An Investigation on the Mechanical Properties of Cement Mortar under Axial Loading Conditions at High Temperature

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Abstract. Concrete preloaded during heating always shows higher compressive strength than that unloaded, and the reason was confused. As one of the main components of concrete, cement mortar has an important impact on the performance of concrete at high temperatures. However, few studies have conducted on the stressed mechanical properties of mortar at high temperature. In this paper, a series of mechanical tests were conducted to investigate the mechanical properties of cement mortar specimens under axial loading conditions. Seven temperatures (20 °C, 100 °C, 200 °C, 300 °C, 400 °C, 500 °C, 600 °C) and three pre stress ratios (0.2, 0.4, 0.6) were set during the in-door laboratory tests. Test results showed that temperature and pre-stress have significant influences on the compressive strength and the failed mode of cement mortar specimens at high temperature. The compressive strength of mortar under stressed condition was even higher than that at room temperature which might be a reason for the improvement of stressed compressive strength.

Keywords. Mechanical properties, cement mortar, high temperature, pre-stress ratio.

1. Introduction
Concrete is widely used around the world as a building material [1, 2] and may be subject to high temperatures in applications such as those used in nuclear power plants or due to fires etc. [3, 4]. As exposed to fire, a series of the physical and chemical transformations take place in concrete, the strength of concrete reduces dramatically [5], and even leaded to collapse of the structures [6, 7]. Accidental fires not only cause a lot of economic damage, but also cause many injuries and deaths, especially in tall, bulky buildings, which make the outcome even worse [1]. So the fire safety of the concrete structure is more important [8, 9], and the strength of the concrete at high temperature was the crucial parameter.

Many researchers have investigated the compressive strength of concrete at/after high temperature. [10-13]. The investigations indicated that temperature has a great influence on the compressive strength of concrete and the compressive strength decreased dramatically after 400°C. The w/c, mineral admixtures, cooling manner, etc. could affect the concrete strength at high temperature or after thermal treated. Due to the difficulty of measurement at high temperature, most of the tests were tested for the residual strength of concrete after thermal treated at room temperature and under the non-stressed condition. However, the actual structures have design loads and the concrete components in structures are stressed by the loads and constrained by the other members. And due to the stresses and constraints, thermal behavior of stressed concrete were different from unstressed ones [14, 15].
Tests on the specimens strained during heating always showed higher compressive strength [4, 8]. The first experiments on preloaded concrete were reported by Malhotra in 1956. The results showed that the compressive strength of concrete specimens restrained during heating was higher [16]. Later, may researchers conducted tested on the stressed concrete [17-19] and their tested results confirmed the conclusion. Kim et al. [20] found that the external loading not only influenced the residual mechanical properties of concrete but also increased the risk of spalling and the brittle failure.

Reasons for improvement in compressive strength of stressed concrete specimens were complicated and not understood well. And as concrete is considered to be a composite consisting of mortar and coarse aggregate, its strength depend on the mortar strength and coarse aggregate strength [21]. Wang et al. [22] advised that determine mortar and concrete behavior separately to advance the constitutive modelling at meso-scale. The properties of the cement mortar at high temperature were conducted and showed a similar compressive strength reduction with the concrete [23-26]. However, most of these tests were carried out for the residual strength and unstressed. So in order to understand the properties of the cement mortar at high temperature and analysis the reason for the improvement of the stressed concrete, strained test of cement mortar at high temperature were carried out.

2. Experimental Program

2.1. Raw Material and Specimens Prepare
The ordinary cement mortar was concerned in this study. Specimens for the tests were cubic of 40×40×40 mm. The ordinary Portland cement of P42.5, river sand and clear water were selected as the raw materials and the mixture ratio(water: cement: sand) was 1:2:5. The fineness modulus of the sand was 2.03. The specimens were demolded after cured at room temperature for 24 hours and then were cured for 28 days in a curing room with a stand temperature 20 ± 2 ℃ and 95 ± 5 % relative humidity (RH). After the curing, the specimens were taken out and dried in the air at least 7 days before tested.

2.2. Temperature Regimen
The temperature for the compressive test were 20 ℃, 100 ℃, 200 ℃, 300 ℃, 400 ℃, 500 ℃ and 600 ℃. An electric furnace which was used to heat the specimens was installed into a universal testing machine for the purpose of loading and heating the mortar specimens at the same time. The electric furnace maximum temperature capacity was 700 ℃. After reaching the preset temperature, the furnace automatically entered the constant temperature mode with a range of ± 5 ℃. The heating process time lasted one hour.

2.3. Test Procedure
In this study, a force was loaded on the specimens by the universal testing machine before heating and kept the loading position during the heating process. The pre-stress ratio 0.2, 0.4 and 0.6 were selected and the test conditions were shown in table 1.

| Maximum temperature/℃ | Pre stress ratio |
|------------------------|-----------------|
| 20                     | 0               |
| 100                    | 0.2 0.4 0.6     |
| 200                    | 0.2 0.4 0.6     |
| 300                    | 0.2 0.4 0.6     |
| 400                    | 0.2 0.4 0.6     |
| 500                    | 0.2 0.4 0.6     |
| 600                    | 0.2 0.4 0.6     |

At first, the average strength value of 78.9 kN was taken as the mortar bearing capacity at room temperature. The per-stress ratios were 0.2, 0.4 and 0.6, corresponding to 16 kN, 32 kN and 48 kN,
respectively. After the heating procedure, the constrained load was applied at the speed of 0.5 mm/s on the specimen to the crush. In each condition, at least three specimens were taken and the average strength of the specimens was used.

The letter C and G stood for the room temperature and the high temperature. The number after the letters was the temperature that the specimen tested. The third number was the pre-stress ratio that the specimen was applied on.

3. Results and Discussion
The color, density, porosity, mass and so on changed in heating. And color change was the apparent indicator which was changed from normal to pink which was shown in figure 1. The mass loss was due to the evaporation of moisture, especially exceeded 400 °C. The porosity were coarsen due the dehydration of the of the cement mortar components at high temperature. All of the changes were due to the evolution of the moister content and material reaction [27].

![Figure 1. Post-test mortar specimen.](image)

### 3.1. The Stress-Strain Curves under the Constrained Conditions
The stress-strain curves at room temperature and at constrained conditions with different pre-stress ratios were shown in figure 2. It can be observed that: First, the failure modes of the specimens were near the same. The failure modes at the room temperature was brittle, and the constrained specimens at
high temperature were brittle too, especially after 300 °C. Second, with the increasing of temperature, the peak strain (corresponding with the peak stress) decreased gradually, and the peak strain of the G600-0.6 was the minimal, which was just about 1/10 of that of C20. Last, in most cases, the strengths under the constrained conditions increased compared with that at room temperature.

**Figure 2.** Stress-strain curves of mortar specimens.

### 3.2. The Strength of the Specimens under Different Pre Stress Ratios

As shown in figure 3, C20 was tested at room temperature without additional restraint load. Under the constrained conditions, at 100 °C and 200 °C, the strength of the cement mortar was lower than that at the room temperature. However, at the other temperatures, the strength of the cement mortar was higher than that at room temperature except the strength of G600-0.2. At every pre-stress ratio, the strength of the mortar at 300 °C and 400 °C was higher than that at the other temperatures.

**Figure 3.** The strength at different preload ratio.

The deviations caused by the pre-stress ratio at the same temperature were shown in figure 3. At 100 °C and 200 °C, the impact of different pre-stress was small and the deviations of the cement mortar strength were small. At 300 °C, the strength of cement mortar increased and the deviations of cement mortar strength caused by the different pre-stress ratios were increased too. The largest deviation of the strength was 11.97 kN at 600 °C. Abrams [28] suggested that the difference of per-stress ratios had insignificant effects on the compressive strengths of specimens. So based on Guo et al. [29], the formulas of cement mortar strength under the stressed conditions were fitted and shown as equation (1) and (2), and shown in figure 4.
At 20 °C-200 °C
\[ \frac{f_T}{f_{\text{max}}} = \frac{1}{1+0.165 \left( \frac{T}{1000} \right)^{0.444}} \quad (R^2=0.84) \]  
(1)

At 300 °C-600 °C
\[ \frac{f_T}{f_{\text{max}}} = \frac{1}{1+1.26(T - 20)} \quad (R^2=0.6) \]  
(2)

where, \( f_T \) is the strength of the mortar under the constrain condition.
\( f_{\text{max}} \) is the strength of the strength at room temperature.
\( T \) is the temperature at which the experiment was carried out.

3.3. Comparison of Strength under Constrained and Unconstrained Conditions

Many researchers have conducted investigations on the mechanical properties of cement mortar which was unstressed during heating [23-26]. Collected the tests results in these literatures, and compared with the results of this experiment, there were many obviously differences. First, under the unstressed conditions, the compressive strength of mortar decreased with the increasing temperature. However, under the stressed conditions, the compressive strength of mortar decreased slightly at 100 °C and 200 °C and increased after 300 °C, even higher than that at room temperature. Second, under the unstressed conditions, the slope of the compressive stress-strain curves which corresponding with the elastic module of the cement mortar decreased with the increasing temperature. However, under the stressed conditions, the slope did not change much. Last, under the stressed conditions, the peak strain (the strain at the peak strength) and the post peak strength increased with the increasing temperature. However, under the stressed conditions, the peak strain decreased with the temperature, and there were no post peak strain almost.

At high temperature, the strength of cement mortar could decrease due to the evaporation of water, cracks caused by the thermal expansion mismatch for the hardened cement matrix and the sand, decompose of the hydrations [1, 25, 26]. At the same time, the moisture evaporation and the hydration of the unhydrated cement grains could improve the strength of cement mortar [24, 30]. These above conditions were the same both for the stressed and the unstressed specimens. However, the stress increasing in the specimen during the test time was different which was shown in figure 5.
The force loaded on the specimen of G300-0.2 changed due to the thermal expansion and was recorded by hand. Before heating, a vertical constrained load $0.2F_m$ (16 kN) was applied on the specimen by the universal testing machine. As the heating began, the specimen was heated and expanded. Thermal stress appeared and increased with the increasing temperature continuously. The temperature of the core reached 300 °C at $t_1$, and load applied on the specimen increased form $0.2F_m$ (16 kN) to $F_1$ (53.01 kN). The time $t_1$ to $t_2$ was the constant temperature stage, and the load increased to $F_T$ (75.23 kN) at $t_2$. After $t_2$, the specimen was loaded to failure at $F_{T_{max}}$ (98.29 kN).

Under the constrained conditions, due to the thermal stress, thermal crack formed in the mortar specimen and reduced the strength. For the loading beginning at $t_2$, the load increased from $F_T$ to $F_{T_{max}}$ quickly, and in most conditions, $F_{T_{max}}$ was higher than $F_m$, but the increasement of the load was less than that under the unconstrained conditions.

On the other hand, under the unconstrained conditions, the specimens could expand freely, there were no temperature stress. So as the loading beginning at $t_2$, the load increased from 0 to the peak load $F_m$, then the specimen failed.

The reasons for the mechanical difference between the stressed and unstressed cement mortar at high temperature were confused. The micro-structure could be damaged by the high temperature. The pore structure coarsened due to the decomposition of the cement hydrate and the evaporation of water [11, 31]. But the preload and the thermal stress would compress and densify the pore structure of cement mortar, which was good for the improvement of the compressive strength [32]. Another reason was the friction between the contact faces of the specimen under the applied preload, which could restrain the thermal cracking of the specimen [18].

4. Conclusions
In this paper, a series of tests were conducted on cement mortar at different temperatures ranging from 20 °C to 600 °C to investigate the mechanical properties of mortar at high temperature. The mortar was heated under different pre-stress ratio. Based on the experimental results, the following conclusions were drawn:

(1) The compressive strength of mortar was affected by temperature and preload. The compressive strength of mortar under the stressed condition has a slower reduction compare with that under the unstressed condition. The compressive strength at 300 °C and 400 °C was the highest in the test temperatures, even higher than that at room temperature.

(2) The peak strain and the post peak strain of mortar under stressed condition was much smaller than that and the room temperature. The failure mode of mortar at room temperature and under the stressed condition was brittle failure. The slopes of the stress-strain under the stressed conditions did not change much compare with that at room temperature.

(3) Concrete is considered to be a composite consisting of mortar and coarse aggregate, the stressed compressive strength was higher than that unstressed which might be a reason for the improvement of
stressed compressive strength.

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