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Effect of Moderately Elevated Temperatures on Performance of Portland Cement Concrete

Song Gao[1], Min Liu[2], Qingxun Kong[2] and Kefei Li[1*]

[1]Department of Civil Engineering, Tsinghua University, Beijing 100084, PR China, gaos22@mails.tsinghua.edu.cn (Song Gao), likefei@tsinghua.edu.cn (Kefei Li, Corresponding author)

[2]China Nuclear Power Engineering Co., Ltd., CNNC, Beijing 100840, PR China, liumin@cnpe.ee (Min Liu), 02062012@163.com (Qingxun Kong)

Abstract. *High temperature is one of the critical factors leading to the change in concrete performance since it affects the physical structure and chemical components of concrete. However, some concrete structures are continuously subjected to moderately elevated temperatures (typically less than 200 °C) when operating, such as chimneys for the metallurgical industry and structures in nuclear power plants. The deterioration process of these structures could be caused and accelerated by a high-temperature environment. Thus, the safety and performance of these concrete structures at elevated temperatures during service life are crucial. This paper aims to investigate the change in concrete performance exposed to sustained moderately high temperatures. The concrete cured for 56 days was subjected to temperatures ranging from 65 °C to 200 °C for 28 days. The mechanical properties of concrete at different heating temperatures were tested, including compressive strength, splitting tensile strength and modulus of elasticity. Meanwhile, concrete's durability after heating was evaluated using the concrete electrical resistivity test. The concrete elevated-temperature performance was compared to identical concretes at room temperatures, and the evolution of each property was analyzed. Based on experimental results, the long-term performance of concrete in a moderately elevated temperature environment is predicted.*

Keywords: *Concrete mechanical properties, Concrete electrical resistivity, Concrete performance, Moderately elevated temperature; Long-term heating*

1 Introduction

Concrete, as a common construction material, is widely used for many structures exposed to various environments. High temperature is one of the main environmental conditions to which concrete structures in oil, power, nuclear and metallurgical industries (e.g., chimneys for the metallurgical industry and temporary storage structures in nuclear power plants) are exposed. These structures are continuously subjected to moderately elevated temperatures (i.e., less than 200 °C) throughout their entire service life. Although this temperature range is not as high as a fire accidence, exposure to moderately high temperatures for a considerable exposure period affects the physical structure, chemical components and moisture content in concrete, eventually altering concrete performance (Kizilkanat et al., 2013). Thus, understanding the long-term behavior of concrete exposed to sub-high temperatures is crucial.

Many studies have been made to investigate the behavior of cement-based materials at elevated temperatures. However, previous studies had great variation or even opposite conclusions from various test variables. Some indicated that the compressive strength of concrete exposed to temperatures up to 300 °C kept constant or slightly increased (Ma et al., 2015), but some found that concrete compressive strength decreased with elevated temperature (Vodak et al., 2004; Shen & Xu, 2019). The flexural strength, splitting tensile strength and elastic modulus of concrete decreased with the elevated temperature (Ma et al., 2015; Naus, 2006). In addition, it is shown that the main factors changing concrete mechanical properties at moderately elevated temperatures are moisture migration and evaporation, and chemical change of unhydrated cement and hydrated products, which modifies concrete pore structures (Noumowe et al., 2009; Rani & Santhanam, 2012; Shen et al., 2020).

Although many investigations were made to analyze the effect of high temperatures on concrete, the study on concrete performance under long-term moderately elevated temperature exposure is insufficient. In this study, the long-term performance of concrete at temperatures up to 200 ^oC is analyzed by measuring compressive strength, splitting tensile strength, dynamic modulus of elasticity and bulk electrical resistivity of concrete heated for 28 days. The changes in these mechanical and electrical properties under different heating temperatures are discussed by comparing them with unheated concrete.

2 Experimental Program

2.1 Materials and Mix Design

Chinese GB175 Type PO - ordinary Portland cement (PO 42.5) was used to prepare concrete specimens. A commercially available compound mineral admixture made of fly ash and ground granulated blast furnace slag was used as a supplementary cementitious material. The fine and coarse aggregates for mixtures were natural sand and 19-mm crushed granite, respectively. A liquid polycarboxylate admixture was used as a water reducer. The mix proportion of a concrete mixture in this study is listed in Table 1.

Table 1. Mix proportion of concrete mixture (kg/m^3)

Water	Coarse aggregate	Fine aggregate	Portland cement	Compound mineral admixture	Water reducer	w/c ratio
160	1045	795	320	105	5.88	0.376

2.2 Concrete Casting and Curing

Concrete was mixed in a 60-L capacity concrete mixer at a temperature of 23$\pm$2 ^oC and cast in three types molds, including 100-mm concrete cubes, concrete prisms of 100 x 100 x 300 mm and concrete cylinders of 100 mm diameter and 200 mm height. Concrete molds were covered with plastic sheets to prevent moisture loss. Concrete specimens were demolded after 24 hours and cured in a moist room for 56 days.

2.3 Heating Procedure

After 56-day moist curing, concrete specimens were taken out from the moist room and air dried for 7 days to get rid of excess surface water. Concrete specimens were placed in four electric ovens and heated to 65 ^oC, 95 ^oC, 150 ^oC and 200 ^oC, respectively, with a heating rate of 11 ^oC per hour, followed by a 28-day heating period. After heating at desired temperatures for 28 days, concrete specimens were removed from ovens and tested immediately.

2.4 Experimental Tests

2.4.1 Compressive strength test

After a 28-day heating treatment, three concrete cubes from each elevated temperature were taken out and immediately tested for compressive strength in accordance with GB/T 50081 *Standard for test methods of concrete physical and mechanical properties*. The average compressive strength results were calculated.

2.4.2 Splitting tensile strength test

At the test age, the splitting tensile strength of concrete specimens at different temperatures was tested according to GB/T 50081. To measure the splitting tensile strength, a supplementary bearing plate is used to apply a load along the entire length of concrete cubes. Two 20 x 150 mm bearing strips of 3-mm thick plywood were placed between the specimens and bearing plates. A constant loading rate of 0.08 MPa/s was applied until concrete failure.

2.4.3 Dynamic modulus of elasticity test

The concrete dynamic modulus of elasticity at different temperatures was measured by the transverse resonant frequency approach based on JTG E30 *Test Methods of Cement and Concrete for Highway Engineering*. The resonance frequency of concrete was determined by finding the frequency corresponding to the maximum amplitude when applying the impacts on concrete. The dynamic elastic modulus was calculated based on the resonance frequency, specimen mass and dimension, as shown in Equation 1:

$$E_d = 9.46 \times 10^{-4} \frac{WL^3 f^2}{a^4} K \qquad (1)$$

where, E_d is concrete dynamic modulus of elasticity (MPa), L is specimen length (mm), a is side length of cross-section of prism (mm), W is specimen weight (kg), f is transverse resonance frequency (Hz), and K is correction factor for dimension of specimens (K=1.68 for L/a=3; K=1.4 for L/a=4; K=1.26 for L/a=5).

2.4.4 Bulk electrical resistivity test

The ø100 x 50 mm concrete cylinders cut from the 100 x 200 mm cylinder after heating were tested for bulk electrical resistivity. Before testing, concrete specimens were taken out from ovens and naturally cooled to room temperature. Then samples were vacuum saturated in saturated limewater to make them fully saturated. The Resipod resistivity meter from Proceq SA was used to measure concrete bulk electrical resistivity by placing two plate electrodes on both end faces of a specimen according to ASTM C1876. An AC voltage was applied across the whole cross-section of the sample, and the current passing through the sample and voltage drop was measured to determine electrical resistivity based on Equation 2:

$$\rho = \frac{V}{I} \cdot \frac{A}{L} \qquad (2)$$

where, V is voltage, I is current, L is average specimen length and A is specimen cross-sectional area.

3 Results and Discussions

Tables 2 and 3 list the compressive strength, splitting tensile strength, dynamic modulus of elasticity and electrical resistivity results measured from concrete specimens subjected to 65 ^oC, 95 ^oC, 150 ^oC and 200 ^oC for 28 days. Concrete specimens stored at a room temperature of 25^oC were also tested at the same age as heated concretes.

Table 2. Mechanical properties of concrete exposed to different temperatures for 28 days

Properties	25^{o}C	65^{o}C	95^{o}C	150^{o}C	200^{o}C
Compressive strength (MPa)	68.1	71.1	76.8	73.6	76.6
Splitting tensile strength (MPa)	5.14	5.59	5.09	5.21	4.80
Dynamic modulus of elasticity (GPa)	45.9	40.3	36.8	31.6	26.8

Table 3. Electrical resistivity of concrete exposed to different temperatures for 28 days

Properties	25^{o}C	65^{o}C	95^{o}C	150^{o}C	200^{o}C
Electrical resistivity (Ω-m)	519	251	143	95	89

3.1 Concrete Compressive Strength

It is indicated that the concrete compressive strength increased with elevated temperatures up to 200 ^oC, as shown in Figure 1. The compressive strength increased by 4.4%, 12.8%, 8.1% and 12.5% for concretes exposed to 65 ^oC, 95 ^oC, 150 ^oC and 200 ^oC, respectively, compared with unheated concrete. The growth of compressive strength can result from the hydration of unhydrated cement due to moisture migration during heating (Rani & Santhanam, 2012).

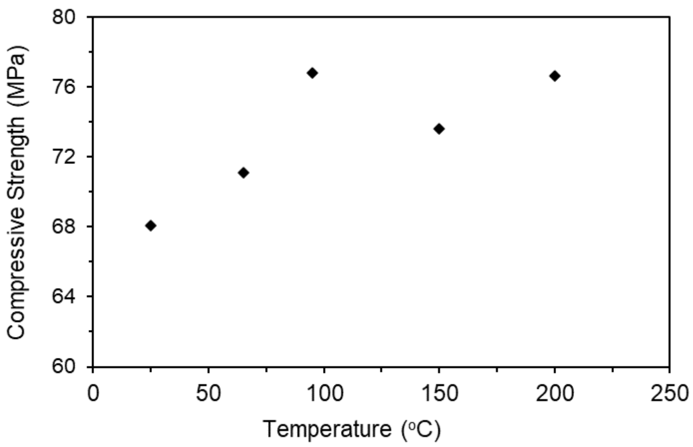

Figure 1. Compressive strength of concrete subjected to different elevated temperatures for 28 days.

3.2 Concrete Splitting Tensile Strength

Figure 2 displays the splitting tensile strength of concrete exposed to different temperatures. Compared with the unheated concrete, the concrete splitting tensile strength was improved by 8.8% after exposure to 65 ^oC for 28 days. Meanwhile, the concrete splitting strength did not change obviously at 95 °C and 150 °C. The 28-day exposure at 200 °C led to a 6.6% decrease in the splitting tensile strength of concrete, which is less than 5 MPa.

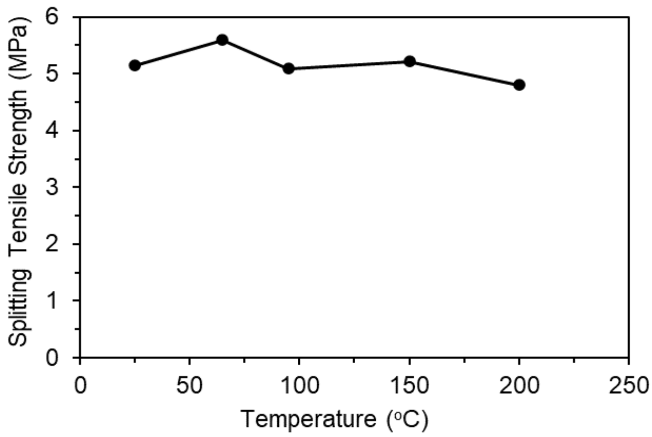

Figure 2. Splitting tensile strength of concrete subjected to different elevated temperatures for 28 days.

3.3 Concrete Dynamic Modulus of Elasticity

The concrete dynamic modulus of elasticity decreased as the temperature rose. Compared to the unheated concrete, the dynamic elastic modulus of concrete declined by 12.2%, 19.8%, 31.2% and 41.6% at 65 °C, 95 °C, 150 °C and 200 °C, respectively. This reduction can result from the change of the microstructure in concrete under elevated temperatures (Farage et al., 2003). Furthermore, a strong linear correlation was found between dynamic elastic modulus and elevated temperature, with an R^2 of 0.99, as shown in Figure 3.

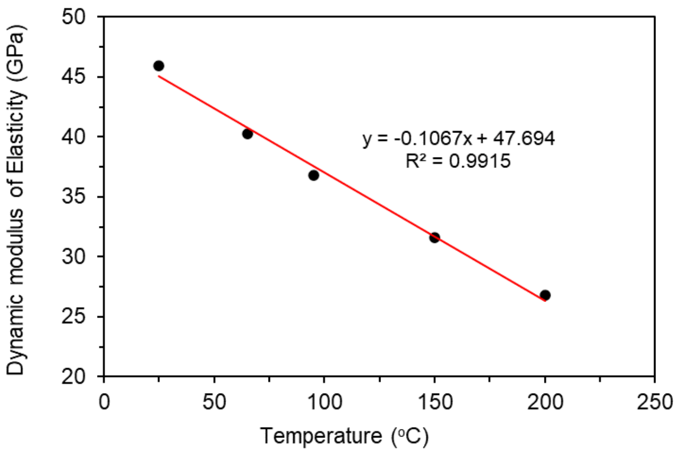

Figure 3. Dynamic modulus of elasticity of concrete subjected to elevated temperatures for 28 days.

3.4 Concrete Electrical Resistivity

It is noted that the moderately elevated temperature has a significant impact on concrete electrical resistivity. The bulk electrical resistivity of concrete without heating was 519 Ω-m, but the concrete electrical resistivity declined by 51.6%, 72.4%, 81.7% and 82.9% for 65°C, 95 °C, 150 °C and 200 °C, respectively. Compared with the change in mechanical properties of heated concrete, concrete electrical resistivity after heating decreased significantly, and a higher elevated temperature caused a greater reduction in concrete electrical resistivity, as shown in Figure 4. This decline in electrical resistivity can be attributed to increased porosities of capillary pores and air voids and the generation of microcracks (Farage et al., 2003; Shen & Xu, 2019).

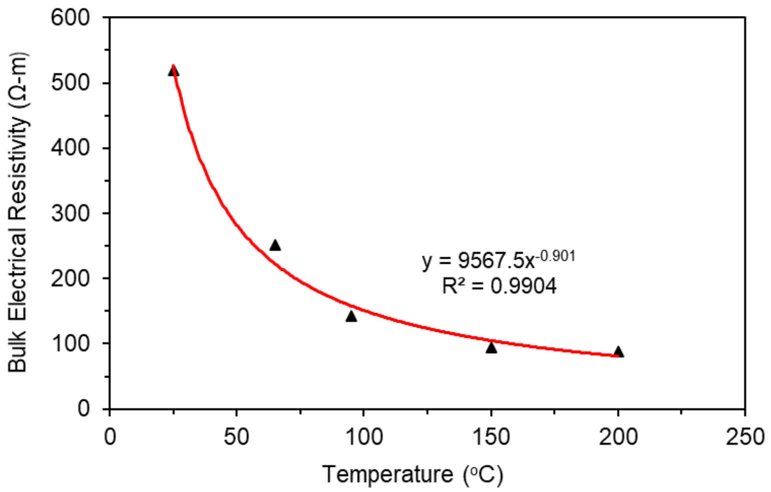

Figure 4. Electrical resistivity of concrete subjected to different elevated temperatures for 28 days.

4 Conclusions

To determine the effect of moderately elevated temperature on concrete performance, concrete specimens exposed to four different heating temperatures (i.e., 65 °C, 95 °C, 150 °C and 200 °C) for 28 days were tested for compressive strength, splitting tensile strength, dynamic modulus of elasticity and bulk electrical resistivity. The following conclusions are drawn:

- The moderately high temperatures up to 200 oC enhanced concrete compressive strength compared with concrete at room temperature. The compressive strength increased with elevated temperatures. However, the dynamic modulus of elasticity decreased linearly with elevated temperatures. The splitting tensile strength of concrete may not be sensitive to sub-high temperatures; it did not alter obviously at temperatures below 200 oC, but decreased to below 5 MPa after exposure to 200 oC.
- The concrete bulk electrical resistivity dramatically decreased after a 28-day high-temperature exposure compared to concrete without heating. Moreover, a higher exposure temperature caused a lower concrete electrical resistivity, meaning that the resistance of concrete to fluid and chloride ingress was reduced due to heating.
- Concrete mechanical properties were not influenced significantly in the moderately elevated temperature environment, but the electrical properties of concrete were decreased significantly, which reveals that concrete transport property is changed dramatically by elevated temperatures.

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