3 °C and

**Table 2.** Properties of titanium dioxide and silica dioxide

| Parameter | Specification | |
|---|---|---|
| | Nano-$SiO_2$ | Nano-$TiO_2$ |
| Particle size | 20 to 30 nm | 20 to 30 nm |
| Appearance | White powder | White powder |
| Density | 2460 kg/$m^3$ | 4220 kg/$m^3$ |
| Surface volume ratio | 1280 to 1380 $m^2$/g | 143 to 167 $m^2$/g |
| PH value | 4-8 | 5-6.8 |
| Purity | 99.9% | 99.7% |
| Melting point | 1600 °C | 1843 °C |
| Boiling point | 2230 °C | 2972 °C |

**Table 3.** Mix proportion design for 1.0 $m^3$ of concrete

| No | Sample | Cement (kg) | Coarse aggregate (kg) | Fine aggregate (kg) | Water-cement ratio | Nano-$SiO_2$ (kg) | Nano-$TiO_2$ (kg) |
|---|---|---|---|---|---|---|---|
| 1 | CC | 310 | 1224 | 602 | 0.53 | 0 | 0 |
| 2 | C-S1 | 306.9 | 1224 | 602 | 0.53 | 3.10 | 0 |
| 3 | C-S3 | 300.7 | 12/24 | 602 | 0.53 | 9.30 | 0 |
| 4 | C-S5 | 294.5 | 1224 | 602 | 0.53 | 15.50 | 0 |
| 5 | C-T1 | 306.9 | 1224 | 602 | 0.53 | 0 | 3.10 |
| 6 | C-T3 | 300.7 | 1224 | 602 | 0.53 | 0 | 9.30 |
| 7 | C-T5 | 294.5 | 1224 | 602 | 0.53 | 0 | 15.50 |
| 8 | C-ST1 | 306.9 | 1224 | 602 | 0.53 | 1.55 | 1.55 |
| 9 | C-ST3 | 300.7 | 1224 | 602 | 0.53 | 4.65 | 4.65 |
| 10 | C-ST5 | 294.5 | 1224 | 602 | 0.53 | 7.75 | 7.75 |

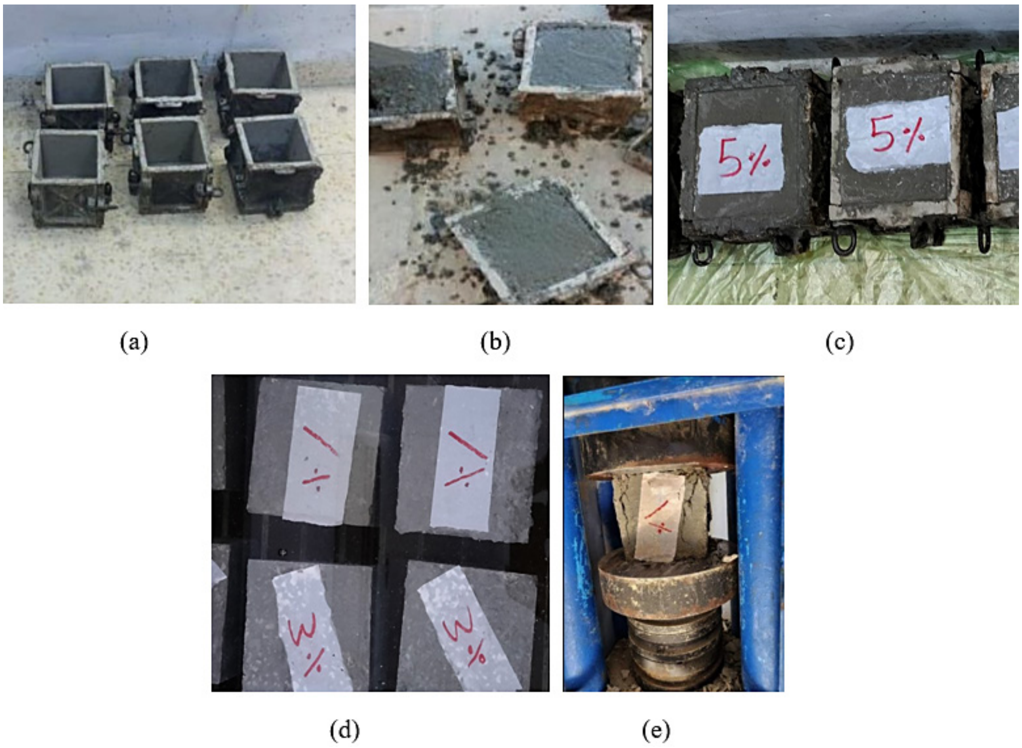


**Figure 2.** Photos of experiments: (a) models before casting, (b) casting of samples, (c) models after casting, (d) samples in the duration tank, and (e) shape of the failed sample

55 ± 5% relative humidity. Eventually, the specimens were ready for testing the main coefficients ($k$, $C$, $\alpha$, and $\sigma$). Table 3 presents the mix proportion design for 1.0 $m^3$ of concrete.

Table 4 shows the tested concrete samples with different fractions of nano-$SiO_2$ and nano-$TiO_2$ particles as a cement substitute. Initially, modified concrete mixtures were prepared by adding individual nanoparticles in percentages of 1%, 3%, and 5% as cement substitutes. Then, both nanoparticles (i.e., nano-$SiO_2$ and nano-$TiO_2$) were added in percentages of 0.5%, 1.5%, and 2.5% as cement substitutes for the combined effect. Finally, all modified concrete specimens were compared to those

**Table 4.** Symbol proportions

| Symbol | Description |
|---|---|
| CC | Control concrete without additives |
| C-S1 | Concrete with 1% $SiO_2$ nanomaterial |
| C-S3 | Concrete with 3% $SiO_2$ nanomaterial |
| C-S5 | Concrete with 5% $SiO_2$ nanomaterial |
| C-T1 | Concrete with 1% $TiO_2$ nanomaterial |
| C-T3 | Concrete with 3% $TiO_2$ nanomaterial |
| C-T5 | Concrete with 5% $TiO_2$ nanomaterial |
| C-ST1 | Concrete with 0.5% $SiO_2$ and 0.5% $TiO_2$ nanomaterial |
| C-ST3 | Concrete with 1.5% $SiO_2$ and 1.5% $TiO_2$ nanomaterial |
| C-ST5 | Concrete with 2.5% $SiO_2$ and 2.5% $TiO_2$ nanomaterial |

of CC. The letters C-S, C-T, and C-ST denote the nano-$SiO_2$, nano-$TiO_2$, and combined nano-$SiO_2$/$TiO_2$, respectively, as a substitution percentage of the cement weight. For instance, the C-S1 specimen indicates a specimen with 1% replaced nano-$SiO_2$ as a partial substitution of cement. In addition, the letter CC denotes conventional concrete, indicating a sample with a 0% cement substitute (i.e., control concrete without additives).

### Thermal conductivity (*k* coefficient) test

The material's capability to transfer heat refers to the *k* coefficient. The thermally insulating nanoconcrete has an extremely low *k* coefficient, preventing heat flow from the inside to the outside, resulting in energy-saving potential. Thus, efficient thermal insulation typically depends on the *k* coefficient. Conductivity is affected by standard environmental conditions (e.g., relative humidity and ambient temperature) and the density of the concrete mix (air content, the porosity in the mixture, and the nature of the concrete composition specifications) during the preparation and testing of the samples. Where *k* coefficient increases with increasing relative humidity, ambient temperature, and density (Kim et al., 2003).

The *k* coefficient of concrete specimens can be assessed using a transient energy evaluation technique. In the present study, concrete specimens of 150, 150, and 30 mm for length, width, and height, respectively, were used to estimate the *k* coefficient values. Following the curing period, all specimens underwent oven drying at 90 ± 3 °C for 24 hours to remove all moisture. Next, all of the specimens' surfaces were then smoothed to ensure adequate contact between the electrical heating source and the specimen. Samples were tested under standard conditions with a relative humidity of 55 ± 5% and a room temperature of 20 ± 3 °C.

The specimen is clamped between the heated and cooled section of the *k* coefficient device. An electric heater of 100 kW/$m^2$ is placed on the specimen's top surface, while cold water flows at maintained constant flow rate through the specimen's bottom surface in the cooled section. As a result, the samples' top and bottom surfaces remain at different temperatures. The other four sides of the concrete specimen are insulated by 30 mm thick fiberglass layers placed around the sample to prevent heat transfer between the specimen sides and the environment. The concrete specimens are to get one-dimensional heat flow from their top to bottom surfaces (30 mm in height) by applying uniform heat. Two thermocouples (T-type) were placed on the samples' top and bottom surfaces, and the temperature difference was monitored. The difference in temperature on the samples' top and bottom surfaces was measured using thermocouples. The distance between thermocouples is the same as the specimen thickness (i.e., 30 mm). The concrete specimen was subjected to a constant heat source of 100 kW/$m^2$ for about 6 ± 2 minutes. Eventually, temperatures were recorded accordingly to obtain more precision and stability data. Testing the *k* coefficient was repeated three times for each specimen. The average value was regarded as the *k* coefficient value of the concrete specimen. The *k* coefficient of the concrete specimens was evaluated as (Saleh et al., 2023):

$$k = \frac{Q.L}{A \cdot \Delta T} \tag{1}$$

where: *k, Q, L, A,* and *ΔT* are the *k* coefficient (W/m·°C), the heat transferred between the samples' top and bottom surfaces (W), the thickness of the sample (m), the surface area of the sample perpendicular to the heat flow lines ($m^2$), and the difference in temperature on the samples' top and bottom surfaces (°C), respectively.

### Specific heat capacity (*C* coefficient) test

The *C* coefficient is the ratio of energy delivered to a substance with a change in temperature that results. The *C* coefficient of concrete is a feature that can be used to measure the concrete's capability to save thermal energy. In the current study, heat capacity was assessed using the calorimetric method (Saleh et al., 2021; Talebi et al., 2020). A calorimeter made of an insulated ice box was employed. The box was insulated by 30 mm thick fiberglass layers to prevent heat transfer. Calorimetry generally involves combining a concrete specimen with an unknown *C* coefficient with a reference material (e.g., water) with known properties. Between these materials (concrete specimen & water) there is a heat transfer process in which the heat produced by one material is balanced by the heat received by another. In the present study, concrete specimens of 150, 150, and 30 mm for length, width, and height, respectively, were used to estimate the *C* coefficient values. The samples were conditioned at room temperature for at least 24 hours.

The mass and temperature of the concrete specimen and water were measured. A hot water of about 50 °C was initially inserted into the box, and a thermometer was placed inside the box to record the temperature for three hours. The drop in water temperature during an hour was estimated to be roughly 0.7 °C (1.9 °C in the three hour), demonstrating that the box was well insulated. Next, samples were rapidly submerged in water and the box was promptly covered to keep the temperature constant inside the box. Due to the temperature difference between the concrete specimen and water, heat is transferred between the two materials inside the box. As a result, the water temperature inside the box starts to decrease until it reaches a stable temperature. The reduction in water temperature inside the box was monitored to determine the stable temperature eventually. Equilibrium temperature (stable temperature) was achieved after around 46 minutes. However, the equilibrium temperature was recorded after 60 minutes to obtain more precision and stability data. The *C* coefficient test was also repeated three times for each specimen to achieve accurate results. The average value was considered the *C* coefficient value of the concrete specimen. The *C* coefficient was computed as follows (Saleh et al., 2021).

$$m \cdot C \cdot (T_s - T_{eq}) = m_i \cdot C_i \cdot (T_{eq} - T_i) \quad (2)$$

where: $m$, $C$, $T_s$, $T_{eq}$, $m_i$, $C_i$, and $T_i$ are the mass of the sample (kg), the *C* coefficient of the sample (J/kg·°C), the temperature of the sample (°C), the equilibrium temperature (°C), the mass of water (kg), the *C* coefficient of water (J/kg·°C), and the initial temperature of water and calorimeter (°C), respectively.

### Thermal diffusivity (*α* coefficient) test

The α coefficient is defined as the heat transfer rate across a medium. Reduced thermal diffusivity causes longer heat transfer time through the material. As a result, efficient thermal insulation depends not only on the *k* coefficient but also on the α coefficient. Efficient thermal insulation should have lower *k* and α coefficients. The α coefficient is calculated by dividing *k* coefficient by the product of density and specific heat. Therefore, it's necessary to determine the *C* coefficient, density, and *k* coefficient of the concrete specimens to estimate the α coefficient of the samples. The α coefficient is the rate at which heat transmits through a material, and it is the reference to measure the concrete's temperature fluctuations; it can be calculated as follows (Bilski et al., 2023) with thin asphalt layers (from 1 cm to 4 cm.

$$\alpha = \frac{k}{\rho \cdot C} \quad (3)$$

where: α, *k*, ρ, and *C* are the α coefficient ($m^2/s$), the *k* coefficient (W/m·°C), the density of the sample ($kg/m^3$), and the *C* coefficient of the sample (J/kg·°C), respectively.

### Compressive strength (*σ* coefficient) test

The compressive strength coefficient of concrete is the ability of concrete to carry loads on its surface without any deflection or crack. The compressive strength coefficient test was performed according to BS EN 12390-3:2019 at 7 and 28 days after curing. A cubical concrete specimen of 150 mm sides was placed in the machine, and the load was gradually applied at a constant rate of 0.7 MPa/s until the test specimens fail. In this study, three replicated specimens were tested for each mixed condition. The average value of compressive tests on replicated specimens was recorded.

## RESULTS AND DISCUSSION

### Experimental results

The outcomes of the coefficients (*k*, *C*, *α*, and *σ*) tests were recorded, as shown in Table 5. Each test was conducted three times for each single condition to assess the repeatability of the data. These findings are estimated for the tested concrete specimens as the average value. For all cases, adding nanoparticles to the CC for a curing period of 28 days provides superior mechanical and thermal properties over the curing period of 7 days. The results indicated that adding nanoparticles to CC improves its mechanical and thermal properties. However, the combined effect of nanoparticles causes the compressive strength coefficient of nanoconcrete to decrease.

Figures 3 to 6 show the thermal properties of the nanoconcrete (*k*, *C*, and *α* coefficients). Also, Figures 7 and 8 show the mechanical properties of the nanoconcrete (compressive strength coefficient). The findings demonstrated that using nano-$SiO_2$ particles significantly improved the thermal and mechanical properties of nanoconcrete, and it was the best nanoparticle tested. The results revealed that the optimal thermal properties of nanoconcrete were achieved when 5% nano-$SiO_2$ (C-S5 specimen) was added. The *k* and α coefficients of sample C-S5 compared to the CC specimen were reduced by 65.6% and 80.3%, respectively, while the *C* coefficient was increased by 12.8%. On the other hand, the optimal compressive strength coefficient values of nanoconcrete were achieved when 3% nano-$SiO_2$ (C-S3 specimen) was added, where the compressive strength coefficient value of sample C-S3 compared to sample CC was increased by 19.6%.

One of the potential benefits of using $SiO_2$ and $TiO_2$ nanoparticles in concrete is the improvement in energy efficiency. Incorporating nanoparticle technologies into concrete enhances insulation properties, reducing the heating and cooling costs of buildings. At the same time, nanoparticles improve mechanical properties, such as increased compressive strength and durability, resulting in reduced maintenance and repair costs over the long term.

Noteworthy is the fact that the effectiveness of nanoparticles in enhancing concrete's long-term performance and durability can depend on various factors, including the type and concentration of nanoparticles used, the quality of mixing and dispersion, and the specific environmental conditions to which the concrete is exposed. Thus, long-term studies and monitoring are also essential to confirm the sustained benefits of nanoparticle-enhanced concrete.

## Thermal conductivity (*k* coefficient) results

The *k* coefficient results of the replicated specimens under different conditions are shown in Figure 3. The average value was regarded as the *k* coefficient value of the concrete specimen. Different percentages of nano-$SiO_2$ and nano-$TiO_2$ were tested to examine the characteristics of nanoconcrete compared to CC. The average variability in the *k* coefficient was about 5.2% between replicated specimens for both curing periods of 7 and 28 days. The results indicated that adding of individual or combined nanoparticles to CC improves its thermal properties. It is also noted that adding nanoparticles to the concrete mix reduces *k* coefficient, resulting in high-performance concrete. Consequently, providing thermal insulation concrete for an efficient approach to saving energy in a building. Compared to all mixes tested at all curing periods, the optimal *k* coefficient was achieved when 5% nano-$SiO_2$ (C-S5 specimen) was added to the concrete mixture.

Figure 4 demonstrates the average *k* coefficient results of the concrete specimens for 7 and 28 days of curing. Results indicated that adding nanoparticles to the concrete mix reduces *k* coefficient for all samples. It is noted that the *k* coefficient of samples for 7 and 28 days of curing was in the range of (0.80 to 1.76) W/m·°C and (0.55 to 1.60) W/m.°C, respectively. Moreover, the results revealed that samples with a curing period of 28 days provided a further reduction in *k* coefficient (good thermal properties) compared to samples with a curing period of 7 days. Concrete with a lower *k* coefficient introduces

**Table 5.** Summary of experimental results for the tested concrete specimens

| Symbol | *k* (W/m·°C) | | *C* (J/kg·°C) | | *α* (μm²/s) | | *σ* (MPa) | |
|---|---|---|---|---|---|---|---|---|
| | 7 days | 28 days | 7 days | 28 days | 7 days | 28 days | 7 days | 28 days |
| CC | 1.76 | 1.60 | 790 | 825 | 0.92 | 0.71 | 16.0 | 21.4 |
| C-S1 | 1.07 | 0.96 | 822 | 878 | 0.51 | 0.38 | 18.5 | 23.4 |
| C-S3 | 0.90 | 0.72 | 838 | 902 | 0.39 | 0.19 | 19.5 | 25.6 |
| C-S5 | 0.73 | 0.55 | 861 | 931 | 0.32 | 0.14 | 17.6 | 22.6 |
| C-T1 | 1.20 | 1.11 | 802 | 856 | 0.70 | 0.52 | 18.0 | 22.8 |
| C-T3 | 1.09 | 1.00 | 817 | 869 | 0.61 | 0.39 | 19.0 | 25.1 |
| C-T5 | 0.99 | 0.90 | 839 | 878 | 0.53 | 0.30 | 16.7 | 21.4 |
| C-ST1 | 1.07 | 0.95 | 813 | 868 | 0.58 | 0.45 | 15.0 | 19.2 |
| C-ST3 | 0.95 | 0.83 | 829 | 888 | 0.52 | 0.31 | 16.0 | 19.9 |
| C-ST5 | 0.80 | 0.70 | 849 | 896 | 0.45 | 0.23 | 14.5 | 18.0 |

**Note:** *k* – thermal conductivity coefficient (W/m.°C), *C* – specific heat capacity (J/kg.°C), *α* – thermal diffusivity coefficient (μm²/s), *σ* – compressive strength (MPa).

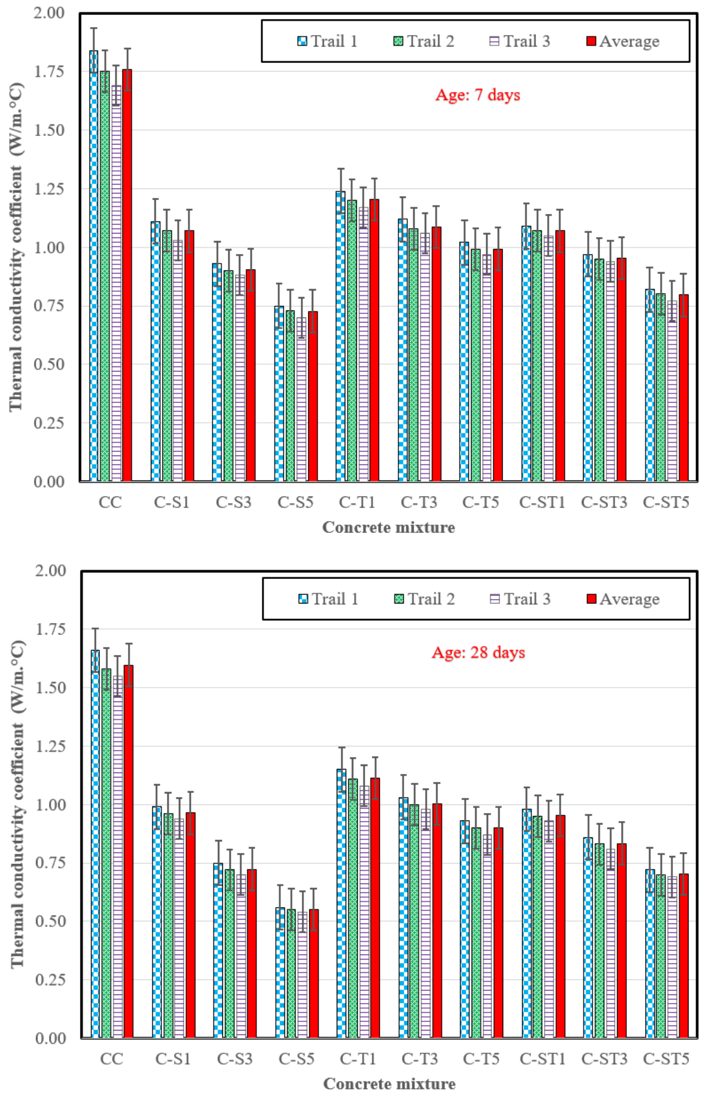


**Figure 3.** Repeatability of the thermal conductivity coefficient (*k* coefficient) measurements of concrete specimens

thermal insulation concrete, resulting in high-performance concrete. The optimal *k* coefficient value was achieved when 5% nano-$SiO_2$ (C-S5 specimen) was added to the concrete mixture, where the *k* coefficient value of nanoconcrete decreased to 0.55 W/m·°C. This corresponds to a decrease of about 65.6%. This result was consistent with the finding reported in a previous study (Saleh et al., 2021). In that study, the optimal *k* coefficient value was achieved by adding up to 3% of nano-$SiO_2$ to the concrete mixture, where the *k* coefficient value was decreased to 0.50 W/m·°C.

The presence of air space in the concrete mixture that impedes heat transfer causes a decrease in *k* coefficient, resulting in a lower sample weight. The larger the air pores ratio, the lighter the specimen and the lower its *k* coefficient. Similar observations can be found in previous studies (Ren et al., 2018; Kaya and Kar, 2016; Saleh et al., 2023). Additionally, the density of concrete represents its compactness and porosity. Meanwhile, nanoparticles significantly impact the compactness and porosity of concrete. The reduction in the *k* coefficient of the nanoconcrete is due to the insulating effect of nanoparticles. It is evident from these results that adding nanoparticles to the concrete mixture produced less *k* coefficient composite. This is consistent with the results of previous studies (Saleh et al., 2021; Nazari and Riahi, 2011; Oh et al., 2023; Ren et al., 2018; Khaloo et al., 2016; Syamsunur et al., 2022). It can be concluded that adding some of the nano-$SiO_2$ as a cement substitute has positive economic effects due to its merits; nano-$SiO_2$ is a desirable, reliable, and inexpensive substitute compared to other nanomaterials.

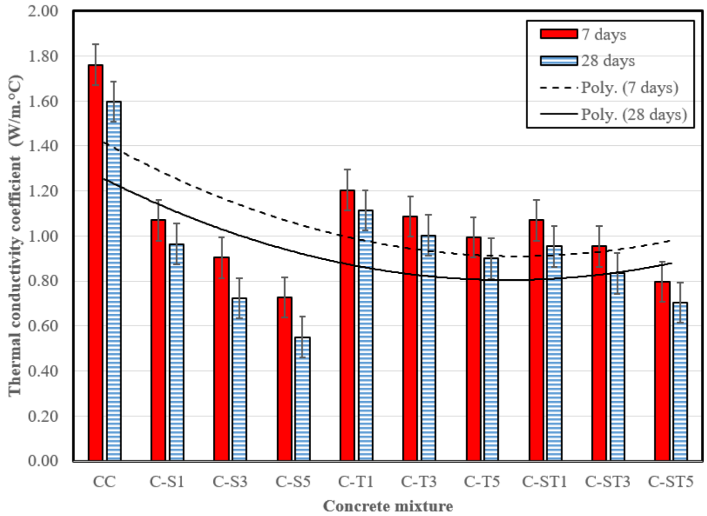


**Figure 4.** Mean thermal conductivity coefficient (*k* coefficient) measurements of concrete specimens

## Specific heat capacity (*C* coefficient) results

The average *C* coefficient values of the concrete specimens for 7 and 28 days of curing are shown in Figure 5. The results indicated that adding nanoparticles to the concrete mixture increases the *C* coefficient for all specimens. It is noted that the *C* coefficient of specimens for 7 and 28 days of curing was in the range of 790 to 861 J/kg·°C and 825 to 931 J/kg·°C, respectively. The optimal *C* coefficient value was achieved when 5% nano-$SiO_2$ was added to the concrete mixture, where the *C* coefficient value of nanoconcrete increased to 931 J/kg·°C. This corresponds to a decrease of about 12.8%. The findings exhibited that concrete containing 5% nano-$SiO_2$ (C-S5 specimen) remains the best percentage for achieving the highest *C* coefficient regardless of the curing duration. Concrete with a higher *C* coefficient improves the concrete's capability to preserve thermal energy, resulting in high-performance concrete. This increase is due to inherent material composites.

## Thermal diffusivity (*α* coefficient) results

Figure 6 shows the average *α* coefficient values of the concrete specimens for 7 and 28 days of curing. The results revealed that adding nanoparticles to the concrete mix decreases the α coefficient for all specimens. It is noted that the α coefficient of specimens for 7 and 28 days of curing was in the range of 0.32 to 0.92 μm²/s and 0.14 to 0.71 μm²/s, respectively. The optimal α coefficient value was achieved when 5% nano-$SiO_2$ (C-S5) was added to the concrete mix, where the α coefficient value of nanoconcrete decreased to 0.14 μm²/s. This corresponds to a decrease of about 80.3%. The findings exhibited that concrete containing 5% nano-$SiO_2$ (C-S5)

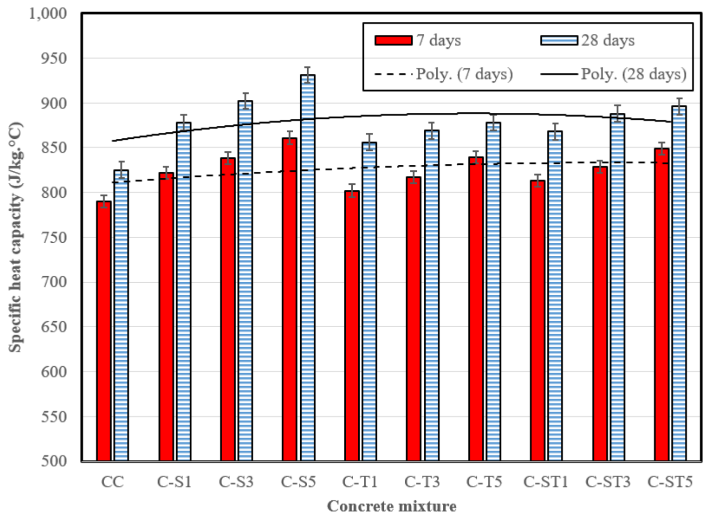


**Figure 5.** Mean specific heat capacity (*C* coefficient) measurements of concrete specimens

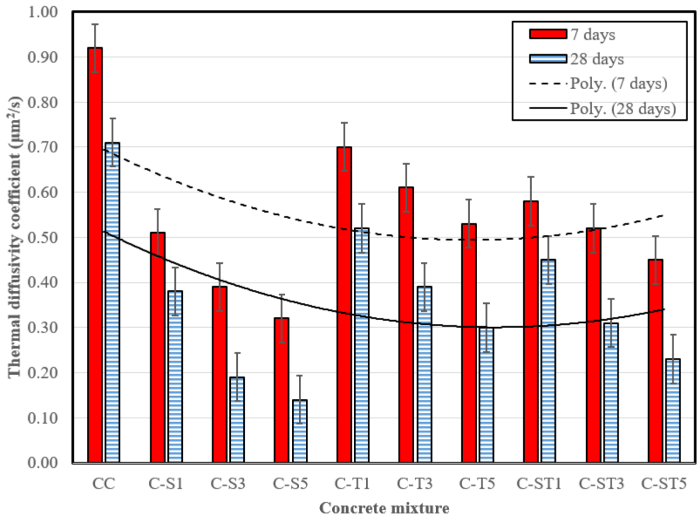


**Figure 6.** Mean thermal diffusivity coefficient ($\alpha$ coefficient) measurements of concrete specimens

remains the best percentage for achieving the highest $\alpha$ coefficient regardless of the curing duration. Concrete with a lower α coefficient impedes heat loss, resulting in high-performance concrete. Equation (3) states that $k$ and $\alpha$ coefficients have a direct relationship, which accounts for this reduction.

## Compressive strength ($\sigma$ coefficient) results

Figure 7 depicts the compressive strength coefficient values of the concrete specimen for curing periods of 7 and 28 days. The compressive strength coefficient value of the concrete specimen was determined by taking the average values of the replicated specimens. Different fractions of nano-$SiO_2$ and nano-$TiO_2$ particles were employed to examine the compressive strength coefficient of the nanoconcrete compared to CC. Concrete with a higher compressive strength coefficient results in high-performance concrete. The average variability in the compressive strength coefficient was about 4.6% between repeated tests for each sample tested for both curing periods of 7 and 28 days. Compared to all mixes tested at all curing periods, the optimal compressive strength coefficient was achieved when 3% nano-$SiO_2$ (C-S3 specimen) was added to the concrete mix.

The average compressive strength coefficient values of the concrete specimens for different curing periods are shown in Figure 8. The results indicated that adding nanoparticles to the concrete mix by up to 3% increases compressive strength coefficient for all samples. An increase of nanoparticles beyond 3% decreased compressive strength coefficient because the saturation stage had been reached for all samples. It is noted that the compressive strength coefficient of samples for 7 and 28 days of curing was in the range of 14.5 to 19.5 MPa and 18.0 to 25.6 MPa, respectively. The workability of nanoconcrete was substantially impacted by nanoparticle admixture by up to 3%, where the compressive strength coefficient increased. The optimal compressive strength coefficient was achieved when 3% nano-$SiO_2$ (C-S3) was added to the concrete mix, where the compressive strength coefficient value of nanoconcrete increased to 25.6 MPa. This might be explained by the nanoparticles added to the concrete mixture, accelerating the hydration reaction rate and producing more hydration products. As a result, due to the dense microstructure, the frictional bond between the concrete composites is strengthened, thereby improving concrete's mechanical properties such as compressive strength coefficient. The porosity of cement may be reduced by adding nano-$SiO_2$, resulting in a denser microstructure of concrete composites. Additionally, nano-$SiO_2$ particles have a higher compressive strength coefficient than nano-$TiO_2$ and combined nano-$SiO_2$/$TiO_2$ particles because of their larger surface area. However, increasing the nanoparticles admixture beyond 3% could have resulted in substantial internal agglomeration due to the extremely small particle size of nanoparticles. This might significantly affect the workability of nanoconcrete, then reduces the compressive strength coefficient of nanoconcrete. Similar observations can be found in References (Ren et al., 2018; Zhou et al., 2021; Pathak and Vesmawala, 2022; Selvasofia et al., 2021; Zegardło and Kobyliński, 2021; Mesrar et al., 2023). According to Nuaklong et al. (2018),

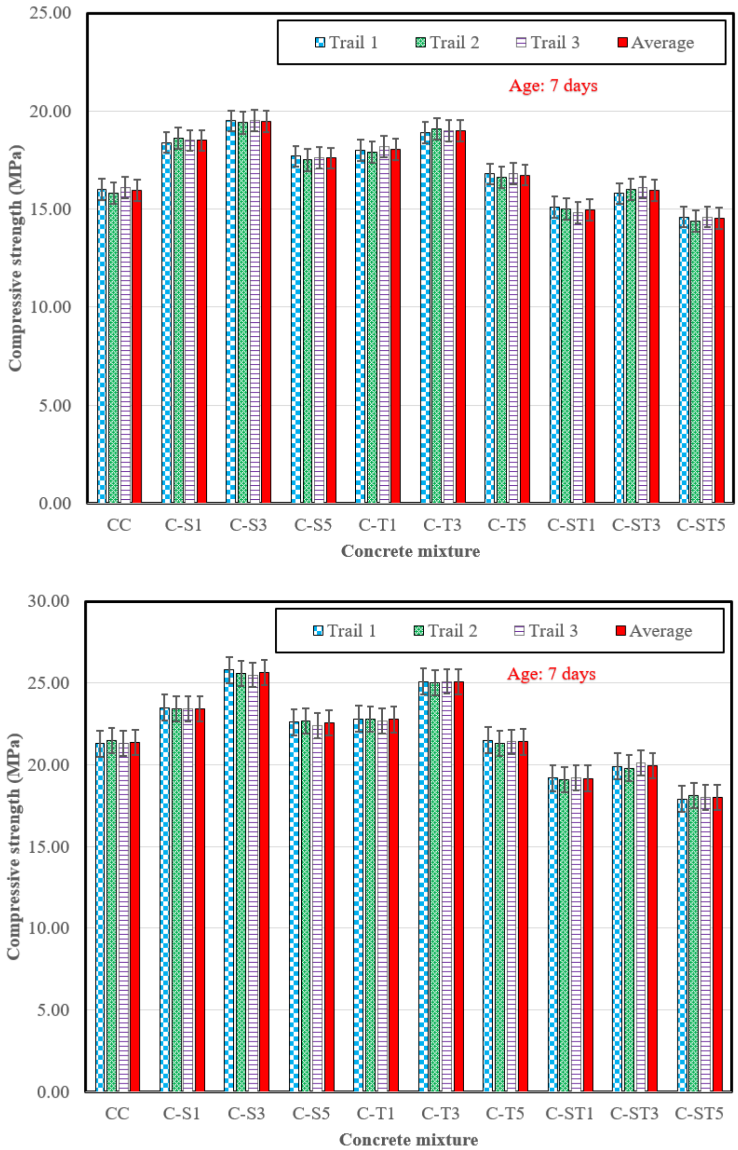


**Figure 7.** Repeatability of the compressive strength coefficient measurements of concrete specimens

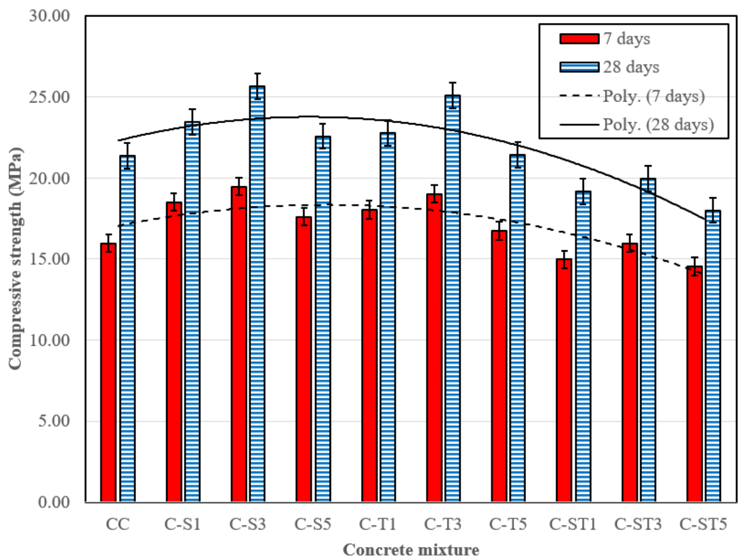


**Figure 8.** Mean compressive strength coefficient measurements of concrete specimens

adding up to 2% of nano-$SiO_2$ to the concrete mixture enhanced its compressive strength coefficient; however, beyond 2% nano-$SiO_2$ addition, compressive strength coefficient reduced.

## Microstructure analysis

The microscope DM750P was used in the study to investigate the effect of nanomaterials on concrete microstructure. The main benefits of nanomaterials on the microstructure and performance of concrete mixture are an improvement in contact zone that results in a better bond between mixture materials (i.e., aggregate and cement past), a reduction in pores, a reduction in segregation, and an increase in compressive strength. Moreover, nanomaterials with finer particle sizes fill up the voids in the mixture and produce denser concrete. A control specimen and specimens with 5% nanomaterials after 28 days of curing are imaged and presented in Figure 9. The results indicate that including more nanomaterials (i.e., $SiO_2$ and $TiO_2$) in concrete mixtures produces denser and compacted mixtures than others. nano-$SiO_2$ and nano-$TiO_2$ improve the microstructure through increased pozzolanic reactivity, encouraging cement hydration and forming more C-S-H gel. As mentioned earlier, producing more C-S-H gel will fill up non-porous in the mixture and thus increase strength. The results also showed that the specimens containing 5% nano-$SiO_2$ had fewer pores than others.

Table 6 shows the effect of adding various nanoparticles on the properties of concrete for several previous studies. The results found that using nanoparticles in the concrete mixture is beneficial in enhancing some concrete properties, although it has deficiencies in others. For example, adding Polystyrene granules enhanced the *k* coefficient of concrete

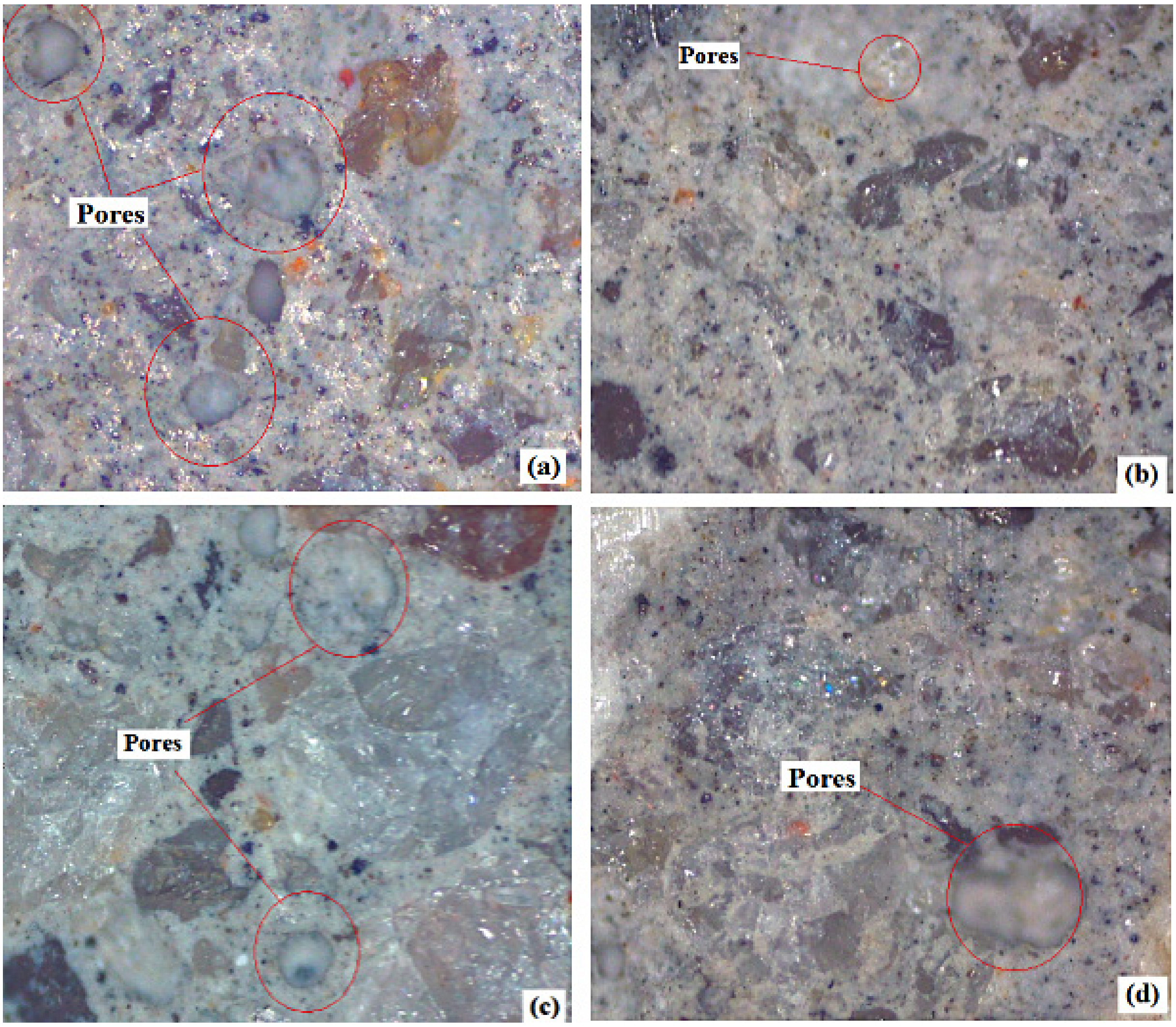


**Figure 9.** Microscopic images of concrete with (a) 0% nanoparticles, (b) 5% of nano-$SiO_2$, (c) 5% of nano-$TiO_2$, and (d) 2.5% of nano-$SiO_2$ and 2.5% of nano-$TiO_2$

**Table 6.** Main outcomes of using various nanoparticles in literature

| Type of nanoparticles | % of nanoparticles studied | Curing time (days) | Main outcomes | | Ref. |
|---|---|---|---|---|---|
| | | | Optimal % | Effects | |
| $SiO_2$ | 1, 2, 3 | 7, 14, 28 | 3 | Increased the $\sigma$ coefficient by 32.45% at 28 days of curing.<br>Increased the $C$ coefficient by 7.96% at 28 days of curing.<br>Decreased the $k$ coefficient by 65.57% at 28 days of curing.<br>Decreased the $a$ coefficient by 64.52% at 28 days of curing. | (Saleh et al., 2021) |
| $TiO_2$ | 1, 2, 3, 4 | 7, 28, 60 | 2 | Increased the $\sigma$ coefficient by 32.5% at 60 days of curing.<br>Increase in split tensile strength by 41.3% at 60 days of curing. | (Selvasofia et al., 2021) |
| $TiO_2$<br>Nano clay (NC) | 2<br>1, 2, 3, 4 | 7, 28, 60 | 2<br>3 | Increased the $\sigma$ coefficient by 48.5% at 60 days of curing.<br>Increased the split tensile strength by 62.4% at 60 days of curing. | |
| $SiO_2$ | 1, 2, 3 | 7, 14, 28 | 3 | Increased the $\sigma$ coefficient by 32.45% at 28 days of curing.<br>Decreased the $k$ coefficient | (Saleh et al., 2023) |
| Polystyrene granular (EPS) | 0.8, 1, 2, 3 | 7, 14, 28 | 0.8 | Decreased the $\sigma$ coefficient by 23.1% at 28 days of curing.<br>Decreased the $k$ coefficient by 28.4% | |
| $SiO_2$<br>EPS | 3<br>0.8 | 7, 14, 28 | 3<br>0.8 | Decreased the $\sigma$ coefficient by 53.3% at 28 days of curing.<br>Decreased the $k$ coefficient by 65.9% | |
| $SiO_2$ | 0.5, 2, 4 | 28, 90 | 4 | Increased the $\sigma$ coefficient by 4.3% at 90 days of curing. | (Niewiadomski et al., 2015) |
| $TiO_2$ | 0.5, 2, 4 | 28, 90 | 2 | Increased the $\sigma$ coefficient by 3.0% at 90 days of curing. | |
| $Al_2O_3$ | 0.5, 1, 2, 3 | 28, 90 | 0.5 | Increased the $\sigma$ coefficient by 3.0% at 90 days of curing. | |
| $TiO_2$<br>Flay ash (FA) | 1, 2, 3, 4, 5<br>20 | 3, 7, 28, 90 | 4<br>20 | Increased the $\sigma$ coefficient by 3.98% at 90 days of curing.<br>Decreased the flexural strength by 4.44% at 90 days of curing.<br>Decreased the split tensile strength by 1.16% at 90 days of curing. | (Pathak and Vesmawala, 2022) |
| $Cr_2O_3$ | 1, 2, 3, 4, 5 | 3, 7, 28, 90 | 2 | Increased the $\sigma$ coefficient by 5.63% at 90 days of curing.<br>Increased the Flexural strength by 15.40% at 90 days of curing. | (Yang et al., 2015) |
| $ZnO_2$ | 1, 2, 3, 4, 5 | 3, 7, 28, 90 | 4 | Increased the $\sigma$ coefficient by 24.18% at 90 days of curing.<br>Increased the Flexural strength by 10.95% at 90 days of curing. | |
| MgO | 1, 2, 3, 4 | 7, 28 | 2 | Increased the $\sigma$ coefficient by 33.0% at 28 days of curing.<br>Increased the Flexural strength by 59.0% at 28 days of curing.<br>Increased the tensile strength by 20% at 28 days of curing. | (Ebrahimi Fard and Jabbari, 2017) |

**Note:** All nanoparticles were used as cement replacement except nano clay which used as fine aggregate replacement.

while reducing its compressive strength coefficient (Saleh et al., 2023). The current study found that the *k* and α coefficients of sample C-S5 compared to the CC specimen were reduced by 65.6% and 80.3%, respectively, while the *C* coefficient was increased by 12.8%. Meanwhile, the optimal compressive strength coefficient of nanoconcrete was achieved when 3% nano-$SiO_2$ (C-S3 specimen) was added, where the compressive strength coefficient of sample C-S3 compared to sample CC was increased by 19.6%. In contrast, the current results indicated that using combined nanoparticles in concrete mixtures did not significantly enhance the properties of concrete. These conclusions are consistent with the findings of previous studies (Saleh et al., 2023; Pathak and Vesmawala, 2022).

## CONCLUSIONS

According to the findings of this study, the following conclusions were drawn:

1. The reduced heat transfer rate is attributed to the superior nature properties of nanoparticles in concrete. Nano-$SiO_2$ functions as a better heat retardant agent in concrete, reducing the consumption of traditional energy (often derived from fossil fuels) in structures. It was determined that employing nano-$SiO_2$ addition reduces the heat flow into buildings, and the optimum amount of nano-$SiO_2$ (C-S5) was 5% by weight of cement.
2. Results revealed that nano-$SiO_2$ addition to conventional concrete could significantly enhance the early strength of concrete more than both nano-$TiO_2$ and combined nano-$SiO_2$/$TiO_2$ additions. The thermal properties of concrete were also improved.
3. The findings demonstrated that using nano-$SiO_2$ addition significantly improved the mechanical and thermal properties of nanoconcrete, and it was the best nanomaterial tested. The results revealed that the optimal thermal properties of nanoconcrete were achieved when 5% nano-$SiO_2$ (C-S5) was added. The thermal conductivity and diffusivity of sample C-S5 compared to sample CC (i.e., conventional concrete) were reduced by 65.6% and 80.3%, respectively, while the specific heat capacity was increased by 12.8%.
4. On the other hand, the optimal compressive strength values of nanoconcrete were achieved when 3% nano-$SiO_2$ (C-S3) was added, where the compressive strength value of sample C-S3 compared to sample CC was increased by 19.6%.
5. Although adding combined nano-$SiO_2$/$TiO_2$ particles to conventional concrete improved the thermal properties of nanoconcrete, it reduced the compressive strength. Therefore, incorporating nano-$SiO_2$ and nano-$TiO_2$ particles in the concrete mixture is not recommended.
6. It is evident that the characterization of nanoconcrete contributes to the advancement of concrete technology and the industrial revolution while improving the sustainability of concrete structures.
7. Microscopic images are also used to determine changes in the microstructure of modified concrete in the present study. The presence of nano-$SiO_2$ and nano-$TiO_2$ additions improves the microstructure of modified concrete through increased pozzolanic reactivity, encouraging cement hydration and forming more C-S-H gel. Consequently, producing more C-S-H gel will fill up nonporous in the mixture and thus increase strength. The results also showed that the specimens containing 5% nano-$SiO_2$ had fewer pores than others.
8. Overall, the experimental findings in this work offer valuable information about the impact of nanotechnology on the performance of concrete. Thermal insulation is the most effective way to save energy in buildings. The findings exhibit the relevance of developing concrete with superior mechanical and thermal characteristics using nanoparticles. This study suggested employing silica nanoparticles with conventional concrete as a partial replacement for cement to produce modified concrete economically and efficiently.

To identify if there is an optimal ratio of combined addition of nano-$SiO_2$/$TiO_2$ that provides a balance between thermal properties and compressive strength in concrete, the study recommends conducting additional studies using different percentages. Also, the effect of temperature was not investigated in this study, despite the fact that it plays a vital role in the thermal properties of the concrete composites. As a result, systematic research is required to investigate the effect of temperature on the mechanical and thermal properties of the concrete composites. In addition, future research can be extended to analyze the effect of adding nano-$SiO_2$ on the mechanical properties of concrete, such as water content, split tensile, flexure strength, and hardness.

**Acknowledgments**

The authors gratefully acknowledge Tafila Technical University for their assistance and cooperation in carrying out this study.

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