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Experimental and modeling study of dynamic mechanical properties of cement paste, mortar and concrete

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HIGHLIGHTS

- Compressive behaviors of cement-based materials are sensitive to strain rate.
- Existing relations of dynamic increase factor (DIF) are discussed.
- A compressive constitutive model with strain rate effects was modified.

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ABSTRACT

Understanding the strain rate effects on cement-based materials are important for accurately modeling concrete structure damage to high-velocity impact and blast loads. This paper reports experimental results of the strain rate effect on paste, mortar and concrete. A pulse-shaped split Hopkinson pressure bar (SHPB) was employed to determine the dynamic compressive mechanical responses and failure behavior of paste, mortar and concrete under valid dynamic testing conditions. Quasi-static experiments were conducted to study material strain rate sensitivity. Strain rate sensitivity of the materials is measured in terms of the stress–strain curve, elastic modulus, compressive strength and critical strain at peak stress. Empirical relations of dynamic increase factor (DIF) for the material properties are derived and presented. A compressive constitutive model with strain rate and damage effects was modified to accurately describe the dynamic compressive stress–strain curves of the materials.

1. Introduction

The response of concrete to dynamic loading is of interest in a variety of civilian and military applications. Understanding the response of concrete to impact or explosive loading is important for the successful destruction of military targets and for the effective protection of defense structures [1–3]. For example, the protective shells of nuclear power plants are expected to survive the impact loading of an incoming missile or other sources [4]. Airport runways must withstand repeated dynamic loading due to aircraft takeoff and landing. Dynamic loading on concrete structures arising from natural hazards such as tornadoes, earthquakes and ocean waves is also of great practical concern. Characterization of the behavior of concrete under impact or impulsive loading is a prerequisite for the design and analysis of these structures.

The strain rate sensitive behavior of concrete has been under investigation for several decades [5–7]. The rate sensitivity has generally been measured in terms of the strength [8–12], elastic modulus [13–17], or the strains at the maximum stress [18–21] in compression. In spite of the considerable number of studies on the rate sensitivity of concrete and its constituents, there are significant disagreements. The disagreements can sometimes be attributed to changes in test conditions, such as the moisture content of specimens, the curing conditions, or the range of strain rates used. For example, the insignificant increase in compressive strength with increasing strain rate observed by Scott et al. [22] was most widely due to the low moisture content of their specimens, caused by storage in air in 10 weeks. Some investigators [7,8] has suggested that the strain rate effects are more significant in high strength concrete, while others [15,20] have concluded from test results that the concrete compressive strength has no influence on the strain rate tests. There is little agreement among researchers on the rate sensitivity behavior of the strain at maximum stress. Some have found it to increase [17,19], while others have found it to remain almost constant [14] or even decrease [23,24] with increasing strain rate.

Various experiments devices have been used to explore a wide range of strain rates. Compression tests have been performed, from static loading up to strain rates of $10^{-1}\ s^{-1}$, with a hydraulic servo-controlled testing machine [25–28]. With drop weight impact tests, rates of $10^{-1}\ s^{-1}$ may be reached, but the energy transmitted

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to the specimen by the size of device [21,29,30]. Higher strain rates as large as $10^2\ s^{-1}$ can be obtained with a split Hopkinson pressure bar (SHPB) test, which has now been very popular. It has been used by various investigators to elucidate the dynamic compressive properties of solid materials, range from hard to soft, isotropic to anisotropic, and homogenous to non-homogeneous [31–35]. Constitutive models that account strain rate effects are very limited. A reliable constitutive model must be supported by reliable and accurate experimental data. However, experimental studies of the dynamic behavior of cement-based materials at high strain rates are still relatively limited. There are still many experimental difficulties associated with the accurate characterization of the dynamic behavior of cement-based materials under valid testing conditions. Although the SHPB has been applied to study the dynamic properties of various materials for many years, it should be noticed that there are conditions to satisfy in order to obtain valid experimental data with a SHPB. A nearly constant strain rate should be maintained during a test because the stress–strain curve of a cement-based material is strongly sensitive to strain rate. Varying dynamic strain rate during an experiment will lead to an inaccurate or even erroneous family of dynamic stress–strain curves for differing strain rates. Pulse shapes have been used to control precise profile of the incident loading pulse used to achieve dynamic stress equilibrium [36,37]. In this paper, a SHPB with a pulse shaper were employed to study dynamic compressive behavior of cement paste, mortar and concrete.

The primary objective of this research was to enhance the understanding of the response of cement paste, mortar and concrete to high strain rate loading. The anticipated results of the study are determination of dynamic material properties, failure mechanisms, and crack patterns of failure in compression. To summarize the experimental results in a concise form, a dynamic constitutive model that accounts for strain rate effects and damage accumulation within the specimen has been modified from an existing model. The material constants associated with the model have been determined using the date from the experiments.

2. Experimental procedure

2.1. Material and specimens

ASTM type I cement was used in the production of paste, mortar and concrete specimens. A common water–cement ratio 0.45 was used for cement paste. For mortar, the fine aggregate was river sand consisting mainly of quartz, with 10% feldspar. The gradation test showed that the particle size of the sand was continuously distributed within the range of 0.4–2.5 mm with 80% of sand. The water–cement ratio 0.45 was also used for cement mortar. The concrete was mixed in the proportion of 1:2:4 (cement: sand: coarse aggregate) by weight with a water–cement ratio of 0.45, using gravel of 9 mm maximum size.

The standard specimens were cast in steel molds with dimensions of 150 mm × 150 mm × 550 mm. Following casting, the specimens were covered with a plastic membrane to prevent the moisture from evaporating. The specimens were de-moulded after 24 h, and then moist-cured in a water tank. After curing for 90 days, the specimens were cored from the standard specimens. Cores were cut and grinded smooth to produce 74-mm-diameter cylindrical specimens of 37 mm in thickness for split Hopkinson pressure bar test.

2.2. Quasi-static compressive behavior

Cylindrical specimens of cement paste, mortar and concrete were tested to failure using ASTM C 39 [38]. During the experiments, the load P applied to the specimen was recorded. The maximum load recorded at specimen failure was used to calculate the failure stress $\sigma_{\max}$, using $\sigma_{\max} = P/A$, where A is the cross-sectional area of the specimen. For quasi-static compression specimens, cylinder size of D74 × 148 mm was used. The cylinder had the same diameter as those used for SHPB tests but with a length/diameter (L/D) of 2.0 to satisfy the requirements of ASTM C 192 [39]. The reasons for selecting such specimen size to determine the quasi-static strength has been discussed in details by Wang et al. [40]. The specimens were tested using a servo-hydraulic material testing machine with a 1000 kN load cell. Fig. 1 shows the stress–strain curve of cement paste, mortar and concrete under quasi-static loading.

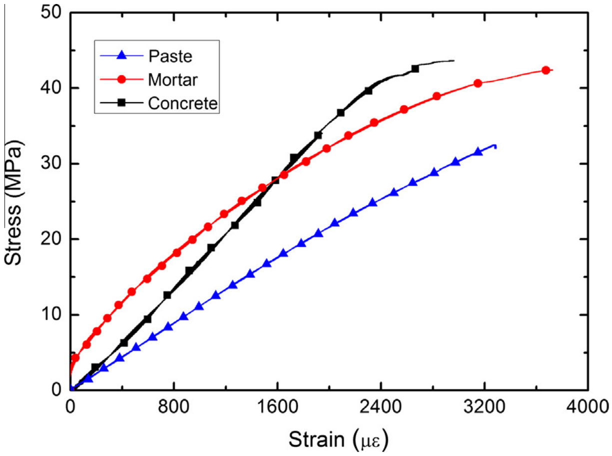

Fig. 1. Static compressive stress–strain curve of specimens.

2.3. Split Hopkinson pressure bar (SHPB) experiments

2.3.1. Basic principle for split Hopkinson pressure bar (SHPB)

A split Hopkinson pressure bar consists of a bullet, an incident bar and a transmitted bar, as shown in Fig. 2. The specimen under investigation is placed between the incident and transmitter bars. The striker bar is launched at a known velocity toward the incident bar. The impact generates a stress pulse in the incident bar which travels toward the specimen. The amplitude of the stress pulse depends on the velocity of the bullet [41,42]. Because of the impedance mismatch between the specimen and the bar, part of the pulse is reflected back into the incident bar as a tensile pulse, and the rest of the pulse is transmitted as a compression pulse into the output bar. Based on one dimensional calculation it has been established that the amplitude of the transmitted pulse is a measure of stress in the specimen and the amplitude of the reflected pulse is proportional to the strain-rate in the specimen. Integrating the strain-rate with respect to time t gives the axial strain in the specimen. Assuming axial wave propagation and homogeneous stress distribution in the specimen, the resulting stress $\sigma_s(t)$, strain $\varepsilon_s(t)$ and strain-rate $\dot{\varepsilon}$ of the specimen are obtained by the following equations [43]:

$$\sigma_s(t) = E_b\left(\frac{A_b}{A_s}\right)\varepsilon_T \tag{1}$$

$$\varepsilon_s(t) = -\frac{2C_0}{l}\int_0^t \varepsilon_R(t)\mathrm{d}t \tag{2}$$

$$\dot{\varepsilon} = \frac{\mathrm{d}\varepsilon_s(t)}{\mathrm{d}t} \tag{3}$$

where A_b, E_b, C_0 are the cross-sectional area, the Young's modulus and the wave velocity of the bar material, and l, A_s are the length and cross-sectional area of the specimen.

2.3.2. Determination for representative strain-rate

The definition of the representative strain-rate in SHPB tests need to be clarified though most publications avoided this issue. Usually, a mean strain-rate is defined as the total strain during loading divided by the total period [17]. However, this averaging definition does not represent the actual strain-rate that may influence the brittle failure of the specimen since the instantaneous strain-rate in an SHPB test can be appreciably higher than the average one [30]. Moreover, the mean strain-rate over the loading period in SHPB test is less relevant to the compressive failure of the specimen than the strain-rate corresponding to the ultimate strength since majority of the loading period is in elastic deformation stage for brittle materials. Zhang et al. [44] introduce another mean strain-rate defined as the average magnitude of the strain-rate histories over a period, in which the strain-rate is within 80% of the strain-rate at the failure point. Their results showed that the mean strain-rate over a defined period is more or less the same as the strain-rate at the failure point. Therefore, the strain-rate at the failure point is used as the representative strain-rate in a SHPB test in the present paper.

2.3.3. Pulse shaping technique

Inherent limitations preclude the use of classical SHPB for compression testing of brittle materials like rocks and concrete. For these materials under uniaxial compression, elastic response is predominant before failure. During SHPB test under compression, these materials can fail before stress uniformly is achieved within the specimen. Thus, modification of the incident pulse to closely match the elastic