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High speed photography technique for measuring impact strength of porous concrete

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HIGHLIGHTS

- An impact strength measurement method based on high speed photography was introduced.
- A reverberation application of dynamic impedance mismatch method was used.
- The method only involved the known dynamic impedance properties and the velocity measurements of the impactor.
- Different types of porous concretes at different frame rates were tested to verify the method.

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ABSTRACT

In this study, an impact strength measurement method based on high speed photography, that has been developed for testing porous concrete, was introduced. In the experiments, a drop weight impact test set-up instrumented with a high speed camera was used. The impact strength analyses were conducted using impedance mismatch method, where the wave reverberations were investigated in detail. The measurement configuration carries the advantage of being a fast, non-contact and accurate experimental method where only the known material properties and particle velocity data of the drop weight are required. The target cementitious material itself is not actually involved in the measurements or the subsequent analyses. The method also facilitates the observation of the crack patterns throughout the experiment. The measurement method was verified to be accurate and consistent by testing different types of porous concretes and by comparing the results with those from other dynamic monitoring techniques, such as laser Doppler velocimetry and direct stress gauge measurements.

1. 1 Introduction

Numerous contact and noncontact measurement techniques have been developed and adopted by researchers to analyze the impact properties of engineering materials. After the first known experiment using high speed photography, conducted by Talbot in 1851, high speed photography has been a topic of research in dynamic testing [1]. Since then, vast developments in high speed photography techniques and devices have taken place [2–5]. Laser interferometry is another high technology method for monitoring the motion of specimens under impact using several different experimental set-ups. The method is capable of monitoring very high velocity impact [6–11]. Other than non-contact measurement methods, using in-material stress transducers, such as piezo-resistive stress gauges, is another technique that is extensively used in planar impact studies [12,13]. For piezo-resistive stress gauges, the change in resistance as a function of applied pressure is linear up to extremely high pressures [14–16].

High-speed photography has been used for monitoring a numerous dynamic events in various disciplines. In several research studies, it has been used to examine the dynamic failure mechanisms to better understand the failure modes that are present [3–6]. It has also been used to acquire and quantify the deformation history of the whole specimen itself or particularly the vicinity of a dynamically growing crack-tip in impact tests [17–19]. It has also been utilized in plate impact experiments. In those studies, the planar compression, that induces a uniform region of strain behind a shock front in the target medium, is visualized based upon high-speed photography [20]. High speed photography is effectively being employed in the mechanical tests of cementitious materials as well. In the pioneering applications, it was used

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in examining the crack patterns and failure modes [21,22]. Since then, it has been used in concrete testing, especially in ballistic impact studies [23]. In high speed photography studies, digital image correlation is frequently used to analyze the digital image data with the aid of displacement and strain field estimation algorithms [24].

In this study, high speed photography measurements and the subsequent analyses, which have been conducted for quantifying the impact strength of porous concrete, were introduced. The method also facilitated the visualization of the fragmentation behavior of the material. The results attained using high speed photography were also compared with the results obtained using Laser Doppler Velocimetry (LDV), which is a method based on laser interferometry [25,26]. One of the porous concrete mixtures was also tested using piezoresistive (manganin) stress gauges and the results were compared with those from high speed photography. Stress gauge measurements were used as a verification because, provided that the calibration of the gauges is done properly, the impact stress is directly measured using stress gauges without any further analyses.

2. Hi-speed photography investigations

Porous concrete is a special type of concrete designed for a high meso-scale pore content. Owing to its porous structure, it is preferred in several different applications that necessitate properties such as water permeability and noise or thermal insulation [28–32]. To be able to attain a highly porous material, the mixture content as well as the casting method of porous concrete have to be different from normal concrete. In terms of mixture design, gap-graded aggregates and a low cement paste content are the main features, while the concrete should be compacted in layers because the workability of such a mixture is usually very low.

Protective structures, such as safety walls outside important buildings or munition magazines for storing explosives, which have a higher probability to experience extreme dynamic loadings i.e., explosions, during their service lives have to be designed by also considering the mitigation of hazard. Because in case of an explosion, the large concrete fragments broken from the structure are sometimes as fatal as the explosive itself. With this goal, a PhD project was undertaken on designing and analyzing a cementitious material with sufficient static strength to carry the service loads and fractures into small-size fragments when subjected to an explosion [33]. The design procedure of such a material, the static and dynamic experiments and the respective numerical analyses were the main investigations that have been undertaken. During the research, a sensitivity study was conducted on various forms of cementitious materials and enhanced strength porous concretes fracturing into small fragments when exposed to impact loading, were obtained and analyzed. In the process of designing a material with desired dynamic performance, accurate but also repeatable and fast dynamic testing techniques were highly required. Various experimental configurations were adapted and introduced for determining the dynamic response of porous concretes in a drop weight impact test. This paper concentrates on a new measurement technique based on high speed photography, that has been introduced to test porous concretes in the design process. The measurement configuration is fast and accurate while it also provides important visual information in terms of the fragmentation of the material. The stress gauge measurements that have been conducted were also presented in the paper because they provide more direct stress data even though there are some disadvantages that should also be considered when evaluating it as a testing method for a material design process, which was mentioned in detail in Section 4.1.

In the research, series of experiments were performed on porous concrete samples to measure their impact strengths and observe their fragmentation behaviors using high-speed photography. In high-speed photography measurements, monitoring the displacement of the impactor was the key feature [34]. The impact strength analyses were then performed by defining the wave reverberation situation using the impedance mismatch method.

2.1. Hi-speed photography test set-up and measurement method

To conduct the impact tests, a drop weight impact test set-up was used. The set-up included a steel base structure, which functioned as a steel buffer plate, that is also a wave sink. The concrete sample was placed on the steel base structure. A steel impactor was dropped from approximately 1.2 m, which corresponds to impact velocities between 4.3 and 4.5 m/s. The test set-up is shown in Fig. 1. The high speed camera was located about 1.5 m from the sample. It was placed in a shielding container to protect it from the scattering fragments of concrete during testing. In the high speed photography experiments, the displacement measurements were taken on a fixed point on the impactor (see Figs. 2–4). In order to monitor the point more clearly, a retro-reflective sticker band, with a 4 mm thickness (see Figs. 2–4), was attached on the lateral surface of the impactor. The rest of the impactor was painted in black to maximize the contrast. In the experiments, a Phantom V 5.0 digital high speed camera with a sensor size of 1024 × 1024 pixels was used. It had a variable exposure independent of the sample rate down to 10 microseconds. The framing rate of the camera could be varied between 1000 and 10,000 frames per second (fps). Because the total recording time depends on the frame rate and the size of storage medium, at 6134 fps the recording time was about 3 s while at 10,000 fps it was about 1.85 s. Since all the collisions had a duration which is orders of magnitude less than such times, those recording times were sufficient in all the tests conducted. In terms of using the available amount of memory for the higher frame rate measurements, taking partial frames was a solution. Therefore, at 10,000 fps frame rate, smaller size images were taken compared to 6134 Hz. This can be inferred from the comparison of Figs. 3 and 4.

Light sources are very important in high speed photography. The time that the imaging sensor is exposed to light depends on the frame rate and, therefore, the shutter time, as well as the available light source [35,36]. Short exposure times require a substantial intensity of illumination. In order to overcome the problems of illumination especially at the frame rate of 10,000 fps, three halogen work lamps were placed at three free sides of the test set-up.

To be able to follow a fixed point on the sticker, the images acquired by the high speed camera were first converted to black and white or binary images by taking a global image threshold as reference using the image processing toolbox of MATLAB. In a black and white image, each pixel has a discrete value (either 0 (black) and 255 (white) or similarly 0 and 1 in binary format). The image that is expressed in pixel coordinates is represented with a grid of elements as shown in the schematic presentation in Fig. 2. Pixel coordinates take values that are integers between 1 and the dimension of the row or column. The pixel coordinates and the spatial coordinates, that show the actual coordinates, do not correspond to each other on a one-to-one basis. However, by default, the toolbox of the program itself uses its own spatial coordinate system for an image and that coordinate system can directly correspond to the pixel indices of the image. This is called the intrinsic coordinate system of the program [37].

The x and y coordinates given in the inserts in Figs. 3 and 4, showing the upper and lower edges of the sticker, are the values that belong to that intrinsic coordinate system. They are not the