



Thermal degradation of dynamic compressive strength for two mortars

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HIGHLIGHTS

- The CT values for two mortars decrease with the increase of temperatures.
- The damage variable is introduced to quantify the thermally induced damage.
- The dynamic compression experiments are performed using the SHPB system.
- The dynamic UCS increases with the loading rate and decreases with the temperature.
- A formula is used to describe rate dependence and thermal effect on dynamic UCS.

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ABSTRACT

Concrete-like materials are prone to simultaneous high temperature and blasting or impact load. Effects of thermally induced damage on the dynamic mechanical properties of concretes are thus paramount for hazard mitigation and blasting-proof design of concrete structures. We investigate the influence of thermally induced damage on the dynamic uniaxial compressive strength (UCS) of two mortars. The specimens were manufactured in cylindrical shape and heat-treated at 150 °C, 250 °C, 350 °C, 450 °C, 600 °C and 850 °C, before being tested at room temperature of 25 °C with a split Hopkinson pressure bar (SHPB) apparatus. X-ray Computer Tomography (CT) scanning was used to quantify the thermally induced micro-cracks and chemical changes of two mortar specimens in terms of the average CT value. In addition, P-wave velocities and densities of two mortars were also measured before dynamic tests. The CT value, P-wave velocity and density decrease with the increase of the heat-treatment temperature. These observations are explained by the evolution of micro-structures such as the increase of micro-cracks and the undesirable chemical reactions in the mortar specimens. The results of dynamic tests show that the dynamic UCS increases with the loading rate and decreases with the increase of the heat-treatment temperature. The thermally induced damage is a combination of (a) the thermally induced micro-cracks and various chemical changes (which is characterized by the CT value), and (b) the deterioration of the binding property of reaction products. Thus the damage variable is introduced to quantify the thermally induced damage for two mortars. The formula for describing the dependence of the dynamic UCS on the thermal effect and the loading rate effect is established using the damage variable. The formula predicts the trend of the dynamic UCS for two mortars well.

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1. Introduction

More and more structures may be subjected to high temperatures (e.g. tunnel or building fire, geothermal energy extraction, and deep burial of nuclear wastes) and inevitably to impact or

explosive loading (such as chemical or gas explosions in factory, operational blasting, or terrorist attacks). Thus critical infrastructures have a risk of being simultaneously exposed to high temperature and blasting or impact loads.

Both ordinary and high performance concretes (e.g. high strength concrete (HSC), high-workability concrete, high-durability concrete and radiation shielding concrete) are widely used in the construction industry [1–31]. The exposure to high temperature would not only deteriorate the microstructures of

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concrete materials, but also lead to a significant adverse influence on the dynamic mechanical properties of concrete materials. Therefore, the accurate determination of dynamic response of concretes after exposure to high temperature at a wide range of loading rates is desirable for the improvement of impact resistance of buildings, the successful protection of defense structures and the effective destruction of military targets [1–6,31].

The behaviors of cement paste, mortar, ordinary and high performance concretes exposed to high temperatures have been extensively studied [1–39]. These studies revealed that both the compressive and tensile strengths of concretes or mortars under quasi-static loading decrease with the increase of temperature in “hot-test” strength testing (i.e. samples tested at elevated *in situ* temperature) [19,20,32–34,36–38] or with the increase of the heat-treatment temperature in residual strength testing (i.e. samples heated first, and then cooled and tested at ambient temperature) [1,2,7–17,21,22]. In addition, thermal-stressing due to the increase of ambient or heat-treatment temperature substantially influences a wide range of physical properties (e.g. porosity, permeability, ultrasonic wave velocity, elastic modulus, Poisson's ratio) [1–20,22–30,39]. Furthermore, many investigations indicated that the combination of two main mechanisms generally contributes to the deterioration of strengths and physical properties of concrete and mortar exposed to high ambient and heat-treatment temperature [1,9,17,20,22,24,25,40,41]: (a) thermal micro-cracking (thermal gradients during the heating and cooling, anisotropic thermal expansion within individual minerals, and the mismatch in expansion between the different minerals in the concrete aggregate [17,20,41–43]) and (b) chemical changes in the cement matrix (e.g. the dehydration of calcium silicate hydrate ($\text{CaO-SiO}_2\text{-H}_2\text{O}$ gel or C-S-H gel) at about 150 °C [22]; the dehydroxylation of calcium hydroxide (Ca(OH)_2 or CH) at around 400–450 °C [29]; α/β transition in quartz at 573.5 °C [1,44]; the decarbonation of calcium carbonate at about 700 °C [45,46]). Both the strengths and physical properties of the concrete or mortar generally decrease at elevated temperatures due to the thermally induced damage, which is attributed to severe micro-cracking and chemical changes in the concrete or mortar. Thus the quantification of thermally induced damage of concrete or mortar is essential to the interpretation of the macroscopic experimental observations of strengths and physical properties.

The traditional methods for observing the damage in rock-like material, such as acoustic wave measurement [1,47] and the optical or electronic microscopic method [42,48,49], are insufficient to provide the 3D information of the thermally induced damage. Recently, the flourishing development of 3D X-ray micro-computed tomography (CT) technique provides a non-destructive method examining the physical properties (such as air-void space, spatial distribution, clogging, fracture density, fracture volume, fracture distribution etc.) and failure mechanics of rock-like material [50–59], especially the damage evolution of granite [51,56] and the pore structure and fracture inside the heat-treated sample of rock-like material [57–59]. Thus in this study, the thermally induced damage in the heat-treated concrete or mortar is systematically quantified using 3D X-ray CT method.

There have been a number of studies on the dynamic compressive strength of concrete or mortar exposed to elevated temperatures under impact or blasting loading. These studies showed that under various temperatures, the effects of strain-rate on the compressive strength of concrete or mortar are significantly different [60–64], and both the strain rate and temperature can influence the peak strain and the stress-strain curves of concrete or mortar [62–67]. For example, He et al. [61] demonstrated that the dynamic properties of concrete at elevated temperatures tend to be more strain-rate sensitive with the increase of high temperature except for 200 °C. Soroushian et al. [67] stated that the

mechanical strain under dynamic loading is less than the static strain, and the failure strain of concrete decreases with the increasing of failure strain rate. Liu et al. [60] indicated that the enhancements of strain rates on the compressive strength of concrete significantly depend on temperatures, and both strain-rate and temperature can enhance the peak strain of concrete. Huo et al. [63] showed that there is no obvious effect of temperature and strain rate on the shape of the ascending branches of normalized stress-strain relation curves of concrete after exposure to high temperatures.

Furthermore, some investigations revealed that the elevated temperature and strain rate have a complex and nonlinear effect on the compressive strength of concrete and mortar. Li et al. [62] reported that the dynamic compressive strength of an limestone aggregate concrete at elevated temperatures up to 400 °C slightly changes compared with that of at room temperature, while the decrease in the dynamic compressive strength becomes significant with the temperature increasing from 400 to 800 °C. Huo et al. [64] indicated that the strain-rate effects on the compressive strength of concrete at 200 °C and 300 °C are obviously higher than the effect at room temperature. The strain-rate effects of concrete at 600 °C and 800 °C deteriorate sharply compared with those of concrete at lower temperature than 600 °C. Chen et al. [65] stated that the dynamic strength of normal weight concrete at high *in situ* temperature still experiences remarkable strain-rate effects. In summary, most of the previous studies showed that the dynamic compressive strength of concrete and mortar generally increases significantly with the strain/loading rate [5,6,67–72], and the dynamic compressive strength of concrete usually decreases with the increase of temperature although discrepancies exist due to differences in material and dimensions of the specimen and the measurement method [61,62,72,73]. However, the coupled effect of the thermally induced damage and the loading rate on the dynamic compressive strength of concrete-like material has yet to be quantitatively determined, which is important for the numerical analysis and safety design of infrastructures.

From the above discussion, it can be concluded that despite of the existing research efforts on the effect of elevated temperatures on the dynamic behaviors of concrete or mortar, there is no attempt to systematically quantify the thermally induced damage due to elevated temperatures and to establish a quantitative relationship between the dynamic compressive strength of concrete or mortar and the thermally induced damage. Therefore the objective of this work is to fill such a research gap. To achieve that goal, the dynamic uniaxial compressive strength (UCS) of two mortars at different heat-treatment temperatures is systematically measured using the split Hopkinson pressure bar (SHPB) system. The thermally induced damage is a combination of (a) the thermally induced micro-cracks and chemical changes, and (b) the deterioration of the binding property of reaction products. The thermally induced micro-cracks and chemical changes are measured prior to the dynamic test using the 3D X-ray micro-CT method. The deterioration of the binding property of reaction products is obtained with back analysis. A damage variable is introduced based on the CT value and back analysis to quantify the damage due to heat-treatment temperature for the two mortars. In the last, a quantitative relationship between the dynamic UCS and the thermally induced damage and the loading rate is established.

The paper is organized as follows. After the introduction, Section 2 presents the sample preparation process of two mortars. The characterization results of two mortars after different heat-treatment temperatures are detailed in Section 3. Section 4 introduces the principles of SHPB system and the dynamic compression test, and the experimental results and the empirical relationships between the dynamic UCS and the thermally induced damage of

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