Case Studies in Construction Materials 19 (2023) e02373

Contents lists available at ScienceDirect

Case Studies in Construction Materials

journal homepage: www.elsevier.com/locate/cscm

Research on performance monitoring of binary nano modified concrete based on temperature variation

Deprizon Syamsunur [a,c,*], Li Wei [a,b,*], Muhammad Noor Hisyam [a], Zubair Ahmed Memon [d,**], Basel Sultan [d]

[a] Department of Civil Engineering, Faculty of Engineering, Technology and Built Environment, UCSI University, Kuala Lumpur 56000, Malaysia
[b] Jiangsu SinoRoad Engineering Research Institute, Nanjing, Jiangsu 211806, China
[c] Postgraduate Studies, Universitas Bina Darma Palembang, Kota Palembang 30111, South Sumatera, Indonesia
[d] College of Engineering, Prince Sultan University, Riyadh 11586, Saudi Arabia

ARTICLE INFO

Keywords:
Nano-CaCO3
Nano-SiO2
Climate warming
Concrete durability
Decay of mechanical properties
Visual deformation

ABSTRACT

The use of concrete is widespread, but it poses challenges due to its high consumption of Earth's raw resources and difficulties in recycling and reclamation. Today, the pressing climate issues, including global warming and the emergence of a complex climate, continue to test cement-based polymers in the civil engineering industry. As a result, there is a growing demand for higher performance, renewable resources, and reduced carbon dioxide production, leading to a shift in the traditional industrial revolution. Composite nano concrete has emerged as an effective solution to address the challenges related to concrete mechanics and durability, aligning with the principles of sustainable development goals. The research focuses on utilizing composite nano-modified concrete to enhance the life cycle of structures. This nano-modified concrete incorporates Nano-SiO_2 (NS) and Nano-CaCO3 (NC) particles to create a new composite nano-concrete structure called NSC concrete. The research paper explores different dosages of composite nano concrete, specifically 2.5 %, 3.0 %, and 3.5 %, denoted as NSC25, NSC30, and NSC35, respectively. It examines the performance of the composite nano concrete under various temperature conditions, including 25 °C, 200 °C, 400 °C, and 600 °C, to simulate real-world scenarios and evaluate its value-based applications. The article analyzes multiple aspects, including mechanical properties, durability, visual appearance, and economic benefits of composite nano concrete. It also assesses NSC concrete's temperature dissipation capacity and insulation level and investigates the interfacial transition zone influenced by nanoparticles and temperature. The results indicate that the new composite nano concrete retains substantial enhancements in mechanical properties, with a maximum increase of 1.22 % in splitting strength and up to 45.69 % improvement in flexural strength at a temperature of 600 °C. Additionally, it demonstrates commendable durability and economic efficiency

* Corresponding authors at: Department of Civil Engineering, Faculty of Engineering, Technology and Built Environment, UCSI University, Kuala Lumpur 56000, Malaysia.
** Corresponding author.
E-mail addresses: deprizon@ucsiuniversity.edu.my (D. Syamsunur), lw15751023132@163.com (L. Wei), muhammad.noor@ucsiuniversity.edu.my (M.N. Hisyam), zamemon@psu.edu.sa (Z.A. Memon), basel.sultan@psu.edu.sa (B. Sultan).

https://doi.org/10.1016/j.cscm.2023.e02373
Received 13 June 2023; Received in revised form 17 July 2023; Accepted 3 August 2023
Available online 9 August 2023

1. Introduction

In conjunction with the UN's 2030 Sustainable Development Goals, the concepts of green and durability are becoming more familiar to the general public, and the research process is being given far-reaching significance [1–3]. As humankind's quest for a better life drives the speed of urbanization and construction, ancillary facilities are everywhere. Super tall buildings, bridge projects, and water projects consume large amounts of concrete resources [4–6]. It also poses a particular risk that fire will damage the structure of the building and that this effect is irreversible [7]. Innovative approaches are being explored to mitigate the environmental and social issues arising from the generation of large quantities of construction waste. One such approach involves utilizing waste concrete fines (WCF) and waste brick fines (WBF) as substitutes for cement and sand. Research indicates that WCF/WBF exhibit pozzolanic activity and positively contribute to nucleation and micro-aggregate filling [8]. Additionally, incorporating recycled plastic fiber (RPF) into mortar/concrete enhances tensile strength through effective bridging with cementitious materials, offering economic and environmental benefits [9]. Moreover, using high-quality recycled manufactured sand, produced by crushing recycled coarse aggregate as a substitute for river sand, shows improved density, lower water absorption, and enhanced properties compared to recycled fine aggregate [10]. The extreme conditions caused by natural climate change also continue to test the performance of concrete, on the other hand proactively preventing the possibility of hot weather surges [11]. Thus, improving concrete's high-temperature resistance and durability has become an essential topic of scientific research. Nanotechnology-based materials manufacturing is playing an increasingly important role in long-term sustainability. The concept of nano concrete has been proposed, where nanomaterials in concrete help to improve the engineering quality of cement-based polymers, especially when creating self-healing and durable concrete [12]. Nanomaterials are active and nanoscale particles filling tiny voids that nucleate and bridge in cementitious materials, accelerating the reaction rate to form a particular C-S-H gel structure [13]. Examination using microscopic electron microscopy SEM revealed that the hydrated nanoparticles' internal material composition and morphology were optimized to form a more dense microstructure [14–16]. Nanomaterials alter the excess interfacial zone of concrete, creating a higher bond between aggregate and paste, increasing compressive and splitting tensile strength and flexural strength, making cementitious materials more rigid and extending their service life [17]. Manufacturing nanoparticles for cementitious materials that meet specific criteria can improve their mechanical properties, durability, and long-term sustainability. Using nano-based concrete structural components requires less maintenance, reduces resource reuse, and increases the planet's environmental protection [18].

NS has a high volcanic ash activity, and the volcanic ash reaction in the cement matrix is adequate, reducing the substantial pore volume and increasing the concrete density. The early strength of the concrete is significantly increased [19]. As the curing time gradually increases, the consumption of NS weakens the volcanic ash reaction, and the effect on the later concrete strength decreases [20]. Wang et al. [21] described an increase in compressive strength of 64.15 % and 18.24 % in the early and late stages of the material, respectively, after incorporating NS. NS can also be combined with nano cellulose fibers, increasing mechanical property enhancement by up to 54 % [22]. An experimental study of NS-modified concrete was conducted, where 3 % was the optimum percentage to replace the cementitious material [23]. Wu et al. [16] explored the effect of NC on cementitious properties and showed that the tensile strength of specimens increased by 25 % at 1.5 % of the weight of cement replaced by NC. The experiments further increased the amount of NC incorporated, and the tensile strength was reduced due to the formation of multistage hydration. Ariyagounder and Veerasamy [24] added composite nano (2 % NS + 2 % NC, 5 % NS + 5 % NC) to benefit the concrete's compressive strength, splitting strength, and flexural strength. Both NS and NC affected the consistency and collapse of the concrete, and incorporation into the cement matrix mix resulted in a reduction in rheological properties. Water-reducing agents and high-speed mixing can be used to adjust the state of compatibility of nano concrete [25]. However the high-temperature resistance of NS and NC-modified concrete was notably superior to that of standard concrete. Particularly, the concrete modified with NC demonstrated greater durability against high-temperature effects compared to the NS samples [26]. According to Alanazi et al. [27] the replacement of 10 % of the silica sand with lightweight aggregate (LWA) led to an increase in the compressive strength from 100 MPa to 110 MPa after exposure to 200 °C; however, the flexural strength decreased from 23.6 MPa to 18.3 MPa. that 2 %NS is effective in mitigating strength loss in concrete containing crumb rubber up to 10 %. According to Adamu[28], the incorporation of 2 % NS into RCC with 10 % CR resulted in strength improvements of 10.3 %, 12.7 %, and 27.4 % at 3 days, 7 days, and 28 days, respectively. The prediction of mechanical properties in modified concrete using rubberized concrete, incorporating Fly Ash and Nano Silica by Artificial Neural Network Technique, demonstrates that the calculated proportional deviation mean (MoD) values for Fc, Fs, Ff, and Ec were − 0.28 %, 0.14 %, 0.87 %, and 1.17 %, respectively, which are close to zero. The resulting ANN model's mean square error (MSE) values and coefficient of determination (R2) are 6.45×10^{-2} and 0.99496, respectively [29]. The concrete modified with NC demonstrated greater durability against high-temperature effects compared to the NS samples.

Due to the highly complex environment in which concrete is used, changes in a single property cannot adequately reflect the external environmental effects of concrete throughout its actual use. The study of the sensitivity to the temperature needs to be extended by the changing influencing variables of nano concrete in a complex environment. Based on the research of many authors [30,31], this project seeks to develop a new composite nano-modified concrete structure by mixing the biased active NS and the low-cost NC in the same proportions. Concrete is exposed to nature and is constantly affected by climate change. The durability of dense nano-concrete, when exposed to elevated temperatures, requires extensive experimental studies and theoretical analysis. The performance of concrete deteriorates gradually due to the effects of high fire temperatures. Concrete's compressive, flexural, and tensile properties are essential indicators of its mechanical properties, which significantly impact its ability to resist cracking and durability. Experiments were carried out to test the mechanical development of NSC concrete of different sizes by controlling the variables of temperature Conclusion. The modifying effect of nano affects the temperature transfer effect of concrete to some extent. The thermal conductivity within the nano has yet to be clarified when encountering fires and areas with significant temperature differences, and the pattern of changes in the more dense NSC concrete will be further investigated in the experiments. The bulk engineering application of nano-concrete is the ultimate aim of the experimental study. The configuration price of nanomaterials is much higher than the market price of concrete required to determine the best ratio of nanomaterials and analyze the economic benefits of nano-concrete. Through research into the market price of raw materials, the thesis illustrates the combined economic cost and benefit of nano concrete.

2. Experiments and methods

2.1. Materials

The experimental work was carried out using bagged ordinary silicate cement (P.O 42.5), the quality of which complies with the technical requirements in the Chinese standard GB 175-2007 (General purpose silicate cement), and the performance results are shown in Table 1. The fine aggregate used in the concrete was ordinary river sand with a yellow appearance, a moisture content of 7.7 %, and a passing rate of 48 % on a 600 μm sieve. The maximum size of coarse aggregate used was 20 mm standard basalt gravel (1.21 % moisture content, specific gravity 2.6 g/cm^3). To control the workability of the concrete, a Poly carboxylic acid liquid water-reducing agent was used to adjust the compatibility (water reduction rate 5 %). The experiment used 20 nm NS produced by Shanghai Yuanjiang Chemical Co., Ltd. and NC produced by Beijing Boyu Hi-Tech New Material Company, with a nanoscale of 15–40 nm, with the physical property results described in Table 2 and the morphology of nano-SiO2 (nanoparticles of silicon dioxide) and nano-CaCO3 (nanoparticles of calcium carbonate) varies in terms of their shapes and structures. Nano-SiO2 exhibits rod-shaped and fibrous structures, while nano-CaCO3 is cubic-shaped, forming particles with six faces that resemble boxes, as depicted in Fig. 1.

2.2. Experimental design

The experimental design uses the DOE (Design of Experiments, British) test method to find the ideal ratio of cement concrete, replacing the same amount of cement with NS and NC to systematically investigate the effect of NS and NC on the modification of concrete properties [32]. At the same time, this proposal illustrates the link between nano-synergy and sustainable growth, compounding nanoparticles to develop new high-performance structures for novel concrete. Considering nanoparticles' strong water absorption properties, many articles were reviewed, and the optimum admixture levels for NS alone ranged from 1.5 % to 3.5 %, and for NC alone ranged from 2.0 % to 4.0 % [33,26,34,35]. The tests set the nanomaterial content at 0 %, 2.5 %, 3.0 %, and 3.5 %, respectively. According to the investigated research background, research significance, and experimental status, the replacement cement with composite nanoparticles was used as an influencing factor to configure the matching ratio to meet the requirements. To investigate different purposes, beam, cube, and cylindrical specimens were prepared experimentally. After curing, the nano concrete's compressive, flexural, and tensile strengths were tested. Changes in extreme temperature environments as part of the simulation process, some specimens were heated at different temperatures to test the change in mechanical strength of nanomaterials with different admixture ratios and thus assess the practicality and durability effects of nano concrete. Through linear analysis of the experimental data, the NSC concrete study concludes new findings on different nanomaterials driving engineering applications.

2.3. Mix proportions

The properties of concrete are primarily influenced by the dispersion of NS and NC elements [36]. Because of their small particle size, NS and NC can quickly form agglomerates and are adsorbent to materials such as cement and aggregates on the surface. Currently, there are two methods of combining NS and NC materials; one method is to mix the nanomaterials directly with cement and then add water and aggregates to form concrete, and the second dissolves the nanomaterials in water and then combines them with cement and aggregates to form concrete [37,38]. The former does not effectively solve the agglomeration problem, and the advantages of high activity and small particle size of NS cannot be fully utilized. The second technique can mitigate some of the harmful effects of nanomaterial agglomeration. The experiments set the mixing ratio of NS and NC at 1:1 to improve the strength of concrete by controlling different amounts of NS and NC. Many authors have used concrete batching processes with different routes to specific design methods and processes [37,39,40]. Two different stirring methods, ultrasonic and nano-magnetic, were compared. The former dispersion effect is better than the latter. In order to avoid damaging the structure of the nano-crystals, this experiment uses the relatively stable performance of the nano-magnetic stirrer dispersion of 5 min of time control. The dosing process started with using a magnetic stirrer to prepare the nano solution by premixing NS and NC with water for stirring. Water-reducing agents are increasingly used in concrete design to modify the flow of concrete effectively. Concerning the properties and uses of the materials, the water-reducing agent was experimentally introduced into the mixed nano solution. The prepared composite solution is put into the

Table 1
Technical indexes and results of cement.

Type	Item	MgO	SO3	Specific surface (m^2/kg)	Initial setting time (min)	Final setting time (min)	7 d compressive strength (MPa)	28 d compressive strength (MPa)
P.O. 42.5	Standard	≤ 5.0	≤ 3.5	≥ 300	≥ 45	≤ 600	≥ 23.0	≥ 42.5
	Inspection	1.55	2.8	371	175	235	28.5	51.2

Table 2
Parameters of nano-SiO2 and nano-CaCO3.

Type	Particle size (nm)	Purity (%)	PH value	Specific surface area (m^2/g)	Specific gravity (g/cm^3)	Crystal form
Nano-SiO2	20	99.9	5.0–6.0	≥ 230	2.2–2.6	Sphere
Nano-CaCO3	15–40	99	8.5–9.5	≥ 28	2.5—2.6	Sphere

Fig. 1. Morphology of nano-SiO2 and nano-CaCO3.

mixer and mixed with the raw materials (fine aggregate, coarse aggregate, and cement).

The target strength of the experimental design was M30, and the mix proportions are shown in Fig. 2. The mass of each material detailed in the concrete mix was determined, as shown in Table 3. The quantity of NS and NC, particle replacement cement, was 5.63 kg, 6.75 kg, and 7.88 kg, respectively.

2.4. Methods and casting

The compressive strength test is an essential indicator for testing the mechanical grade of concrete, and the strength results are indicated as standard cubic specimens passing through the press with dimensions of 150 mm * 150 mm * 150 mm. Cylindrical concrete was prepared to test the splitting tensile properties of concrete, with specimen dimensions of Φ150 * 300. Beam specimens were used to test the results of force values resulting from damage to the nano concrete beams, with dimensions of 100 * 100 * 400. The 172 specimens were formed according to the experimental requirements and accordingly for detecting the nano concrete's water absorption and temperature dissipation capacity, as detailed in Table 4. The 35 days were allowed for the curing of the cast NSC concrete specimens. The 28 days specimens were removed from the water curing box and placed indoors in an ambient temperature site for seven days to allow the water absorbed within the concrete to evaporate naturally. At the end of the water curing cycle, compression, flexural, tensile, and durability tests were carried out to test the mechanical properties of the concrete for temperature variables. Concrete specimens with different nanomaterial contents had to be subjected to complex temperature environments of 200 °C, 400 °C, and 600 °C.

3. Mechanical properties of nano-concrete under different temperatures

3.1. Mechanical properties

The experiments compared the mechanical properties in a high-temperature environment were carried out on samples that had

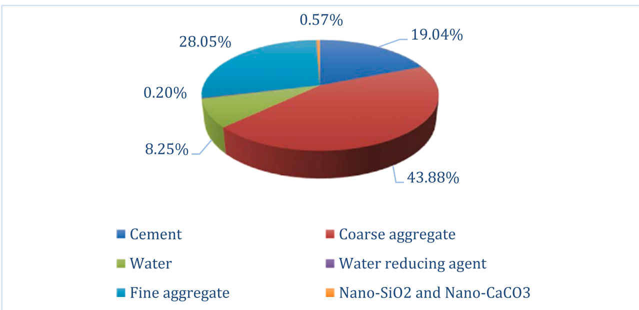

Fig. 2. Material composition of nano concrete mix proportions.

Table 3
Proportions of concrete mixtures.

Type	Cement (kg)	Water (kg)	Fine aggregate (kg)	Course aggregate (kg)	Water reducing agent (kg)	Nano-SiO2 (kg)	Nano-CaCO3 (kg)
Control	450	195	663	1037	4.8	0	0
NSC25	438.75	195	663	1037	4.8	5.63	5.63
NSC30	436.5	195	663	1037	4.8	6.75	6.75
NSC35	434.25	195	663	1037	4.8	7.88	7.88

Table 4
Casting concrete sample information.

Item	Sample size (mm)	Sample quantity	Total sample
Compressive strength test	150 × 150 × 150	60	172
Tensile strength test	Φ150 × 300	48	
Flexural strength test	100 × 100 × 400	48	
Water absorption inspection	150 × 150 × 150	12	
Temperature dissipation capacity detection	100 × 100 × 400	4	

been formed for 35 days. Separate sets of the cube, beam, and cylindrical concrete specimens were selected from the cured specimens and tested for mechanical properties at room temperature (25 °C). The experimental work was carried out to test the compressive strength of concrete by reference to the procedure in BS 1881-116: Testing of Concrete Part 116 (Method of Determination of Compressive Strength of Concrete Cubes). The beam specimens were cracked at the middle third of the span at the cross-sectional level. They were calculated using the concrete bending strength Eq. (1) following ASTM C78: Standard Test Method for Bending Strength of Concrete (Using Simple Beam with Third-Point Loading). The cylindrical specimens are 150 mm × 300 mm in diameter and were tested for splitting strength by ASTM C496/C496M (Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens), so the splitting compressive strength Eq. (2) is used for calculation.

$$R = \frac{PL}{bd^2} \tag{1}$$

Where: R is the modulus of rupture, MPa. P is the maximum load the test machine indicates, N. L is span length, mm. B is the average width of the specimen, mm. D is the average depth of the specimen, mm.

$$R = \frac{PL}{bd^2} \tag{2}$$

Where: T is splitting tensile strength, MPa. P is the Maximum load indicated by the testing machine, N. L is length, mm. D is diameter， mm.

3.2. High-temperature resistance of nano concrete

Three sets of specimens were heated at 200 °C, 400 °C and 600 °C for 2 h in an industrial oven and then cooled to room temperature to record the crack expansion on the concrete surface under different high-temperature environments and to analyze the causes and assess the visual appearance of the deformation of the nanoparticles at different dosing levels. The degree of decay of the residual mechanical properties of the nano concrete after the influence of different high-temperature environments, the experiments were carried out for the compressive strength test, splitting strength test, and flexural strength test, respectively.

4. Durability of nano-concrete

There are differences in the activity of NS and NC particles and their ability to modify concrete differently. Nano-concrete specimens are made to fill tiny internal voids due to their hydration, affecting concrete's microstructure and durability properties [41]. Experiments were carried out to compare the change in water absorption between NSC concrete specimens with different dosing levels and plain concrete. Water absorption tests were carried out using 12 concrete cubes made with three nano-dosage levels, referring to ASTM C 642 (Standard Test Method for Density, Absorption, and Voids in Hardened Concrete). Due to the addition of different dosing levels of nanoparticles, the thermal conductivity of the control concrete, NSC25, NSC30, and NSC35, was further investigated under rapid temperature changes. The four types of beam concrete specimens were heated at a constant temperature of 100 °C for 2 h in a standard oven and exposed to room temperature conditions. The temperature dissipation information was monitored simultaneously until the temperature data did not change within 5 min. By comparing the changes in the different data, the experiments led to new conclusions about the temperature dissipation and insulation capacity between the nano concrete.

5. Results and discussion

Investigating the effects of temperature on nano admixtures in concrete is crucial for assessing their durability, performance, and suitability for various applications. Temperature changes can lead to thermal expansion, contraction, and fire incidents, all of which can impact the behavior and properties of concrete. By studying nano admixtures under different temperature situations, researchers can gain valuable insights into their potential to enhance concrete's resistance to temperature-related challenges, ensuring its reliability in different environments.

5.1. *Visual appearance*

By exposing the NSC concrete to high temperatures of 200 °C, 400 °C, and 600 °C, different color and appearance conditions were visualized. 25–200 °C for 2 h after heating, the color began to glow white, 200–400 °C deepened and gradually turned slightly brown at elevated temperatures from 400 °C to 600 °C. Fig. 3 cube specimens and Fig. 4 beam specimens are more pronounced than others. Fig. 5 shows cylindrical specimens' appearance color changes slowly and is presented as white. After different high-temperature heating, the surface state of the concrete also changed; in Fig. 3 cube visualization appearance at 600 ℃ high temperature, four kinds of concrete specimens have appeared cracks, which control concrete and NSC25 concrete surface appeared ring crack, the former ring crack is more concentrated and more than NSC25 concrete; NSC30 concrete specimens surface did not produce ring crack; irregular line distribution and the number was less than that of the control concrete; while irregular cracks had started to appear on the surface of the specimens of NSC35 at a high temperature of 400 °C. The surface of the specimens at 600 °C was covered with annular cracks and irregular lines, and no breakage in the appearance of the specimens was found. The internal structure of the specimens might be damaged at this time. Fig. 4 shows the visual appearance of the beam concrete after heating; several irregular linear cracks appeared on the surface of the control concrete after 2 h of heating at 600 °C; the number of cracks on the surface of NSC25 concrete became significantly higher after 2 h of heating at 600 °C. The number of cracks in the appearance of NSC30 concrete continued to increase as the doping level was increased to 3.0 %, showing more dense ring and line shapes; as the composite nano dosing continued to be increased to 3.5 %, the appearance of NSC35 specimens spalled directly, and the structure of the specimens was damaged. Fig. 5 (cylindrical) specimens were heated at 200–600 °C for 2 h with no significant change in appearance condition, and no cracks or breakage visible to the naked eye were observed.

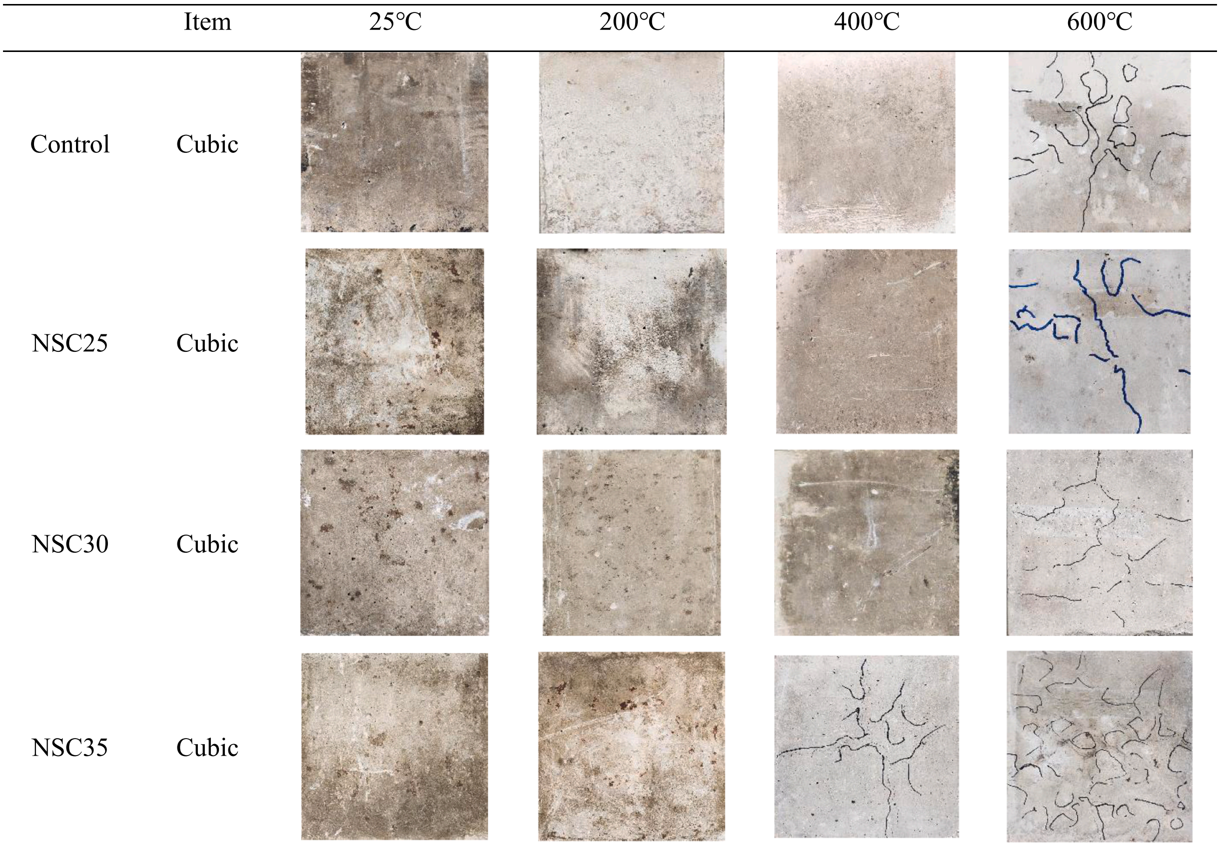

Fig. 3. Visual appearance of cubic specimens at 25–600 °C.

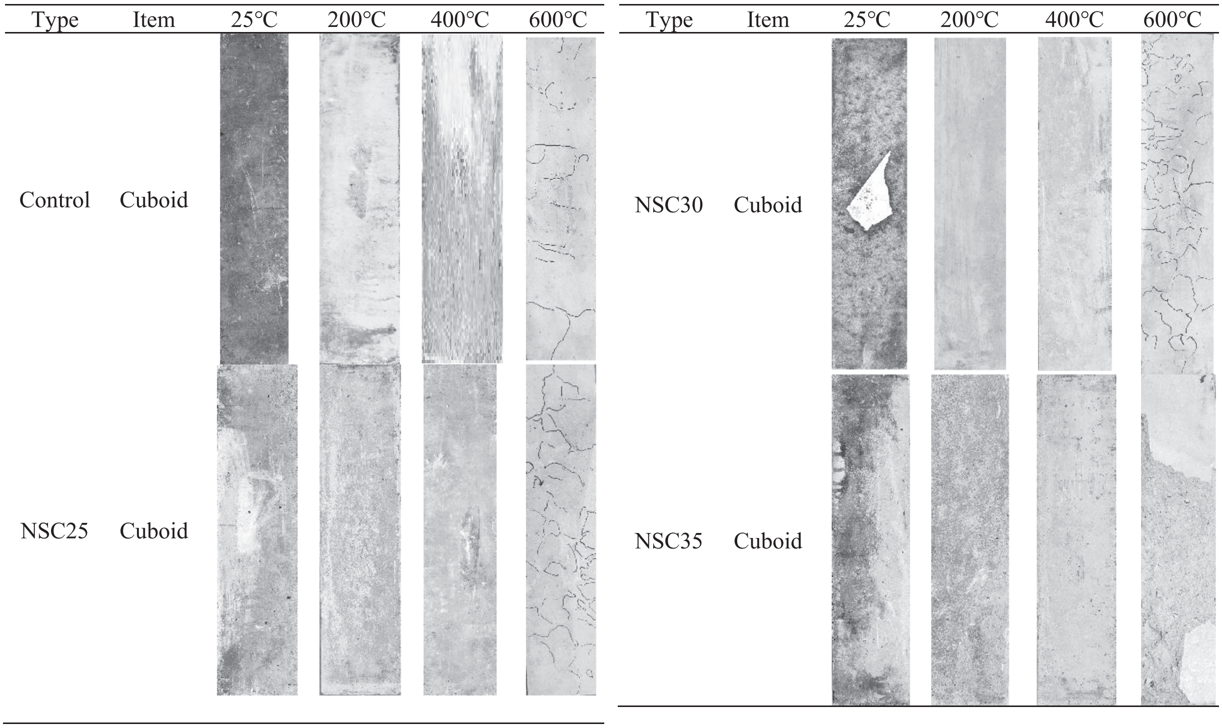

Fig. 4. Visual appearance of cuboid specimens at 25 °C to 600 °C.

5.2. Mechanics performance

5.2.1. Failure model

Fig. 6 shows the cross-sectional condition of control concrete, NSC25 concrete, NSC30 concrete, and NSC35 concrete, respectively, under the influence of different temperature environments, where ① and ② are cylindrical samples after splitting tensile strength tests and the rest are beam samples after bending strength tests. The experimental tests with a maximum nanoparticle admixture of 3.5 % resulted in some of the coarse aggregates being exposed intact on the outside after force loading of the apparatus, marked by red circles in Fig. 6, and some of the NSC concrete cracking directly from the interface transition zone. According to the microstructural studies by the authors [16,41], this is due to the densification of the nano, resulting in the accumulation of smaller particles in the interfacial transition zone, which cannot be fully hydrated and decomposed, resulting in a decrease in mechanical properties. After nano-filling and hydration, the damage state of the section after being mechanically damaged is much smoother and essentially homogeneous, and the performance of NSC25 and NSC30 concrete is sufficiently enhanced. Comparing the damage sections in Fig. 6 (③)–(⑥), the nano-concrete is affected by the high temperature, and the bubbles produced by the heating can be seen gradually. As the temperature increases to 600 °C, the bubble size is more prominent, as is more evident at the interface in (⑥) in Fig. 6.

On the other hand, the concrete of NSC35 has more bubbles than the concrete of NSC25. These may be due to the higher pore pressures generated by heating, which undergo disintegration and consolidation internally. When the concrete structure resists less than these pressures, cracks gradually develop.

5.2.2. Mechanics properties analysis

After the mechanical properties tests of the compressive strength test, splitting strength test, and bending strength test, the experiments yielded the residual mechanical property changes of NSC concrete after the influence of different temperature environments, respectively. The results of the three different nano-doping levels set in the experiments are shown in Table 5, which resulted in 19.91 %, 24.15 %, and 25.37 % increase in compressive strength, flexural strength, and splitting strength, respectively, at room temperature; 37.59 %, 33.66 % and 10.77 % increase in mechanical properties of NSC30 concrete at 200 °C; and 26.04 % and 28.04 % increase in mechanical properties of NSC30 concrete at 400 °C. At 400 °C, the mechanical properties of NSC30 concrete were improved by 26.04 %, 28.57 %, and 10.53 %, respectively; at 600 °C, the mechanical properties of NSC30 concrete were improved by 19.15 %, 45.69 %, and 1.22 % respectively. As seen in the table below, NSC25, NSC30, and NSC35 all exhibited enhancement effects, and the mix of composite NS and NC improved the mechanical properties of the concrete, with the high-temperature conditions demonstrating the same pattern of change as the ambient environment. The optimum admixture of composite NS and NC was 3 % of the replacement cement quantity, and the mechanical properties of NSC35 at 400 °C and 600 °C were lower than those of the control concrete at the same temperature by 9.31 % and 10.57 %, respectively, due to the excessive admixture of nanomaterials. The advantages of the composite nano-NSC-modified concrete gradually decreased with increasing temperature, with similar trends in

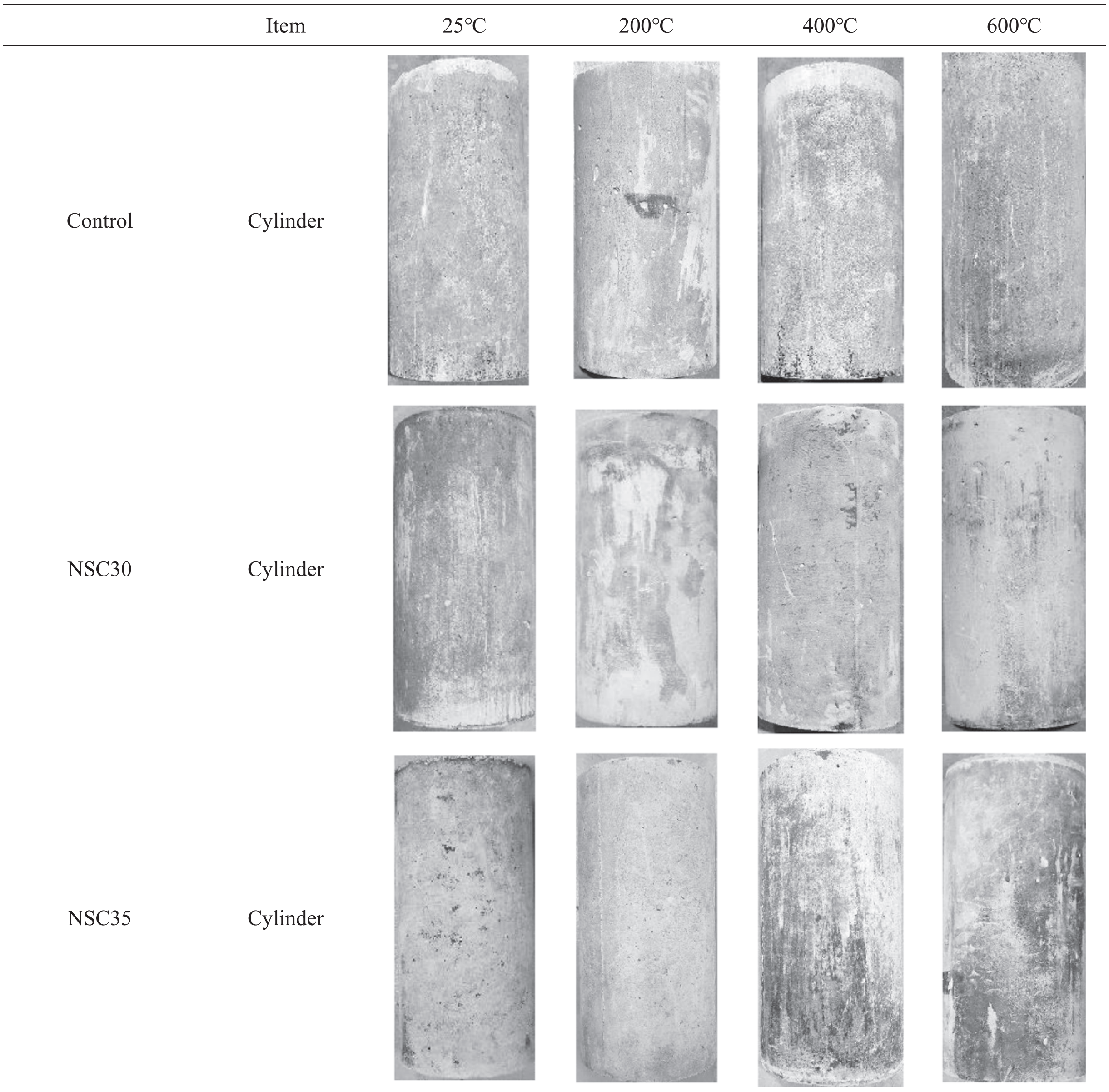

Fig. 5. Visual appearance of cylindrical specimens at 25–600 °C.

compressive strength, flexural strength, and splitting strength.

The variation of the high-temperature environment from 25 to 600 °C severely affected the mechanical properties of the concrete, showing a certain regularity, with the trend shown in Fig. 7. The regularity of the concrete compressive strength data is even more apparent, as seen in (a) in Fig. 7, where the highest compressive strength values were found for the composite NSC with 3.0 % admixture at the same temperature environment and then began to decrease. Increasing the temperature environment of the concrete from the ambient environment of 25 °C, heated to 200 °C, 400 °C and 600 °C respectively, the temperature stresses in the four groups of concrete became more significant, and the compressive strength results gradually decreased, as shown in (b) in Fig. 7. The splitting test results differ from the compressive ones in that temperature had a lower degree of influence on the splitting strength of the control concrete, and the data was more concentrated, as shown in (c) in Fig 7. Between 200 °C and 400 °C, the data overlap, with the splitting strength of NSC35 dropping sharply after heating at 400 °C, below the other three concrete specimens and almost flush with the strength fold at 600 °C, with the change shown in Fig. 7(c). The specimens in Fig. 6 were not damaged in appearance by comparison, probably due to the effect of temperature heating on the internal organization of the specimens. After 600 °C, the control concrete, NSC25 concrete, and NSC30 splitting strength fold lines fitted closer together, indicating that the temperature had a more significant effect on the cylindrical added composite nanomaterial specimens, reducing the mechanical property advantage, at which point the

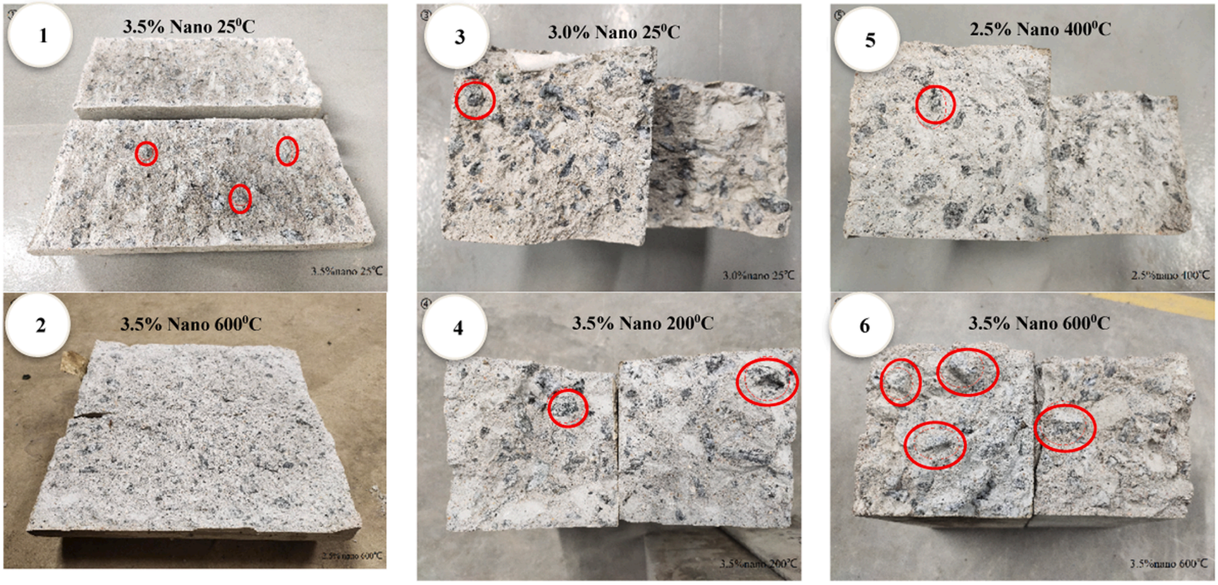

Fig. 6. Failure cross sections after experimental test at different temperatures.

Table 5
Mechanical properties of nano-concrete in different experiments.

Type	Temperature (°C)	Nanomaterial dosage (%)	Compressive strength (Mpa)	Change (%)	Splitting strength (Mpa)	Change (%)	Flexural strength (Mpa)	Change (%)
Control	25	0	34.70	0	2.72	0	5.30	0
NSC25	25	2.5	39.02	12.45	3.33	22.43	6.51	22.83
NSC30	25	3.0	41.61	19.91	3.41	25.37	6.58	24.15
NSC35	25	3.5	40.18	15.79	3.26	19.85	6.43	21.32
Control	200	0	29.76	0	2.60	0	4.10	0
NSC25	200	2.5	34.34	15.39	2.71	4.23	4.72	15.12
NSC30	200	3.0	37.59	26.31	2.88	10.77	5.48	33.66
NSC35	200	3.5	35.80	20.30	2.78	6.92	5.37	30.98
Control	400	0	27.57	0	2.47	0	3.78	0
NSC25	400	2.5	29.69	7.69	2.62	6.07	3.94	4.23
NSC30	400	3.0	34.75	26.04	2.73	10.53	4.86	28.57
NSC35	400	3.5	32.51	17.92	2.24	-9.31	3.82	1.06
Control	600	0	26.01	0	2.46	0	3.13	0
NSC25	600	2.5	27.53	5.84	2.48	0.81	3.50	11.82
NSC30	600	3.0	30.99	19.15	2.49	**1.22**	4.56	**45.69**
NSC35	600	3.5	27.45	5.54	2.20	-10.57	3.38	7.99

splitting strength of NSC30 concrete was still higher than that of the control concrete and NSC25 concrete, as shown in Fig. 7(d). the bending of NSC35 strength also lost more at 400 °C, lower than the strength of the NSC25 concrete specimens in the same temperature environment but higher than the control concrete, as shown in Fig. 7(e–f). The narrower beam (10 * 10 * 400) specimens used for the bending experiments resulted in a high degree of heat per unit, causing damage to the appearance of the highly doped nanomaterial specimens (Fig. 4) and a significant reduction in mechanical properties. Notably, the concrete specimens with NSC30 exhibited superior modification at 400 °C and 600 °C high temperatures and possessed higher heat resistance than standard concrete.

5.3. Durability

The paper further investigates the effect of composite nanoparticles on the durability of concrete using changes in the water absorption and temperature dissipation capacity of concrete. The water absorption of plain concrete was measured to be 3.2 %, and with increasing amounts of nanoparticles, the water absorption results decreased continuously to 2.87 %, 2.59 %, and 2.39 %, respectively, as shown in Fig. 8. The experiments confirmed that replacing the cement with the composite nanoparticles increased the compactness of the concrete, which also responded to a decrease in the permeability of the NSC concrete, reflecting the conclusion of a change between nanoparticles and density. Within a specific range, increasing the admixture of nanoparticles resulted in a relative increase in the density of NSC concrete and a decrease in the water absorption properties of the concrete.

The relative thermal insulation effect of nano concrete was confirmed by detecting the temperature dissipation rate and heat

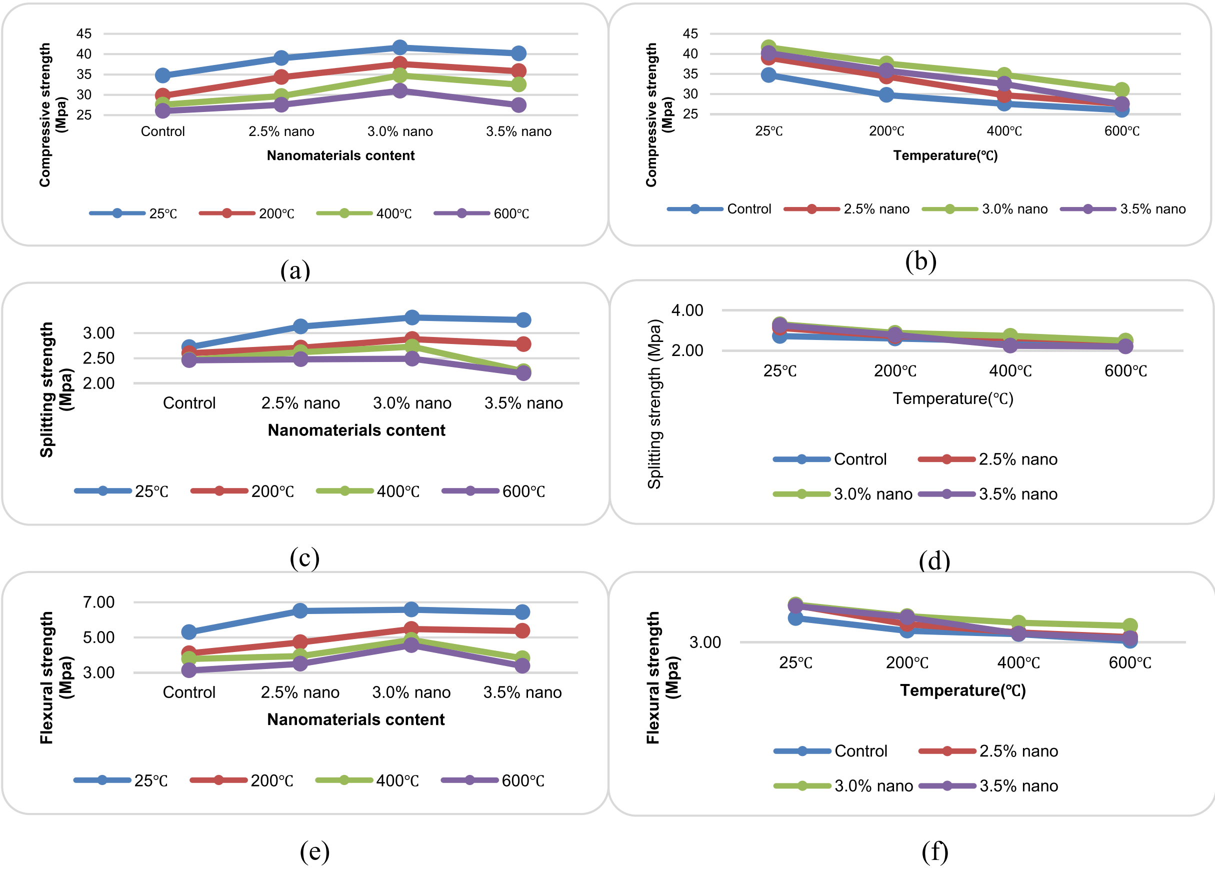

Fig. 7. (a–f) Changes in mechanical properties between different nano concrete specimens and different temperatures.

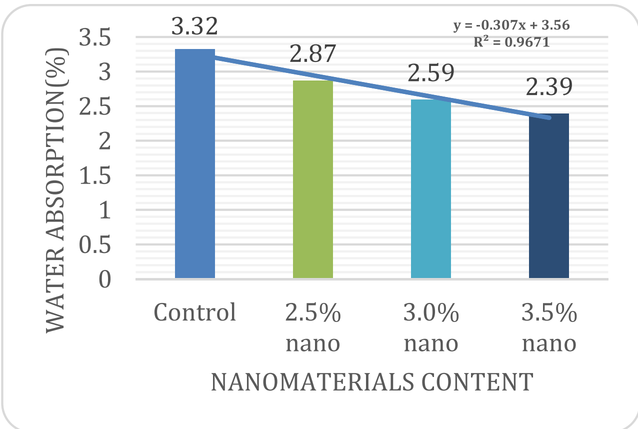

Fig. 8. Water absorption test.

storage level of NSC concrete at different dosing levels, with the dissipation rate comparable to that of standard concrete. The relative temperature of the specimens with 3.5 % composite nanoparticles was significantly higher than that of the control concrete at the same time until the end of the 200-min experiment. The relative temperature of the specimens with 3.0 % composite nanoparticles was higher than that of the control concrete for the first 20 min. Then essentially the same as the control concrete (subject to an accelerated reduction in outside air temperature during the rain) and the relative temperature of the specimens with 2.5 % composite nanoparticles was higher than that of the control concrete for 130 min and then essentially the exact, Fig. 9 illustrates the curve of temperature dissipation capacity.

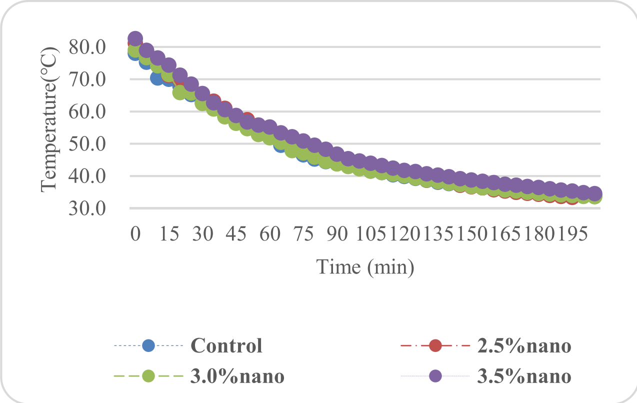

Fig. 9. Temperature dissipation capability.

5.4. Costs and revenues

In summary of Section 2.1, two nanomaterials (NS and NC) were used for the experiments. The raw materials were fine aggregate, coarse aggregate, cement, and water-reducing agent. Table 6 shows the cost of the combined concrete materials according to the proportion of M30 concrete. Comparing the price deviation between conventional concrete and NSC concrete per 1 m^3 of consumption, the cost of conventional concrete is 251.75MYR, and the cost of NSC concrete is 261.102MYR. Based on the table of the cost of concrete combination materials, 1 m^3 of NSC concrete uses 6.45 kg more of industrial NS and industrial NC, respectively, which increases the price by 13.5. On the other hand, the optimum dosage for the experimental study was 3 % of the replacement cement, effectively reducing the cement used by 13.5 kg. The economic increase of 9.32175 MYR per 1 m^3 of NSC concrete resulted in a 19.91–25.37 % improvement in the mechanical properties of the concrete at 25 °C for ambient environments and 1.5 % for different high-temperature environments (200–600 °C) the mechanical properties are improved by 1.22–45.69 %, as elaborated in Table 7.

6. Conclusions and recommendations

The paper investigates a new type of high-temperature resistant NSC concrete, using cubic, beam, and cylindrical concrete specimens to analyze and compare the residual mechanical properties and visualize the decaying deformation of the appearance of the nano concrete when exposed to different extremes of high-temperature, performing water absorption experiments, thermal insulation detection, economic cost, and benefits evaluation respectively.

- The appearance of the NSC concrete gradually changed to white through the change in external temperature from 25 °C to 400 °C, with a slight brown color at 600 °C. At 600 °C, the cube and beam specimens cracked or broke, while the cylinders did not change significantly.
- The optimum dosage of NS and NC composite nanoparticles is 3.0 %, both at the ambient temperature of 25 °C and different high temperatures, resulting in the most significant improvement in the mechanical properties of concrete. The compressive properties of the concrete were increased by 19.91 %, the splitting properties by 24.15 %, and the flexural properties by 25.37 % at ambient temperatures. 1.22–45.69 % at high temperatures between 200 °C and 600 °C compared to standard concrete at the same temperature.
- Composite nano concrete (NSC concrete) has a lower water absorption capacity and reflects a higher degree of compactness than conventional concrete. The temperature dissipation capacity of composite nano-concrete is comparable to that of conventional concrete, and some insulation properties exist.
- The cost and benefit analysis shows that NS is more expensive compared with other concrete, and the addition of NC effectively reduces the unit cost of concrete, replacing an equivalent amount of cement with NSC at an additional cost of only 9.32175 MYR per cubic meter, resulting in a new type of concrete with excellent mechanical properties and durability.

Table 6
Cost of concrete combined materials.

Item	Industrial nano-SiO2	Industrial nano-CaCO3	Cement	Water	F. Ag.	C. Ag.	W. R. Ag.	Cost (RM)
kg/1 m^3	0/6.75	0/6.75	450/436.5	195	663	1037	4.8	-
Unit price	2 RM/kg	0.061 RM/kg	0.34 RM/kg	0.57 RM/T	37 RM/T	34 RM/T	8.1 RM/L	-
Standard concrete (RM/m^3)	0	0	153	0.111	24.531	35.258	38.88	251.78
NSC concrete (RM/m^3)	13.5/RM	0.41175	148.41	0.111	24.531	35.258	38.88	261.102

Table 7
Benefits of NSC concrete.

Item	Industrial nano-SiO2	Industrial nano-CaCO3	Cement	Deviation (RM)	Performance increase (%)
Material change kg/1 m^3	+ 6.75	+ 6.75	-13.5	-	-
Cost change RM/1 m^3	+ 13.5	+ 0.41175	-4.59	+ 9.32175	19.91–25.37 (25 ℃), **1.22–45.69** (200–600 ℃)

※Regular concrete material prices refer to the Malaysian construction market and website display information, nanomaterial prices are provided from Chinese suppliers, and quotations include regular sea freight.

- The experiments confirm that NSC concrete exhibits outstanding mechanical properties, durability, and certain insulation properties. However, the specific durability properties of the concrete after exposure to various temperature environments remain unknown. Extensive experimental studies are required to thoroughly investigate and draw appropriate conclusions regarding the effects of different temperature conditions on the durability of NSC concrete.

CRediT authorship contribution statement

DS and LW conceived the presented idea, LW developed the theory, to the analysis of the result, and took the lead in writing the manuscript. DS, ZAM, BS, and MH were involved in planning and supervising the work. DS, and LW conceived the original ideas. All authors discussed the results and commented on the manuscript.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Zubair Ahmed Memon reports financial support was provided by College of Engineering, Prince Sultan University, Riyadh. Zubair Ahmed Memon and Basel Sultan reports a relationship with College of Engineering, Prince Sultan University, Riyadh that includes. NA has patent NA pending to NA. NA.

Data Availability

All the data used in this article are original and have been generated by the authors through our work. The experiments conducted in the laboratory were carried out in a proper manner.

Acknowledgments

The authors would like to acknowledge the support of Prince Sultan University (PSU) Riyadh Saudi Arabia for paying the Article Processing Charges (APC) of this publication and thanks to Prince Sultan University for their support. Also, Centre of Excellence for Research, Value, Innovation and Entrepreneurship (CERVIE) UCSI University, Malaysia for providing the facilities of the research (REIG-FETBE-2022/052).

References

[1] S. Weiland, T. Hickmann, M. Lederer, J. Marquardt, S. Schwindenhammer, The 2030 agenda for sustainable development: transformative change through the sustainable development goals? Polit. Gov. 9 (1) (2021) 90–95, https://doi.org/10.17645/PAG.V9I1.4191.
[2] T.A. Tsalis, K.E. Malamateniou, D. Koulouriotis, I.E. Nikolaou, New challenges for corporate sustainability reporting: United Nations' 2030 Agenda for sustainable development and the sustainable development goals, Corp. Soc. Responsib. Environ. Manag. 27 (4) (2020) 1617–1629, https://doi.org/10.1002/csr.1910.
[3] G. Habert, et al., Environmental impacts and decarbonization strategies in the cement and concrete industries, Nat. Rev. Earth Environ. 1 (11) (2020) 559–573, https://doi.org/10.1038/s43017-020-0093-3.
[4] J. Nie, J. Wang, S. Gou, Y. Zhu, J. Fan, Technological development and engineering applications of novel steel-concrete composite structures, Front. Struct. Civ. Eng. 13 (1) (2019) 1–14, https://doi.org/10.1007/s11709-019-0514-x.
[5] M. Zhou, W. Lu, J. Song, G.C. Lee, Application of Ultra-High Performance Concrete in bridge engineering, Constr. Build. Mater. 186 (2018) 1256–1267, https://doi.org/10.1016/j.conbuildmat.2018.08.036.
[6] L. Assi, K. Carter, E. (Eddie) Deaver, R. Anay, P. Ziehl, Sustainable concrete: building a greener future, J. Clean. Prod. 198 (2018) 1641–1651, https://doi.org/10.1016/j.jclepro.2018.07.123.
[7] D. Anupama Krishna, R.S. Priyadarsini, S. Narayanan, Effect of elevated temperatures on the mechanical properties of concrete, Procedia Struct. Integr. 14 (2019) 384–394, https://doi.org/10.1016/j.prostr.2019.05.047.
[8] Huixia Wu, Ruihan Hi, Dingyi Yang, Zhiming Ma, Micro-macro characterizations of mortar containing construction waste fines as replacement of cement and sand: a comparative study, Constr. Build. Mater. 383 (2023), https://doi.org/10.1016/j.conbuildmat.2023.131328.
[9] Zhenhua Duan, Qi Deng, Chaofeng Liang, Zhiming Ma, Huixia Wu, Upcycling of recycled plastic fiber for sustainable cementitious composites: a critical review and new perspective, Cem. Concr. Compos. 142 (2023), https://doi.org/10.1016/j.cemconcomp.2023.105192.
[10] Zhiming Ma, Jiaxin Shen, Changqing Wang, Huixia Wu, Characterization of sustainable mortar containing high-quality recycled manufactured sand crushed from recycled coarse aggregate, Cem. Concr. Compos. 132 (2023), 0.1016/j.cemconcomp.2022.104629.
[11] S. Kaewunruen, L. Wu, K. Goto, Y.M. Najih, Vulnerability of structural concrete to extreme climate variances, Climate 6 (2) (2018) 1–13, https://doi.org/10.3390/cli6020040.

[12] G.F. Huseien, K.W. Shah, A.R.M. Sam, Sustainability of nanomaterials based self-healing concrete: an all-inclusive insight, J. Build. Eng. 23 (January) (2019) 155–171, https://doi.org/10.1016/j.jobe.2019.01.032.
[13] D. Prasad, S. Singla, R. Garg, Microstructural and strength parameters of nano-SiO2 based cement composites, Mater. Today Proc. 46 (5) (2021) 6743–6747, https://doi.org/10.1016/j.matpr.2021.04.276.
[14] C. Luan, et al., Effects of nano-SiO2, nano-CaCO3 and nano-TiO2 on properties and microstructure of the high content calcium silicate phase cement (HCSC) Congqi, Constr. Build. Mater. 314 PA (125377) (2022) 1–13, https://doi.org/10.1016/j.conbuildmat.2021.125377.
[15] C.D. Atis, Influence of nano SiO2 and nano CaCO3 particles on strength, workability, and microstructural properties of fly ash-based geopolymer, Struct. Concr. 454 (012016) (2020) 1–16, https://doi.org/10.1002/suco.201900479.
[16] Z. Wu, K.H. Khayat, C. Shi, B.F. Tutikian, Q. Chen, Mechanisms underlying the strength enhancement of UHPC modified with nano-SiO2 and nano-CaCO3, Cem. Concr. Compos. 119 (103992) (2021) 1–14, https://doi.org/10.1016/j.cemconcomp.2021.103992.
[17] Z. Zhao, et al., A review on the properties, reinforcing effects, and commercialization of nanomaterials for cement-based materials, Nanotechnol. Rev. 9 (1) (2020) 349–368, https://doi.org/10.1515/ntrev-2020-0023.
[18] K.P. Bautista-Gutierrez, A.L. Herrera-May, J.M. Santamaría-López, A. Honorato-Moreno, S.A. Zamora-Castro, Recent progress in nanomaterials for modern concrete infrastructure: advantages and challenges, Materials 12 (21) (2019) 1–41, https://doi.org/10.3390/ma12213548.
[19] H. Liu, Y. Yu, H. Liu, J. Jin, S. Liu, Hybrid effects of nano-silica and graphene oxide on mechanical properties and hydration products of oil well cement, Constr. Build. Mater. 191 (2018) 311–319, https://doi.org/10.1016/j.conbuildmat.2018.10.029.
[20] C. Zhuang, Y. Chen, The effect of nano-SiO2 on concrete properties: a review, Nanotechnol. Rev. 8 (1) (2019) 562–572, https://doi.org/10.1515/ntrev-2019-0050.
[21] J. Wang, P. Du, Z. Zhou, D. Xu, N. Xie, X. Cheng, Effect of nano-silica on hydration, microstructure of alkali-activated slag, Constr. Build. Mater. 220 (2019) 110–118, https://doi.org/10.1016/j.conbuildmat.2019.05.158.
[22] M.S. El-Feky, P. Youssef, A.M. El-Tair, S. Ibrahim, M. Serag, Effect of nano silica addition on enhancing the performance of cement composites reinforced with nano cellulose fibers, AIMS Mater. Sci. 6 (6) (2019) 864–883, https://doi.org/10.3934/matersci.2019.6.864.
[23] T.A. Tawfik, M.A. Abd EL-Aziz, S. Abd El-Aleem, A. Serag Faried, Influence of nanoparticles on mechanical and nondestructive properties of high-performance concrete, J. Chin. Adv. Mater. Soc. 6 (4) (2018) 409–433, https://doi.org/10.1080/22243682.2018.1489303.
[24] J. Ariyagounder, S. Veerasamy, Experimental investigation on the strength, durability and corrosion properties of concrete by partial replacement of cement with nano-SiO2, nano-CaCO3 and nano-Ca(OH)2, Iran. J. Sci. Technol. - Trans. Civ. Eng. 46 (1) (2022) 201–222, https://doi.org/10.1007/s40996-021-00584-0.
[25] T. Yunchao, C. Zheng, F. Wanhui, N. Yumei, L. Cong, C. Jieming, Combined effects of nano-silica and silica fume on the mechanical behavior of recycled aggregate concrete, Nanotechnol. Rev. 10 (1) (2021) 819–838, https://doi.org/10.1515/ntrev-2021-0058.
[26] S. S, N.I.M.Y, Deprizon Syamsunur, Li Wei, Zubair Ahmed Memon, Concrete performance attenuation of mix nano-SiO2 and nano-CaCO3 under high temperature: a comprehensive review, Materials 15 (7073) (2022) 1–27, https://doi.org/10.3390/ma15207073.
[27] Hani Alanazi, et al., Mechanical and microstructural properties of ultra-high-performance concrete with lightweight aggregates, Buildings 12 (11) (2022) 1–13, https://doi.org/10.3390/buildings12111783.
[28] M. Adamu, S.I. Haruna, Y.E. Ibrahim, H. Alanazi, Investigating the properties of roller-compacted rubberized concrete modified with nanosilica using response surface methodology, Innov. Infrastruct. Solut. 7 (1) (2022), https://doi.org/10.1007/s41062-021-00717-4.
[29] M. Adamu, A.B. Çolak, Y.E. Ibrahim, S.I. Haruna, M.F. Hamza, Prediction of mechanical properties of rubberized concrete incorporating fly ash and nano silica by artificial neural network technique, Axioms 12 (1) (2023) 81, https://doi.org/10.3390/axioms12010081.
[30] G. Asadollahfardi, A. Katebi, P. Taherian, A. Panahandeh, Environmental life cycle assessment of concrete with different mixed designs, Int. J. Constr. Manag. 21 (7) (2021) 665–676, https://doi.org/10.1080/15623599.2019.1579015.
[31] R. Jayaseelan, Investigation on the performance characteristics of concrete incorporating nanoparticles, Jordan J. Civ. Eng. 13 (2) (2019) 351–360.
[32] S.Y.N. Chan, M.K.C. Tsang, J.K.W. Chan, A systematic mix design method for high strength concrete, HKIE Trans. Hong. Kong Inst. Eng. 3 (2) (1996) 1–6, https://doi.org/10.1080/1023697X.1996.10667697.
[33] A. Al Ghabban, B. Al Zubaidi, M. Jafar, Z. Fakhri, Effect of nano SiO2 and nano CaCO3 on the mechanical properties, durability and flowability of concrete, IOP Conf. Ser. Mater. Sci. Eng. Pap. 454 (012016) (2018) 1–11, https://doi.org/10.1088/1757-899X/454/1/012016.
[34] A. Zhang, W. Yang, Y. Ge, Y. Du, P. Liu, Effects of nano-SiO2 and nano-Al2O3 on mechanical and durability properties of cement-based materials: a comparative study, J. Build. Eng. 34 (101936) (2021) 1–61, https://doi.org/10.1016/j.jobe.2020.101936.
[35] R. Sakthivel, N. Balasundaram, Experimental investigation on behaviour of nano concrete, Int. J. Civ. Eng. Technol. 7 (2) (2016) 315–320.
[36] P. Feng, H. Chang, X. Liu, S. Ye, X. Shu, Q. Ran, The significance of dispersion of nano-SiO2 on early age hydration of cement pastes, Mater. Des. 186 (108320) (2020), https://doi.org/10.1016/j.matdes.2019.108320.
[37] Z. Xu, et al., Research progress on key problems of nanomaterials-modified geopolymer concrete, Nanotechnol. Rev. 10 (1) (2021) 779–792, https://doi.org/10.1515/ntrev-2021-0056.
[38] P. Brzozowski, J. Strzałkowski, P. Rychtowski, R. Wróbel, B. Tryba, E. Horszczaruk, Effect of nano-SiO2 on the microstructure and mechanical properties of concrete under high temperature conditions, Materials 15 (166) (2022) 1–19, https://doi.org/10.3390/ma15010166.
[39] W. Meng, K.H. Khayat, Effect of graphite nanoplatelets and carbon nanofibers on rheology, hydration, shrinkage, mechanical properties, and microstructure of UHPC, Cem. Concr. Res. 105 (May 2017) (2018) 64–71, https://doi.org/10.1016/j.cemconres.2018.01.001.
[40] L.A. Sbia, A. Peyvandi, P. Soroushian, A.M. Balachandra, Optimization of ultra-high-performance concrete with nano-and micro-scale reinforcement, Cogent Eng. 1 (1) (2014) 1–11, https://doi.org/10.1080/23311916.2014.990673.
[41] L. Nie, X. Li, J. Li, B. Zhu, Q. Lin, Analysis of high performance concrete mixed with nano-silica in front of sulfate attack, Materials 15 (21) (2022) 7614, https://doi.org/10.3390/ma15217614.