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Effect of Hot Environment on Strength and Heat Transfer Coefficient of Nano-Clay Concrete Paper Title

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Abstract

This study selected water-cement ratio 0.5 and slump 16 cm for ACI mix design, and used nano-clay to replace 0.1%, 0.3% and 0.5% of cement by weight to make cylinder and angle column specimens. The effects of different high temperatures on the compressive strength and heat transfer coefficient were tested, and the ignition loss of nano-clay cement paste was measured. The results showed that an appropriate replacement of nano-clay for 0.3% - 0.5% of cement can enhance the strength and heat transfer coefficient of concrete, especially 0.3% replacement. The 0.1% nano-clay replacement for cement reduces the strength and heat transfer coefficient of concrete. When the ambient temperature exceeds 300˚C, the nano-clay concrete strength begins to decline, and the heat transfer coefficient decreases greatly, the effect of hot environment on the strength trend of nano-clay concrete is similar to that on normal concrete. When the nano-clay replaces cement by 0% - 0.5%, the ignition loss is approximately in exponential and logarithmic relationships to the compressive strength respectively when the ignition loss is smaller than and greater than 6%.

Keywords

Nano-Clay, Cement Paste, Concrete, Ignition Loss

1. Introduction

When the dimensions of materials enter into the nano range, conventional theories of material science no longer hold true. Nano materials have special characteristics, including the surface effect, small-size effect, quantum size effect, macroscopic quantum tunneling effect, and others [1] [2]. Clay can be divided into two broad categories: natural clay and synthetic clay [3].

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

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rate; at 250˚C - 300˚C, most of the hydrate bonded water containing Al_2O_3 and Fe_2O_3 and about 20% of the bonded water in the C-S-H gel are lost; at 400˚C - 700˚C, the remaining 80% of the bonded water in the C-S-H gel breaks down completely; between 500˚C - 580˚C, $Ca(OH)_2$ starts to disintegrate; at 750˚C, calcium carbonate starts to disintegrate, releasing CO_2, and producing CaO, which swells when it comes into contact with water and causes the concrete to crack [4].

This study simulates the concrete under the effect of fire to research the effect of nano-clay on the compressive strength and heat transfer coefficient of concrete. In addition, the feasibility of using the ignition loss test result to evaluate the retained strength of concrete is analyzed.

2. Test Planning

2.1. Materials and Mix Proportions

This study conducted ACI mix design using a 0.5 water-cement ratio and a slump of 16 cm and created specimens with 0%, 1%, 3%, and 5% weight of cement replaced by nano-clay (numbered as W5N0, W5N1, W5N3, and W5N5, respectively). The mix proportions are shown in **Table 1**. Materials used included Type I Portland cement; coarse aggregate with maximum particle diameter of 3/4", 2.54 specific gravity with saturated surface dry, a 1.25% water absorption capacity, and 1475.4 kg/m^3 dry-rodded unit weight; fine aggregate with a fineness modulus of 2.75, 2.53 specific gravity with saturated surface dry, and a 2.15% water absorption capacity. The nano-clay used in the tests was light yellow in color with purity greater than 95% and 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, pH value between 8 - 9, Portland suction amount of 142.5 mmol/100g, cation exchange capacity equal to 98, and moisture content less than 3.5%.

2.2. Test Items and Specimen Production

There are three test items:

1) Compressive strength of concrete at different curing ages

A ψ10 × 20 cm cylinder specimen is made according to the mix proportion, stripped on the following day and cured in saturated limewater. The compressive strength on Days 7, 14, 28, 49, 56 and 90 is measured respectively.

2) Compressive strength of concrete in hot environment

A ψ10 × 20 cm cylinder specimen is made according to mix proportion, stripped on the following day and cured in saturated limewater for 28 days for simulation test for the effect of different high temperatures on the compressive strength. The specimen is taken out of the water and put in 105˚C oven for 3 days, and then put in high temperature furnace, the specimen is exposed to 25˚C, 300˚C, 440˚C, 500˚C, 580˚C, 800˚C and 1000˚C respectively. It is indicated in literature that the compressive strength of concrete decreases mainly in one-hour delay under the effect of high temperature [5]. Therefore, there is a delay of one hour after the temperature reaches the preset temperature, the compression test is implemented when it is cooled to room temperature. All data are mean values of test results in triplicate.

The cement paste is extracted from the damaged specimen (including a small amount of fine aggregate in small particle size which cannot be removed) to test the ignition loss. The ignition loss test procedure is: 1) take 10 g sample, weighed W_{25}; 2) put in 105˚C oven for 24 hours, weighed W_{105} after cooling; 3) put in full

Table 1. Mix design.

Unit: kg/m^3

Material \ Number	W5N0	W5N1	W5N3	W5N5
Coarse aggregate	926.0	926.0	926.0	926.0
Fine aggregate	758.1	758.1	758.1	758.1
Cement	410.0	409.6	408.8	408.0
Water	205.0	205.0	205.0	205.0
Nano-clay	0.00	0.41	1.23	2.05

electronic high temperature furnace, heated to 440˚C and delayed 8 hours, weighed W_{440} after cooling; 4) heated in full electronic high temperature furnace to 580˚C and delayed 8 hours, weighed W_{580} after cooling; 5) heated in full electronic high temperature furnace to 1007˚C and delayed 8 hours, weighed W_{1007} after cooling; 6) calculate ignition loss (IL), expressed as Equation (1).

$$IL = \left(W_{105} - W_{1007}\right) / \left(W_{105} - \left(W_{105} - W1007\right)\right) \times 100\% \tag{1}$$

3) Thermal conductivity of concrete in hot environment

A 15 × 15 × 24 cm square angle column specimen is made according to mix proportion, stripped on the following day and cured in saturated limewater for 28 days. This test only considers the longitudinal transfer of heat in concrete. Two 15 × 15 cm surfaces are heating surface and radiating surface, wrapped in refractory wool with good heat insulation to avoid the heat energy in the concrete dissipating from sides. The temperature is increased to 800˚C at heating rate of 5˚C/min. The temperature data acquisition unit records the temperature change per second. The heat transfer coefficient is calculated by Equation (2).

$$k = -Q / \left(A\left(dT/dx\right)\right) \tag{2}$$

where k = heat transfer coefficient (W/m-˚K); Q = heat-flow rate (W); A = cross-section area normal to direction of heat flow (m^2); dT/dx = temperature gradient of direction of heat flow (˚K/m).

3. Results and Discussion

3.1. Effect of Small Replacement of Nano-Clay for Cement on Concrete Strength

The test results are shown in **Table 2** and **Figure 1**. For normal concrete (W5N0), the concrete strength increases with the curing age, the compressive strength on Day 28 is 33.7 MPa, the strength on Days 7 and 14 is 73.6%

Table 2. Compressive strength of concrete at different curing ages.

Unit: MPa

Curing time (days) \ Number	W5N0	W5N1	W5N3	W5N5
7	24.8	21.0	27.4	25.8
14	28.1	25.6	31.7	30.4
28	33.7	30.0	35.7	34.8
49	36.4	32.4	38.1	36.9
56	36.8	32.8	38.4	37.3
90	37.9	35.0	40.0	38.8

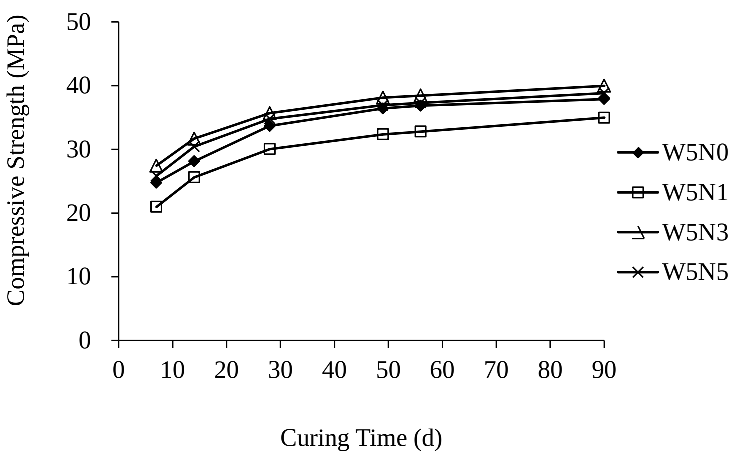

Figure 1. Compressive strength of concrete at different curing ages.

and 83.4% of the strength on Day 28 respectively. The compressive strength on Days 56 and 90 is increased by 9.2 and 12.5% respectively, meaning the strength grows rapidly during the first 28 days of curing, the strength develops slowly after 28 days. The concrete with a small replacement of nano-clay for cement (W5N1, W5N3 and W5N5) has a strength development trend similar to normal concrete, meaning a small amount of nano-clay has no significant impact on the time varying development trend of concrete strength.

Take the curing age of 28 days as an example, 0.1%, 0.3% and 0.5% nano-clay replace cement by weight, the strength is reduced by 11.0% and increased by 5.9% and 3.3% respectively. The strength of specimens at other ages has similar trends, meaning a proper amount of nano-clay replacing cement by 0.3% - 0.5% can increase the concrete strength, and the 0.3% replacement increases the concrete strength significantly, the 0.1% nano-clay replacement for cement reduces the concrete strength.

3.2. Effect of Hot Environment on Concrete Strength

The test results are shown in **Table 3** and **Figure 2**. For normal concrete (W5N0), there is a delay of one hour at 25˚C and 300˚C, the strength is increased by 13.4% and 9.5% respectively compared with the strength on curing Day 28. This result matches the result of Ref. [6] that the residual strength of concrete is not reduced apparently from normal temperature to 300˚C. However, when one hour delayed in 440˚C, 500˚C, 580˚C, 800˚C and 1000˚C environment, the strength is reduced by 14.2%, 26.7%, 46.9%, 76.3% and 93.8% respectively compared with the strength on curing Day 28. This result matches the result of Ref. [6] that 400˚C - 600˚C is the main strength reduction interval, the residual strength of concrete is mostly lower than 30% of the original strength when the temperature is higher than 700˚C.

Figure 2 shows that the effect of hot environment on the strength trend of nano-clay concrete is similar to that on normal concrete. In different hot environments, the 0.1% nano-clay replacement for cement can reduce the concrete strength, the 0.3% - 0.5% replacement for cement can increase the concrete strength, and the 0.3% replacement increases the concrete strength significantly.

Table 3. Compressive strength of concrete in different hot environments.

Unit: MPa

Temperature (˚C) \ Number	W5N0	W5N1	W5N3	W5N5
25	38.2	37.5	41.6	41.1
300	36.9	35.9	41.1	40.3
440	28.9	26.3	32.9	31.4
500	24.7	18.5	27.3	26.0
580	17.9	14.5	21.1	20.4
800	8.0	6.0	8.8	8.6
1000	2.1	2.1	2.8	2.6

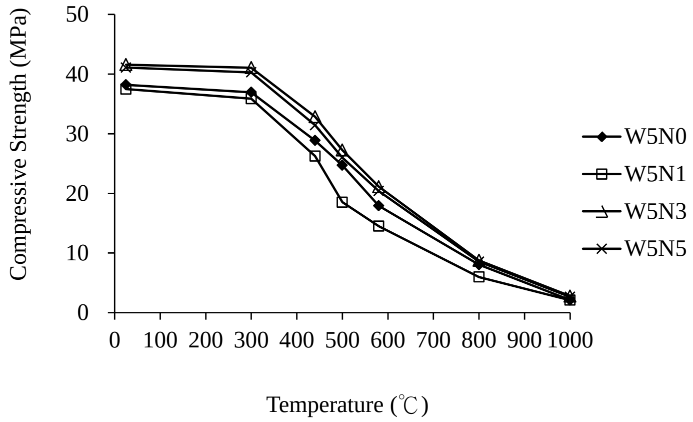

Figure 2. Compressive strength of concrete in different hot environments.

3.3. Effect of Hot Environment on Thermal Conductivity of Concrete

Table 4 shows that the heat transfer coefficient of concrete decreases as the ambient temperature rises, matching the findings of Ref. [7]. **Figure 3** shows that the maximum decreasing amplitude occurs at 200˚C - 300˚C, and then the decreasing amplitude decreases as the temperature increases. When the temperature exceeds 100˚C, the pore water in the concrete evaporates gradually, the heat transfer is slowed down. When the temperature is higher than 300˚C, the thermal strain difference between the aggregate and hardened cement paste results in microcracks, increasing the heat transfer paths, and the C-S-H colloid is decomposed gradually, the thermal conduction capability is reduced as a part of aggregate is damaged, so that the heat transfer coefficient decreases faster. When the temperature is higher than 600˚C, the heat is transferred between pores mainly by radiation [8]. The 0.1% nano-clay replacement for cement can reduce the heat transfer coefficient of concrete, and the 0.3% and 0.5% nano-clay replacement can increase the heat transfer coefficient of concrete.

Figure 4 shows the relationship between heat transfer coefficient and compressive strength. It is observed that the heat transfer coefficient decreases with the compressive strength. The decrease of the compressive strength in **Figure 4** is resulted from high temperature. Therefore, hot environment reduces the compressive strength and heat transfer coefficient of concrete. According to **Table 2** and **Table 3**, based on the compressive strength of concrete on the curing Day 28, when the ambient temperature is 800˚C, the compressive strength of W5N0, W5N1, W5N3 and W5N5 concrete is reduced by 76.1%, 80.1%, 75.4% and 75.4% respectively. According to **Table 4**, based on the heat transfer coefficient of concrete at ambient temperature of 200˚C, when the ambient temperature is 800˚C, the heat transfer coefficient of W5N0, W5N1, W5N3 and W5N5 concrete is reduced by 64.4%, 63.6%, 61.8% and 62.3% respectively.

Table 4. Heat transfer coefficient of nano-clay concrete in hot environment.

Unit: W/m-˚K

Number / Temperature(˚C)	W5N0	W5N1	W5N3	W5N5
200	2.05	1.95	2.17	2.12
300	1.52	1.45	1.65	1.57
400	1.22	1.18	1.34	1.26
500	1.04	1.00	1.16	1.07
600	0.90	0.88	1.01	0.96
700	0.81	0.79	0.91	0.87
800	0.73	0.71	0.83	0.80

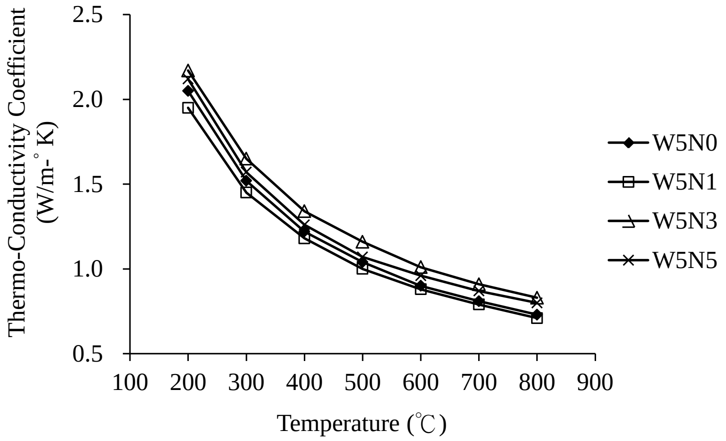

Figure 3. Heat transfer coefficient of nano-clay concrete in hot environment.

3.4. Effect of Hot Environment on Ignition Loss of Nano-Clay Cement Paste

The test results are shown in **Table 5** and **Figure 5**. For normal concrete (W5N0), when the temperature is 300˚C to 580˚C, the mortar ignition loss decreasing amplitude is increased markedly. Because when the temperature is 300˚C - 500˚C, most of bonding water of C-S-H colloid has been lost, and $Ca(OH)_2$ begins to be decomposed at 500˚C - 580˚C [4]. The 0.1% - 0.5% nano-clay replacement for cement has no significant impact on the paste ignition loss trend at high temperature.

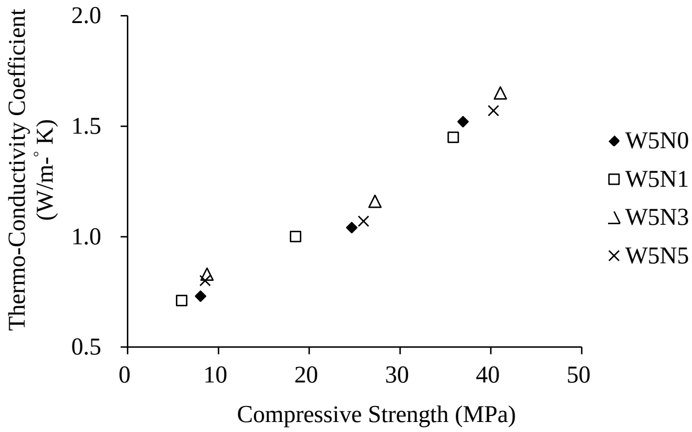

Figure 4. Relationship between heat transfer coefficient and compressive strength.

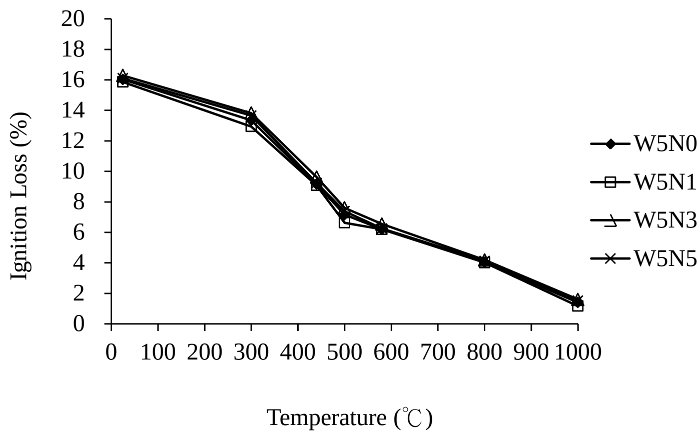

Figure 5. Nano-clay cement paste ignition losses in different hot environments.

Table 5. Nano-clay cement paste ignition losses in different hot environments.

Unit: %

Number / Temperature (˚C)	N0	N1	N3	N5
25	16.0	15.9	16.3	16.1
300	13.3	12.9	13.8	13.7
440	9.2	9.1	9.6	9.2
500	7.2	6.6	7.6	7.4
580	6.2	6.2	6.5	6.2
800	4.1	4.0	4.2	4.1
1000	1.4	1.2	1.6	1.5

3.5. Relationship between Paste Ignition Loss and Compressive Strength

Figure 6 shows that the compressive strength increases with ignition loss. Because the ignition loss of paste reflects the degree of cement hydration, and the hot environment results in chemical reaction of cement hydration product. When the temperature is 200˚C, the bonding water begins to deviate from C-S-H colloid. The paste has lost most water when the temperature is 500˚C, and $Ca(OH)_2$ begins to be decomposed when the temperature is 500˚C - 580˚C, so that the ignition loss of paste is reduced, namely, the degree of cement hydration is reduced, the higher the ignition loss is, the higher is the degree of cement hydration.

When the water-cement ratio of paste is 0.5, and the nano-clay replacement for cement is 0% - 0.5%, the ignition loss is approximately in exponential relationship to the compressive strength when the ignition loss is lower than 6%, $y = 1.267e^{0.443IL}$, the correlation factor (R^2) is 0.969; when the ignition loss is higher than 6%, the ignition loss is approximately in logarithmic relationship to the compressive strength, $y = 22.832\ln(IL) - 22.003$, the correlation factor is 0.920. Therefore, the compressive strength of concrete can be calculated by ignition loss, or the ambient temperature of concrete can be calculated by ignition loss (**Figure 5**).

4. Conclusions

This study selects water-cement ratio 0.5 and slump 16 cm for ACI mix design, and uses nano-clay to replace cement 0.1%, 0.3% and 0.5% by weight respectively. Cylinder specimens are made to test the effect of different high temperatures on the compressive strength and heat transfer coefficient, and the ignition loss of nano-clay cement paste is measured, concluded as follows:

1) For the specimen at the curing age of 28 days, 0.1%, 0.3% and 0.5% nano-clays replace cement by weight, the strength is reduced by 11.0% and increased by 5.9% and 3.3% respectively. The strength of specimens at other ages has similar trends and the 0.3% replacement increases the concrete strength significantly, the 1% nano-clay replacement reduces the concrete strength.

2) In 25˚C and 300˚C environments, the strength of normal concrete is increased by 13.4% and 9.5% respectively compared with control group. However, in 440˚C, 500˚C, 580˚C, 800˚C and 1000˚C environments, the strength is reduced by 14.2%, 26.7%, 46.9%, 76.3% and 93.8% respectively. In different hot environments, the 0.1% nano-clay replacement can reduce the concrete strength, the 3% - 5% replacement can increase the concrete strength, and the 0.3% replacement increases the concrete strength significantly.

3) For 0.1% - 0.5% nano-clay concrete, when the temperature is 300˚C to 580˚C, the paste ignition loss decreasing amplitude is increased markedly.

4) The heat transfer coefficient of concrete decreases as the ambient temperature increases, the maximum decreasing amplitude occurs at 200˚C - 300˚C. The 0.3% and 0.5% nano-clay replacement can increase the heat transfer coefficient of concrete.

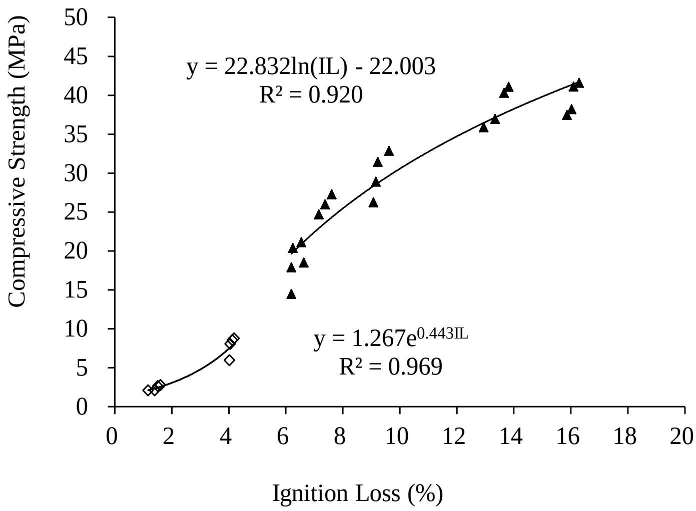

Figure 6. Relationship between ignition loss and compressive strength of nano-clay cement paste.

5) When the nano-clay replaces 0% - 0.5% of cement, and the ignition loss is lower than 6%, the ignition loss is approximately in exponential relationship to the compressive strength. When the ignition loss is higher than 6%, the ignition loss is approximately in logarithmic relationship to the compressive strength.

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