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FACTORS INFLUENCING FRACTURE TOUGHNESS OF MORTAR-AGGREGATE INTERFACE IN CONCRETE

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Abstract
Factors influencing fracture toughness of mortar-aggregate interface are evaluated by testing sandwiched Brazilian disk specimens. It is observed from the test results that the interfacial fracture toughness increases with a greater shear loading effect. Both the mortar strength and the roughness of the aggregate surface strongly influence the interfacial fracture toughness but the aggregate type does not. It is also found that the interfacial fracture toughness considerably increases with time.
Key words: mortar-aggregate interface, fracture toughness curves, roughness, curing age

1 Introduction

The interfacial zone in concrete materials is extensive, geometrically complex, and constitutes inherently weak zones that limit the concrete performance. Mortar-aggregate interfaces play a major role in the fracture processing in concrete composites. Also, the interfacial bond considerably influence mechanical properties of concrete such as modulus of elasticity, strength, and fracture energy. Characterization of the interfacial properties is, therefore, essential to overcome the limitations associated with interfaces.

Fracture toughness of mortar-aggregate interface might be influenced by such factors as the mortar strength and age, the aggregate type, and the roughness of aggregate surface. In this study the factors are evaluated by testing sandwiched Brazilian disk specimens which are developed to assess the fracture toughness under mixed mode loading conditions.

2 Measurement of Interfacial Fracture Toughness

2.1 Modulus Mismatch Parameter

Concrete can be considered as a composite consisting of mortar matrix and aggregate inclusions. The important parameter is, then, the modulus mismatch between mortar matrix and aggregates as follows(Dundurs 1969):

$$\alpha = \frac{\overline{E}_m - \overline{E}_a}{\overline{E}_m + \overline{E}_a}, \qquad \beta = \frac{1}{2}\frac{\mu_m(1-2\nu_a) - \mu_a(1-2\nu_m)}{\mu_m(1-\nu_a) + \mu_a(1-\nu_m)} \tag{1}$$

where $\overline{E} = E/(1-\nu^2) = 2\mu/(1-\nu)$, and E, μ, and ν are Young's modulus, shear modulus, and Poisson's ratio, respectively; the subscripts m and a refer to mortar and aggregate, respectively. The modulus mismatch strongly influences the mechanical behavior(Neville 1997).

2.2 Sandwiched Brazilian Disk Specimen

Sandwiched Brazilian disk specimen shown in Fig. 1 can be used to measure the fracture toughness of mortar-aggregate interface under mixed mode loading conditions(Lee and Buyukozturk 1993, 1995). In this specimen the energy release rate, *G*, is calculated from the initial precrack length at interface, *a*, the applied load, *P*, the disk radius, *R*, and the thickness, *t* as

$$G = \frac{P^2 a}{\overline{E}_m \pi R^2 t^2}\left(N_1^2 + N_2^2\right) \tag{2}$$

where, N_1 and N_2 are the nondimensional coefficients in association with mode I and mode II loading condition depending on the relative crack length, *a/R*, and the angle of the inclination, θ, respectively.

The phase angle for tip A, representing the relative ratio of sliding to opening at the interface crack, is calculated as

$$\psi = \tan^{-1}\left(\frac{N_2}{N_1}\right) + \omega(\alpha, \beta) \tag{3}$$

where ω represents the phase shift caused by the modulus mismatch parameters, α and β (Suo and Hutchinson 1989). By measuring the critical load, P_C, and the inclination angle, θ, the interfacial fracture toughness, Γ_i, can be obtained as a function of the phase angle, ψ.

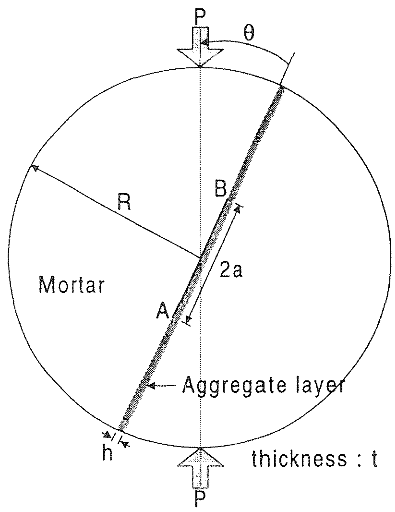


Fig. 1 Sandwiched Brazilian disk specimen

3 Experimental Work

3.1 Test Parameters

An experimental study was performed to investigate the following factors influencing the fracture toughness of mortar-aggregate interfaces in concrete: (1) loading condition – mode I to mode II; (2) mortar type – 40 MPa and 60 MPa; (3) aggregate type – granite and quartzite; (4) roughness of aggregate surface – smooth and rough; and (5) curing age of mortar – 1 day to 28 day. Table 1 lists the test model types for the interfacial fracture toughness measurement.

3.2 Materials

Two kinds of mortar mixture such as M40(40 MPa) and M60(60 MPa) were used to manufacture the sandwiched Brazilian disk specimens in combination with two kinds of rocks such as granite and quartzite. Table

2 shows the mix proportions of the mortar mixtures. For the production of M60, silica fume and a naphtalene sulfanate type high range water reducer were added.

3.3 Preparation of Specimens

The radius (R) and thickness (t) of the sandwiched Brazilian disk specimens shown in Fig. 1 were 37.5 mm and 25.0 mm, respectively. The thickness of the aggregate layer (h) was 2.5 mm and the relative crack size (a/R) was 0.25. Surface condition of the aggregate layer was selected as either rough (R) or smooth (S) to simulate the surfaces of actual aggregates such as crushed rocks and gravels. In order to introduce a sharp pre-crack, a thin plastic notch plate with a thickness of 0.1 mm was attached to one side of the aggregate layer. The layers were put in the center of plexiglass molds. Mortar mixtures were poured in the molds and the specimens were covered with plastic for 24 hours. After the notch plate was removed the specimens were placed into water until testing.

Table 1. Test model types

Mortar Type	Aggregate Type	Surface Roughness	Model Type
M40 (40MPa)	Granite (G)	Rough (R)	M40G/R
		Smooth (S)	M40G/S
	Quartzite (Q)	Smooth (S)	M40Q/S
M60 (60MPa)	Granite (G)	Rough (R)	M60G/R
		Smooth (S)	M60G/S
	Quartzite (Q)	Smooth (S)	M60Q/S

Table 2. Mixture proportion of two mortar mixtures (kg)

	Cement	Silica Fume	Fine Agg.	Water	HRWR/ (C+SF)(%)	S/a (%)	W/B
M40	400.0	0	702.2	200.0	0	42	0.50
M60	475.0	25	680.4	165.0	1.5	40	0.33

3.4 Test Procedure

Mechanical properties of both mortars and rocks were measured. Diametral compression tests in the sandwiched Brazilian disk specimens were carried out using UTM. The inclination angle of the specimens was adjusted, ranging from 7 to 25 degrees, while the angle was fixed as 10 degrees for tests on the effect of mortar age.

4 Results and Discussion

4.1 Properties of Tested Materials

Mechanical properties of the tested materials are listed in Table 3. The 28-day compressive strength of M40 and M60 are 38.5 MPa and 58.3 MPa, respectively. The target strengths were achieved within a 4% error. For the four mortar-aggregate combinations, the modulus mismatch parameters, α and β, and the phase shift angle, ω, are given in Table 4. The parameter, β, is relatively small compared to the parameter, α, and the phase shift is about 3.0 degrees for all combinations.

Table 3. Mechanical properties of the tested materials

Specimen	f_c' (MPa)	E_c (GPa)	K_{IC} ($MPa \bullet m^{1/2}$)	G_{IC} (J/m^2)	v
M40	38.5	26.7	0.42	6.72	0.22
M60	58.3	29.6	0.51	7.92	0.20
Quartzite	214.6	65.6	-	-	0.11
Granite	167.2	50.3	-	-	0.21

Table 4. Modulus mismatch parameters and phase shift angle

Combination	α	β	ω (°)
M40 / Granite	-0.304	-0.106	3.0
M60 / Granite	-0.261	-0.101	2.6
M40 / Quartzite	-0.406	-0.122	3.5
M60 / Quartzite	-0.366	-0.117	3.3

4.2 Interfacial Fracture Toughness Curves

Fracture toughness test results for four types of mortar-aggregate interfaces are presented in Fig. 2. The fracture toughness curves in the figures are drawn by the following equation

$$\Gamma_i(\psi) = G_i^C\left[1 + \tan^2\{(1-\lambda_2)\psi\}\right] \tag{4}$$

where, G_i^C and λ_2 are constants and their fitting values are given in Fig. 3 for each interfacial fracture toughness curve. Two different types of failure modes of the tested specimens, such as interface cracking only (Failure Mode 1) and mortar cracking combined with interface cracking or/and aggregate cracking (Failure Mode 2), are schematically shown in Fig. 2. The measured values with Failure Mode 2 would be estimated as the lower values of the interfacial fracture toughness. Therefore, the curves are adjusted to fit well with the experimental data exhibiting Failure Mode 1. These pheonomena had been previously observed by Lee and Buyukozturk(1995).

The test results and discussion about factors influencing interfacial fracture toughness are as follows:

(1) Effect of loading condition

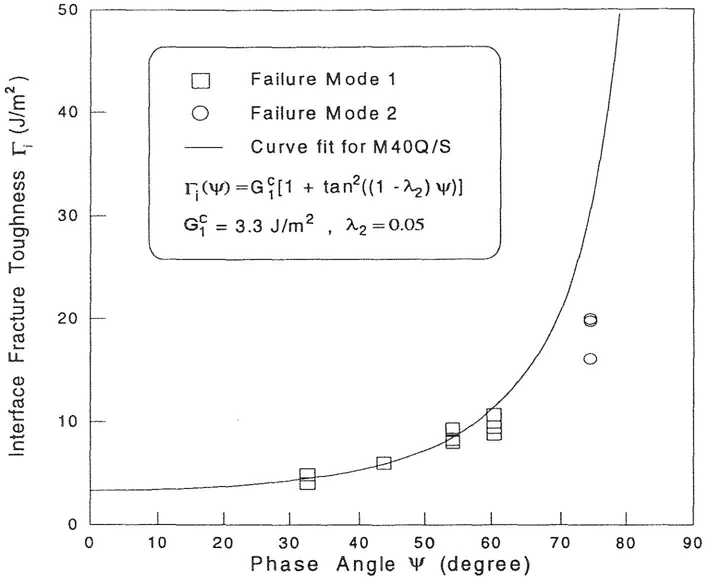
It is observed from Fig. 2 that the interfacial fracture toughness increases with the increase of the loading phase angle, i.e., the increase of the shear loading effect due to a shielding effect. These results are comparable to the test results by Lee and Buyukozturk(1995).

(2) Effect of mortar type (M40Q/S vs. M60Q/S)

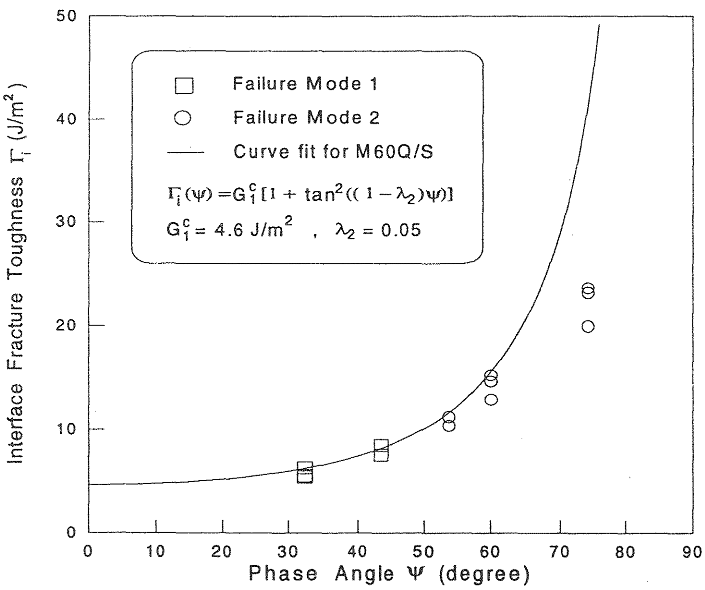
The fracture toughness of M60Q/S interface is about 50% higher than that of M40Q/S interface when the phase angle is 45 degrees, indicating that the microstructure of the interfacial zone is greatly influenced by the mortar matrix. This might result from the effects of the silica fume and HRWR in the M60 mixture with a low water-cementitious materials ratio. Failure mode of M40Q/S specimen is significantly different from that of M60Q/S specimen in which the phase angle ranges 50 to 65 degrees.

(3) Effect of aggregate type (M60Q/S vs. M60G/S)

The fracture toughness of M60Q/S interface is slightly greater than that of M60G/S interface, implying that the aggregate type barely influences the interfacial characteristics. However, it should be noted that the microstructure of rocks could affect the production of $Ca(OH)_2$ at the interfacial zone.

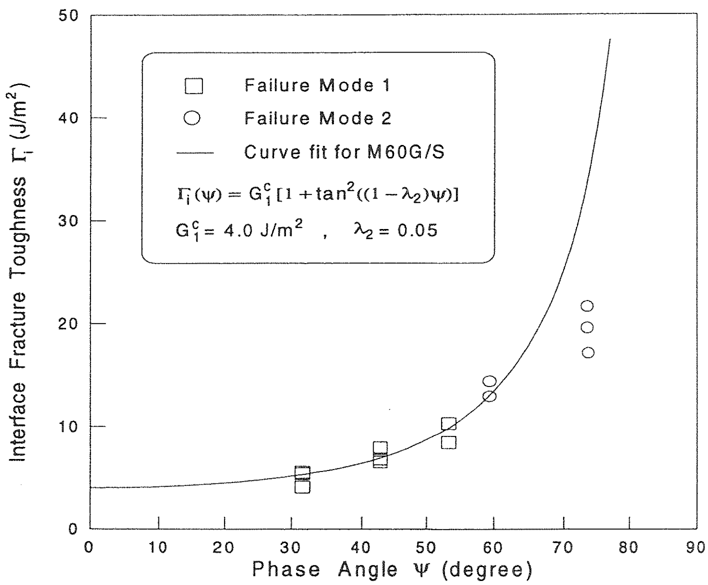


(a) M40Q/S Interface

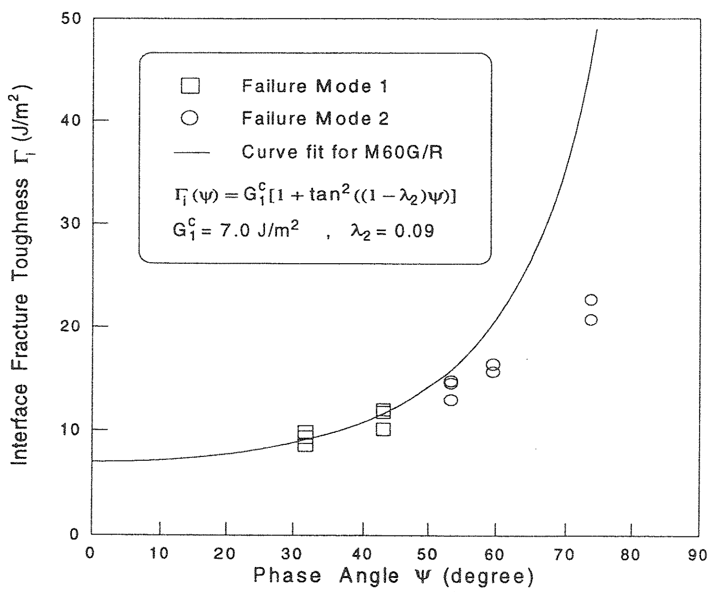


(b) M60Q/S Interface

Fig. 2. Interfacial fracture toughness curves (continued)



(c) M60G/S Interface



(d) M60G/R Interface

Fig. 2. Interfacial fracture toughness curves

(4) Effect of roughness of aggregate surface (M60G/S vs. M60G/R)

The fracture toughness of M60G/R interface is about twice as much as that of M60G/S interface when the phase angle is up to 45 degrees, meaning that the roughness of aggregate surface strongly influences the fracture process of the interfacial zone.

The common practice of utilizing crushed rocks with a rough surface for the production of high strength concrete is proved to be appropriate in order to improve its strength and stiffness. It is found from Fig. 2(c) and 2(d) that the constant λ_2 is estimated as 0.5 for polished surface and 0.9 for rough surface.

4.3 Aging Effect

Fig. 3 shows the variation of the fracture toughness of both M40G/R interface and M60G/R interface over time. The phase angle is about 43 degrees for all of test results. Fracture toughness for both M40G/R interface and M60G/R interface rapidly increases at an early age and the rate of increase is gradually reduced. The fracture toughness of M60G/R interface is two or three times greater than that of M40G/R interface at the age of 1 day or 3 days, implying that the interfacial bond of high strength concrete with silica fume is developed much earlier than that of normal strength concrete. Therefore, it may be seen that the interfacial effect could play a major role in concrete strength development.

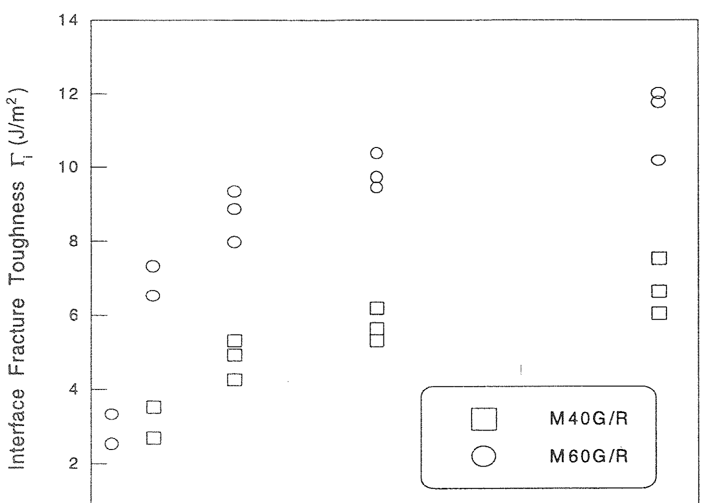


Fig. 3. Interface fracture toughness with mortar age

5 Conclusion

Conclusions resulting from this study are as follows:

(1) The major factors influencing the interfacial fracture toughness are the composition of the mortar matrix and the roughness of the aggregate surface. Concrete properties can be controlled by adjusting the above factors properly.

(2) The interfacial fracture toughness increases rapidly at the early age of mortar matrix and the rate of its increase gradually decreases. The mechanical properties of the early-age concrete, exhibiting a similar trend, would be co-related with the characteristics of the interfacial zone.

(3) The interfacial effect on concrete properties should be quantitatively investigated with the development of high performance concrete.

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