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

Sumanta Das¹, Matthew Aguayo², Nihat Kabay³, Barzin Mobasher⁴, Gaurav Sant⁵⁶, Narayanan Neithalath⁷

ABSTRACT

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 (CTODₐ), 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 CTODₐ, 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.

Keywords: Inclusions; Digital Image Correlation, Fracture toughness; Fracture process zone; Finite element analysis

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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.

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. Figure 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 Figures 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 x 76mm 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 two seconds during the mechanical test. The cameras imaged a rectangular area of dimensions 120 mm x 60 mm above the notch [17,18] at a resolution of 10 pixels/mm. The resolution of 10 pixels/mm has been shown to yield satisfactory results in bending in [19]. The imaged areas were analyzed using a commercial software (VIC-3D™). The correlations between the subsets of images from the deformed and undeformed states were applied to calculate the displacement fields. The relevant mathematical formulations are described in detail elsewhere [15,20]. The crack tip opening displacements (CTOD) and the crack extension are extracted from the horizontal displacement fields, and the in-plane Lagrangian strain fields provide information on strain localization at the crack tip.

3. Results and Discussions
3.1. Mechanical response of PCM-containing mortars

The global fracture response of PCM-modified mortars was evaluated through multiple loading-unloading cycles. These loading-unloading cycles are used to obtain the unloading compliance which serves as the basis for the crack growth resistance (R) curves discussed later. The results for mortars containing PCM-E are described prominently, to focus on the ability of such inclusions to improve the fracture behavior [9]. Representative load-CMOD responses are shown in Figure 2 (a) for the plain OPC mortar and the mortar containing 10% PCM-E by volume as sand-replacement. Figure 2 (b) depicts the peak load and residual load at a CMOD of 0.16 mm for the mortars containing 0, 5, 10 and 20% PCM-E by volume as sand-replacement. The influence of PCM-E volume fraction (with up to 20% of PCM-E replacing sand) on the peak load of notched beams is minimal. In other words, mechanical property reductions endemic to mixtures dosed with soft inclusions (such as lightweight aggregates or rubber particles) are not noticed [21,22]. Rather, flexural strengths determined on un-notched beams (Fig. 2 (c)) show that there is some strength enhancement when low volumes of PCM-E replace sand in the composite – for equivalent paste (matrix) contents. Note that the cement paste volume fractions in all the mortars are identical. Finite element (FE) simulations of PCM-containing mortars are detailed below to shed light into this observation.
3.1.1 Finite element (FE) simulations for microstructural stress distributions in mortars containing PCM

Finite element analysis was performed using two-dimensional plain strain elements to better understand the mechanisms of stress distribution in the microstructure when PCM-E particles replace sand. A sufficiently large (4.15 mm x 4.15 mm) representative element area (REA) is considered in the analysis. Representative random, periodic 2D-microstructures were generated using a stochastic particle packing algorithm [23–26]. The algorithm accepts the particle size distribution (PSD) and the volume fraction of particles as inputs and packs circular inclusions with an interface layer of predefined thickness around them inside the REA. The sand particles are considered to be spherical and have a uniform distribution.
within a size range of 0.5-to-0.7 mm whereas a size distribution corresponding to that shown in Figure 1(a) is adopted for PCM-E. The material (PCM-E, quartz, and cement paste matrix) properties of the different material components are shown in Table 1, which were obtained from [27–33].

Table 1: Elastic properties of the components of the mortar for FE simulations

<table>
<thead>
<tr>
<th>Elastic property</th>
<th>Hardened cement paste</th>
<th>Quartz</th>
<th>PCM - E</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Core</td>
<td>Shell</td>
<td>Homogenized</td>
</tr>
<tr>
<td>Young's Modulus, E (GPa)</td>
<td>20</td>
<td>70</td>
<td>0.056</td>
</tr>
<tr>
<td>Poisson's Ratio, (\nu) (-)</td>
<td>0.22</td>
<td>0.17</td>
<td>0.495</td>
</tr>
</tbody>
</table>

After the generation of the microstructure, the REA is meshed with a Python script through ABAQUS\textsuperscript{TM} and an orphan mesh file is obtained. Periodic boundary conditions (PBC) [34–36] are imposed on the 2D-REA to eliminate boundary effects and unrealistic stress concentrations. PBC ensures displacement continuity (neighboring unit cells cannot be separated or they cannot penetrate each other) and traction continuity at the boundary of all neighboring unit cells. PBC is implemented on the REA as nodal displacement constraints through a Python script appended to the orphan mesh file containing the periodic microstructure information. A strain-controlled testing scenario is simulated using nodal displacement constraints. An axial strain of 0.12% is used to examine compressive behavior. This is well within the linear elastic regime of cementitious materials. Details on the development of the microstructural packing algorithm, FE analysis procedure, and post-processing are reported elsewhere [37]. The constitutive response of the material in the linear elastic regime can thus be obtained using this “microstructure-guided” simulation approach.

Figures 3 (a-1) and (b-1) show the generated microstructures for a mortar with 50% sand by volume and mortar with a sand-PCM combination (40% sand + 10% PCM-E,, i.e. 10% sand replacement by PCM-E) respectively. Figures 3 (a-2) and (b-2) show the dominant principal stress (\(\sigma_{22}\) in this case) distributions in the microstructures corresponding to an axial strain of 0.12%. Magnified representations of principal stress distributions in both microstructures are shown in Figures 3 (a-3) and (b-3) for clarity. General trends in stress distribution suggest that, for the same imposed strain (in the linear elastic regime), expectedly the stiffer quartz particles experience higher stresses due to their higher stiffness whereas the softer PCM particles experience relatively higher amount of deformations due to their lower stiffness. This results in a stress relaxation effect in the microstructure when PCM particles are distributed randomly in
the microstructure. The smaller size of the PCM particles relative to the sand particles also helps in better distributing stresses in the microstructure – thereby reducing preferential paths of (stress induced) failure. At higher PCM dosages, the stress in the cement paste matrix increases significantly because of the presence of a large number of weaker inclusions close to each other – which are effective at dissipating stress, but not as effective at bearing stress – thus provoking through-paste failure as the critical mechanism.

Figure 3: Random microstructures and FE-based stress distributions for: (a-1,2,3) cement mortar with 50% quartz inclusions by volume; and (b-1,2,3) cement mortar containing 40% quartz and 10% PCM inclusions by volume. (For interpretation of the references to color in this figure legend, the
3.2. Fracture parameters (\(K_{IC}\) and CTOD\(_C\)) of PCM-containing mortars

The two main fracture parameters of interest for quasi-brittle cementitious materials are the critical stress intensity factor (\(K_{IC}\)) and the critical crack tip opening displacement (CTOD\(_C\)). These parameters were determined at 95\% of the peak load from the horizontal displacement fields extracted from DIC, as shown in Figure 4. The critical crack tip opening displacement (CTOD\(_C\)) is determined directly from the CTOD value corresponding to 95\% of the peak load in the post-peak regime, from the measured horizontal displacement field. The fracture toughness (\(K_{IC}\)) was computed using Equation 1 [38,39]. The \(K_{IC}\) values determined based on DIC measurements of crack extension have been shown to be correlated to those determined using conventional methods such as the two-parameter fracture model (TPFM) [10,40–42].

\[
K_{IC} = \frac{PL}{bd^{3/2}} \left[ 2.9 \left( \frac{a_{eff}}{d} \right)^{1/2} - 4.6 \left( \frac{a_{eff}}{d} \right)^{3/2} + 21.8 \left( \frac{a_{eff}}{d} \right)^{5/2} - 37.6 \left( \frac{a_{eff}}{d} \right)^{7/2} + 38.7 \left( \frac{a_{eff}}{d} \right)^{9/2} \right] \quad [1]
\]

Where \(d\) is the depth of the beam. The effective crack length \(a_{eff} = a_0 + \Delta a\), where \(a_0\) is the initial notch depth and \(\Delta a\) is the crack extension.

The fracture toughness (\(K_{IC}\)) represents the ability of the material to resist fracture whereas CTOD\(_C\) indicates the onset of unstable crack propagation. Figure 5 shows the fracture parameters for the plain and PCM-E modified mortars as a function of PCM-E volume fraction. \(K_{IC}\) follows a similar trend to that of the flexural strength and peak load response, where the PCM incorporated mortars perform similar to or slightly better than the plain mortar until a certain replacement level of sand by PCM-E. CTOD\(_C\), which primarily accounts for the interlock effects of the microstructural constituents, increases slightly as the volume of PCM-E increases. A reduction in material stiffness in the vicinity of the crack (due to the incorporation of the softer, microscopic PCM particles) results in the material being able to undergo larger inelastic deformations in the crack-opening direction before the formation of a macro crack, thereby increasing the CTOD\(_C\). These results indicate that the incorporation of compliant PCM inclusions, within limits, at the expense of the stiffer quartz particles can act to improve the fracture properties.
Figure 4: Horizontal displacement field corresponding to 95% of the peak load obtained from DIC, used to determine CTOD, and effective crack length.

Figure 5: Fracture toughness ($K_{IC}$) and critical crack tip opening displacement (CTODc) for the plain and PCM-E modified mortars.

3.3. Crack growth resistance of PCM-containing mortars

The crack growth resistance ($R$) and spatial data of the fracture process zone (FPZ) can provide a better understanding of the influence of PCM inclusions on the fracture response of the mortars. The resistance ($G_R$) curves are obtained using a compliance-based approach, which is based on the idea that stable crack propagation leads to an increase in compliance of the specimen [17,42–45]. Contributions from both the elastic and inelastic strain energy release rates are incorporated in the determination of crack growth resistance ($G_R$). The elastic component of $G_R$ is computed using the unloading compliance, whereas the inelastic CMOD is used to determine the inelastic component. The total crack growth resistance ($G_R$) is given as [17,42,46–49]:

$$G_R = G_{R el} + G_{R in}$$
\[ G_R = G_{\text{elastic}} + G_{\text{inelastic}} = \frac{P^2}{2t} \frac{\partial C}{\partial a} + \frac{P}{2t} \frac{\partial (\text{CMOD}_{\text{inelastic}})}{\partial a} \]  \hspace{1cm} [2]

Here, ‘C’ is the unloading compliance, ‘P’ is the applied load, ‘t’ is the thickness of the specimen and ‘a’ is the crack length. The unloading compliances and the inelastic CMOD values are obtained from the cyclic load-CMOD responses (Figure 2(a)). The unloading compliance is determined as the slope of fit line to the linear part of unloading cycle whereas the residual CMOD upon unloading (unloading to approximately 10% of the capacity to ensure adequate contact between the clip gage and the specimen) in each cycle is quantified as the inelastic or non-recoverable CMOD. The crack extensions are obtained using each of the unloading compliances from the cyclic load–CMOD curves [17,42]. The unloading compliance and the inelastic CMOD are plotted as a function of crack extension (\( \Delta a \)), which on further differentiation yields the rate terms in Equation 2.

![Graphs showing strain energy release rates for different conditions](image)

Figure 6: Strain energy release rates for the plain and 10% PCM incorporated mortars: (a) Overall \( G_R \), (b) inelastic component of \( G_R \), (c) elastic component of \( G_R \), and (d) comparison of \( G_R \) and its elastic and inelastic components as a function of PCM volume fraction. The values in (d) correspond to the plateaus in the R-curve response.
Figure 6 (a) shows the strain energy release rates as a function of crack extension for the plain mortar and the mortar containing 10% PCM-E by volume. Increasing crack extension results in increasing strain energy release rates until the plateau region in the R-curve is reached, where there is no change in energy demand for crack propagation. In both the rising and the plateau regions, the energy release rate is higher for the mortar containing 10% PCM-E particles – suggesting higher energy dissipation at the same crack extension. This is consistent with the values of the fracture parameters ($K_{IC}$ and CTOD$_C$) determined earlier.

Since the total crack growth resistance is a combination of both elastic and inelastic contributions, these contributions are separated and shown in Figures 6 (b) and (c) respectively for the plain and 10% PCM-E incorporated mortars. Figure 6 (d) shows the total strain energy release rates (corresponding to the plateau) as well as its inelastic and elastic components as a function of PCM-E inclusion levels. The total strain energy release rate as a function of PCM inclusion level follows a similar trend to that of the peak load sustained (Figure 2(b)) and fracture toughness (Figure 5). The elastic component of the strain energy release rate arises from the incremental crack growth whereas the inelastic component has its origins in other effects including frictional loss and permanent deformation caused due to crack-opening [50–52]. From these figures, it can be seen that the trends in the total, inelastic, and elastic components of the R-curve are similar, with the inelastic component being the dominant one. The dominance of the inelastic contribution for both the plain and PCM-incorporated mortars indicates that more energy is being dissipated through inelastic deformations. The increase in inelastic deformations compared to the plain OPC mortar that results in a higher CTOD$_C$ is postulated to be due to crack blunting and/or enhancement in crack path tortuosity in systems containing PCMs.

3.4. Fracture process zone (FPZ) in PCM-modified mortars

This section investigates the local processes occurring at the tip of the advancing crack through a careful evaluation of the fracture process zone (FPZ). The FPZ includes the microcracked, inelastic region around the traction-free crack tip which collectively accounts for the inelastic toughening mechanisms including microcracking, crack deflection, increase in crack path tortuosity, and crack blunting. These toughening mechanisms are influenced by the cement paste matrix characteristics [18] and the size of inclusions (e.g., aggregates) present in the mixture. Energy dissipation at the tip of the crack which results in toughening, increases with increase in inclusion size. Thus it is logical to consider that the FPZ depends on the inclusion size, which has been confirmed for inclusions that are at least a few millimeters in size [53–58]. Little data exists in literature on the influences of the presence of soft(er) microscale particles and their dispersion on crack propagation in cementitious systems.
It has been shown in this paper that when sand is replaced by PCM-E up to 10 % volume, the strain energy release rate and fracture toughness are slightly improved as compared to the plain OPC mortar. It has also been shown that the peak load [9] slightly increases up to a PCM-E volume fraction of 10%. An examination of Equations 1a and 2 reveal that both the fracture toughness and strain energy release rates (both elastic and inelastic) are dependent on the peak load. Thus, it is necessary to evaluate if the observed increase in resistance to crack propagation is a by-product of an increased load carrying capacity, or if energy dissipation at the tip of the crack is indeed influenced by microscale inclusions. The reasons for increased load carrying capacity (which is a consequence of microstructural stress dissipation by softer inclusions that reduce preferential paths of stress-induced failure) has been described by the simulations (Figure 3) and detailed in [9]. This is accomplished by characterizing strain localization at the tip of the advancing crack using the FPZ [10,59].

The width of the FPZ (defined as the extent of strain localization perpendicular to the direction of crack growth) is generally fully developed when the peak load is reached, and unstable crack propagation starts beyond this region [57,60–63]. The FPZ width at a given distance above the notch is determined by fitting the surface strain profile with a normal distribution, where the standard deviation (σ) of the distribution is a representation of the FPZ width [18,61,64]. Considering that a normal distribution curve truly represents the horizontal strain profile, the FPZ width can be considered to be equal to 4σ since 95% of the values of the normal distribution function are within ±2σ of the mean value.

The FPZ dimensions corresponding to several points in the load-CMOD plot are determined, but two of them are shown here for illustrative purposes: the first corresponding to 95% of the peak load in the post-peak regime, which corresponds to CTODc, and second, at a CMOD of 0.06 mm, which is in the post-peak region where the FPZ height would have substantially increased from the previous case, owing to unstable crack propagation. Figure 7 shows the representative load-CMOD responses for the plain OPC mortar and the mortar containing 10% PCM-E, and the corresponding strain fields at 95% peak load in the post-peak regime and at a CMOD of 0.06 mm. The height (or length) of the FPZ is taken to be the distance along the direction of crack propagation, from the tip of the notch to the location where the localized strain value drops to a quarter of the strain at the tip [18]. The FPZ height is also dependent on specimen size and geometry. A qualitative observation of Figure 7 indicates similarities in the FPZ characteristics for the plain and the 10% PCM-E modified mortar at a particular load or CMOD level. The FPZ lengths increase significantly for both the mortars beyond the peak load, but without a concomitant increase in width.
3.4.1 Influence of size and volume fraction of PCM inclusions on the FPZ

In this section, the development of FPZ dimensions in mortars containing equal volumes of two different-sized microencapsulated PCMs, PCM-E (d$_{50}$ = 7 µm) and PCM-M (d$_{50}$ = 130 µm) is evaluated. Figure 8 shows backscattered SEM images highlighting the dispersion of these two types of PCM particles within a cement paste matrix. PCM-E (Figure 8(a)), discussed extensively so far in this study, shows a more uniform distribution throughout the matrix as compared to PCM-M (Figure 8(b)) because of the size of the particles.
Figure 8: Microstructure (BSE-SEM) of cement pastes incorporating 10% by volume of two different size PCMs: (a) PCM-E with a median particle size of 7 µm and (b) PCM-M with a median particle size of 130 µm.

It is postulated that, if the crack propagation response is influenced by PCM particle sizes and volume fractions (within limits), then a careful evaluation of the FPZ widths and heights at several CMOD levels will reveal it. To obtain such insights, the FPZ widths and heights for mortars containing both the types of PCMs were obtained from DIC. Figures 9(a) and (b) depict the average FPZ widths and heights determined from DIC for plain mortar and the mortar where 10% of sand is replaced by PCM (PCM-E or PCM-M). The FPZ widths were determined just above the tip of the crack for a given CMOD. The crack extension limit is identified from the slight jump in the in the horizontal (u) displacement.

Figure 9: (a) FPZ width, and (b) FPZ height as a function of CMOD for plain mortar and 10% PCM-E and PCM-M mortars
It is noticed from Figure 9 (a) that the FPZ widths are quite similar irrespective of the PCM type, especially after the peak load. Also, the FPZ width plateaus after a CMOD of ~ 0.06 mm. Other researchers [65] have also found that the FPZ width in quasi-brittle materials remains rather invariant in the post-peak region. The drop in FPZ width around 95% of the peak load in the post-peak region observed in all the mortars can be attributed to microcracks coalescing into larger cracks beyond this level. The width of the FPZ is fully developed at this level beyond which the increase in CMOD does not result in significant changes in the width. As seen from the micrograph in Figure 8(b), the PCM-M particles are separated from each other by larger distances as compared to the PCM-E particles, which reduces their probability of intersecting the crack at its tip. Figure 9 (b) shows the FPZ height-CMOD relationships for the three chosen mortars. The FPZ heights are also not significantly influenced by the PCM type. Similar to the FPZ widths, the FPZ heights also plateau at a CMOD value between 0.06-0.08 mm.

Figure 10 illustrates the influence of volume fractions of both the PCMs replacing sand, on the surface strain profiles. The FPZs corresponding to 95% of the peak load in the post-peak zone are shown because the FPZ widths have completely developed at this load level, as has been explained elsewhere [18].

Figure 10: Fracture process zone corresponding to 95% of the peak load in the post-peak regime for PCM modified mortars at: (a) 0%, (b) 5% PCM-E, (c) 10% PCM-E, (d) 20% PCM-E, (e) 5% PCM-M, (f) 10% PCM-M, and (g) 20% PCM-M.

The changes in FPZ widths and heights as a function of PCM volume fraction are highlighted in Figures 11(a) and (b) for mortars containing PCM-E, both immediately after the peak load (corresponding to Figure 10) and at a larger CMOD value (corresponding to full development of the FPZ). The FPZ widths slightly
increase with an increase in PCM volume fraction as seen from Figure 11(a). The FPZ heights show minimal
difference as a function of PCM-E volume fraction, but they are much higher in the post-peak zone than
the values at or close to the peak load, because of unstable crack propagation as has been shown in Figure
7. Similar results are obtained for PCM-M also. Figure 11(c) demonstrates a strongly linear relationship
between CTOD$_c$ and the corresponding FPZ widths for mortars containing PCM-E. This relationship shows
that the inelastic deformations in the crack opening direction at the tip of the crack, though subtle, are
indeed influenced by the PCM particles. It needs to be mentioned that an increase in volume fraction of
PCMs in the mortar (beyond the 20% by volume of sand) could result in more pronounced differences in
the FPZ widths because of the improved dissipation of energy through inelastic deformations (including
processes such as crack tip blunting, and crack path deflection). However, as compared to the influence
of larger aggregates or the presence of cement replacement materials that fundamentally alter the matrix
properties and thus the crack propagation response [17,18,44,58], the influences of microencapsulated
PCMs (at replacement levels considered) on the FPZ and fracture properties are more subtle.
Figure 11: (a) FPZ widths, and (b) FPZ heights corresponding to 95% of peak load in the post peak regime and a CMOD of 0.06 mm, as a function of levels of PCM-E incorporation (replacing sand by volume; and (c) relationship between CTODc and FPZ widths for mortars containing different volume fractions of PCM-E.

4. Conclusions

This research article has reported the influence of microscale PCM inclusions on the fracture response and fracture process zone (FPZ) in cementitious mortars. Until a certain volume fraction of PCM-E replacing sand, the fracture toughness ($K_I$), critical crack tip opening displacement (CTOD$_c$) and strain energy release rate ($G_I$) of the PCM-modified mortars are similar to or greater than those of the plain OPC mortar. This is in line with the strength of PCM-E modified mortars, the reasons for which have been
elucidated using microstructural simulations. These results indicated that the incorporation of the chosen softer PCM inclusions within limits at the expense of the stiffer quartz particles did not adversely influence the fracture resistance of mortars. This paves the way for the development of concretes containing such inclusions without compromising the mechanical properties.

Digital image correlation (DIC) was used to identify and measure the fracture process zone (FPZ) to understand the influence of small volumes of microscale inclusions on the energy dissipation process at the tip of the advancing crack. The FPZ widths were found to have fully developed close to the peak load while the FPZ heights plateaued at a CMOD level of ~ 0.06 mm. The FPZ widths were similar throughout the load-CMOD response for both the PCM types (PCM-E of $d_{50} = 7 \mu m$ and PCM-M of $d_{50} = 130 \mu m$), but slightly increased with the PCM volume fraction. The FPZ widths close to the peak load (when they are fully developed) were well related to the CTOD$_c$ in mortars, denoting the influence of PCM microcapsules on the inelastic deformations at the crack tip. The FPZ heights remained unchanged with the PCM type or volume fraction at similar load or CMOD levels.

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6. REFERENCES


