Fracture Mechanics of Concrete and Concrete Structures -
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Optimum treatment of PCM-concrete interfaces

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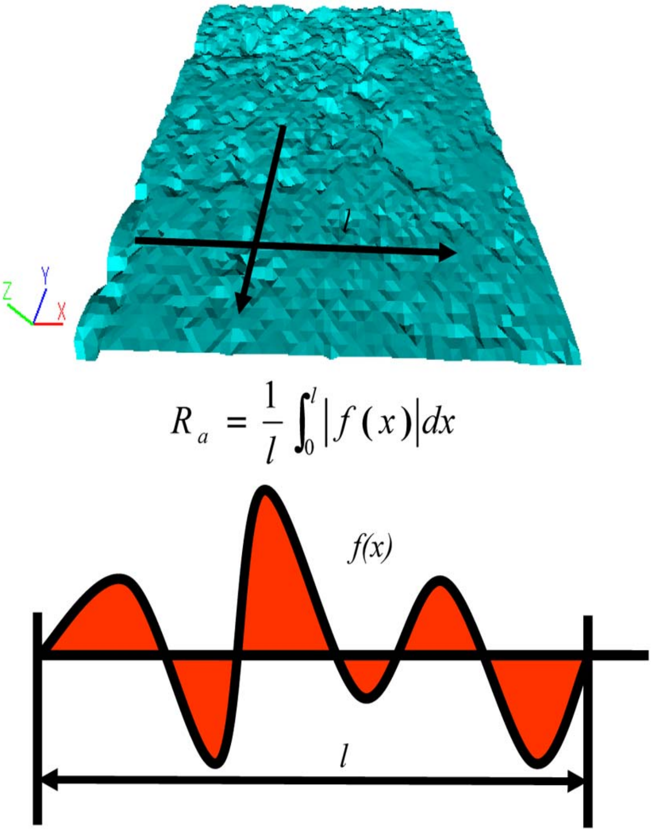
ABSTRACT: Experimental work including splitting tensile, three point bending, and direct shear tests on PCM-concrete composite specimens with various interface roughness R_a and substrate concrete was conducted. The PCM-concrete bond strength, fracture energy as well as fractured surface were investigated qualititatively and quantitatively. In case the substrate concrete was untreated, the bond strength as well as fracture energy was rather small, and the fracture developed along the PCM-concrete adhesion layer with even surface. The bond strength and fracture energy kept increasing with increase of interface roughness until the fracture mode was shifted from PCM-concrete adhesion layer to concrete cohesion layer. The effect of aggregate type (river gravel or crushed rock) on bond strength and fracture energy was not distinct. Regarding the bond properties and retrofitting cost, the $R_a \approx 1$ mm ($0.9 \leq R_a \leq 1.1$ mm) could be the optimum value of interface roughness.

1 INTRODUCTION

Polymer Cement Mortar (PCM) possess higher flexural strength and ductility, impermeability and higher adhesion with substrate concrete compared with normal cement mortars. Therefore, PCM has been used widely in all kinds of anticorrosion projects and as repairing materials for concrete structures and pavement. In recent years, more research has focused on the clarification of bond mechanism between PCM and substrate concrete. The PCM-concrete interface is the most critical component in most of PCM structural retrofitting applications. Therefore, in order to improve the bond properties and to optimize the overall structural performance, a deep understanding on the interfacial bond mechanism and the factors affecting the bond should be reached firstly. The evaluation of the bond properties of PCM-concrete interface either experimentally or analytically has been of particular interest.

The properties of bond interface mainly depend on adhesion in interface, cohesion in substrate concrete or PCM, friction, aggregate interlock, and other time-dependent factors. Each of these main factors, in turn, depends on other variables. In practice, the surface of a joint is treated to be rough in order to obtain good bond properties. It has been well known that this roughness of joint affects the performance of jointed members (Eduarado 2004, Momayez & Ehsani 2005, Furuuchi et al. 2006, Zhang et al. 2009). There are also some published works on bonding of repair materials to a concrete substrate where the preparation of the substrate surface with different techniques is mentioned. Water-jetting (*WJ*) is one of the best surface preparation methods according to several authors (Hindo 1990, Silfwerbrand 1990). Other procedures are referred to in the literature such as sand-blasting, grinding, wire-brushing, and shot-blasting; etc. However, in spite of the unanimous references to the importance of interface treatment for achieving a good bond between the original substrate and the new added materials, the effects of interface roughness and substrate concrete strength, as well as type of aggregate (river stone, crash stone) in substrate concrete, to PCM-concrete bond strength and fracture mechanism, have not been clearly clarified and quantified.

This paper aims at the objective of qualititatively and quantitatively study of the PCM-concrete interface bond strength and fracture energy. The first part of chapter describes the experimental work including splitting tension, three-point bending, and direct shear tests. The second part presents the experimental results. The experimental data are analyzed and presented to illustrate the contribution of interfacial roughness and substrate concrete to the bond properties. Finally, optimum treatment implications in practical PCM retrofitting applications are suggested.



$$R_a = \frac{1}{l}\int_0^l |f(x)|dx$$

Figure 1. Evaluation of interface roughness R_a.

2 EXPERIMENTAL OUTLINE

2.1 *Specimen preparation*

Five types of bonding concrete substrates with different compression strength and one type of PCM were prepared to simulate the actual bonding situation in real retrofitting fields. In order to investigate the effect of aggregate type in the substrate concrete, a ready-mixed concrete (*CS*) with crushed stone as coarse aggregate was introduced and compared with other series (*LS, MLS, MHS, HS*), in which river stone were used. Both the river stone and the crushed stone have a maximum diameter of 20 mm.

Table 1. Material properties of concrete and PCM.

Test Series	*W/C*	f_c	E_t
		MPa	GPa
LS	63%	29.29	26.77
MLS	50%	39.63	30.92
MHS	40%	52.62	33.39
HS	33%	78.83	36.77
CS	-	59.40	33.01
PCM	13.4%*	57.23	23.46

(*)Value of Water/ Compound
(-)Ready-mixed concrete

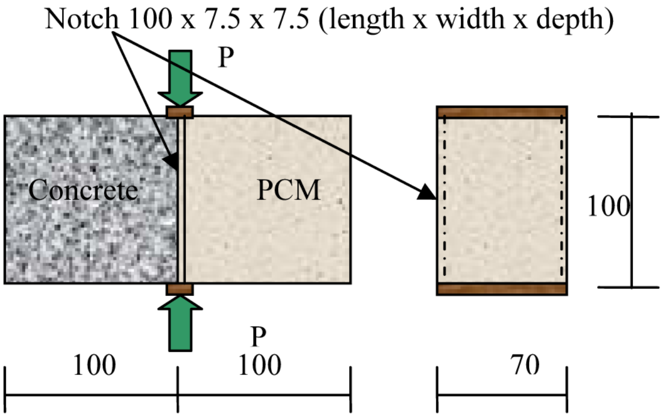


Figure 2. Splitting tensile test setup (unit: mm).

The W/C ratio and material 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 supplied as a ready to use blend of dry powders, which requires only the site addition of clean water to produce a medium weight repair mortar. The bond strength of PCM (28 days, 20°C) based on JIS A 1171 (2000) test method is 2.44 MPa.

The concrete substrates surfaces in this study were either untreated or treated with *WJ* method. Special attention was paid to provide adequate moisture on the substrate concrete surface. The substrate concrete was placed in water for 48hrs and free water was removed before casting PCM. The PCM was sprayed to the substrate concrete and the connected interface was separated with right-angled triangle wooden prism to induce the notch.

Firstly, the interface roughness was roughly controlled by a given *WJ* treatment depth from substrate surface as shown in Table 2. Then it was measured using a 3D shape measurement apparatus. The treatment depth varied from 0 to 8 mm. There is less practical meaning if treatment depth is greater than 8mm with normal size coarse aggregate (diameter≤ 25 mm). As shown in Figure 1, the roughness is quantified by the arithmetic mean value (R_a) of the difference between the average height of the peaks and the average height of the valleys from an arbitrary baseline based on JIS B 0610 (2001).

Table 2. Number of specimens and treatment depth for each series.

	Treatment Depth (mm)			
	0(untreated)	0-3	3-5	5-8
Splitting	3 (0)	2 (2)	2 (2)	1(2)
Shear	2 (0)	2 (2)	2 (2)	2 (2)
Bending	3 (0)	3 (2)	3 (2)	2 (2)

(*): the CS series

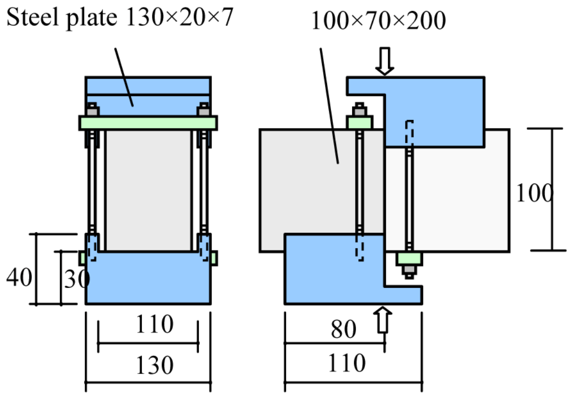


Figure 3. Set-up of splitting tension test (unit: mm).

2.2 *Splitting tension test*

The splitting tension test is used worldwide to measure the tensile strength of concrete. In this study, splitting tension test as shown in Figure 2 was conducted to evaluate the tensile strength of the PCM-concrete interface. To prevent local failure in compression at the loading points, two thin strips made of plywood were placed between the loading plates and the specimen to distribute the load. A notch with size of 7.5×7.5×100 (width x depth x length) mm at each side was induced during the PCM casting procedure. The contact area between the concrete substrate and the PCM is 100 x 55 mm. The maximum tensile stress can be calculated by the following Equation:

$$\sigma_{\max} = \frac{2P}{\pi A} \tag{1}$$

where $\sigma_{\max}$ is the maximum tensile strength in the specimen when the applied load is P, A is the area of the contacting surface.

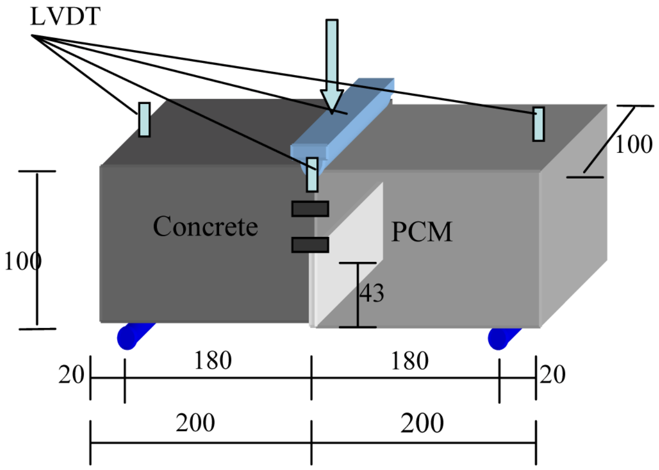


Figure 4. Set-up of bending test (unit: mm).

2.3 *Direct shear test*

Direct shear tests are commonly used in determination of shear strength of concrete. In this study, the direct shear test on composite specimens based on JCI-SPC3 (2004) was conducted. Figure 3 shows the basic configuration of the apparatus. The apparatus consists of upper and lower half boxes inside which the test specimen was mounted. The size of specimens was the same as those for splitting tension tests. The maximum shear stress can be calculated by the following equation:

$$\tau_{\max} = \frac{P}{A} \tag{2}$$

where $\tau_{\max}$ is the maximum shear strength in the specimen when the applied load is P, A is the area of the contacting surface.

2.4 *Three point bending test*

To investigate the effect of interface roughness on the PCM-concrete flexural bond strength and fracture energy, the three point bending test on notched composite beam as shown in Figure 4 was conducted. The deflection of the composite specimens was measured by linear variable differential transducers (LVDTs). The size of composite specimens was 100x100x400 (width x depth x length) mm and the free span between the supports was chosen to be 36 cm. All the specimens were tested under displacement controlled loading condition. The loading speed was 0.1mm/min. The flexure strength was calculated considering the material behavior as linear-elastic by the following equation:

$$f_{fl} = 1.5 \cdot \frac{\left(P + \frac{mg}{2}\right) l}{b\left(d - a_0\right)^2} \tag{3}$$

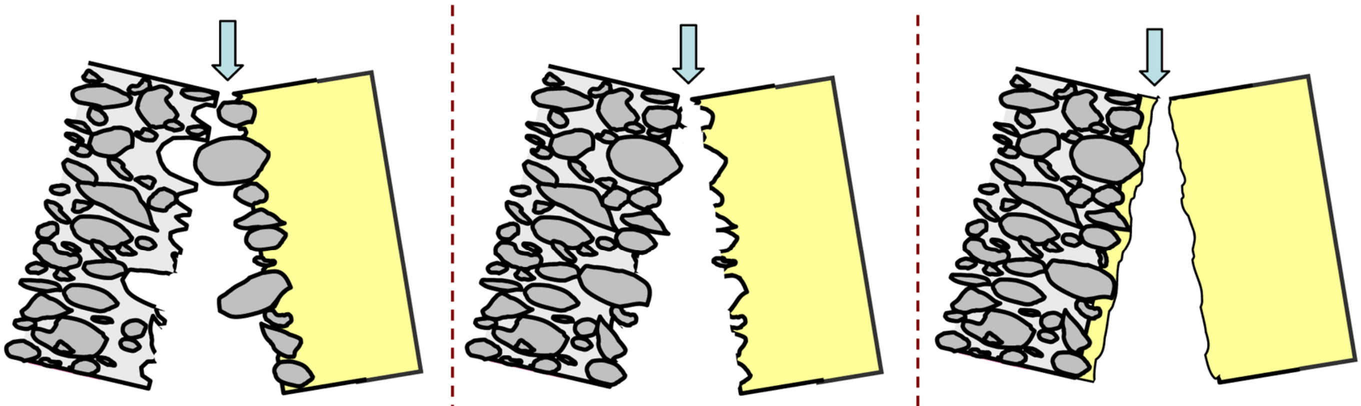
where f_{fl} is the flexural strength when the applied load is P and mg is the weight of the beam. The geometric dimensions are explained in Figure 2.

The details of number of specimens for each loading test and the *WJ* treatment depth can be found in Table 2.

3 TEST RESULTS AND DISCUSSION

3.1 *Observation on failure mode*

To quantitatively describe failure mechanisms, the PCM-concrete interface is considered as a three-phase composite consisting of PCM cohesion layer, concrete cohesion layer and interaction between these two constituents, which is modeled with PCM-concrete joint adhesion layer. The failure modes were characterized by the location of the failure in the specimens as illustrated in Figure 5. Generally speaking, in comparison with fracture surface of concrete cohesion layer, the fracture surface of adhesion layer or PCM cohesion layer was smoother



(a)Failure predominantly in concrete cohesion layer

(b)Failure predominantly in PCM adhesion layer

(c)Failure predominantly in PCM cohesion layer

Figure 5. Illustration of failure surface.

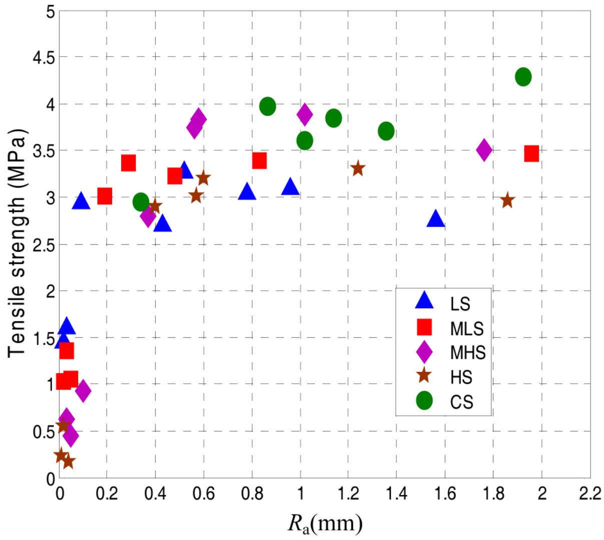


Figure 6. Tensile strength-R_a relationships.

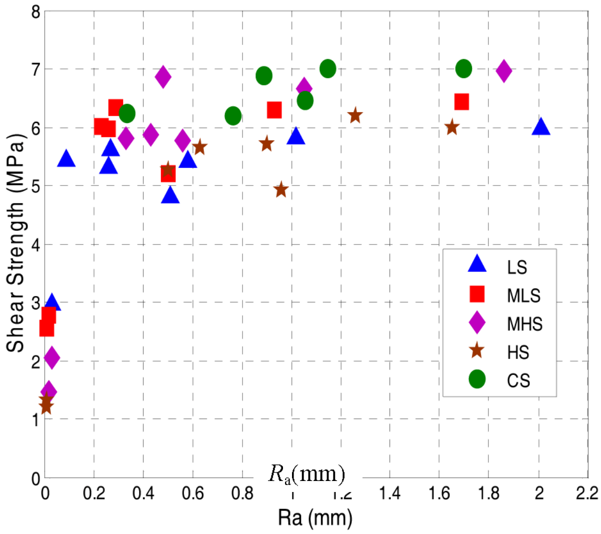


Figure 7. Shear strength-R_a relationships.

and the amount of aggregates attached on the PCM side were fewer. For normal strength substrate concrete (*LS, MLS, MHS* series) with concrete cohesion failure, since the stiffness and strength of aggregate and joint adhesion were much greater than those of hydrated cement paste (*HCP*), undamaged aggregates could be observed. For high strength substrate concrete *(CS, HS* series), the *HCP* was sufficiently strong to cause the crushing of aggregate or joint adhesion layer, with crushed aggregate attached to the PCM side.

In summary, in case of composite beams without surface treatment, all specimens failed in the joint adhesion layer regardless of the series of substrate concrete. In case of low strength substrate concrete series (*LS, MLS, MHS*), with further increase of R_a, the failure mode started to vary from fracture at adhesion layer to fracture at concrete cohesion layer, and became stable even with further increase of R_a. While in case of the high strength substrate concrete series (*CS, HS*), the failure mode started to vary from fracture at adhesion layer to fracture at mixed layer among joint adhesion layer, PCM and concrete cohesion layer. With further increase of Ra (R_a>2mm), the failure at PCM cohesion layer could be observed.

3.2 *Bond Strength*

Figures 6-8 show the relationship between splitting tensile strength, flexure strength and shear strength, respectively, and the interface roughness R_a. The interface bond strength without surface treatment is rather low when compared to that of treated interfaces. This indicates that the pure (or nearly pure with small R_a) PCM-concrete interface adhesion capacity originated from the van der Waals forces of attraction is relatively weak and the necessity of surface treatment to increase the surface roughness is undoubted.

In comparison with bond flexure strength, the full bond tensile and shear strength can be achieved even with a small roughness ($R_a \approx 0.1$ mm) as in Figures 6-7, and kept nearly constant with further increase of R_a. This indicates the full bond tensile and shear strength can be realized with a small treatment depth (0-3 mm), just after elimination of the surface weak mortar layer.

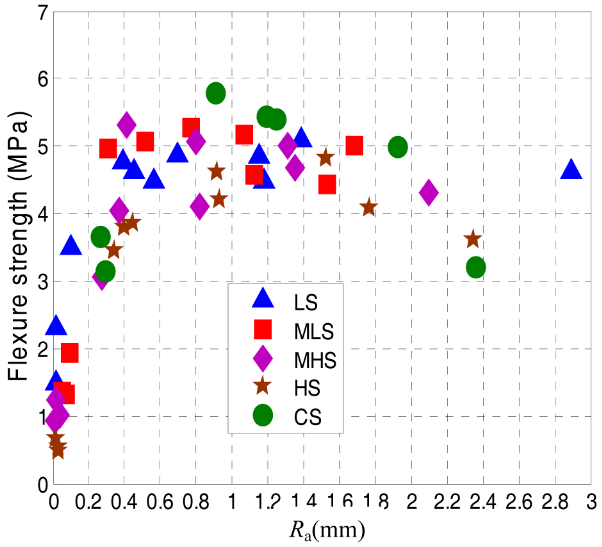


Figure 8. Flexural strength-R_a relationships.

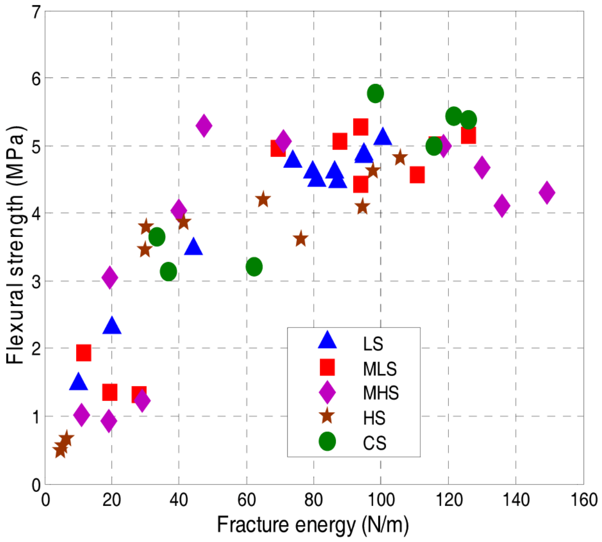


Figure 10. Flexural strength-fracture energy relationships.

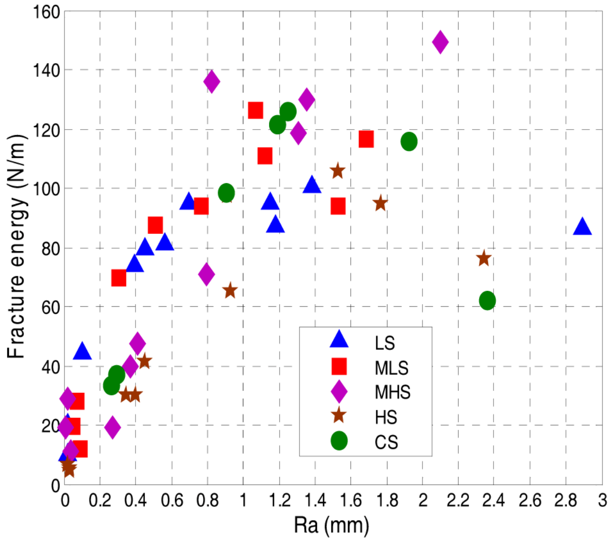


Figure 9. Fracture energy-R_a relationships.

As shown in Figure 8, in *LS*, *MLS and MHS* Series with compression strength equal or smaller than that of PCM, the bond flexural strength increases with an increase of R_a and reaches the maximum value at R_a around 0.4 mm, then it is almost constant until R_a is greater than 1.5 mm and shows a decreasing tendency thereafter. In *MHS*, *HS* and *CS* Series with compression strength higher than that of PCM, flexure bond strength increases with an increase of R_a and reaches the R_a(mm) um value at R_a around 1mm, then it shows a tendency of decreasing with further increase of R_a. Generally speaking, the full bond flexural strength of all the series can be achieved when R_a is greater than 1 mm. The effect of aggregate type (crushing stone or river stone) on the bond strength is not distinct.

3.3 *Fracture energy*

The Mode I interfacial fracture energy was calculated based on the experimental load-deflection curves using RILEM recommended expressions (1985). Figure 9 shows the values of fracture energy, which is affected by interface roughness. Similar to the bond strength, the fracture energy without surface treatment is relatively small and it keeps increasing with the increase of R_a to a certain value. The effect of aggregate type (crushing stone or river stone) on fracture energy is not distinct as well. Further experiments with precisely measured treatment depth should be conducted to clarify the effect of aggregate type on the interface roughness with the same treatment depth.

The increase of interface roughness leads to an increase of joint area and subsequently to an increase of the fracture energy of adhesion layer until the failure mode shifts from adhesion layer to concrete cohesion layer with $R_a \approx 1$ mm ($0.9 \leq R_a \leq 1.1$ mm). The fracture energy is not sensitive to the variation of R_a with failure at concrete cohesion layer even with further increase of R_a. The fracture of PCM-concrete interfaces in real retrofitting may contain and in some cases be dominated by Mode I component such as fracture energy, which can be guaranteed with enough roughness ($R_a \geq 1$ mm). Therefore, regarding the bond strength and repair cost in the practical retrofitting, the $R_a \approx 1$ mm ($0.9 \leq R_a \leq 1.1$ mm) could be the optimized value of interface roughness.

Figure 10 shows the relationship between the bond flexural strength and fracture energy. For all the substrate series, the flexural strength increased with the increase of fracture energy especially when the fracture energy was relatively small. Because of the existence of stress gradient in the three point bending test, the fracture formation and development have pronounced effect on the flexural strength due to the full development of fracture zone. As shown in Figure 8 and Figure 9, in case of *HS* and *CS* series, with increase of R_a, the flexure strength as well as fracture energy was decreased when failure mode shifted from PCM-concrete interface adhesion failure to PCM cohesion failure at $R_a \approx 2.4$ mm. This is because PCM cohesion layer failure surface is smoother and has lesser aggregate interlock effects due to the lack of coarse aggregates along the fracture surface, resulting in smaller fracture energy and flexural strength.

4 CONCLUSIONS

Based on the experimental and analytical studies in this paper, the following conclusions may be drawn:

1. The interface bond strength and fracture energy without surface treatment are rather low compared to that of treated interfaces. This indicates that the weakness of the real PCM-concrete interface adhesion capacity appears when interface roughness is very small. At least the surface weak mortar layer (0-3 mm) should be removed in order to gain enough bond strength.
2. The failure mode as well as condition of fracture surface has important effect on the interface bond strength and fracture energy. For a given substrate concrete, the bond flexural strength and fracture energy with failure at adhesion layer are smaller than those of concrete cohesion layer failure.
3. The full bond tensile and shear strength can be achieved with a small roughness ($R_a \geq 0.1$ mm); however, the full bond flexural strength requires $R_a \geq 0.4$ mm when compression strength of substrate concrete is equal or lower than that of PCM, and $R_a \geq 1$ mm when compression strength of substrate concrete is higher than that of PCM. For all substrate series, the full fracture energy can be reached with $R_a \approx 1$ mm. The roughness has more effect on the interface fracture energy and flexural strength than on the tensile and shear strength. Regarding the bond and fracture properties as well as retrofitting costs, the $R_a \approx 1$ mm ($0.9 \leq R_a \leq 1.1$ mm) could be the optimum value of interface roughness.
4. The effect of aggregate type (crushing stone or river stone) on the interface bond strength and fracture energy is not distinct.
5. The flexural strength increases with the increase of fracture energy especially when the fracture energy is relatively small. The fracture energy is proved to be the most appropriate index for evaluation of bond flexural strength.

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REFERENCES

A. Momayez, M.R. Ehsani,et al, 2005, Comparison of methods for evaluating bond strength between concrete substrate and repair materials, Cement and Concrete Research 35, 748-757.

DW, Zhang., H. Furuuchi, A. Hori and T. Ueda, “Bond Strength of PCM-Concrete Interface: Influence of Interface Roughness and Substrate Concrete”, Proceedings of JCI, Vol.31, No.1, pp. 1969-1974.

H, Furuuchi, R. Sakai, T.Ueda, 2006, Effects of interface roughness and size of coarse aggregate on bond characteristics of PCM, Proceedings of JCI, Vol.28, No.2,1567-1572.

J. Silfwerbrand, 1990, Improving concrete bond in repaired bridge decks. Concrete Int, 121-6.

JCI Standard , 2004.4, Japan Concrete Institute.

JIS A 1171, 2000, Test methods for polymer-modified mortar.

JIS B 0601, 2001.1, Geometrical Product Specifications (GPS) - Surface texture: Profile method- Terms, Definitions and surface texture parameters, JIS.

KR. Hindo, 1990, In-place bond testing and surface preparation of concrete. Concrete Int, 127-9.

N.B.S., Eduarado et al, 2004, Concrete to concrete bond strength. Influence of roughness of the substrate surface, Construction and Building Materials 18, 675-681.

RILEM Draft Recommendation (50-FMC),1985, Determination of the Fracture Energy of Mortar and Concrete by Means of Three Point Bend Tests on Notched Beams, Materials and Structures, Vol.18, No.106, pp. 287-297.