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Suggested continued heat-treatment method for investigating static and dynamic mechanical properties of cement-based materials

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HIGHLIGHTS

- To investigate mechanical properties of mortar subjected to continued heat treatment.
- To simulate a more accurate predictive formula using a continuous equation.
- To find critical damaged points using a more accurate predictive formula.
- To investigate the feature width of process zones using acoustic emissions.

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ABSTRACT

Thermo-induced damage affects the structural and material safety of civil engineering structures; the damage can induce direct or indirect extensive structural collapse.

An innovative continued heat-treatment method to obtain several specimen pieces in a single cylinder of mortar was described in this paper; the intended purpose of the method was to predict the effects of heat treatment on the static and dynamic mechanical properties and characteristic width of process zones.

All of the results can be regressed by a continuous equation; therefore, the regression equations obtained from the results of continued heat-damaged specimen pieces represented more accurate prediction equations. Moreover, using the Log–Log method resulted in a critical damage temperature of approximately 547.5 °C. For a temperature range between room temperature and approximately 547.5 °C; the variation of all of the mechanical properties decreased by approximately 10–11% per 100 °C, but they decreased by approximately 29–31% per 100 °C between 547.5 °C and the highest temperature used in the tests. Finally, the fracture characteristics and the width of the process zones could be investigated using the acoustic emission technique; the width was wider at lower temperatures than at higher temperatures.

1. Introduction

Thermal effects are an important factor in various aspects of material engineering, such as building/tunnel fire design, geothermal energy extraction, and nuclear waste storage. Previous studies have investigated the effect of heat treatment on various mechanical properties, including P-wave velocity and compressive and tensile strength and the fracture toughness of cement-based materials, such as mortar [1], concrete [2], and high-performance concrete [3–6].

Heat treatment changes mortar components chemically and physically. At temperatures of approximately 200 °C, the C–S–H in cement becomes C–S + H_2O. At approximately 500 °C, the $Ca(OH)_2$ in cement becomes CaO + H_2O, and the cement volume decreases by 0.5%. Quartz, which is the main component of siliceous aggregate, changes from α to β phase and increases in volume by 0.4% at approximately 573 °C [7].

Furthermore, Li and Marasteanu [8] and Pirmohammad and Ayatollahi [9] previously used the SCB method to study asphalt and mixed concrete with low-temperature and mixed-mode fractures, respectively. The final test results showed that the SCB method achieved fracture-toughness results that were equivalent to the results obtained by common methods. Yin et al. [10] investigated the effect of thermal treatment on the dynamic fracture

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toughness of Laurentian granite (LG). Their results showed that fracture toughness decreased with the loading rate but increased with the treatment temperature. In addition, Young et al. [11] investigated the fracture toughness and velocity of Westerly granite subjected to five unitary temperatures; they indicated that the biggest drop in the toughness and velocity occurred between 450 and 650 °C, again probably as a result of the α to β quartz phase transition. Funatsu et al. [12,13] studied the fracture toughness of rock under increasing temperatures and confining pressure; they found that under a confining pressure of 7 MPa, the fracture toughness of sandstone decreased with temperatures up to 75 °C and then increased between 75 °C and 100 °C.

However, those previous studies conducted mechanical experiments (i.e., beam test) on specimens heated to discrete and unitary temperatures in a furnace. Furthermore, the experimental method in those studies could not capture accurate critical damage points (Fig. 1). Consequently, the temperature and response spectrum, which is critical for measuring fracture strength, has yet to be reliably simulated using mathematical equations.

Thus, the authors propose a new method for preparing specimens, particularly cement-based materials, for heat treatment (Fig. 1). This method allows us to use the heat conduction method to obtain several experimental pieces from one sample column with different steady-state temperature ranges and with damaged specimen slices showing continuous variation. In this paper, we used a single cylinder sample with continued temperature distributions to produce several test specimen slices. Hence, each of the specimen slices was also produced with continued temperature distributions. For this method, several specimen slices with continued thermo-induced damage could be obtained from a single cylinder sample, representing continued damage in each specimen slice. Certainly, the mechanical response of each specimen slice is also a comprehensive result because of its continuous temperature region within every specimen slice. As a result, we can obtain a continued damage investigation, as shown in the figures of this paper.

There are several advantages using this method. First, the differences in the composition of the materials are eliminated and allowed to obtain continuous damaged specimen slices. In previous research, many specimens were subjected to different temperatures in a furnace. However, those specimens were not often obtained from unitary material mass; instead, they were produced individually in a lab. The productions have differences in their material properties (e.g., P-wave velocity, strength, etc.) between individual productions because they are not the same material. As a result, to avoid these differences in the properties of the materials in this paper, we used a single cylinder sample for acquiring several specimen slices, implying that we can acquire more uniform experimental specimen slices and that the differences between experimental specimen slices will be eliminated before obtaining created damaged specimens. Then, this method permits the precise description of the target output parameters (e.g., indirect tensile strength, fracture toughness, etc.), and the simulation of the prediction equation (e.g., indirect tensile strength, fracture toughness, etc.) from experimental results is permitted by a continuous mathematical function. Finally, the identification of the critical damage point was obtained from an experimental regression equation using the Log–Log method proposed by Jose et al. [14]. They obtained a point of intersection by expanding two straight-lines from both sides of a regression curve under Log–Log coordination. The intersection point corresponds to the critical damage temperature. Considering the critical damage temperature is a reference point, two situations will be defined for the discussion of the percentages of decreasing strength in this paper: room temperature to the critical temperature (situation 1) as well as the critical temperature to the highest temperature used in this research (situation 2).

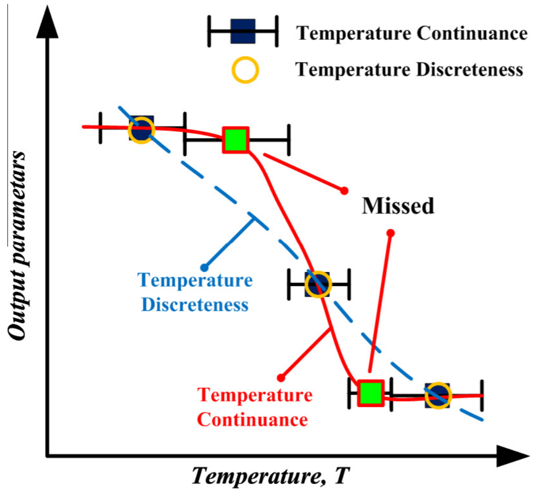

Fig. 1. Schematic of output parameters with temperature discreteness and continuance.

This paper discusses the behavior of the materials using the static-mechanical (indirect tensile strength and fracture toughness) and dynamic-mechanical (dynamic elastic modulus and Poisson's ratio by calculating with P- and S-wave velocity) parameters of continued-heat treatment with the above-mentioned method.

Generally, the notched-bend [2,15–17], double-cantilever beam [18], and wedge-splitting test methods [19] were previously used to assess the fracture toughness of cement-based materials. Nevertheless, because these two methods are not valid for use on specimens subjected to continued-heat treatment, we suggested the use of the semi-circular bend method (SCB) as an alternative approach; The theoretical model and its applications of SCB have been studied by several researchers [8,20–33].

The authors used indirect-tensile and semi-circular bend methods to obtain indirect tensile strength and fracture toughness with continued-heat treatment. Moreover, the acoustic emission sensors were attached to SCB specimen surfaces during the tests to investigate the fracture characteristics and the width of the process zone.

In this paper, all of the experimental results that were obtained also seem "discrete". Nevertheless, the distribution of temperature within each specimen slice was continuous because the slice was obtained from a single cylinder sample with continued-heat treatment. The thermo-induced damage within the single-cylinder specimen is continuous, such that the thermo-induced damage in each experimental slice from the single-cylinder specimen is also continuous. As a result, each experimental result of the slice is also a reflection of the continued temperature. Although the results displayed discrete data, they were a continued performance of mechanical behavior. Essentially, we want to emphasize the concept of continuity. Each result with a temperature region from an experimental slice was drawn in this paper. The temperatures on the boundaries of each slice are continuous or overlap (obtained from repeated testing). The temperature is without intermission, and in this study, most of the temperature results included from room temperature to the highest designated temperature. Thus, the results are not "discrete". Conversely, with the traditional method, putting a slice of the specimen into a furnace obtained unitary temperature specimen slices, and the temperature between every slice was "discrete" along with "discrete" thermo-induced damage. If the material properties rapidly decayed at a certain critical temperature and that critical temperature was lost during the preparation process (because the method is a discrete