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Influence of heating on the dynamic tensile strength of two mortars: Experiments and models

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ABSTRACT

The dynamic tensile failure mechanism of concretes after high-temperature exposure is important for evaluating the material load carrying capacity and for reinstating thermo-damaged structures. We investigate the influence of thermal damage on the dynamic tensile strength of two mortars. The Brazilian disc (BD) mortar specimens are heat-treated at temperatures of 150 °C, 250 °C, 350 °C, 450 °C, 600 °C and 850 °C. The thermal damage of two mortars is then quantified via the CT values measured using the X-ray Computer Tomography (CT) technique, the P-wave velocity and the density. These quantities are observed to decrease with the increase of the heat-treatment temperature, which can be explained by the increase of microcracks, the undesirable chemical changes and the deterioration of the binding capacity. Dynamic tension tests of untreated and heat-treated BD specimens are then conducted at room temperature with a split Hopkinson pressure bar (SHPB) apparatus. The results show that the dynamic tensile strength increases with the loading rate and decreases with the increase of the heat-treatment temperature. The damage variable based on the CT value is introduced to quantitatively describe the thermo-induced damage for two mortars. The effect of the loading rate and the thermal damage on the dynamic tensile strength is further represented through an empirical formula in terms of the damage variable. In the last the experimentally obtained dynamic tensile responses of the mortars with and without thermal damage are interpreted using the Dominant Crack Algorithm (DCA) model. The DCA model parameters for the mortars are obtained and their dependences on the heat-treatment temperature are analyzed.

1. Introduction

Ordinary concrete infrastructures may be exposed to high temperatures in applications such as geothermal energy extraction and fire accidents, and barite based radiation shielding constructions for deep burial of nuclear wastes may also be commonly subjected to high temperature up to 400 °C [1–3]. The exposure to high temperature has a distinct influence on both the microstructures and the mechanical properties of concrete-like materials and therefore may contribute to failures of these concrete structures [4–12]. Further these structures may be subjected to impact loads caused by gas explosions, operational blasting, earthquakes and terrorist attacks [13,14]. It is therefore desirable to understand the dynamic failure mechanism of concretes after high-temperature exposure. As tensile failure is the main failure mode of concrete-like materials [15], the accurate determination of the dynamic tensile strength of concrete-like materials after exposure to high temperature is critical [15–17].

A number of researchers have investigated the properties of various types of concrete-like materials (e.g. ordinary concrete, high performance, radiation shielding concrete, cement paste and mortar) after exposure to high temperatures [1,6,10,11,15,18–24]. These studies have revealed that due to the increase of heat-treatment or ambient temperature, the material tensile strength under static loading is significantly reduced and other physical properties (e.g. porosity, permeability, ultrasonic wave velocity, elastic modulus, Poisson's ratio) are considerably changed [1,5–7,9–12,15,16,18,22–28]. The deterioration of these mechanical and physical properties of concretes has been attributed to the microstructure changes and internal chemical reactions due to heating [9,16,22,25,29,30]. First, the heat-treatment could induce the micro-cracking as a result of thermal gradients and the thermal expansion anisotropy of minerals [7, 24]. It could also trigger the chemical changes in the cement matrix: the dehydration of calcium silicate hydrate (C-S-H) gel at about 150 °C [16], calcium hydroxide (CH) decomposition from 400 to 450 °C [30], the decarbonation of calcium carbonate at 700 °C [4]. The micro-cracking and chemical changes are responsible for the material thermal damage.

Researchers have also investigated the effect of heat-treatment on the dynamic tensile strength of concrete and mortar [31–33]. Yagishita

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et al. [31] conducted dynamic tension tests of concretes with split Hopkinson pressure bar (SHPB) system. The results showed that the dynamic tensile strength of concretes in the range of 10^{-6}/s – 60/s is reduced when the temperature increases from 20 °C to 90 °C. Yan and Lin [32] used the dumbbell shape specimen to measure the tensile strength of concrete in the range of 10^{-5}/s–1/s and concluded that at a low temperature of −30 °C, the tensile strength is less sensitive to the strain rate as compared with that under room temperature condition. Caverzan et al. [33] investigated the uniaxial tensile strength of high-performance fiber reinforced cementitious composites after high-temperature exposure up to 600 °C at low (10^{-6}/s–1/s) and high (150/s–300/s) strain rates. They found that for all temperatures investigated, the tensile strength weakly increases at low strain rate and remarkable increases at high strain rate. In summary, the existing studies have shown that the dynamic tensile strength of concretes or mortars is rate dependent and the temperatures elevation has a significant influence on the dynamic tensile strength of concretes or mortars [34–36].

Despite of existing research efforts, the thermal damage of concretes due to elevated temperatures has not been systematically studied. It is desirable to develop a quantitative relationship between the thermal damage and the dynamic tensile strength of concrete-like materials [24]. To achieve such goal, an ordinary mortar and a barite based radiation shielding mortar are chosen in this study. The dynamic tensile strength of these two mortars with and without heat-treatment is systematically measured using the SHPB system. Before the dynamic test, the CT values of two mortars at different heat-treatment temperatures are accurately measured using the X-ray micro-computed tomography (CT) method [13,37,38]. Two types of thermal damage mechanisms are identified: (a) the thermally induced microcracks and chemical changes in grains and (b) the deterioration of the binding capacity of C-S-H gel. A damage variable is proposed to quantitively describe the thermal damage in the mortars based on the CT value and the damage mechanisms. Using the damage variable, an empirical formula is developed to quantify the effect of the thermally induced damage and the rate dependence of the dynamic tensile strength for two mortars. Finally, the Dominant Crack Algorithm (DCA) model is adopted to predict the dynamic tensile failure response of the mortars with thermal damage.

After the introduction, Section 2 presents the preparation and characterization of the thermal damage of the mortar specimens. The principles of dynamic tension test using the SHPB system is given in Section 3, and Section 4 discusses the experimental results and illustrates the empirical relationships between the dynamic tensile strength and the thermal damage of the mortars. The dynamic tensile response of the thermally damaged mortars predicted using the DCA model is described in Section 5. Section 6 summarizes the entire paper.

2. Sample preparation and characterization

As mentioned above, both ordinary concrete and radiation shielding concrete are concerned in this study, we thus prepared two mortars to mimic these two types of concretes. The mix proportions of these two mortars are listed in Table 1 [13,39], where Mortar 1 is an analog of radiation shielding concrete and Mortar 2 is a commercially available ordinary mortar. Ordinary Portland cement (PC) (with a specific gravity of 3.15 g/cm^3) is used here because of its commercial availability and wide applications to the civil structures [40]. The water/cement ratio is 0.28 for Mortar 1 and 0.41 for Mortar 2. The particle size distribution of sand can be found in our early study [13] and all the sand particles are smaller than 4.75 mm. The specific gravity of sand is 2.43 g/cm^3. Meanwhile, barite powder (with a specific gravity of 4.2 g/cm^3) is chosen in radiation shielding Mortar 1 since barite is an excellent radiation barrier material used in radiation shielding constructions [1–3]. The mean particle diameter of the barite powder in this study is 24.86 µm, and 90% of the barite powder particles are smaller than 56.26 µm. In addition, the relative volume of the aggregate and cement is 3.4 for Mortar 1 and 1.7 for Mortar 2. Furthermore, the physical properties of two mortars at the age of 28 days are given in Table 2 [13,39], in which these properties were measured as soon as practicable in the same ambient condition to reduce the moisture influence. One can see that the distinct mix proportions of two mortars generally lead to different physical properties.

Table 1
Mix proportions for two mortars.

	Material	Proportion (by weight)
Mortar 1	Sand	0.62
	Type 10 PC	0.25
	Water	0.07
	Barite ($BaSO_4$)	0.06
Mortar 2	Sand	0.48
	Type 10 PC	0.37
	Water	0.15

Table 2
Summary of physical properties of mortars.

Material	P-wave velocity (km/s)	S-wave velocity (km/s)	Density (g/cm^3)	Poisson's ratio	Young's modulus (GPa)
Mortar 1	4.70	2.27	2.43	0.35	33.85
Mortar 2	4.20	2.26	2.15	0.30	28.45

In this study, the block mortar specimens were first cured for 28 days in a curing room with a standard temperature of 23 ± 2 °C and approximately 100% relative humidity [41], and then mortar cores with diameter of 40 mm were drilled from the block. Brazilian disc (BD) specimens with a 40 mm diameter and 20 mm thickness were then prepared according to the International Society for Rock Mechanics (ISRM) suggested method for measuring the dynamic tensile strength of rock-like materials [42,43]. For each mortar, six groups of BD specimens thermally treated at 150 °C, 250 °C, 350 °C, 450 °C, 600 °C and 850 °C and one reference group of BD specimens without heat-treatment were prepared. The specimens were thermally treated under different heat-treatment temperatures in a servo-controlled electrical furnace with a 2 °C/min heating/cooling speed to avoid cracking due to thermal shock [44]. After the anticipated temperature was reached in the furnace, the specimens were kept at the corresponding temperature for 2 hours to ensure a uniform temperature field was obtained inside the mortar specimens [45].

After the heat-treatment, mortar samples were scanned by using X-ray micro-CT technique to investigate 3D thermal damage (e.g. microcracking and chemical changes) under different heat-treatment temperatures [6,7,9,16]. 3D X-ray micro-CT scans were conducted using a GE Micro-CT system with an 80 W X-ray source at 80 kV at Spatio-temporal Targeting and Amplification of Radiation Response (STTARR) in Canada. As shown in Fig. 1, X-rays propagate through the sample with a fan geometry from the X-ray source and are collected by a detector. 2D image slices from projections are reconstructed to produce a 3D structure. It is well known that the attenuation of the X-ray is different when passing through different material compositions, thus leading to various gray-levels in the CT images. As the CT image in Fig. 1, microcracks and minerals in the specimens is reflected by the gray-level of the pixel and the CT value (Hounsfield radiological density) is calculated from the gray-level data of the CT images after scaled with standard materials (−1000 *Hu* for air and 0 *Hu* for pure water). Therefore, the CT value variation represents the changes of microstructures in the materials, and in this study, the thermally induced damage due to microcracks and chemical changes in the specimens is quantified by the CT value [46]. The details of the CT value calculation process can be found in our previous work [13,47].