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COMPOSITE NANOPARTICLE CONCRETE BASE ON FIRE AND EXTREME HIGH-TEMPERATURE ENVIRONMENT

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ABSTRACT

The critical position of concrete plays a decisive role in engineering applications where extreme high-temperature environments severely affect the durability and life cycle of concrete structures. Experiments were conducted to mimic fire and extreme high-temperature environments, using different activities of nano calcium carbonate (NC) and nano silica (NS) to replace cement mixed concrete at 2.5%, 3.0% and 3.5% respectively, and a series of data analysis of nano concrete to derive patterns of performance change and drive new momentum for progress in the concrete industry. Experimental studies were conducted to explore the decaying changes in the mechanical properties of nano concrete after the concrete modified with composite nanomaterials was heated at different temperature environments of 25°C, 200°C, 400°C and 600°C. The results showed that the mechanical compressive strength of the nano concrete increased by 17.05%, 21.81% and 23.00% at 7 days respectively compared to the control concrete, and the nano 3.0% admixture showed excellent mechanical properties in the range of 25°C to 600°C. The results show that the strength checks of the nano-concrete cube and cuboid specimens after heating through different high-temperature environments were similar in rebound tests and no significant differences were found.

***Keywords*:** Composite nanoparticles, nano-concrete, extreme high-temperature environments, high-temperature resistance, climate change

1. INTRODUCTION

As climate change continues to intensify, anomalies such as the melting of Greenland's glaciers and flooding in the Taklamakan Desert in the Xinjiang region of China are occurring. A severe drought in central China in July-August 2022 endangers food security. Global warming and extreme weather are back on the public's radar, deepening mankind's respect for nature. With the rapid development of infrastructure, the use of concrete has increased and caused waste of industrial resources at the same time [1]. The turnover of old and new buildings and the frequent effects of natural disasters can be key constraints. Green and sustainable concrete is the new development goal and the use of cleaner materials will reduce CO2 emissions effectively [2], [3]. The use of waste instead

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of natural resources meets the requirements of material decomposition and consumption, such as using fibres in concrete [4]. Contemporary constructions require higher performance and better durability in extreme environmental changes. Nanomaterials act as a bridge between nanotechnology and concrete, and the use of nanomaterials instead of cement introduces the concept of sustainability into the mix. In addition to this, nanomaterials have optical properties and levels of resistance to ageing that are widely used and developed in many fields such as medicine and industry [5], [6]. Currently, nano-SiO2, nano-TiO2, nano-CaCO3 and nano-Al2O3 are the most popular products on the market, with nano-SiO2 and nano-CaCO3 being relatively inexpensive. Based on the use of industrial concrete, many valuable conclusions have been drawn by more researchers [7]. NS has a high activity and produces hydration reactions with the cementitious materials inside the concrete, reducing the void ratio inside the concrete. NC is less active and the fine nano-particles fill the voids in the internal microstructure. Small amounts of NC also produce hydration reactions and the inert nature contributes to durability. NS and NC can contribute to the mechanical and durability properties of concrete [8]–[10]

Nanomaterial-modified concrete is mainly due to smaller nanoparticles and internal hydration and covers a wide range of hydraulic engineering, bridge engineering and construction work. Concrete structures mixed with nanoparticles have a high degree of compactness, improve water permeability and maintain high performance in extreme cold weather [11], [12]. The average depth of wear of the concrete decreases with an increasing admixture of nanoparticles [13]. A series of experiments confirmed that concrete mixed with NS has a self-healing function and a good protection function for the concrete structure. Certain content of nanomaterials has a great improvement on the mechanical properties of concrete [14], [15]. The incorporation of 3.5% NS can increase the splitting strength of concrete by 253% [16]. The increase in 28-day compressive strength of concrete with 5% nano-clay, composite (1% NS + 4% nano-clay) and 2% NS replacement cement was 17.1%, 15% and 11% respectively compared to normal concrete [17]. Temperature is an important factor affecting the performance of concrete, and composite nano concrete undergoes extreme high-temperature environments where the dense concrete has a reduced ability to dissipate temperature and may be exposed to higher void pressures, and elevated temperatures put the concrete at risk of cracking and damaging the structure of the concrete in severe states [18], [19]. In this paper, experiments are carried out to investigate the high-temperature resistance of composite nano concrete based on fire and extreme high-temperature environments under complex factors.

2. MATERIAL AND METHOD

2.1 Raw Materials

The experiments were carried out using NS produced by Shanghai Yuanjiang Chemical Co., Ltd. with a particle size of 20 nm and a content purity of 99%. The physical properties of NS are shown in Table 1 below.

Table 1. Physical properties of NS

Item	Particle Size(nm)	PH value	Specific surface	Volume density(g/cm^3)	Density(g/cm^3)	Crystal form	Colour

			area (m^2/g)				
SiO_2	20	5-6	230	0.06	2.2-2.6	Sphere	White

NC was purchased from Beijing Boyu Hi-Tech New Material Company, with a particle size of 15-40 nm, a purity content of 99.9% and a white spherical crystal type. The technical parameters of NC are shown in Table 2 below.

Table 2. Characteristics of NC

Item	Average particle size(nm)	Whiteness (%)	PH value	Specific gravity(g/cm3)	Specific surface area(m^2/g)	Al_2O_3 $+Fe_2O_3$(%)
Parameter	15-40	≥95	8.5—9.5	2.5—2.6	≥28	≤0.1

Magnetic stirrer for dispersion of nanomaterials. The maximum dispersion power of the apparatus is 2000 RPM, which is sufficient for the use of a measuring range of 1000 ML beaker to disperse the liquid, and the experiment was carried out in several successive dispersions to prepare the nanomaterials solution. The nanoparticles were dispersed while the temperature of the solution was heated to 30°C. The appearance as well as the mode of dispersion is shown in Figure 1.

Figure 1. Magnetic stirrer with nano-dispersion

Ordinary Portland cement of grade M42.5 was used for the experiments. The fine and coarse aggregates were purchased from the Malaysian building materials market and their technical specifications met the experimental requirements. The water-reducing agent used in the experiment was the Q-SET brand and the actual test yielded a water reduction rate of approximately 5%.

2.2 Mixing and molding

This experiment was carried out using a DOE concrete mix design with a target strength of 30 Mpa. The preliminary mix design was based on the characteristics of the materials and technical parameters. After mixing the materials, the collapse of the concrete was tested and the mechanical strength of the concrete specimens formed with different water-cement ratios was examined. According to the experimental design, the concrete mix ratio was carried out with reference to Table 3 below.

Table 3. Mix proportion of concrete

Type	Cement	Water	Fine aggregate	Course aggregate	Water reducing agent	Nano-SiO_2	Nano-$CaCO_3$
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

※Control is plain concrete without nanomaterials, NSC25, NSC30 and NSC35 are composite nano dosages of 2.5%, 3.0% and 3.5% instead of cement respectively.

The dispersion process of the nanomaterials has a great influence on the performance of the concrete, as very small nanoparticles tend to agglomerate and adhere to the surface of the cement and aggregates. Considering the experimental choice of composite nanomaterials, NS and NC with different activities were pre-mixed with an aqueous solution in the ratio of 1:1, and the dispersion amount was carried out in the order of 30%, 30% and 40%, and the water reducing agent liquid was added successively until 1/2 time, and the prepared nano solution was mixed with fine aggregate, cement and coarse aggregate respectively. The dispersion mode is shown in Figure 1 and the nanoparticle dispersion process is shown in Figure 2

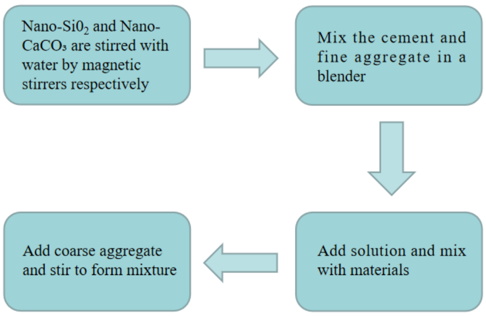


Figure 2. Composite nano concrete material mixing sequence

In this concrete experiment, 60 cube specimens and 48 cuboid concrete specimens were formed and cured for 7 days and 28 days respectively to test the mechanical properties and the change in rebound strength decay under different high-temperature environments.

Figure 3. Formed composite nano concrete specimens

3. MECHANICAL PERFORMANCE TESTING

NS has high activity and provides silica precursors, and scholars believe that early and late compressive strengths are increased by 64.15% and 18.24% respectively, with early compressive strength having a greater effect than late modification [20]. The incorporation of NS into concrete can effectively improve the mechanical compressive strength, flexural strength and splitting strength of concrete [21]. NC particles containing 1.0 ~ 2.0% admixture were able to improve the microstructure of the geopolymer and images examined using SEM showed that NC particles at 2.0% and 3.0% admixture were denser than the control samples, with a significant reduction in voids and microcracks, improving impact resistance and mechanical properties [22]. The experiments were carried out by testing the 7 days and 35 days of compressive strength experiments of the concrete and concluded that the mechanical properties changed differently.

3.1 Initial mechanical properties

The concrete specimens were placed on a compressive strength testing machine for an initial period of 7 days to test the mechanical properties of the different nanomaterial admixtures and to record and analyse the data. Figure 4 shows the concrete compressive strength test.

Figure 4. An experimental test for compressive strength of concrete

3.2 Mechanical properties for 35 days

After 28 days of curing, the concrete was removed from the curing pool and cured in a natural environment for 7 days, and then exposed to constant temperature heating for 2 hours in an industrial oven at a standard temperature with a heating efficiency of 22°C/min, which was used to examine the changes in mechanical properties at different temperatures.

3.2.1 High-temperature environment heating

It has been demonstrated that the exposure of cement paste with MC (micro-nano) and NC additions to a high-temperature environment does not have adverse effects. The compressive strength of control concrete, micro-nano concrete and nano concrete specimens started to decrease at 400°C, 500°C and 600°C respectively. The addition of

NC and MC contrasted the temperature change and both improved the development of compressive strength.NC concrete possessed excellent high-temperature properties, indicating that NC improved the high-temperature properties of the cement paste more significantly than MC [23]. By testing the microstructure and mechanical properties of specimens at 25°C, 200°C, 400°C and 600°C, NS was found to be beneficial in improving the compressive strength of the composite concrete in different high-temperature environments. Blending basalt fibres and NS helped to improve the interface transition zone properties and high-temperature performance of the recycled concrete [24]. To simulate fire or a high-temperature environment and investigate the effect of extreme temperature changes on the performance of composite nano concrete, the experiments were designed for a room temperature environment of 25°C and high temperatures controlled at 200°C, 400°C and 600°C respectively.

3.2.2 Compressive strength test for 35 days

To investigate the changes in the mechanical properties of nano concrete at different curing cycles and the pattern of changes in property decay under a high-temperature environment. The cubic specimens heated at different temperatures were cooled to room temperature naturally and then tested for compressive strength.

4. REBOUND STRENGTH DETECTION UNDER DIFFERENT TEMPERATURES

Based on the compressive testing of nano concrete, the experiment was further investigated to test the surface rebound strength of cubic and cuboid concrete specimens. The heated concrete was cooled to room temperature and the rebound strength was tested using long sections of concrete sides, as shown in Figure 5. The specimens were cured at 7 days and 35 days, with the fresh concrete having a shorter age, and the depth of carbonation of the concrete was calculated as 0. A set of 16 concrete specimens was averaged by removing the 3 maximum and 3 minimum values. The average rebound strength value for each group of measured areas was calculated according to the following equation (1).

Figure 5. Rebound strength inspection of nano concrete

$$R_m = \frac{\sum_{i=1}^{10} R_i}{10} \quad (1)$$

5. ANALYSIS AND DISCUSSION

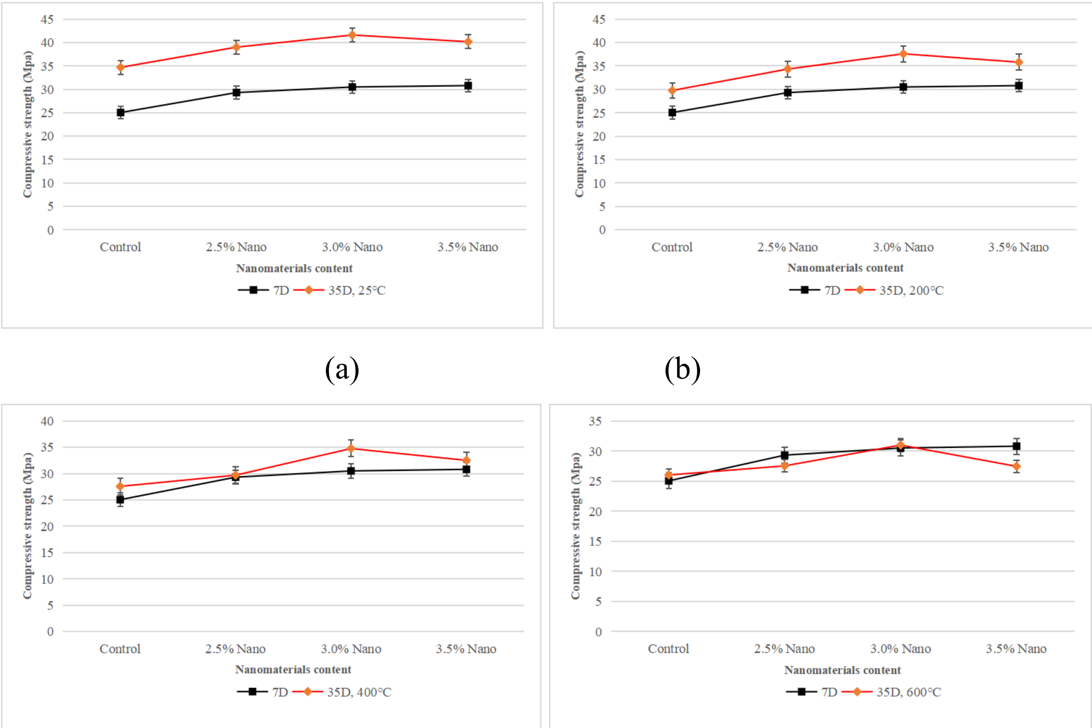
The mechanical properties of nano concrete under different temperature environments were tested by testing the compressive strength of nano concrete under different temperature environments for 7 and 35 days, resulting in the data in Table 4 below.

Table 4. Compressive strength of nano concrete

Curing period(Days)	Temperature(°C)	Compressive strength (Mpa)			
		Control	2.5% nano	3.0% nano	3.5% nano
7	25°C	25.04	29.31	30.5	30.8
28+7	25°C	34.7	39.02	41.61	40.18
28+7	200°C	29.76	34.34	37.59	35.80
28+7	400°C	27.57	29.69	34.75	32.51
28+7	600°C	26.01	27.53	30.99	27.45

Based on the experimental results 7 days of the mechanical properties of the composite NC and NS concrete compressive results show that 2.5% nano, 3.0% nano and 3.5% nano admixtures increased by 17.05%, 21.81% and 23.0% respectively over the control concrete, proving that the mixed composite nanomaterials are effective and the hydration mechanisms reflect the internal structure of the modified concrete. The compressive strength gradually increased to 30.8Mpa with increasing nano-doping, exceeding the design target strength. Comparing the mechanical compressive performance of nano-concrete at 35 days, the 7 days compressive strength of standard specimens at 25°C in an ambient environment increased by 38.58%, 33.13%, 36.43% and 30.45% over control concrete, 2.5% nano, 3.0% nano and 3.5% nano concrete respectively, with the trend shown in Figure 6(a). As the curing time increased, the strength of plain concrete continued to increase and the stronger growth rate of nano concrete was less than that of plain concrete, indicating a faster increase in the first period. High temperature environment 200°C standard specimens than control concrete, 2.5% nano, 3.0% nano and 3.5% nano concrete 7 days compressive strength increased by 18.85%, 17.16%, 23.25% and 16.23% respectively, the trend is shown in Figure 6(b). Through the high-temperature environment, the compressive strength of concrete gradually decreases, with approximately 20% loss in mechanical properties for normal concrete and less loss in strength for 3.5% nano concrete. The 7 days compressive strength of the standard specimens at 400°C in the high-temperature environment increased by 10.10%, 1.30%, 13.93% and 5.55% over the control concrete, 2.5% nano, 3.0% nano and 3.5% nano concrete respectively. With the increase of temperature, the strength of 2.5% nano concrete was lost faster, close to the strength of 7 days with the same dose of nano, and 3.5% dose of nano concrete was higher than 1.71Mpa, the changing trend is shown in Figure 6(c). The 7 days compressive strength of standard specimens for a high-temperature environment of 600°C increased by 3.87% and 1.61% over control concrete and 3.0% nano concrete respectively, while the strength of 2.5% nano and 3.5% nano concrete decreased by 6.07% and 10.88%, with the trend shown in Figure 6(d). The compressive strength of 3.0% nano concrete specimens at 35 days in a high-temperature environment at 600°C was close to the compressive strength at 7 days for the same dosage compared to 7 days and was only 0.49 MPa stronger than the control concrete. The 600°C high-temperature environment caused the compressive strength of 2.5% nano and 3.5% nano concrete to be lower than the compressive strength of the equivalent nano-doped concrete at 7 days.

The results of the study, Figure 7, show that the composite nanoparticles (NC and NS) improved the mechanical properties of the concrete and that high temperatures caused the mechanical properties of the concrete to decrease. The 3.0% modified concrete was the most effective in the temperature range of 25°C to 600°C and was able to raise the strength of the concrete to the highest level.



(a) (b)

(c) (d)

Figure 6. Compressive strength of nano concrete under different high temperatures (a,b,c,d)

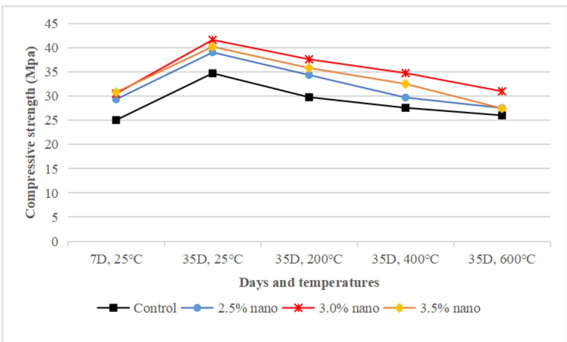


Figure 7. Strength loss of different nano concrete under high temperatures

Figure 8 shows the rebound test results of cubic NC and NS concrete specimens under different high-temperature environments, compared with the rebound test results of cuboid composite nano-concrete specimens under different high-temperature environments in Figure 9, the rebound strength of concrete specimens with the same nano-doping amount was changed after two hours of heating at 25°C, 200°C, 400°C and 600°C. No significant deviation in rebound strength was observed. The results of the rebound tests were different when comparing the compressive strengths of the same specimens.

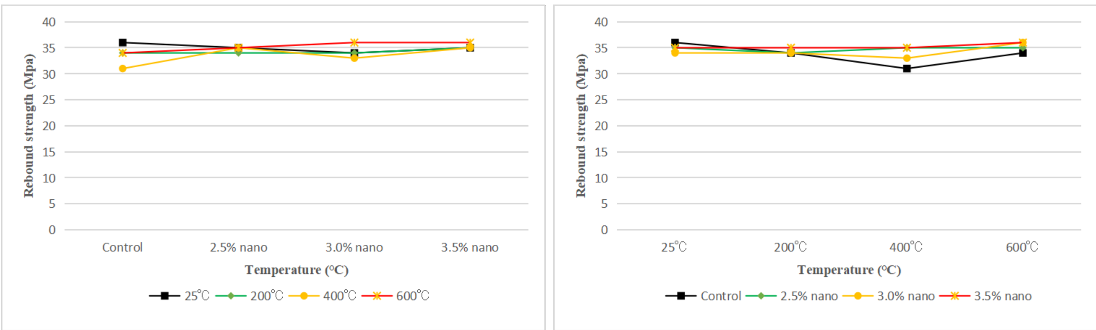


Figure 8. Rebound strength of cubic concrete specimens

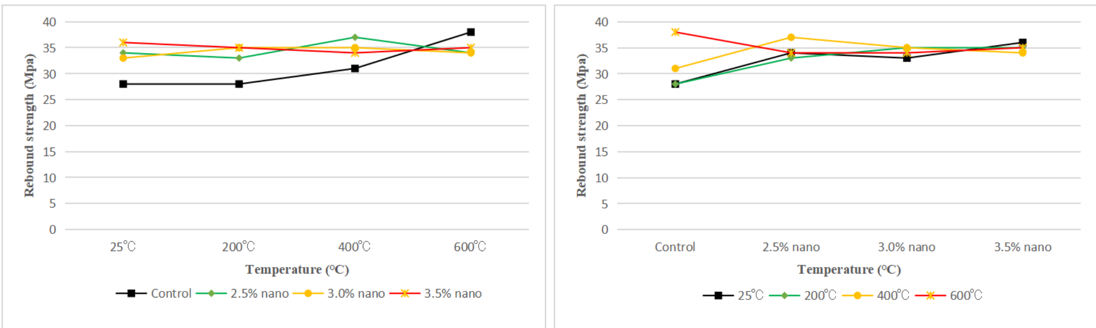


Figure 9. Rebound strength of cuboid concrete specimens

6. CONCLUSIONS

Through the study of composite nanoparticle concrete based on fire and extreme high-temperature environments, the following conclusions can be drawn.

- The compressive strength of nano-concrete is higher than that of normal concrete. The 3.0% composite nanomaterials is the most beneficial to the mechanical properties of the concrete and is the optimum dose for this experimental study.
- Simulating fire and extreme high-temperature environments, the results of compressive strength comparisons between 7 days and 35 days show that high temperatures reduce the performance of the concrete, making the compressive strength of 2.5% Composite Nano and 3.5% Composite Nano lower than 7 days, but still higher than the control concrete.

- The 3.0% nano concrete maintained high mechanical properties at different temperature environments (200°C, 400°C and 600°C) with low strength loss on high-temperature heating. The composite nanomaterial (NS+NC) has a significant modification effect on the compressive strength of concrete.
- The results of the rebound checks showed that the different high temperatures had no significant effect on the rebound strength of the concrete and that the rebound strength of the cuboid and cubic concrete specimens was essentially the same.

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