-Technical Paper -

MODE I FRACTURE BEHAVIORS OF PCM-CONCRETE INTERFACES

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ABSTRACT

Stress analysis of RC structures that have been retrofitted by Polymer Cement Mortar (PCM) based materials requires development of constitutive model of PCM-concrete interface that are sensitive to property of substrate concrete and interface roughness. In this paper, the tensile stress-crack width model for PCM-concrete interface is presented based on experimental results. Analysis of results indicates that the Mode I fracture energy relies greatly on the quality of bonding substrate and interface roughness.

Keywords: retrofitting, PCM, interface, Mode I fracture energy, roughness, tension-softening behavior

1. INTRODUCTION

Various methods like steel plate bonding, continuous fiber sheet bonding, and polymer cement mortar (PCM) overlay method (PCM retrofitting method) are used to increase the load capacity and environmental resistance of bridge slabs. All these methods are currently in use after exhaustive studies by individual organizations responsible for repair and rehabilitation of bridges. However, considering the cost and behavior of fiber based materials, the use of PCM has been on the increase in developing countries. In light of the weak bond strength of normal cement based materials, PCM offers a good compromise in terms of cost and behavior. As a result, there is increasing interest in better knowledge to predict the behavior of such repairs and to find solutions to ensure their durability.

Up to now, PCM based repairs have sometimes posed a problem because of their stochastic durability, essentially due to their debonding. Debonding can start from any discontinuity (boundary, joints or crack cutting the overlay), often with a lifting of the edges of the debonded area. This induces new cracks which accelerate the damage process, and new repair work is needed [1]. On the other hand, no reliable design method is currently available for the practitioner. There are only recommendations relying on experience and very crude design proposals. There is therefore a demand for further study on debonding failure behavior.

As far as the author' reviewed literatures are concerned, there are very limited literatures concerning interfacial Mode I fracture and few literatures have dealt with the interfacial tension softening behaviors, which can be described by using the stress-crack width relation according to the Hilliberg's fictitious crack method. Meanwhile, no test method for Mode I interfacial fracture has been accepted as a common use.

In fact, the fracture of PCM-concrete interfaces in real retrofitting may contain Mode I component, which may be caused by the relative displacement parallel to concrete cracks, the deformation differences among the dissimilar interfacial materials due to shrinkage or temperature effects, the localized stress concentration at cutoff points of PCM and so on. In case of PCM underlay retrofitted bridge slab, the Mode I fracture behaviors are significant once shear cracks occurs. Moreover, in some cases of retrofitting curved concrete structures, such as tunnel lining, the Mode I interfacial fracture may become dominant. So it is necessary to understand Mode I fracture mechanisms parametrically and to build up mode dependent interfacial constitutive model.

2. EXPERIMENTAL OUTLINE

2.1 SPLITTING TENSILE TEST

The splitting tensile test is used worldwide to measure the tensile strength of concrete. It was first proposed by Lobo Carneiro and Barcellos during the Fifth Conference of the Brazilian Association for Standardization in 1943 [2] and was later adopted as a standard test. Ramey and Strickland [3] used the ASTM C496 standard test method as a general guide and developed a splitting test for composite cylinders, constructed with one-half concrete and one-half repair material. Their test showed that the cylindrical splitting tensile gave consistent results.

In this study, splitting tensile test is modified to evaluate the tensile strength (initial cohesive stress) of the PCM-concrete interface. To prevent local failure in

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compression at the loading generators, two thin strips made of plywood are placed between the loading platens and the specimen to distribute the load. A notch with size of 0.75×10 cm at each side is induced during the PCM casting procedure. The contact area between the concrete substrate and the PCM is 10×5.5 cm. As shown in the later section, usually the PCM-concrete interface fractures at the concrete side but in a very thin concrete layer near the interface. Therefore, splitting tensile tests as shown in Fig.1 were conducted.

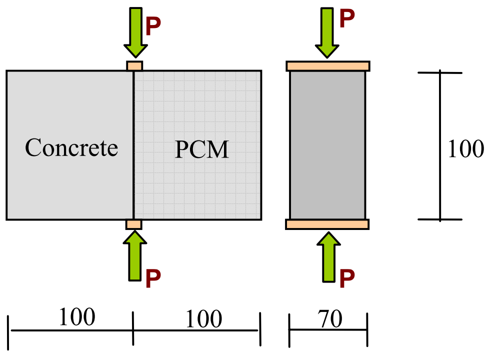


Fig. 1 Splitting tensile test setup

2.2. THREE POINT BENDING TEST

To get the Mode I interfacial fracture energy and characterize the softening behaviors of a material in tension, the most straightforward way is to perform uni-axial tension tests under closed-loop displacement control. However, such a test procedure requires a very specific and precise way to carry out in comparison with bending tests. So conventionally for concrete, the three point bending test for a notched beam is recommended by RILEM [4] to evaluate the Mode I fracture energy. In the present study, the method is modified to test the Mode I fracture energy and tension softening behaviors of PCM-concrete interface as shown in Fig.2. To obtain the crack tip open displacement (CTOD) as well as crack propagation process four one directional π gauges with accuracy of 0.001mm were arranged with the same distance from the position of crack tip to the top of composite beam. All the specimens were tested under the displacement controlled cyclic loading condition. The loading speed was 0.1mm/min.

2.3 PREPARATION OF THE SPECIMENS

In this study, four types of bonding concrete substrates (*LS, MLS, MHS, HS* series) and one type of PCM were prepared to simulate the actual bonding situation in real retrofitting fields. The w/c ratio and strength properties of concrete and PCM can be found in Table.1. The PCM used in this study is premixed PAE (polyacrylate acid ester) powder resin and developed as a splaying mortar for a repairing of a cross section of structures. It has characteristics of high density, high bond strength and low contraction.

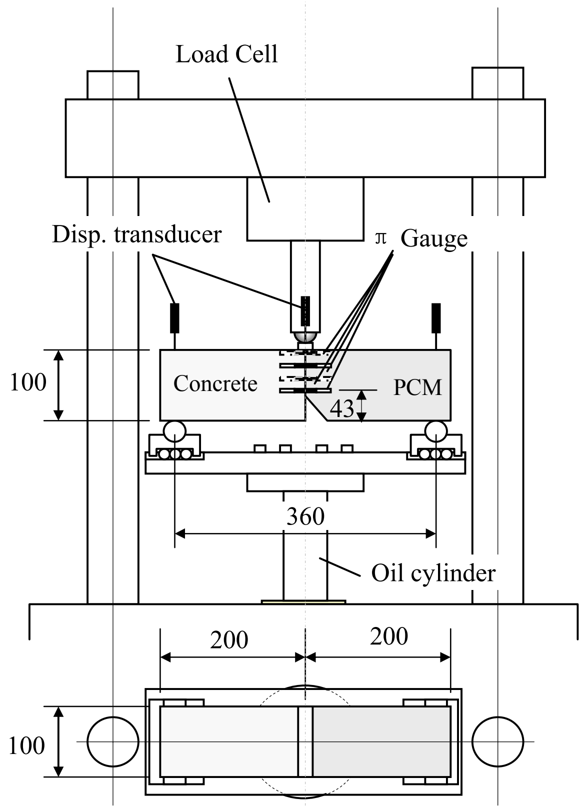


Fig .2 Three-point bending test setup

Table 1 Material properties of concrete and PCM

Test Series	*W/C*	f'_c (MPa)	E_t(GPa)	G_{fc} (N/m)
LS	63%	29.29	26.77	83.67
MLS	50%	39.63	30.92	92.54
MHS	40%	52.62	33.39	101.72
HS	33%	78.83	36.77	116.39
PCM	13.4%	57.23	23.46	—

The concrete substrates surfaces are treated by water jet (*WJ*) method. Special attention was paid to provide adequate moisture on the substrate concrete surface. The substrate concrete was placed in water for 24hrs and free water was removed before casting PCM. The roughness of the concrete-PCM interface was measured using a 3D shape measurement apparatus and quantified by arithmetic mean value of roughness(R_a) calculated based on JIS Standard [5].

In total, 24 composite specimens were prepared. The procedures for preparing the composite specimens are:

(1) Preparing concrete specimens with the size of 10×10 ×20 cm for bending test and 10×10 ×7 cm for splitting tensile test ;

(2) Processing the bonding surfaces of concrete specimens then measuring roughness.
(3) Casting PCM with the same size as the substrate concrete specimens by spraying method. The connected interface is separated with right-angled triangle wood prism to induce the notch.

(a) LS series (b) HS series
PHOTO 1. Fracture of interface

3. TEST RESULTS AND DISCUSSION

3.1 OBSERVATION ON THE FAILURE MODE

PHOTO 1 shows the observed types of fractured interfaces. In common, all of the specimens with concrete substrates of LS and MLS and one with MHS facture at the concrete side of the interfaces (see PHOTO 1 (a)), while all of the specimens with concrete substrate of HS and two with MHS fracture at the joint line between PCM and concrete (see PHOTO 1 (b)). In comparison with the fractured concrete interface, the fractured PCM-concrete joint line is more even and the maximum bending force is lower correspondingly. It can be distinguished by naked eye that the volumes of the concrete aggregate attached to PCM side are different. Especially, in comparison with other concrete substrates, when the strongest concrete substrate HS is used, obviously less concrete volume attaches to the PCM side.

Table 2 Interfacial Mode I fracture test results

Specimen codes	f_{st} (MPa)	R_a (μm)	G_{fi} (N/m)	Failure Mode
F-LS-1		0.564	60.52	a
F-LS-2	3.36	0.451	49.10	a
F-LS-3		0.392	52.64	a
F-MLS-1		0.768	73.06	a
F-MLS-2	3.70	0.512	68.23	a
F-MLS-3		0.305	67.25	a
F-MHS-1		0.272	20.00	b
F-MHS-2	3.79	0.413	44.01	b
F-MHS-3		0.796	74.88	a
F-HS-1		0.399	32.73	b
F-HS-2	3.32	0.449	36.73	b
F-HS-3		0.344	30.30	b

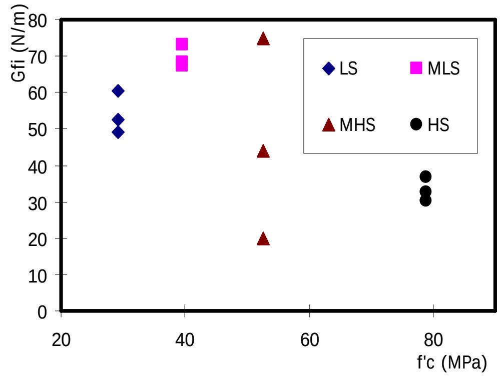


Fig. 3 G_{fi}–f'_c relations

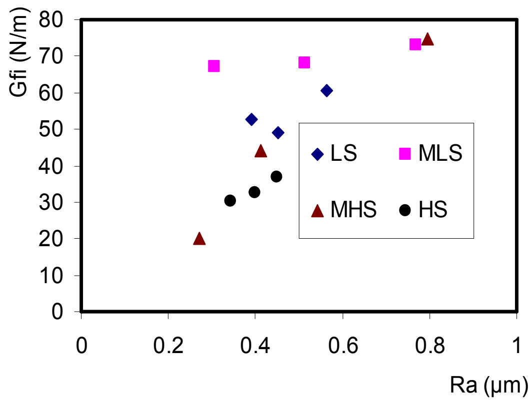


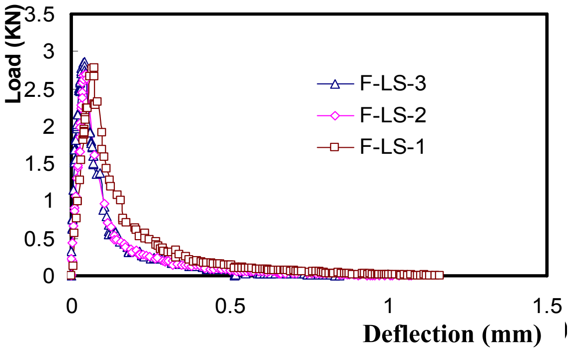
Fig. 4 G_{fi}–R_a relations

When a composite specimen with PCM-concrete interface is subjected to tension, the stress state at failure depends primarily on the efficiency of the bond between PCM and concrete. If the bond is effective, which means tensile bond strength of PCM to concrete is greater than tensile strength of interface concrete layer, the failure is characterized by a fracture at the concrete side. If the bond is insufficient, a fracture occurs along the joint line.

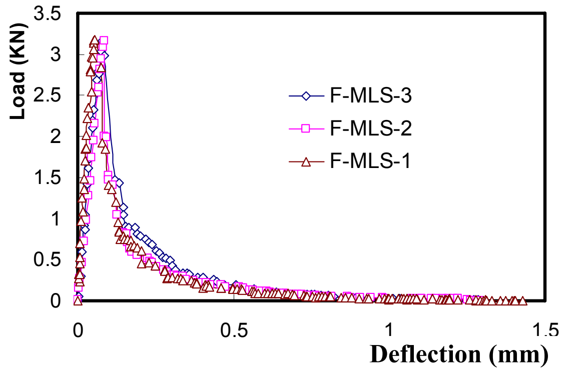
The bending strength shows increasing tendency with substrate concrete compressive strength in case of fracture at concrete side. This indicates that the Mode I interfacial peak strength can be determined based on the concrete tensile strength uniquely only if the bond is efficient. During the surface treatment procedures of HS series, a higher water jet pressure is applied which may cause more damages to the aggregates interlock of the interface layer. This probably leads to a decrease in splitting tensile strength and bending bond strength of PCM-concrete interface.

3.2 MODE I FRACTURE ENERGY OF PCM-CONCRETE INTERFACES

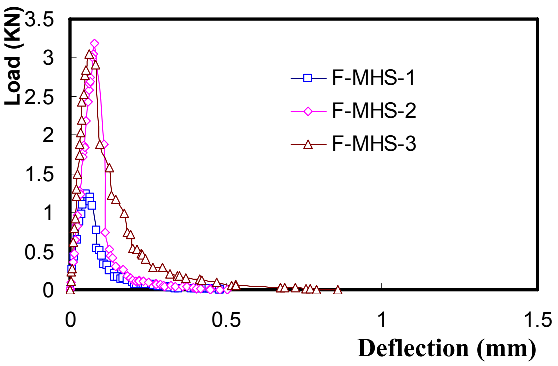
Table 2 shows all Mode I fracture test results of the PCM-concrete interfaces. The Mode I interfacial



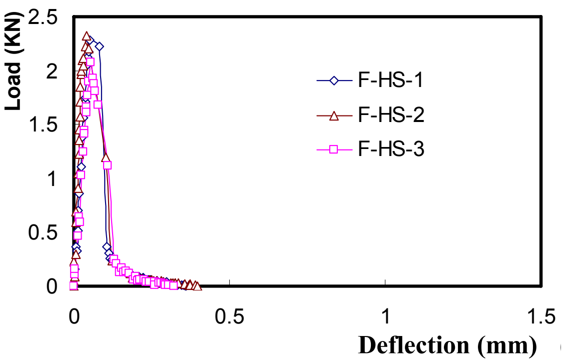
(a) LS series



(b) MLS series



(c) MHS series



(d) HS series

Fig. 5 Load-deflection curves

fracture energy G_{fi} is calculated based on the experimental load-deflection curves (see Fig.5) using RILEM recommended expressions [4]. Fig.3 and Fig.4 show the values of G_{fi}, which is affected by different bonding substrate and interface roughness. Based on Table 1, Table 2 and Fig.3 and Fig.4, all experimental observations can be summarized as follows:

(1) In all the cases, the G_{fi} values are smaller than the fracture energy of corresponding concrete substrate (G_{fc}). In case of fracture at concrete side, the G_{fi} value shows increasing tendency when the substrate concrete changes from LS to MLS and MHS, and then shows decreasing tendency when the substrate concrete changes to HS which fractures at joint line of PCM-concrete interface. Concrete series LS with fracture at concrete side shows obviously higher values of G_{fi} in comparison with the HS with fracture at the joint line though they have similar splitting tensile strength. This is because joint failure surface is more even and has less bridging effects due to the lack of coarse aggregates.

(2) The G_{fi} value shows the increasing tendency with the value of interface roughness R_a. In comparison with MHS concrete series, the G_{fi} value in use of LS, MLS and HS concrete series are not so sensitive to variation of R_a. In the case of MHS series, the failure mode changes from fracture at joint line to fracture at concrete side with the increase value of R_a (see PHOTO 1 (a) and PHOTO 1 (b)). This indicates that the G_{fi} value of interface is greatly affected by failure mode of interface. In order to have a greater value of G_{fi}, the joint surface should be roughened enough to make sure the fracture occurs at concrete side. Unfortunately, the roughness difference in all series is not remarkable enough (R_a ranges from 0.2 to 1.0 μm) in present study, so more experiments should be carried out to clarify the roughness' effects on the G_{fi} of PCM-concrete interfaces quantitatively.

4. TENSION SOFTENING DIAGRAM OF PCM-CONCRETE INTERFACE

To get the tension-softening diagram after the interfacial peak stress, Niwa et al. (1998) proposed a modified J integral method, which can consider the propagation of the crack length and remove of elastic displacement of the beam due to the crack [6]. The J-integral is defined as the energy available for crack extension and can be interpreted as the total absorbed energy of the cracked specimens minus its elastic energy, if the unloading and reloading path can be assumed to be linear, it can be written as follows:

$$J_p = \frac{1}{ab}\left[\int_0^{\delta} P(\delta)d\delta - \frac{1}{2}P(\delta)(\delta - \delta_p)\right] \qquad (1)$$

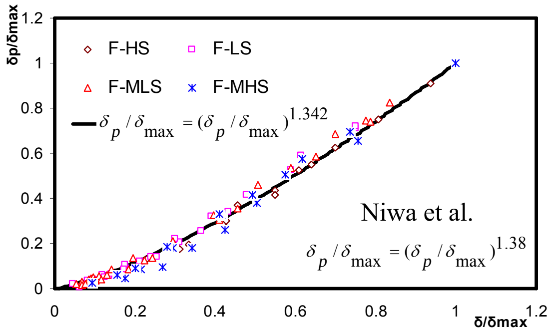


Fig.6 δ_p/δ- δ_p/δ_{max} relations

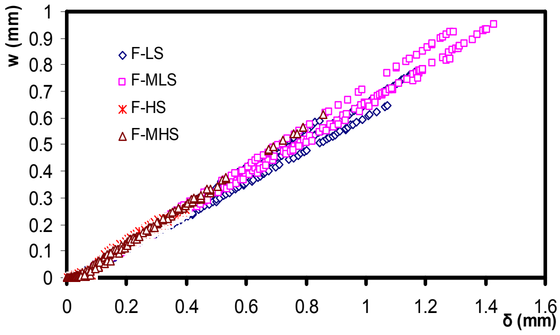


Fig.7 *w*-δ relations

The unit energy absorbed by fictitious crack can be expressed as:

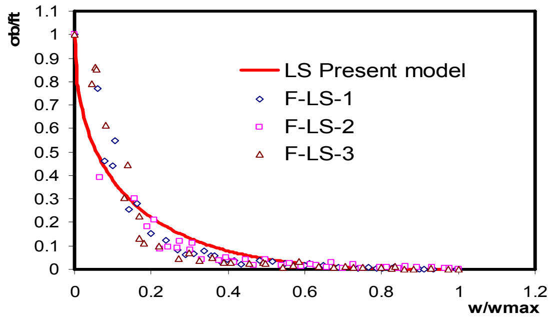
$$e(w) = \int_0^w \sigma(w)dw - \frac{1}{2}\sigma(w)(w - w_p) \qquad \textbf{(2)}$$

where b is the width of beam, the crack propagation length a corresponding to a crack width can be recorded through the arranged four π gauges (see Fig.2), the deformation δ and plastic deformation δ_p of beam and the crack width w and plastic crack width w_p of crack tip are obtained through unloading and reloading procedures.

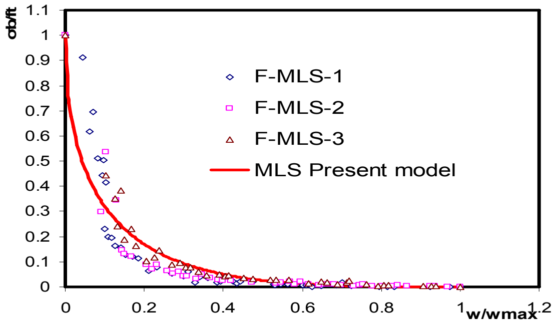
Fig.6 and Fig.7 show the experimental δ-δ_p (normalized by the maximum deflections) and δ-w relations respectively. Despite the existence of the data scattering, it can be seen the δ-δ_p relation for PCM-concrete interfaces is similar to that proposed by Niwa et al (see Eq.3) for ordinary concrete regardless of the concrete types. The δ-w shows linear relation between deflection δ and crack opening w, this indicates that the w- w_p relations (normalized by the maximum crack width) have the same parameter as in δ-δ_p relations (see Eq.4).

$$\frac{\delta_p}{\delta_{max}} = \left(\frac{\delta}{\delta_{max}}\right)^{1.342} \qquad \textbf{(3)}$$

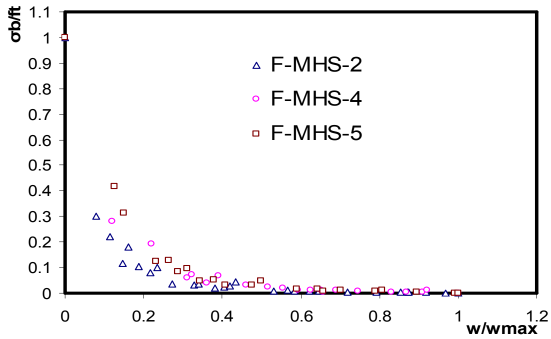
$$\frac{w_p}{w_{max}} = \left(\frac{w}{w_{max}}\right)^{1.342} \qquad \textbf{(4)}$$



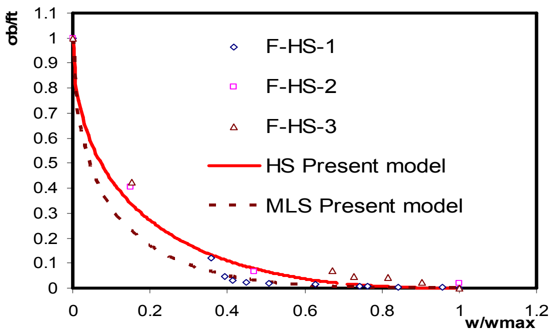
(a) LS series



(b) MLS series



(c) MHS series



(d) HS series

Fig .8 σ ~ w relations

The σ-w relations for all specimens can be obtained as shown in Fig.8, where the interfacial cohesive stresses are normalized by the interfacial tensile strength and the crack width is normalized by the calculated maximum crack width. The interfacial strength is taken from the concrete splitting tensile strength. It can be seen that the HS bonding substrate shows fragile tension softening behaviors (see Fig.8.(d)), which leads to smaller interfacial Mode I fracture energy as discussed previously. According to the way of normalization, the tension softening curves with single failure mode (*LS, MLS, HS* series) can be expressed as the following one:

$$\sqrt[\alpha]{\frac{\sigma}{f_t}} + \sqrt{\frac{w}{w_{\max}}} = 1 \quad \textbf{(5)}$$

where: α is taken as 2.55, 2.99 and 2.21 for LS, MLS and HS series respectively. w_{max} is obtained from calculation result where tensile stress is equal to zero. The average value of w_{max} is taken as 0.30 mm, 0.40mm and 0.10mm for LS, MLS and HS series respectively.

The constitutive law for the Mode I fracture of PCM-concrete interfaces can be separated into three intervals and the corresponding expressions are written as Eqs.6 to 8:

$$\sigma = E_i \cdot w = \frac{f_{st}}{w_e} \cdot w, w \le w_e \quad (6)$$

$$\sigma = f(w), w_e < w < w_{\max} \quad (7)$$

$$\sigma = 0, w > w_{\max} \quad (8)$$

where E_i is the secant elastic modulus derived from the ratio between the tensile strength and the crack width w_e corresponding to the maximum tensile stress. The value of w_e is taken as 0.003mm, 0.004mm and 0.005mm for LS, MLS and HS series respectively based on experimental observations.

5. CONCLUSIONS

Based on the experimental and analytical studies in this paper, the following conclusions can be reached.

(1) Three point bending test method can be applied to evaluate the interfacial Mode I fracture of PCM-concrete interfaces. The interfacial tension-softening diagram can be derived as well based on the modified J-integral method developed for monolithic ordinary concrete.

(2) The Mode I fracture energy relies greatly on the quality of bonding substrate and interface roughness. Different substrate concrete causes significant difference in the Mode I fracture energy even their tensile strengths are similar. Even with the same concrete substrate, the value of Mode I fracture energy varies with different interface roughness. The contributions of concrete substrate strength and interface roughness to the fracture energy mainly depend on the lesser between PCM-concrete interface bond strength and concrete layer tensile strength, which leads to different failure mode of interface. If the tensile bond strength of PCM to concrete is greater than tensile strength of interface concrete layer, the failure is characterized by a fracture at the concrete side, otherwise a fracture occurs along the joint line.

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