Fracture Mechanics of Concrete Structures
Proceedings FRAMCOS-3
AEDIFICATIO Publishers, D-79104 Freiburg, Germany

FRACTURE MECHANICS AND MICROSTRUCTURE OF CEMENT MORTAR

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Abstract

Mechanical properties and fracture behavior of cement mortar with sand were studied after curing for 7 days to 6 months . Decrease of bending strength but increase of Young's modulus for mortar were observed with the increase of sand amount. Large fracture energy was obtained for the mortar with sand/cement ratio = 1.0, and rising R-curve with the crack extension was also clarified for mortar. Particle-bridging at the fracture surface and microcracking at the crack tips mainly contributed to improve fracture toughness. Critical crack length decreased with the increase of curing time, at which many crack generated inside of the sand particles instead of the interface. Large crack length was also estimated for the mortar with high sand/cement ratio due to the aggregating the sand.

Key words: Bending strength, Young's modulus, Fracture toughness, Mortar

1 Introduction

Application of fracture mechanics to cement paste, mortar or concrete has been performed to clarify their fracture behavior and design their suitable microstructure. Several books and review have been written by Shah et al. (1995), Cotterell et al. (1996) and Jennings (1988). A few numerical models based on the metal-matrix-composites (MMCs) were also proposed, regarding the cementitious materials as a two-phase composite with a homogeneous phase and a particle phase. Simenov et al. (1995) studied the elastic behavior of mortar or concrete as a composite with the transition zone. While, effect of mixing with metallic nickel particle by Beaudion et al. (1997), waste sludge by Topcu (1996) and glass powder by Nishikawa (1995) on fracture behavior were also discussed recently. However, cementitious materials exhibited widely from ductile to brittle fracture depending on the cement/water ratio, aggregate/cement ratio and curing time . Systematic and basic data on fracture are also useful for the utilization of the waste and by-product materials as aggregates.

In this study, normal cement mortar was prepared with ordinary portland cement and good-quality sand. The mixed ratio of sand to cement and curing time were discussed in relation to the fracture behavior and microstructure. Mechanical properties, that is, bending strength, Young's modulus, fracture toughness and fracture energy were measured and discussed based on the simple Griffith model.

2 Experimental

2.1 Preparation of cement mortar

Cement mortar was prepared with ordinary portland cement (Dai-ichi Cement Co.,Ltd.) and good-quality sand (Toyoura Standard Sand) as aggregate. The latter mainly consisted of α-quartz with diameter of about 0.2 mm. Mixed ratio of aggregate to cement A/C was from 0 to 3.0. All mortar were added to water containing a water reducer (Kao Co.,Ltd.) of 1 wt% to keep a constant flow value within the water/cement ratio of 0.3 to 0.8. Rectangular specimen 2x2x10 cm^3 was casted and cured for 1 week to 6 months in moist air. A Compact Tension (CT) specimen 5x5x1 cm^3 was also casted for the measurement of the fracture energy, shown in **Fig. 1**.

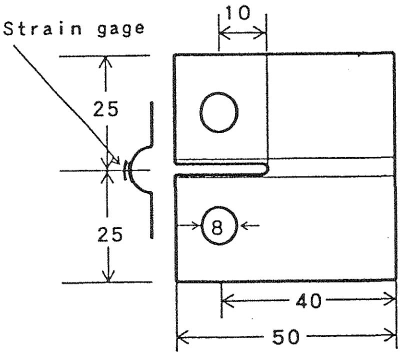

Fig. 1. Compact tension specimen of mortar

2.2 Mechanical properties and fracture mechanics

Three-point bending strength of mortar was measured using more than ten specimens at each experimental condition. Tensile strength was estimated from the bending strength and the statistic Weibull's modulus measured. Young's modulus was measured by the ultrasonic pulse method after bending test.

Fracture toughness, defined as K_R in this study, at each crack length c of CT specimen was calculated based on ASTM E399-83 method with the following equation.

$$K_R = \left(P_Q / BW^{1/2}\right) \times f(c/W), \tag{1}$$

$$f(c/W) = \frac{(2 + c/W)\left(0.886 + 4.64c/W - 13.32c^2/W^2 + 14.72c^3/W^3 - 5.6c^4/W^4\right)}{(1 - c/W)^{3/2}}$$

where, P_Q was maximum load at each repetition, B was specimen thickness and W was specimen width. Crack length propagated was measured by the optical microscope.

Fracture energy was also measured with same CT specimen, from the stress-displacement curve by repetition of load and unload with a crosshead speed of 0.1 mm/min. Total fracture energy γ_t consisted of elastic fracture energy γ_e and plastic energy dispersion γ_p. The latter two were graphically obtained by shifting the irreversible residual displacement to the origin, Sakai et al. (1986). Another fracture toughness, defined as $[K_{IC}]_\gamma$ in this study, was obtained from total fracture energy γ_t and Young's modulus E, assuming that Poisson's ratio is small, as followed.

$$[K_{IC}]_\gamma = \sqrt{2\gamma_t E / (1 - \nu^2)} \tag{2}$$

3 Results and discussions

3.1 Mechanical properties of mortar

Bending strength and Young's modulus of mortar were shown in **Figs. 2** and **3**, respectively. Bending strength gradually increased with the increase of curing time, but almost constant after 1 month. Large strength was observed for mortar containing small amount of aggregate. Excessive water was added to mortar with high A/C ratio to keep constant flow value. Large water remained in mortar caused the decrease of strength. On the other hand, the increase of Young's modulus was observed only for the mortar with A/C ratio=3.0. Other mortar did not indicate the larger Young's modulus. Young's modulus of sand is larger

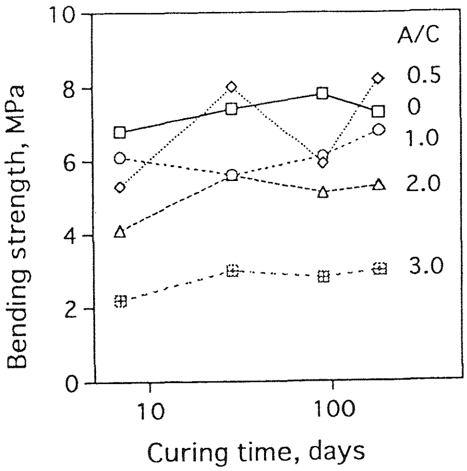

Fig. 2. Bending strength of mortar

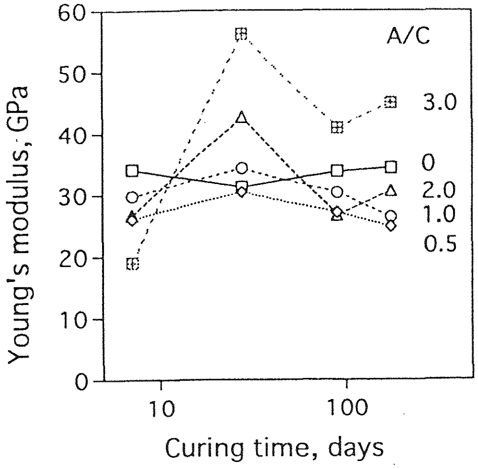

Fig. 3. Young's modulus of mortar

than that of cement paste. Therefore, Young's modulus of mortar increases with increasing sand content. In addition, good cementitious properties and decrease of pore contribute to increase modulus. Young's modulus of mortar with several coarse aggregate of a fixed volume fraction changed depend on the kind of aggregate but independent of curing time, Zhou et al. (1995). In this study, excess water was introduced in mortar to keep the flow value constant, therefore, residual water decreased the bending strength and slightly increased Young's modulus.

Typical microstructure of cement mortar cured for 1month and 6 months were shown in **Fig. 4**. Plate-like calcium hydroxide and whisker-like C-S-H were detected on the surface of aggregates in the cement mortar cured for more than 1 month. Most of cracks existed on the

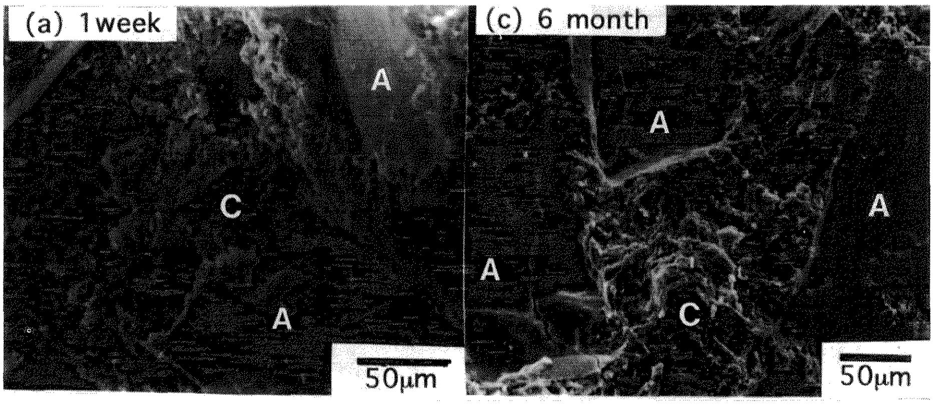

Fig. 4 Microstructure of mortar cured for 1 month(left) and 6 months(right)

interface of aggregate in mortar cured for short period, but interparticle cracks were observed in mortar cured for long period. For the former, cracks propagated along the aggregate, but for the later cracks propagated through the sand particles independent of A/C ratio. These crack path also mostly effect on the mechanical properties, in particular, fracture toughness mentioned below.

3.2 Fracture toughness and fracture energy

Calculated fracture toughness K_R at each crack extension Δc were shown in **Fig. 5**. Changes of K_R was shown at each curing time except those of mortar with A/C =1.0 cured for 1 month. Catastrophic fracture occurred for the latter specimen and crack length during the propagation of crack was not measured. Rising R curve, which means fracture toughness increased with the crack length,was expected for the reinforced concrete, but was observed even for the cement paste having various initial notch length. Fracture process zone at crack tip in cement paste was proposed by Wittmann et al. (1991) . For the mortar in this study,

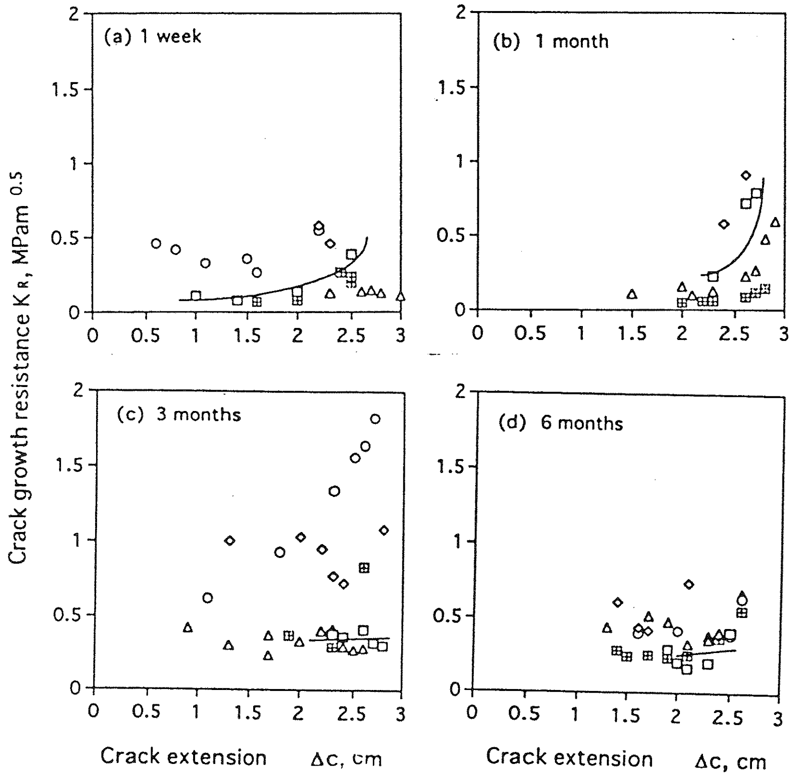

Fig. 5. Crack growth resistance K_R for mortar. Marks corresponded to the data in Figs. 2 and 3. Solid line showed those of cement paste.

sand particle-bridging on the fracture surface and formation of microcracks at the crack tip were mainly contributed to increase of fracture toughness. Furthermore, the frictional interlocking of adjacent particles on the fracture plane increased the resistance of crack propagation for sand rich mortar. After curing for 1 month, cement mortar, A/C=0.5 and 1.0 had sharp R curve. Particle-bridging mainly caused the increase of toughness. While, Hillemeier et al.(1977) also measured the K_R curve with crack extension but concluded that fracture toughness was constant independent of crack extension of hardened cement paste cured for 7 days.

Another fracture toughness of cement mortar could be calculated from equation (2), using total fracture energy. These fracture toughness was described as $[K_{IC}]_\gamma$ and shown in **Fig. 6**. Except cement mortar of A/C=1, fracture toughness of cement mortar having aggregate increased with increase of curing time. In particular, the value for the mortar of A/C=3 was lower, but increased gradually with curing time. These value were corresponded to the last value in Fig. 5, where the specimen had the large fracture surface.

Typical stress-displacement curve of mortar was shown in **Fig. 7**. All curves had the long tail and irreversible residual displacement. Fracture energy of mortar was divided graphically into elastic fracture energy and plastic energy dispersion and shown in **Fig. 8**, separated with A/C ratio and curing time. For the mortar with lower A/C ratio, fracture energy became to be constant after 1 month. Large proportion of plastic fracture dispersion after long curing means plastic behavior and fracture

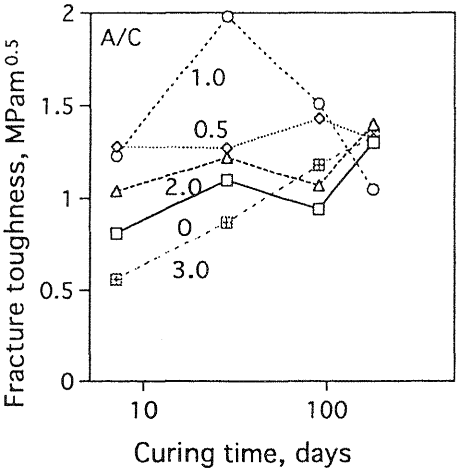

Fig. 8. Fracture toughness of mortar

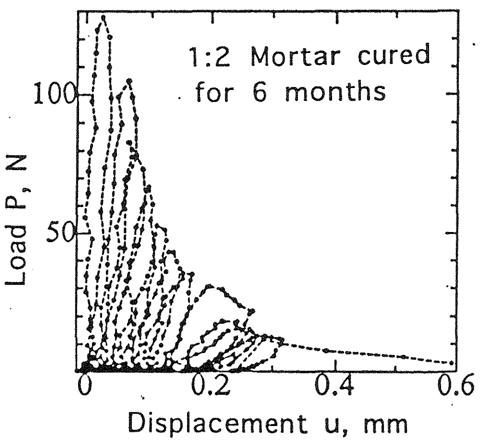

Fig. 7. Stress-displacement curve

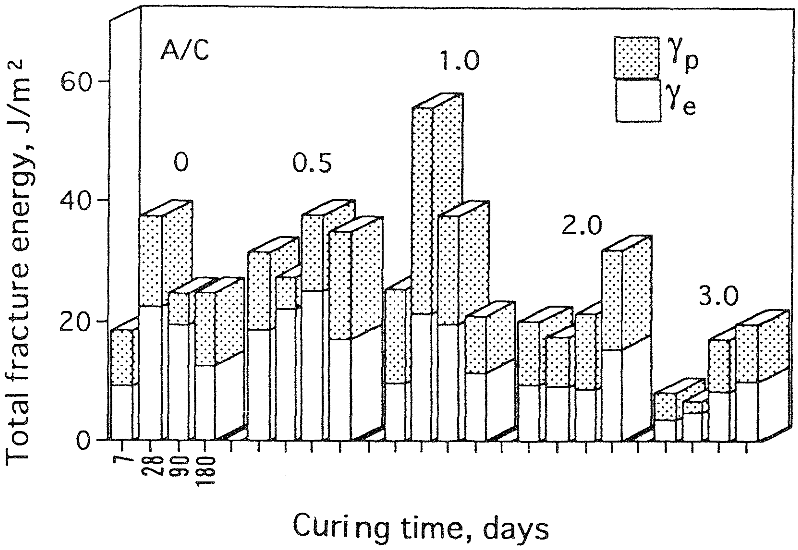

Fig. 8. Fracture energy of mortar with various sand content (A/C)

of mortar. For the mortar with large A/C ratio, fracture energy was very small due to the drop-out of aggregate. Plastic behavior was remarkable after long curing. These fracture energy agreed with those by other researchers reviewed by Jennings (1988).

3.3 Application to Griffith model

Many researcher have been analyzed the strength of ceramic and cementitious materials by using fracture mechanics. Firstly, application to Griffith model, tensile strength of each specimen is necessary. Tensile strength of mortar was calculated by the following equation in this study, supposing the effective volume to be constant.

$$S_T = S_3\left[\frac{1}{2(m+1)^2}\right]^{1/m} \tag{3}$$

where, S_T is tensile strength estimated, S_3 is bending strength measured and m is Weibull's modulus, which is approximately 10.

In general, crack length contributed to fracture strength, is considerably smaller than that introduced at measuring fracture toughness and energy. However, the following equation under linear fracture mechanics, was used for the estimation of critical crack length c, supposing the shape of crack as the lens like pore or pore with small sharp notch reported by Wittmann (1981). Tensile strength of an ideally linear elastic solid with a sharp crack can be described by the following equation.

$$S_T=\sqrt{\frac{2E\gamma_t}{\pi c}} \tag{4}$$

where, S_T is tensile strength, E is Young's modulus and γ_t is total fracture energy. Compressive strength was applied the above equation by Diaz et al. (1997). However, flexural and tensile fracture was predominant with mode I loading and compressive fracture was with mixed mode I and II. These fracture strength and critical intensity values must be distinguished on application to the above equation.

Substituting the mechanical values into above equation introduced the estimation of critical crack length, which is corresponded to the fracture origin of mortar. The relative critical crack length was shown in **Fig. 9**. The steep slope of line is corresponded to the short crack length. The critical crack length for the cement paste after long curing is considered to be the standard length c. The critical crack length for mortar indicated the double or triple as large as standard. These cracks were corresponded to those generated around sand or sand aggregate in mortar, but the crack length became small with the increase of curing time. This decrease of crack length agreed with the microstructural change, that is, from intergranular to transgranular fracture at the fracture surface of mortar.

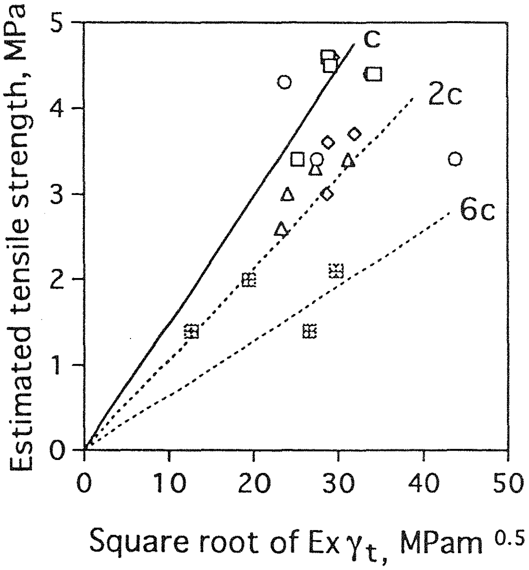

Fig. 9. Relative critical crack length estimated from Griffith model

4 Conclusion

Mechanical properties and fracture behavior of cement mortar with sand was studied and the following conclusions were obtained.
(1) Decrease of bending strength but increase of Young's modulus with increasing sand content were observed for mortar. These mechanical values did not change remarkably with curing time after 7 days.
(2) Large fracture energy was observed for mortar with sand/cement = 1.0. Plastic fracture behavior was remarkable for high sand/cement mortar cured for long time.
(3) Critical crack length as the fracture origin, was estimated by Griffith model. Crack length decreased with increasing curing time, but increased for the mortar with high sand content.

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