Cement and Concrete Composites 94 (2018) 13–23

Contents lists available at ScienceDirect

Cement and Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Elucidating the influences of compliant microscale inclusions on the fracture behavior of cementitious composites

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A R T I C L E I N F O

Keywords:
Inclusions
Digital image correlation
Fracture toughness
Fracture process zone
Finite element analysis

A B S T R A C T

The fracture response of cementitious composites containing compliant microencapsulated inclusions and its influence on the fracture process zone (FPZ) are reported. The incorporation of small amounts of phase change material (PCM) microcapsules (replacing up to 10% by volume of sand) is found to slightly improve the strength, fracture toughness, critical crack tip opening displacement ($CTOD_c$), and the strain energy release rates. Digital image correlation is used to examine the FPZ at the tip of the advancing crack, to better explain the influences of compliant microscale inclusions on energy dissipation. The FPZ widths are found to slightly increase with PCM dosage but its lengths remain unchanged. The increase in FPZ width is linearly related to the $CTOD_c$, showing that inelastic deformations of the crack-tip in the direction of crack opening are indeed influenced by microscale inclusions. It is shown that cementitious systems containing microencapsulated PCMs can be designed to demonstrate mechanical performance (including fracture) equivalent to or even better than their PCM-free counterparts, in addition to the well-described thermal performance.

1. Introduction

Phase change materials (PCMs) have been proposed as a means for thermal energy storage due to the large amount of heat being absorbed or released while undergoing phase change. For the same reasons, the use of PCMs in building elements (i.e., non-structural components such as insulation, and recently in load-bearing roofs and walls) is studied as a means to improve the indoor thermal comfort and building energy efficiency [1–7]. In addition, the phase change response of these materials can be advantageously employed to mitigate thermal cracking in concrete. Thermal cracking in restrained concrete elements (e.g., pavements, bridge decks, flat slabs etc.) is caused by temperature changes that are caused by hydration reactions and/or exposure conditions. A previous study [8] has presented evidence of the beneficial influence of microencapsulated PCMs in mitigating thermal cracking in cementitious systems. When compliant ("soft") inclusions such as PCMs are incorporated into structural materials like concrete, it is possible that the mechanical performance may be compromised. A recent study has investigated the influence of two different types of microencapsulated PCMs on the microstructure and strength of cementitious systems [9] where it was shown that the constitution and properties of the shell and the size distribution of the microencapsulated particles significantly influences the mechanical properties.

This paper examines if beneficial changes in fracture properties and crack propagation behavior can be obtained through the incorporation of compliant inclusions, in spite of the resulting bulk stiffness reduction. This is based on the idea that the fracture process zone (FPZ), i.e., the zone at the crack-tip where energy dissipation occurs, can be influenced by the presence of such inclusions [10–15]. Digital image correlation (DIC) is used to track the FPZ to develop a better understanding of crack propagation behavior in the localized region around the crack tip.

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https://doi.org/10.1016/j.cemconcomp.2018.08.009
Received 29 May 2018; Received in revised form 9 August 2018; Accepted 14 August 2018
Available online 17 August 2018
0958-9465/

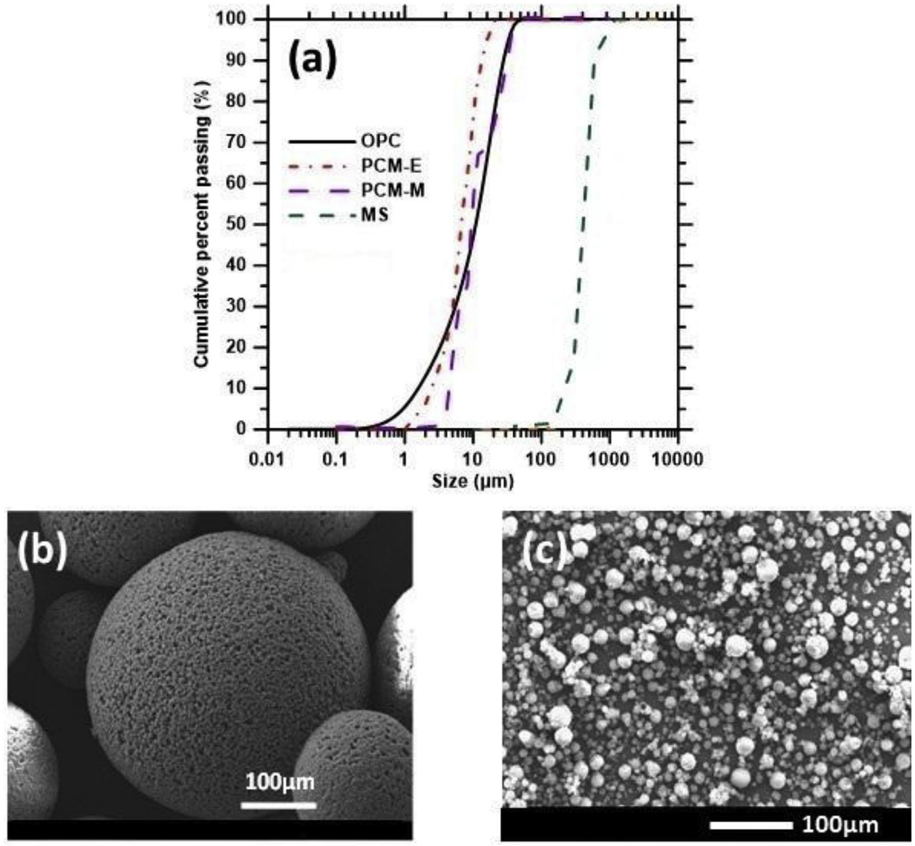

Fig. 1. (a) Particle size distributions of OPC, PCMs, and medium sand (MS); and scanning electron micrographs for: (b) PCM-M and [9] (c) PCM-E [9].

2. Experimental program

2.1. Materials and mixtures

A commercially available Type I/II ordinary portland cement (OPC) conforming to ASTM C 150, and two different microencapsulated, paraffinic phase change materials (PCMs) referred to as PCM-E and PCM-M were used. The major difference between the two PCMs is in their particle sizes, morphology, and the material that forms the shell of the PCM particles (polymethyl methacrylate or PMMA for PCM-M, and melamine formaldehyde or MF for PCM-E). Commercial grade medium silica sand was used for the mortars. The median particle size (d_{50}) of the OPC is 10 μm and that of PCM-E is 7 μm as determined from laser diffraction. The median particle sizes of sand is 400 μm. Fig. 1 (a) shows the particle size distributions (PSD) of the materials used. PCM-E comprises of discrete microencapsulated particles whereas PCM-M consists of agglomerates of finer particles. PCM-M breaks down during dispersion prior to particle size analysis and thus its actual agglomerated state is not reflected in the PSD. Scanning electron micrographs revealed that the median particle size of the PCM-M agglomerate is 150 μm. Scanning electron micrographs of both the PCMs are shown in Fig. 1(b) and (c) respectively.

Cementitious mortars were proportioned using medium sand and a volumetric water-to-binder ratio, $(w/p)_v = 1.26$ (mass-based $w/p \approx 0.40$) to yield a paste volume fraction of 50%. In addition to the control mortar, the mixtures included PCMs (both PCM-E and PCM-M) at three volumetric inclusion levels of 5, 10, and 20% - where the PCM partially replaced the medium sand. While it is well-known that incorporation of PCMs in cement paste as paste-replacement results in detrimental impact on the strengths [8,16], our previous work [9] reflected that incorporation of PCMs in mortars as sand-replacement results in significant strength-enhancement if suitable dosage of PCMs is chosen and PCMs are well-dispersed. That's why the mortars, studied here, contain PCM as sand-replacement. The mortar specimens were stored in a moist chamber (> 97% RH, 23 ± 2 °C) until 28 days, at which time they were tested.

2.2. Experimental methods

The fracture response of mortar beams was determined using three-point bending tests on notched beams (330 mm × 76 mm x 25 mm in size) with a central notch 19 mm deep. Three-point bend tests were performed using a closed-loop testing machine, with the crack mouth opening displacement (CMOD) measured using a clip gage acting as the feedback signal. The test was terminated at a CMOD of 0.18 mm. The flexural strengths of un-notched mortar beams were determined using three-point bending tests in accordance with ASTM C 293. The beams were centered and center-point force was applied continuously at the mid-span perpendicular to the face of the specimen without any eccentricity. The tests were conducted at a constant displacement rate of 0.375 mm/min without any shock or interruption until the samples failed. Both the flexural strength and fracture tests were performed on four replicate beams for each mixture.

Digital image correlation (DIC) analyses was performed on the notched beams to evaluate the fracture parameters (critical stress intensity factor (K_{IC}) and critical crack tip opening displacement ($CTOD_C$)) and fracture process zone (FPZ) development. DIC is a non-contact optical method that tracks displacements of randomized speckle patterns on the surface of the specimen. The beam surfaces were painted white and random black speckles were created on the white surface using black spray paint to provide adequate contrast for image correlation. Two high-resolution (5 megapixel) monochrome cameras acquired images once every 2 s during the mechanical test. The cameras imaged a rectangular area of dimensions 120 mm × 60 mm above the