-Technical Paper -

BOND STRENGTH OF PCM-CONCRETE INTERFACES: INFLUENCE OF INTERFACE ROUGHNESS AND SUBSTRATE CONCRETE

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ABSTRACT

The experimental work including splitting tensile, three point bending, and direct shear tests on PCM-concrete composite specimens with various interface roughness and substrate concrete were conducted. The results indicated that: the flexure bond strength was more sensitive to value of interface roughness than the tensile and shear bond strength. The bond strength increased with substrate concrete strength only when the failure occurs at the concrete cohesion layer and the roughness had more pronounced effect on the bond strength when compressive strength of PCM is equal or lower than that of substrate concrete.

Keywords: bond strength, interface, roughness, adhesion layer, cohesion layer

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 decks. 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 increased 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.

In the PCM applications, the provision of a good bond between the polymer-based repair material and the concrete substrate is an important requirement for restoring monolithic character. The bond between the PCM and concrete usually presents a weak link in the repaired structure. 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. 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.

The bond strength mainly depends on adhesion in interface, friction, aggregate interlock, and time-dependent factors. Each of these main factors, in turn, depends on other variables. Adhesion to interface depends on bonding agent, material compaction, cleanness and moisture content of repair surface, specimen age, and roughness of interface surface. Friction and aggregate interlock on interface depend on parameters, such as aggregate size, aggregate shape, and surface preparation.

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 [1][2][3]. However, in spite of the unanimous reference 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 to bond strength, has not been clearly clarified and quantified.

This paper aims at the objective of deeper insight into the origin of the influence of interface roughness and substrate concrete strength on the bond strength. The first part of paper 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, several design implications in practical retrofitting applications are suggested.

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Table 1 Material properties of concrete and PCM

Test Series	*W/C*	f'_c (MPa)	E_t (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
PCM	13.4%*	57.23	23.46

*Value of Water/ Compound

2. EXPERIMENTAL OUTLINE

2.1 Preparation of 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. The flexure strength and bond strength of PCM (28 days, 20^{o}C) based on JIS A 1171[4] test method are 9.80 MPa and 2.44 MPa respectively.

There are some published works on bonding of repair materials to a concrete substrate where the preparation of the substrate surface with different techniques is mentioned. Sand-blasting and water-jetting (WJ) are the best surface preparation methods according to several authors [5][6] and it has been proved that a saturated substrate with a dry surface is considered to be the best solution[7][8]. The concrete substrates surfaces in this study were treated by 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 PCM was sprayed to the substrate concrete and the connected interface was separated with right-angled triangle wooden prism to induce the notch.

The roughness of the concrete-PCM interface was measured using a 3D shape measurement apparatus. The roughness is quantified by 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 Standard [9].

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 Fig.1 was conducted to evaluate the tension strength of the PCM-concrete interface. To prevent local failure in compression at the loading generators, 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 is 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:

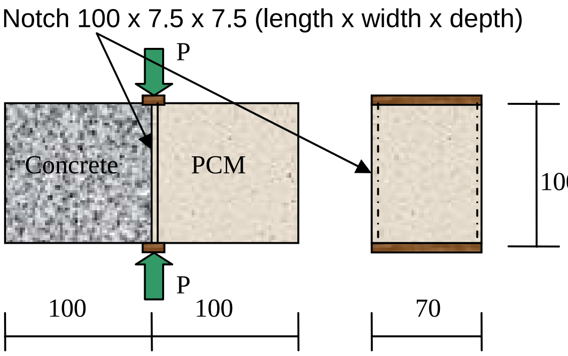


Fig.1 Splitting tensile test setup (unit: mm)

$$\sigma_{\max} = \frac{2P}{\pi A} \qquad (1)$$

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

2.3 Three Point Bending Test

To investigate the effect of interface roughness on the PCM-concrete aggregate interlocking, the three point bending test on notched composite beam as shown in Fig. 2 was conducted. The deflection of the composite beams 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 the displacement controlled loading condition. The loading speed was 0.1mm/min. The flexure strength was calculated considering the material behavior as linear-elastic (see Eq.2).

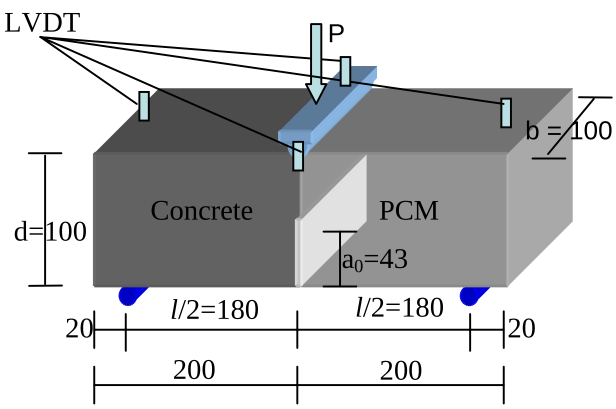


Fig.2 Three point bending test setup (unit: mm)

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

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

2.4 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 [10] was conducted. Figure 3 shows the basic configuration of the apparatus. The apparatus consists of an upper and lower half boxes inside which the test specimen was mounted. During the shearing, displacements in the horizontal and vertical directions are monitored continually by two directional strain gauge type transducers. The size of specimens was same as those for splitting tension tests. The maximum shear stress can be calculated by the following equation:

$$\tau_{\max} = \frac{P}{A} \tag{3}$$

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

3. TEST RESULTS AND DISCUSSION

3.1 Observations on Failure Mode

To quantitatively describe failure mechanisms, the PCM-concrete interface is considered a three-phase composite consisting of PCM cohesion layer, concrete cohesion layer and interaction between these two constituents is modeled with PCM-concrete joint adhesion layer.

The failure modes were characterized by the location of the failure in the specimens. Bond failure is defined when the plane of failure is along the interface adhesion layer. Some of the specimens failed by partial failure of either the substrate concrete cohesion layer or the newly added PCM-concrete adhesion layer.

Photo 1 shows the observed types of fracturing interfaces in splitting tension test and three point bending test. In common, all of the specimens with concrete substrates of LS and MLS and some of MHS fracture mostly at the concrete cohesion layer (see Photo 1 (a)), while all of the specimens with concrete substrate of HS and some of MHS fracture mostly at the joint adhesion layer (see Photo 1 (c)). In addition, some specimens with concrete substrate of MHS failed by partial fracture of either the concrete cohesion layer or joint adhesion

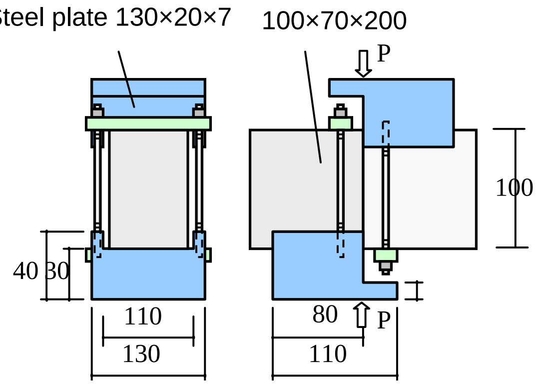


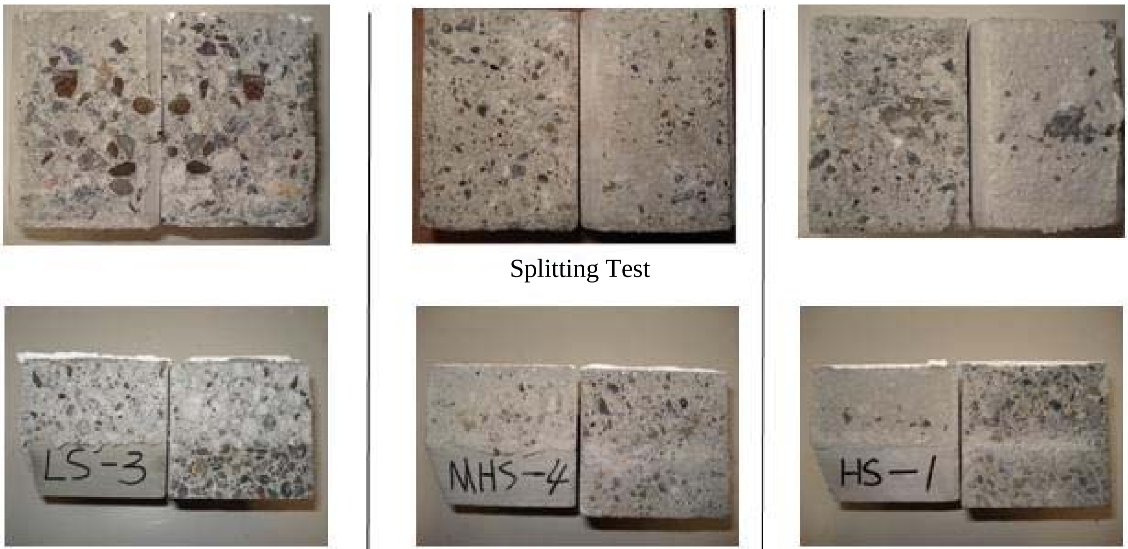
Fig.3 Set-up of splitting tension test (unit: mm)

layer (see Photo 1 (b)). No fracture at the PCM cohesion layer could be observed. In comparison with the fracturing concrete cohesion layer, the fracturing PCM-concrete joint adhesion layer is smoother. It can be distinguished by naked eyes 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.

Photo 2 shows the observed types of fracturing interfaces in direct shear test. Generally two kinds of fracturing mode could be observed. All of the specimens with concrete substrates of LS and MLS and some with MHS had inclined fracture mostly at the concrete cohesion layer with cement paste crushing or cement paste and aggregate separation. While all of the specimens with concrete substrate of HS and some with MHS had inclined fracture mostly at the joint adhesion layer with aggregate crushing. For normal strength substrate concrete (*LS, MLS, MHS series*), the stiffness and strength of aggregate and joint adhesion are much greater than those of hydrated cement paste (HCP). Shear transfer through the shear fracture is dominated by the cement paste-aggregate interlock and the interlock mechanism is characterized with sliding at the contact area between the HCP and aggregates at the opposite sides of the crack and cement paste crushing at contacts. For high strength substrate concrete (*HS series*), the HCP is sufficiently strong to cause the crushing of aggregate or joint adhesion layer, destroying the interlocking structure.

Generally, the adhesive strength in the PCM-concrete adhesion zone is weaker than that in bulk PCM cohesion zone because water films tend to develop around interface aggregates inducing a high local water-cement ratio. Consequently no failure mode of fracturing in PCM cohesion layer could be observed.

When a composite specimen with PCM-concrete interface is subjected to tension or shear, 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 or shear bond strength of PCM to concrete is greater than that of concrete cohesion layer,



Splitting Test

Three Point Bending Test

(a) Fracture mostly at cohesion layer (LS,MLS)

(b) Fracture at both layers (MHS)

(c) Fracture mostly at adhesion layer (HS)

Photo 1 Failure surface

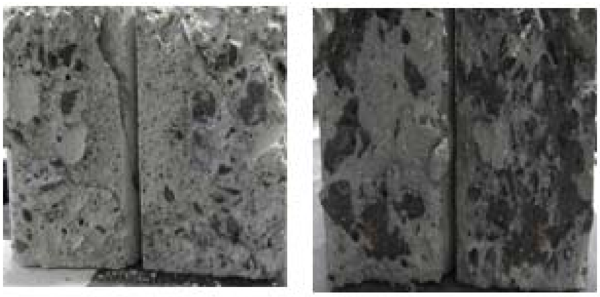
the failure is characterized by a fracture at the concrete side. If the bond is insufficient, a fracture occurs along the joint adhesion layer.

3.2 Bond Strength

The total bond strength of PCM-concrete interface is a combination of effects from the joint adhesion, contact friction, and joint aggregate interlock. The principal source of adhesion is the van der Waals forces of attraction existed between the solid surfaces involved [11]. Friction and aggregate interlocking at PCM-concrete interface depend on aggregate size, shape, and surface preparation.

The term aggregate interlocking is used to describe the process of stress transfer across a crack. Since the existence of stress gradient in the three point bending test, the aggregate interlocking of joint adhesion layer has pronounced effect on the maximum load capacity due to the full development of fracture zone (see Fig.4). The fracture faces hardly touch one-another, but rather seem to rotate away from each other, which suggests that the friction plays a rather significant role in the softening regime under bending (Fig.4). Local confinement of areas with crack overlaps or Poisson effects might actually cause friction [12]. Therefore, the three point bending test can be used to investigate the effect of roughness on the aggregate interlocking and friction of joint adhesion layer. On the other hand, since the lesser influence of aggregate interlocking on the pure tensile bond strength, the splitting tension test is mainly used to study the effect of roughness on the tensile strength of joint adhesion.

The contact friction and interface interlocking may not exert a major influence on the total shear capacity



(a) Cohesion layer (b) Adhesion layer

Photo 2 Shear failure surface

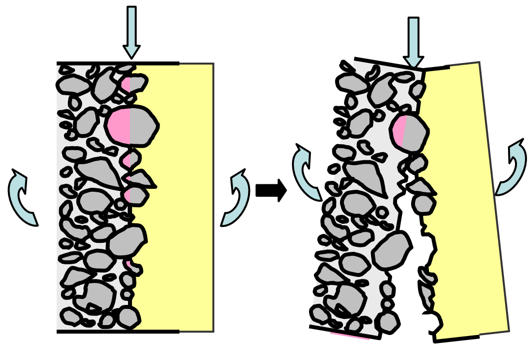


Fig. 4 Illustration of crack surface under bending

observed in the direct shear tests. This is because shear dilation or crack dilation was allowed in the tests. If the test specimen was restrained from horizontal dilation or a high normal stress was applied to the test specimen, contact friction and cement paste-aggregate interlock would become activated. Therefore, in this study, the direct shear test is conducted only for investigating the effect of roughness on the shear strength of joint adhesion before interfacial cracking.

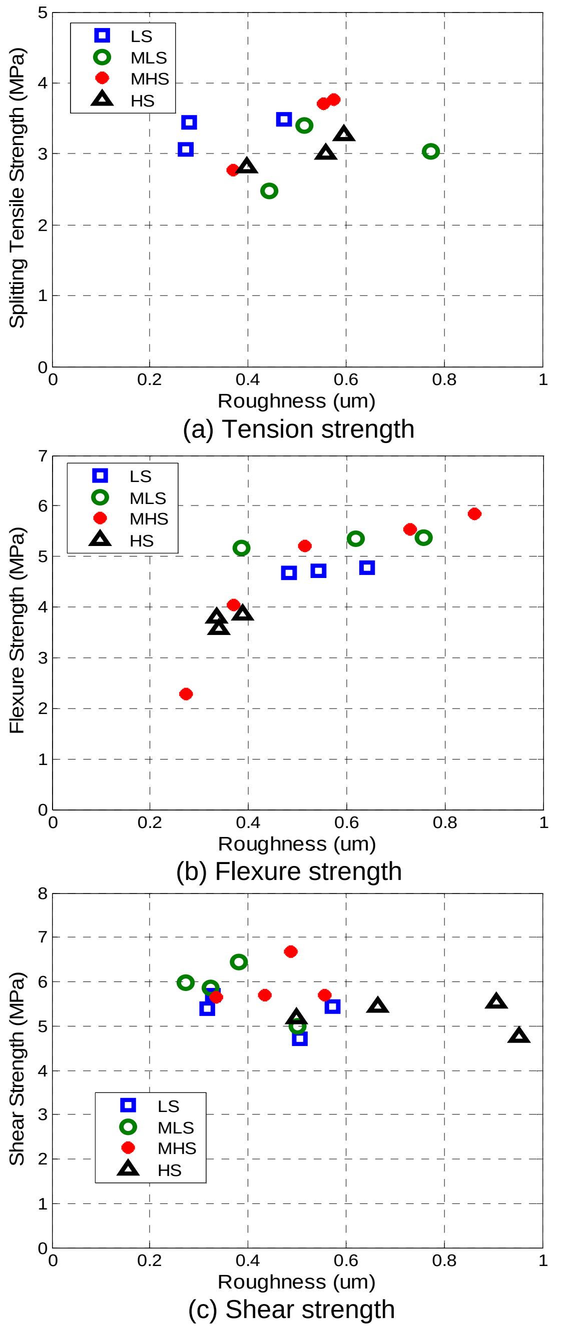


Fig.5 Bond strength-roughness relationship

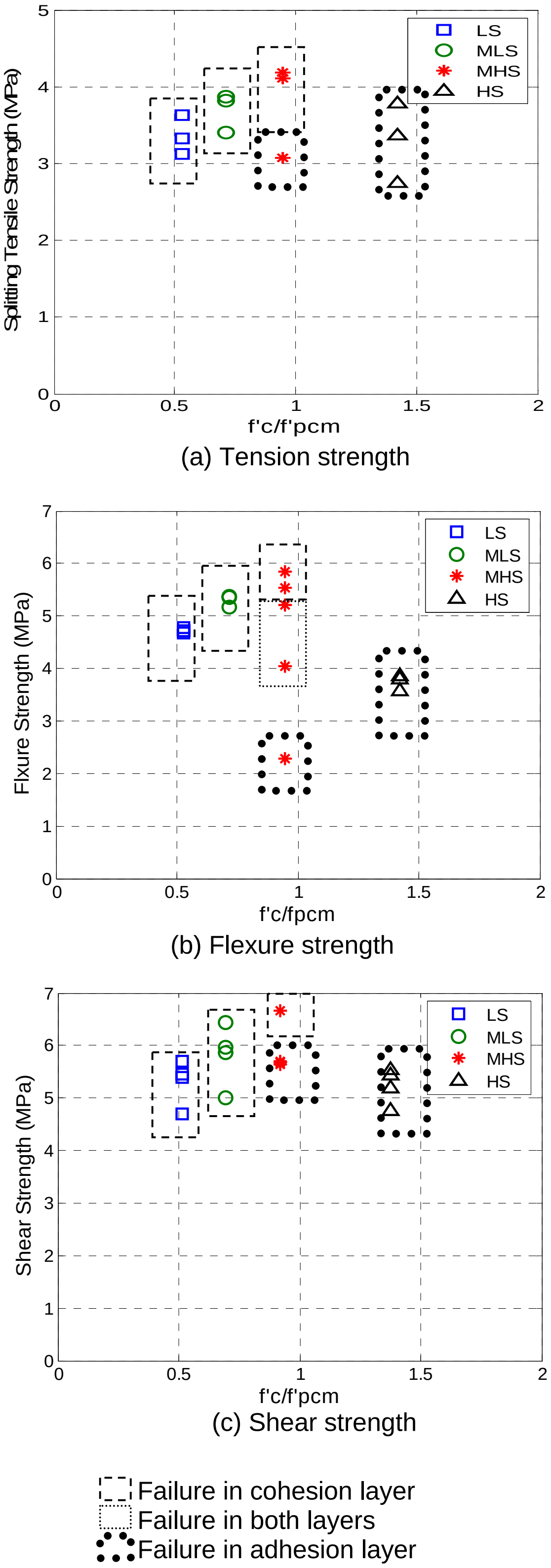


Fig.6 Bond strength- substrate concrete relationship

Fig.5 shows the relationship between splitting tension strength, flexure strength and shear strength with interface roughness separately. It can be seen that in comparison with flexure strength, the splitting tension strength and shear strength are not so sensitive to variation of Ra. It was ascertained that the interface roughness had a profound effect on the aggregate interlocking and friction (flexure strength) than on the joint adhesion (tension and shear strength).

The influence of interface roughness on flexure strength in the case of LS and MLS substrate concrete with failure at concrete cohesion layer is not as much as that of MHS and HS substrate concrete with failure at joint adhesion layer. In the case of MHS substrate concrete, the flexure strength varies a lot with the value of Ra and the failure mode changes from fracture at joint adhesion layer to fracture at concrete cohesion layer. This demonstrates that the roughness has more effect on the aggregate interlock of adhesion layer than on the thin concrete cohesion layer near the interface.

Fig.6 shows the relationship between splitting tensile strength, shear strength and flexure strength with ratio between compressive strength of substrate concrete and PCM separately. It can be observed that the bond strength decreases with an increase in the difference between the compressive strength of PCM and substrate concrete. In the case of fracture at concrete cohesion layer, the bond strength 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 adhesion layer. Concrete series LS with fracture at concrete cohesion layer shows obviously higher values of flexure strength in comparison with the HS with fracture at the joint adhesion layer though they have closer splitting tensile strength and shear strength. This is because joint adhesion layer failure surface is smoother and has less aggregate interlock effects due to the lack of coarse aggregates along the fracture surface.

4. CONCLUSIONS

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

1) The interface roughness had a more profound effect on the aggregate interlock and friction than on the joint adhesion.

2) The condition of fracture surface has important effect on the interface bond strength. The failure at adhesion layer with smooth fracture surface will result in lower flexure bond strength although the tensile and shear bond strength is similar.

3) For a given kind of PCM, the interface bond strength decreases with an increase in the difference between the compressive strength of PCM and substrate concrete.

Therefore, in practical retrofitting applications, the following design implications are suggested:

i) In case the compressive strength of substrate concrete is equal or higher than that of PCM, which the failure is most likely occurring at joint adhesion layer, the interface should be roughened enough to ensure the fracture surface has enough aggregate interlock.

ii) The economical and efficient option is to choose the PCM that has similar compressive strength as that of substrate concrete.

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