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Investigation of interfacial resistance between concrete and polymer – cement mortar and development of constitutive material model for the interface

コンクリートとポリマーセメントモルタル間界面の破壊靱性計測と構成則

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This paper aims to investigate interfacial resistance and to propose a constitutive material model of the interface between concrete and polymer-cement mortar (PCM) in tile systems. The interfacial resistance of the concrete / PCM interface is evaluated in terms of interface fracture toughness based on an interface fracture mechanics method. The experiment is conducted under pure tension and mixed mode conditions (tension and shear) by using four-point bending tests. It is found that the interface fracture toughness is low especially at high mixity of shear stress, and that the tendency of the interface fracture toughness is different from the one of the concrete / fiber reinforce concrete (FRC) interface that is used to be the representative of the concrete / cementitious material interface in this study. Moreover, two models of the interface fracture toughness are derived from a cracking criterion, a linear cracking criterion and an elliptic one respectively, by assuming linear softening behavior. The model derived from the elliptic cracking surface shows good agreement with the experimental result of the concrete / PCM interface fracture toughness.

Key Words: *tile delamination, interface fracture toughness, model of interface fracture toughness, linear cracking surface, elliptic cracking surface.*

1. Introduction

Tiles are widely used in building structures but problems such as cracking and spalling of tiles also occur frequently. Particularly, the external wall tile that is delaminated from a high-rise building causes damage to human life and vehicles around the building area. Moreover, generous money is provided for tile maintenance cost.

From field observation, failure locations are mostly found at two locations that are a concrete / adhesive (normally polymer-cement mortar (PCM) in Japan) interface or a tile / adhesive one[1]. This study is focused only on the concrete / PCM interface.

Generally, testing methods that are used to quantify a performance of the interface between two materials give the value in terms of bonding strength[2]. Although tensile bonding strength or shear bonding strength can be obtained, two modes that are tensile and shear stresses are involved in the tile systems such as tiles on a concrete wall.

Furthermore, defects are always formed during attaching tiles to a structure in reality. The defects that are normally small cracks cause stress concentration at the crack tip, and failure is initiated by fracture propagation[3]. Therefore, the interfacial resistance is expected to be governed by fracture toughness rather than tensile or shear bonding strength.

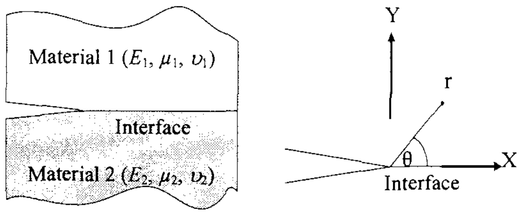


Fig. 1: Interface crack in a bimaterial system

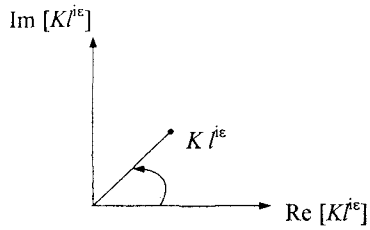


Fig.2: Phase angle

Moreover, the causes of the external wall tile delamination are not clarified because many factors are involved in the tile delamination problem, for example, differential movement among materials, deformation of adhesive due to shrinkage, improper sequence work, and so on[4]. Usually, delamination analysis can be performed by using interface elements in a finite element method (FEM) [5]. Prior to do the FE analysis, a suitable constitutive material model of the interface must be developed.

It can be seen that the determination of the interfacial resistance of the concrete / PCM interface under mixed modes in terms of the interface fracture toughness and the need of the suitable constitutive material model of the concrete / PCM interface are necessary in order to solve the tile delamination problem.

In this study, the fracture failure along the interface between concrete and PCM in the tile systems is considered as the failure of a bimaterial system from an interface fracture mechanics point of view. The mixed modes of tension and shear stresses and also the defects at the interface are taken into account in the experimental determination of the interface fracture toughness. Then, the development of the constitutive material model of the concrete / PCM interface is introduced by using a cracking criterion and a softening behavior concept to derive the interface fracture toughness. Two interface fracture toughness models are derived from a linear cracking criterion and an elliptic one respectively. Finally, the model of the interface fracture toughness derived from the elliptic cracking criterion is used to represent the interface fracture toughness of the concrete / PCM interface and compared with the one obtained from the experimental result.

2. Theoretical Background of Interface Fracture Mechanics

Interface fracture behavior between two materials is commonly found from micro-structures to macro-structures. The interface fracture mechanics is developed and applied to study the fracture behavior along the interface of various fields such as a micro-electronic package[6], plasma facing components of a fusion reactor[7], and aggregate / mortar interfacial zone in high strength concrete[8].

The main objectives of the interface fracture mechanics are to determine the fracture energy release rate of an interface and also to quantify a fracture criterion for crack path prediction[9].

The energy release rate G for crack propagation along the interface under quasi-static loading conditions[10] in a bimaterial system as shown in **Fig. 1** is related to the stress intensity factors.

$$G = \frac{1-\beta^2}{E_*}(K_1^2 + K_2^2) = \frac{1-\beta^2}{E_*}\left|K \cdot \overline{K}\right| \qquad (1)$$

where K_1 and K_2 are real and imaginary parts of the stress intensity factor K that is occurred from the interface crack tip stress filed, σ_{jk}. For any plane problem, it has the form $\sigma_{jk} = \mathrm{Re}[Kr^{i\varepsilon}](2\pi r)^{-1/2}\sigma^{I}_{jk}(\theta,\varepsilon) + \mathrm{Im}[Kr^{i\varepsilon}](2\pi r)^{-1/2}\sigma^{II}_{jk}(\theta,\varepsilon)$ where r and θ are planar-polar coordinates centered at the crack tip as shown also in **Fig. 1** and $\sigma^{I}_{jk}(\theta,\varepsilon)$, $\sigma^{II}_{jk}(\theta,\varepsilon)$ are the dimensionless angular functions[9].

The complex stress intensity factor K for any plane elastic interface crack problems can be written in the general form as

$$K = K_1 + iK_2 = T \cdot L^{1/2-i\varepsilon} F \ , \qquad (2)$$

where T = applied stress, L = in-plane length, and F = complex dimensionless function containing material and geometric information. K_1 and K_2 play similar role to the conventional mode I and mode II intensity factors in homogeneous material. E_* is the effective modulus and defined by

$$\frac{1}{E_*} = \frac{1}{2}\left[\frac{1}{\overline{E}_1} + \frac{1}{\overline{E}_2}\right], \qquad (3)$$

where $\overline{E_i} = E_i / (1 - \upsilon_i)$ for plane strain elastic modulus of material i.

Bimaterial elasticity depends on two elastic mismatch parameters[11] α and β defined by

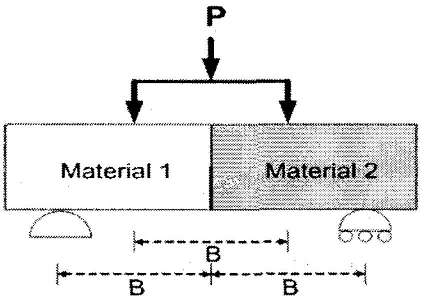


Fig. 3: Symmetric loading set-up

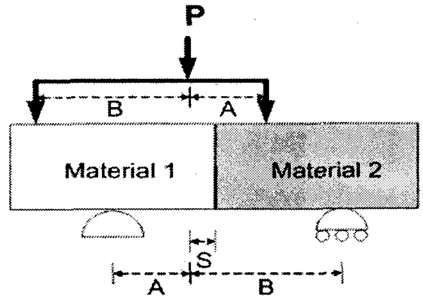


Fig. 4: Asymmetric loading set-up

$$\alpha = \frac{\mu_1(\kappa_2+1)-\mu_2(\kappa_1+1)}{\mu_1(\kappa_2+1)+\mu_2(\kappa_1+1)} \text{ and} \tag{4}$$

$$\beta = \frac{\mu_1(\kappa_2-1)-\mu_2(\kappa_1-1)}{\mu_1(\kappa_2+1)+\mu_2(\kappa_1+1)}, \tag{5}$$

where $\kappa_i = 3 - 4\upsilon_i$ for plane strain condition, μ_i and υ_i represent shear modulus and Poisson's ratio of the material i respectively.

Phase angle ψ in **Fig. 2** is used to measure a relative proportion of the effect of mode 2 to mode 1 stresses on the interface. In other words, it is the ratio of stress intensity factors ahead of the crack tip.

$$\psi = \arctan\frac{\mathrm{Im}[Kl^{i\varepsilon}]}{\mathrm{Re}[Kl^{i\varepsilon}]} \tag{6}$$

where l is arbitrary reference length[9] and $\varepsilon = (1/2\pi)\ ln\ [(1-\beta)/(1+\beta)]$.

The critical energy release rate G_c is a criterion for a crack to initially propagate along the interface when the crack tip is loaded under mixed mode condition characterized by the phase angle ψ.

$$G_c = \Gamma(\psi) \tag{7}$$

where $\Gamma(\psi)$ is represented as a function of the phase angle.

The interface fracture toughness Γ is the property of a given interface system in the sense that it is independent of specimen size and loading condition. On the other hand, it is dependent on nature of the interface, testing environment (such as temperature or humidity), age of bonding, roughness of the free surface, and the reference length l. For a concrete / cementitious material interface, the effect of the reference length l can be neglected[3]. In this study, 200 μm is selected to be the reference length for the concrete / PCM interface system.

In summary, the interface fracture toughness can be obtained if the material properties of both materials and the stress intensity factor are known. Next section explains the method to obtain the stress intensity factor.

3. Measurement of Interface Fracture Toughness by Four-point Bending Test

Several testing specimens such as the sandwich specimen[12], the four-point flexure specimen consisting of two material layers[13], the Brazilian-nut specimen[14], and the four-point bending specimen have been developed for investigating interface fracture toughness between two dissimilar materials. Among them, the four-point bending test has a capability to measure the interface fracture toughness for a whole range of the phase angle that starts from 0 degree and closes to 90 degree by using the same specimen geometry. Therefore, the four-point bending test is selected to evaluate the interface fracture toughness under pure tensile and mixed mode conditions in this study.

Symmetric loading set-up shown in **Fig. 3** is applied to evaluate the interface fracture toughness at pure tension mode, namely 0 degree phase angle. On the other hand, asymmetric loading set-up shown in **Fig. 4** is used to investigate the interface fracture toughness under mixed mode condition.

A relative amount of shear to tensile stress can be changed by adjusting the loading geometry. In other words, the phase angle can be changed by varying the loading offset s that is shown in **Fig. 4**.

If the loading line is exactly the same line as the interface location, the phase angle is close to 90 degree, namely pure shear condition. Therefore, this test method can cover from 0 degree to 90 degree phase angle.

The calibration factors of the four-point bending test for calculating the stress intensity factor K have been developed based on finite element analysis by assuming linear elastic material behavior[15].

For pre-notched beam specimen, K is defined as

$$K = YT\sqrt{a}a^{-i\varepsilon}e^{i\psi_0} \tag{8}$$

where a is crack length, T is nominal stress occurred at the interface, Y is the geometric and material correction factor, and ψ_0 is the phase angle.

For symmetric set-up,

$$T = \frac{P}{t}\frac{3B}{2W^2} \quad , \tag{9}$$

$$Y = \sqrt{f_1^2 + (2\varepsilon g_2)^2} \quad \text{, and} \tag{10}$$

$$\psi_0 = \arctan\left(\frac{2\varepsilon g_2}{f_1}\right) . \tag{11}$$

For asymmetric set-up,

$$T = \frac{P}{tW}\left[\frac{B-A}{B+A}\right] , \tag{12}$$

$$Y = \sqrt{Y_1^2 + Y_2^2} \quad \text{, and} \tag{13}$$

$$\psi_0 = \arctan\left(\frac{Y_2}{Y_1}\right) . \tag{14}$$

In Eq. (9) – (14), $Y_1 = (6sf_1 / W) - 2\varepsilon g_1$, $Y_2 = f_2 + 12(s\varepsilon g_2 / W)$, P is maximum or critical load obtained from the experiment, t is thickness of the pre-notched beam at the interface, W is height of the specimen, and s is the loading offset that is the distance between the interface and the loading line as shown in **Fig. 4**.

The calibration factors f_1, f_2, g_1, and g_2 are determined numerically as functions of (a / W) for different values of two elastic mismatch parameters α and β[15].

Thus, the magnitude of a critical stress intensity factor K_c and its phase angle ψ are given as

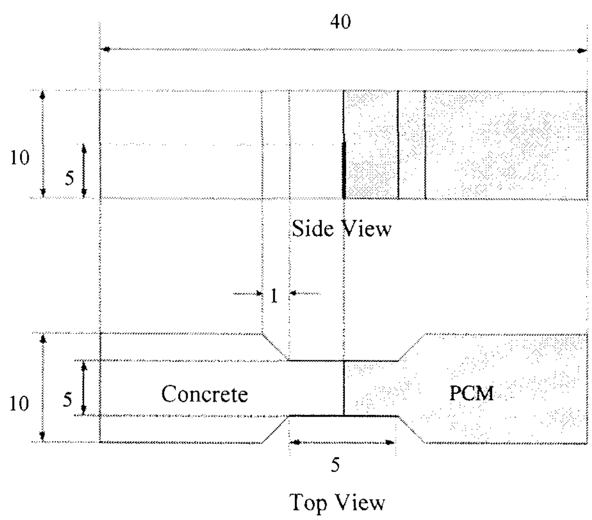


Fig. 5: Specimen geometry

$$K_c = YT_c\sqrt{a} \quad \text{, and} \tag{15}$$

$$\psi = \psi_0 + \varepsilon \ln\left(\frac{l}{a}\right) , \tag{16}$$

where T_c corresponds to the critical load when the interface crack propagates.

Therefore, the critical energy release rate or interface fracture toughness $\Gamma(\psi)$ can be calculated as shown in Eq.(17).

$$\Gamma(\psi) = \frac{1-\beta^2}{E_*}\left|K_c^2\right| \tag{17}$$

4. Experimental Procedure

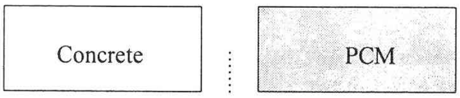
The bending beam specimens that are composed of concrete and PCM are prepared and tested in order to investigate the interface fracture toughness of the concrete / PCM interface system.

The left-hand side of the beam is concrete substrate that is similar to the mixes normally used in the real construction. The right-hand side is the PCM that has four percent of polymer per cement ratio, commonly used in tile construction. Thickness of the specimen that has the geometry as shown in **Fig. 5** is varied for preventing flexure failure in concrete part[3]. The change of thickness is far enough so that there is no effect on the interface fracture toughness[15].

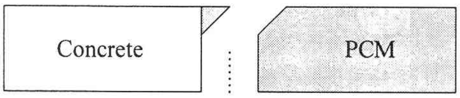
Firstly, the concrete substrate was cast in the steel mold with the smoothly surface wood, painted with primer and put at the bonding interface location of the concrete substrate for being a divider. Then, the concrete substrate was cured for 35 days that consist of 28-day water curing and 7-day air-dried curing. After 35 days, plastic tape was attached to the smooth surface of the concrete substrate to serve as an artificial crack.

Table 1: Material properties

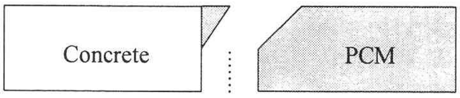
material	Compressive Strength (MPa)		Young's Modulus (GPa)	Poisson's ratio
	28 days	63 days		
Concrete	-	40.96	30.941	0.182
PCM	58.64	-	21.980	0.219



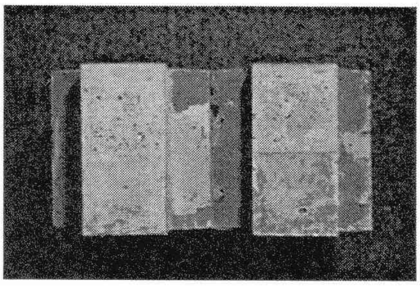
Mode A



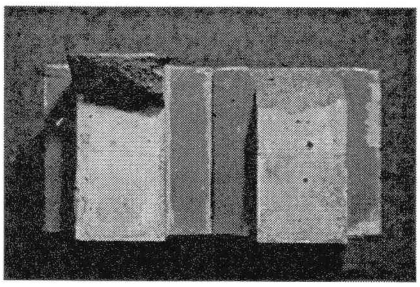
Mode B



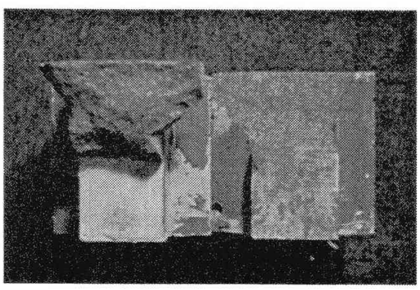
Mode C



Mode A



Mode B



Mode C

Fig. 6: Failure modes of interface between two materials

Then, the PCM was cast against the concrete substrate and the complete specimens were cured for 28 more days.

Compressive strength, Young's modulus, and Poisson's ratio of both concrete and PCM are obtained from a compression test. The properties of each material are tabulated in **Table 1**. The material properties were tested at 63 days for the concrete substrate and 28 days for the PCM.

The elastic mismatch parameters of the concrete / PCM interface system are calculated according to Eq. (4) and Eq. (5) as following: $\alpha = 0.162$, $\beta = 0.046$, and $\varepsilon = -0.015$.

All specimens were tested after determination of the material properties. Four-point bending tests on the beam specimens were performed by using a 200 kN capacity loading machine with displacement control of 0.005 mm/sec.

During the experiment, the ultimate loads and load-deflection curves are recorded. Five cases of phase angle that are 0, 20, 40, 60, 80 degree are selected. The loading offset s of each case is approximately equal to 40, 17, 7.5, 1.3 mm. for 20, 40, 60, and 80 degree phase angle respectively.

4.1 Results of Experimental Program

There are three different failure modes occurring at the concrete / PCM interface during the experiment. Each failure mode is explained below and shown in **Fig. 6**.

Mode A is defined when the interface crack clearly propagates along the interface. Mode B is defined when the interface crack propagates along the interface until one point and then the crack kinks out to the PCM. The reason is maybe due to the change of the stress field when the interface crack reaches the upper part of the beam surface near loading point. Mode C indicates that the bordering material has lower toughness than the interface for that specimen because the crack directly initiates from the crack tip through the PCM. The examples of the fractured surfaces of the tested specimens in each mode are also shown in **Fig. 6**. The left-hand side is the concrete parts and the right-hand side is the PCM parts of the specimens.

The maximum load from the specimens in which mode A and mode B occurred is used to calculate the stress occurring at the interface according to the Eq. (9) and (12) for symmetric set-up and asymmetric one respectively. Then, the stress intensity factor can be calculated by using Eq. (15) and then the interface fracture toughness by Eq. (17).

The data of the specimen that mode C is occurred cannot be used to calculate the interface fracture toughness because the crack does not penetrate through the interface. In other words, the bordering material failed before the interface.

Table 2: Failure in each specimen

Specimen No.	Phase Angle	Failure Mode
1	0 degree	A
2	0 degree	A
3	20 degree	A
4	20 degree	A
5	40 degree	A
6	40 degree	A
7	60 degree	A
8	60 degree	A
9	80 degree	A
10	80 degree	A
11	80 degree	B
12	0 degree	A
13	80 degree	C
14	80 degree	A
15	60 degree	A

Table 2 summarizes the phase angle and the failure mode occurring in each specimen. There are 2 specimens tested at 20 degree and 40 degree phase angle and 3 specimens for 0 degree and 60 degree phase angle. 5 specimens are tested at 80 degree phase angle. Most of the specimens fail in mode A. Only one specimen fails in mode B and one fails in mode C at 80 degree phase angle.

Fig. 7 shows the interface fracture toughness of the concrete / PCM interface calculated from the data obtained from the specimens that have Mode A or Mode B failures and then compared with the concrete / fiber reinforced concrete (FRC) interface reported in the literature[3)].

The value of the interface fracture toughness of the concrete / PCM interface is about 0.05 – 6 J/m^2 when the phase angle ranges from 0 degree to 80 degree. While, the value of the concrete / FRC interface is about 2 – 24 J/m^2 when the phase angle is equal to 0 degree to 75 degree[3)]. It can be seen that the interface fracture toughness of the concrete / PCM interface is lower than the one of the concrete / FRC interface especially at high degree phase angle.

Mostly, the tendency of the interface fracture toughness of bimaterial systems is the same as the one of the concrete / FRC interface[3)]. The interface fracture toughness normally increases when the phase angle increases. From the graph in **Fig. 7**, the tendency of the interface fracture toughness of the concrete / PCM interface is different from the one of the concrete / FRC interface[3)] that have significantly increasing

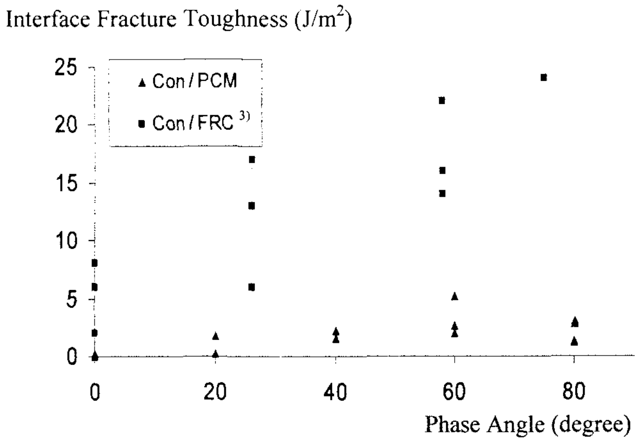


Fig. 7: Result of interface fracture toughness

change of the interface fracture toughness at high phase angle[3)]. It can be seen that the interface fracture toughness of the concrete / PCM interface almost constant when the phase angle ranges from 60 degree to 80 degree. In other words, the shear resistance of the concrete / PCM interface is not high when compared with the one of the concrete / FRC interface[3)].

5. Constitutive Material Model of the Interface between Concrete and PCM

A suitable constitutive material model of the interface between two materials is important in FEM for the analysis of tile delamination. In this study, a cracking criterion and linear softening behavior are introduced to derive the interface fracture toughness in terms of tensile and shear bonding strength, relative displacement in each direction, and the phase angle. The interface fracture toughness model derived from linear cracking criterion by assuming linear softening behavior is discussed first.

Under loading condition, a crack starts to propagate when the crack tip stress reaches a linear envelope as shown in **Fig. 8**.

In pure tension mode, normal stress σ_n is increased horizontally with the normal stress axis when the load increases. On the same way, shear stress τ is increased vertically under pure shear condition. Under mixed mode condition, the propagation of the interface crack occurs when the interface is loaded until normal and shear stresses are equal to σ_I and τ_I respectively.

The equation that is used to represent the linear cracking surface can be written in Eq. (18).

$$\frac{\sigma_I}{\sigma_0}+\frac{\tau_I}{\tau_0}=1 \tag{18}$$

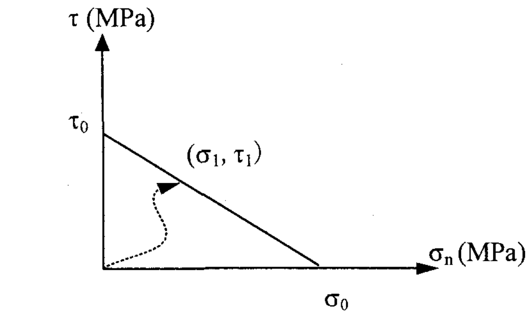


Fig. 8: Linear cracking surface

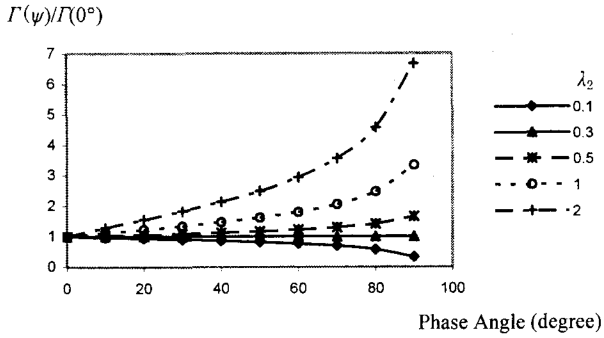


Fig. 10: Effect of λ_2 when $\lambda_1 = 0.3$

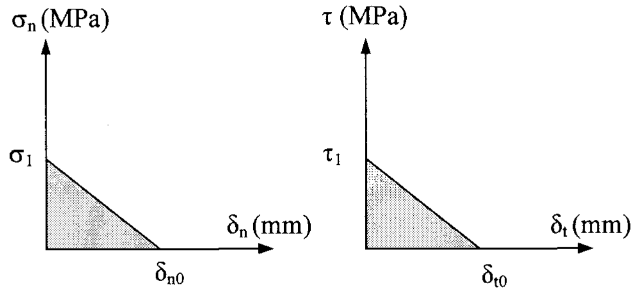


Fig.9: Softening behavior under mixed modes

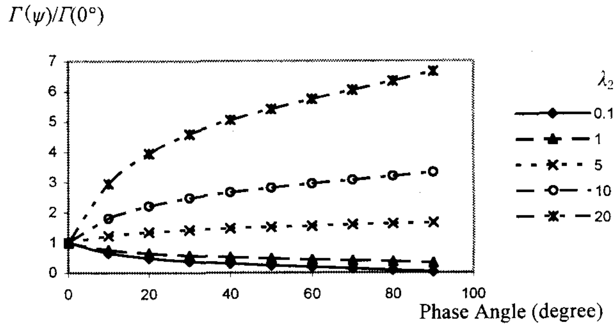


Fig.11: Effect of λ_2 when $\lambda_1 = 3$

where σ_0 and τ_0 are tensile and shear bonding strength of the interface respectively.

If linear softening behavior is assumed, an area under the softening curve is equal to the interface fracture toughness $\Gamma(0°)$ and $\Gamma(\psi_{pure\ shear})$ in pure tension and pure shear modes respectively[5]. Eq. (19) and Eq. (20) show the relation between interface fracture toughness and softening behavior under pure tension and pure shear mode respectively.

$$\Gamma(0^\circ) = \frac{1}{2}\sigma_0\delta_{n0} \tag{19}$$

$$\Gamma(\psi_{pureshear}) = \frac{1}{2}\tau_0\delta_{t0} \tag{20}$$

where δ_{n0} and δ_{t0} are maximum relative displacements in normal and shear direction respectively.

For mixed mode condition, a combination of the area under two softening curves shown in **Fig. 9** is equated to the interface fracture toughness. Therefore, the relation between cracking stresses and the interface fracture toughness can be written in Eq. (21) by assuming that the maximum relative displacements are constant in both tensile and shear direction.

$$\Gamma(\psi) = \frac{1}{2}\sigma_1\delta_{n0} + \frac{1}{2}\tau_1\delta_{t0} \tag{21}$$

where σ_1 and τ_1 are tensile and shear stress occurring at the interface respectively. δ_{n0} and δ_{t0} are the maximum relative displacement in each direction as shown in **Fig. 9**.

Then, the interface fracture toughness can be derived from Eq. (18), (21), and definition of the phase angle that is the ratio between shear to normal stress at the crack tip and given by Eq. (22).

$$\tan(\psi) = \frac{\tau_1}{\sigma_1} \ . \tag{22}$$

Therefore, the interface fracture toughness can be written as following.

$$\Gamma(\psi) = \frac{1 + \lambda_2 \tan\psi}{1 + \lambda_1 \tan\psi}\Gamma(0^\circ) \tag{23}$$

where $\lambda_1 = \sigma_0 / \tau_0$ and $\lambda_2 = \delta_{t0} / \delta_{n0}$.

The interface fracture toughness at 0 degree phase angle can be determined experimentally by using symmetric set-up as shown in the previous section. From Eq. (23), it can be seen that the interface fracture toughness is dependent on the phase angle and two fitting parameters, λ_1 and λ_2.

λ_1 is the ratio of tensile bonding strength σ_0 to shear bonding strength τ_0, and λ_2 represents the ratio of maximum relative displacements of shear to normal direction. If the two fitting parameters are changed, both magnitude and tendency of the interface fracture toughness are changed as shown in **Fig. 10** and **Fig. 11**.

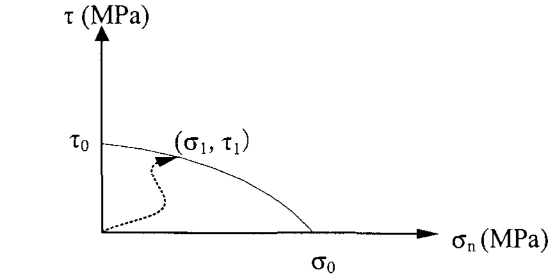


Fig.12: Elliptic cracking surface

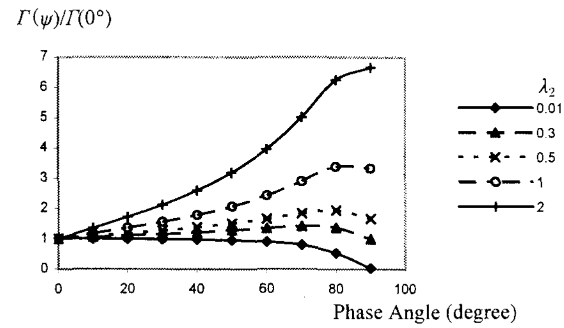


Fig. 13: Effect of λ_2 when $\lambda_1 = 0.3$

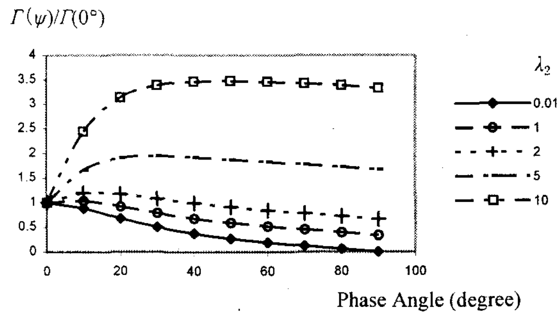


Fig. 14: Effect of λ_2 when $\lambda_1 = 3$

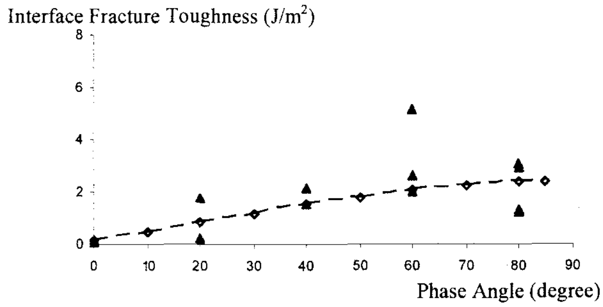


Fig. 15: Result of prediction model

It can be seen that the model derived from the linear cracking surface can denote the exponential change of the interface fracture toughness at high phase angle (**Fig. 10**) or rapidly increasing or decreasing change at low degree phase angle (**Fig. 11**). The model can be used to represent the interface fracture toughness that has increasing or decreasing tendency only. For example, it can be used for the interface fracture toughness of the concrete / FRC interface[3)] that has exponential change at high phase angle as shown in the previous section.

Instead of using the linear cracking surface, the elliptic cracking surface in **Fig. 12** is proposed. Eq. (24) shows the elliptic cracking criterion equation.

$$\left(\frac{\sigma_1}{\sigma_0}\right)^2 + \left(\frac{\tau_1}{\tau_0}\right)^2 = 1 \qquad (24)$$

The same concept is also used to derive the interface fracture toughness. Therefore, the interface fracture toughness model can be developed by using Eq. (21), Eq. (22), and Eq. (24) and written in Eq. (25).

$$\Gamma(\psi) = \frac{1 + \lambda_2 \tan\psi}{\lambda_1 \sqrt{\tan^2\psi + \frac{1}{\lambda_1^2}}} \Gamma(0^o) \qquad (25)$$

where λ_1 and λ_2 have the same definitions as explained previously. The interface fracture toughness is also dependent on the two fitting parameters and the phase angle.

It can be seen that if the interface fracture toughness is increased and then decreased when phase angle increases, this model can denote such tendency as shown in **Fig. 13** and **Fig. 14**.

Therefore, Eq. (25) is used to represent the interface fracture toughness of the concrete / PCM interface and compared with the one obtained from the experimental results as shown in **Fig. 15**. The model, having the average value of the interface fracture toughness at 0 degree phase angle, $\Gamma(0^o)$, equal to 0.126 J/m^2, agrees well with the experimental result when $\lambda_1 = 0.85$ and $\lambda_2 = 16.32$. From the values of two fitting parameters, the interface between concrete and PCM in tile systems shows not much high shear resistance compared with tensile bonding strength (λ_1 is almost equal to 1).

In summary, the interface fracture toughness model derived from the elliptic cracking surface shows good agreement with the experimental result. Therefore the elliptic cracking criterion and linear softening behavior will be used to be a constitutive material model of the interface between concrete and PCM in FEM for tile delamination analysis in future.

6. Conclusion

The four-point bending test method based on interface fracture mechanics is used to investigate the interface fracture toughness between concrete and PCM in tile systems.

The value of interface fracture toughness of the concrete / PCM interface is about 0.05 – 6 J/m^2 when the phase angles ranges from 0 degree to 80 degree. The value is low in the case that it is compared with the other concrete / cementitious material such as concrete / FRC that has the interface fracture toughness equal to 2 – 24 J/m^2 when the phase angle ranges from 0 degree to 75 degree.

Moreover, the tendency of the interface fracture toughness of the concrete / PCM interface is different from the one of the concrete / FRC interface. The interface fracture toughness of the concrete / PCM interface is increased when the phase angle increases from 0 degree to 60 degree and nearly constant when phase angle changes from 60 degree to be 80 degree. On the other hand, the tendency of the interface fracture toughness of the concrete / FRC interface shows significant increase at high degree of the phase angle.

Two models of the interface fracture toughness are derived from a cracking criterion and linear softening behavior in this study. The first model is derived from the linear cracking criterion and the other model is developed from the elliptic cracking criterion. Both interface fracture toughness models are derived in terms of tensile bonding strength, shear bonding strength, and maximum relative displacement in each direction.

The interface fracture toughness model from the linear cracking surface can be used to represent the interface fracture toughness of the interface systems that have increasing or decreasing tendency only. On the other hand, the model derived from the elliptic cracking criterion can denote the tendency that has the increase and then decrease of the interface fracture toughness when the phase angle increases.

Therefore, the interface fracture toughness model from the elliptic cracking criterion is compared with the experimental result of the interface fracture toughness of the concrete / PCM interface. The model has a good agreement with the experimental result when the ratio of tensile strength to shear strength is equal to 0.85 that means the shear bonding strength is nearly the same as tensile bonding strength.

From this study, the elliptic cracking criterion and linear softening behavior will be used as the constitutive material model of the interface element in FEM in order to perform an analysis of tile delamination in future.

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