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Compressive strength and thermal conductivity of concrete with nanoclay under Various High-Temperatures

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HIGHLIGHTS

- Nanoclay concrete exhibits increased strength when temperature is not greater than 300 °C.
- Nanoclay is benefit to the strength and thermal conductivity coefficient of concrete.
- The replacement of cement with 0.3% and 0.5% nanoclay increases the thermal conductivity coefficient of concrete.
- Ignition loss can deduce the strength of concrete in high-temperature conditions.

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ABSTRACT

Concrete with nanoclay is utilized to replace cement of 0.1%–0.5% by weight, observing the compressive strength and thermal conductivity coefficients under 25–1000 °C for one hour. Results show that nanoclay concrete exhibits increased strength when temperature is not higher than 300 °C; strength is significantly reduced at a temperature range of 440–580 °C; and strength is lower than 10% of the original strength when temperature reaches 1000 °C. The thermal conductivity coefficient is reduced with increased temperature. When cement is replaced by 0.3% and 0.5% nanoclay, and the compressive strength and thermal conductivity coefficients of concrete increase.

1. Introduction

Nanoclays (NCs) are essentially nano-sized particles of layered mineral silicates. According to their chemical composition and nanoparticle morphology, NCs can be classified into various groups, including bentonite, kaolinite, montmorillonite, hectorite, halloysite, and organically modified NCs (organo clays). Incorporating small quantities of NCs (approximately 1% by binder mass) into cement-based materials appreciably influence the fresh-state properties of the latter [1]. Non-modified nanokaolinite and nanosmectite provide nucleation surfaces for the enhanced formation of C-S-H, thereby altering the microstructure of cement paste [2]. Morsy et al. [3] explored the effects of 2%, 4%, 6%, and 8% NC on the properties of cement mortars. The compressive strength of NC mortar increases with NC ratio. A dosage of 8% NC achieves 7% and 49% increases in compressive and tensile strengths, respectively. Differential scanning calorimetry tests indicate the formation of ill-crystalline CH and the effective formation of C-S-H owing to the presence of NC. Chang et al. [4] added NC to cement paste at 0.2%, 0.4%, 0.6%, and 0.8% of cement weight; test results show that dosages of 0.6% and 0.4% NC achieve optimum compressive strength and permeability, respectively. XRD tests indicate high CH consumption and high C-S-H production rate in the presence of NC. Patel [5] and Morsy et al. [6] found that the compressive strength of mortars modified with 1% and 2% NC increases with NC ratio. Increasing the replacement levels of NC leads to increasing water demand, which is adjusted by adding a water reducer to maintain workability or flow properties [6]. The diminished mass and compressive strength are significantly lower for mortars added with nanokaolinite clay (NKC) submerged in exposure acid solution than for control mortars [7]. Introducing NKC improves the freezing and thawing resistivity values of cement mortars [8].

The main source of compressive strength of cement paste comes from C-S-H gel and CH crystals, which chemically interact with each other when heated. The properties of cement paste after being subjected to heat are affected mainly by the change in water content, as well as by the decomposition and fusion of minerals. Typically, capillary and gel pore water evaporate when the temperature reaches 105 °C; at 200 °C, the bonded water inside the C-S-H

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gel starts to separate; at 250–300 °C, most of the hydrate bonded water containing Al_2O_3 and Fe_2O_3 with approximately 20% of the bonded water in the C-S-H gel are lost; at 400–700 °C, the remaining 80% of the bonded water in the C-S-H gel breaks down completely; between 500 and 580 °C, $Ca(OH)_2$ starts to disintegrate; $CaCO_3$ starts to disintegrate at 750 °C, thereby releasing CO_2 and producing CaO; CaO swells when it comes into contact with water and causes the concrete to crack [9]. Morsy et al. [10] studied the effects of high temperatures of up to 800 °C on the mechanical properties of cement mortars with 5%–15% nanometakaolin (NMK). The cement mortar pastes were cured under water for 28 days and then exposed to high temperatures. After an increase in the initial compressive strength of the mortars at 250 °C, the compressive strength decreased considerably at higher temperatures. High compressive and flexural strengths were obtained from the specimens containing 15% NMK for all thermal treatments.

In related studies, cement-based materials added with nanomaterials became increasingly compact with improved engineering properties. However, current research mainly centers on cement paste or mortar. Concrete is a heat-resistant material but when burned under high temperatures, its compressive strength declines and its structure may be damaged. The present study utilizes concrete as a specimen, as well as examines the influence of fire damage, discusses the effect of NC on the compressive strength and thermal conductivity coefficients of concrete, and presents the feasibility of evaluating the residual compressive strength of concrete with the test results of ignition loss.

2. Experimental

This study adopted an ACI mix design using water–cement ratios of 0.4 and 0.5 with slumps of 14 and 16 cm, respectively. For the concrete specimens, 0%, 0.1%, 0.3%, and 0.5% weight of cement were replaced with NC. The mix proportions are shown in Table 1. The materials used included Type I Portland cement; coarse aggregate with ¾" maximum particle diameter, 2.54 specific gravity with saturated surface dry, 1.25% water absorption capacity, and 1475.4 kg/m^3 dry-rodded unit weight, as well as fine aggregate with 2.75 fineness modulus, 2.53 specific gravity with saturated surface dry, and 2.15% water absorption capacity. The NC used in the tests was light yellow in color with purity greater than 95%. Furthermore, it primarily consisted of SiO_2, Al_2O_3, Fe_2O_3, MgO, Na_2O, and TiO_2 with an average particle diameter smaller than 10 μm, a pH value between 8 and 9, a Portland suction of 142.5 mmol/100g, a cation exchange capacity equal to 98, and a moisture content of less than 3.5%.

Testing was conducted in two parts, and all the data were the average values of the test results in triplicate.

(1) Compressive strength of concrete in different curing periods

ϕ 10 × 20 cm cylindrical specimens were manufactured according to the designed proportions. The specimens were removed from the mold the next day and then placed in saturated limewater for curing. The compressive strengths of the specimens were measured for curing times of 7, 14, 28, 49, 56, and 90 days.

(2) Influence on concrete properties under high-temperature environment

The tests included the influence on compressive strength, ignition loss, cement hydration degree, and coefficient of thermal conductivity.

In addition, specimens cured for 28 days were used to conduct simulated tests on the effects of high temperatures on the compressive strength of concrete. These specimens were removed from the water and placed in an oven at 105 °C for 3 days; afterwards, they were placed inside a high-temperature furnace and subjected to temperatures of 25, 300, 440, 500, 580, 800, and 1000 °C. The literature indicates that the main period for reducing the compressive strength of concrete occurs during the first hour when concrete is subjected to the effect of high temperatures [11]. Therefore, this study raised the temperatures to the set values, maintained at such levels for 1 h, and then cooled down to room temperature again before the compressive tests were conducted. In addition, cement paste (containing a small amount of fine aggregate with indelible minute particle sizes) was extracted from the damaged specimens to undergo ignition loss tests; the degree of cement paste hydration was then calculated using the measured ignition losses. All of the final data were the averages of the results obtained from three tests conducted under the same conditions.

The steps for the ignition loss test are as follows: (1) approximately 10 g of specimen was collected, and its weight was recorded as W_{25}; (2) the specimen was placed in an oven at 105 °C for 24 h, and its weight was recorded as W_{105} after it was cooled down; (3) the specimen was placed in a full-electronic high-temperature furnace at 440 °C for 8 h, and its weight was recorded as W_{440} after it was cooled down; (4) the specimen was placed in a full-electronic high-temperature furnace at 580 °C for 8 h, and its weight was recorded as W_{580} after it was cooled down; (5) the specimen was placed in a full-electronic high-temperature furnace at 1007 °C for 8 h, and its weight was recorded as W_{1007} after it was cooled down; and (6) ignition loss and degree of cement hydration (α) were calculated as shown in Eqs. (1) and (2).

$$\mathrm{IL} = \frac{W_{105} - W_{1007}}{W_{105} - (W_{105} - W_{1007})} \times 100\%, \tag{1}$$

$$\alpha = \frac{(W_{105} - W_{580}) + 0.41(W_{580} - W_{1007})}{nW_{1007}} \times 100\%, \tag{2}$$

where n is the amount of nonvolatile water in the completely hydrated cement paste, that is 0.24 for ordinary cement, and 0.41 is the molar ratio for the conversion of CO_2 in the calcium carbonate into H_2O.

The steps for the heat transfer test are as follows: a 15 cm × 15 cm × 24 cm column specimen was made according to the mix proportion, stripped on the following day, and cured in saturated limewater for 28 days. This test only considered the longitudinal transfer of heat in concrete. Then, 15 cm × 15 cm heating and radiating surfaces were wrapped in refractory wool with good heat insulation to prevent the heat energy in the concrete from dissipating from the sides. The temperature was increased to 800 °C at a heating rate of 5 °C/min. The temperature data acquisition unit was used to record the temperature change per second. The heat transfer coefficient was calculated using Eq. (3).

$$k = -\frac{Q}{A\left(\frac{dT}{dx}\right)}, \tag{3}$$

where k is the heat transfer coefficient ($W/m - K$), Q is the heat flow rate (W), A is the cross-section area normal to the direction of heat flow (m^2), and dT/dx is the temperature gradient of the direction of heat flow (K/m).

3. Results and discussions

3.1. Influence on concrete compressive strength with a minimal nanoclay replacing cement

Fig. 1 shows that in the W4 and W5 series, the concrete containing a small amount of NC as cement replacement (W4N1, W4N3, and W4N5) shows the same compressive strength development trend as ordinary concrete. Thus, minimal NC exerts no significant influence on concrete compressive strength over time. For example, 0.5% NC concrete (W4N5) of the W4 series is used in this paper. The concrete compressive strength increases as the curing period progresses, and the compressive strength of the concrete on the 28th day is 39.4 MPa. Relative to that on the 28th day; the

Table 1
Concrete mix designs (unit: kg/m^3).

Material	Number							
	W4N0	W4N1	W4N3	W4N5	W5N0	W5N1	W5N3	W5N5
Coarse aggregate	905.6	905.6	905.6	905.6	926.0	926.0	926.0	926.0
Fine aggregate	738.4	738.4	738.4	738.4	758.1	758.1	758.1	758.1
Cement	490.0	489.5	488.5	487.6	410.0	409.6	408.8	408.0
Water	196.0	196.0	196.0	196.0	205.0	205.0	205.0	205.0
Nano clay	0	0.49	1.47	2.45	0	0.41	1.23	2.05