MOISTURE DEGRADATION IN CONCRETE/EPOXY SYSTEMS

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1 INTRODUCTION

Combining several materials to create a structural system has led to a new kind of application previously not possible with conventional materials. Examples are FRP and its strengthening system. Nonetheless, the existence of the interface between two substrates introduces a challenging problem in determining durability of bond systems. In many applications, the durability of individual materials is well-documented. However, the property of the interface can significantly deviate from the constituents and special attention is required. This is because of the different structure at the interface resulted from chemical reaction between the substrates to generate adhesion force as suggested by many studies at microscopic level [1-3].

Concrete/epoxy interfaces are formed when advanced composite materials are applied to strengthen or repair civil infrastructures. One of the most common applications is the retrofitted FRP-bonded concrete. The structural performance of such applications is usually governed by the concrete/epoxy interface [4-6]. Therefore, quantification of concrete/epoxy interface is essential to prevent the pre-mature failure at such interface.

Based on the prior research studies, it is found that the concrete/epoxy interface is the most critical region when subjected to moisture [7]. Hence, this study focuses on the experimental characterization of concrete/epoxy interface toughness. In order to understand the durability and fundamental debonding mechanisms of FRP-bonded concrete systems, experimental studies using a fracture-based approach have been conducted. In the experiments, concrete/epoxy systems were tested under mode-I and mixed mode loading. Fracture-based tests aims to determine the fracture toughness ($\Gamma$) required to produce the debonding failure of a concrete/epoxy interface. In what follows, we introduce the sandwich model for fracture characterization of the interface of concrete/epoxy system. This will be followed by the description of the specimens used in characterizing the fracture toughness properties of concrete/epoxy interface for the investigation of fracture toughness trends at such interface.

2 EXPERIMENTAL STUDY

2.1 Sandwich Specimens

In this study, sandwiched beam specimen is used as physical laboratory models to assess concrete/epoxy interface toughness. Using this specimen, the fracture toughness can be established with a desired phased angle. Mode-I and mixed mode fracture testing will be carried out for the concrete/epoxy system (Figs. 1 and 2). Four-point bending specimens will be used to find the mode-I fracture toughness, while four-point shear specimens [8] will be used for the mixed mode fracture testing. The details of these tests are described below.

We consider the four-point bending specimen with a sandwiched epoxy layer shown in Fig. 1. Proper techniques are required to sandwich an epoxy layer into the concrete and ensure that the crack stays along one of the interface. The apparent stress intensity factor $K_I$ can be obtained from stress analysis of cracks handbook [9] as:

$$K_I = f_1 \sigma_r \sqrt{aD}$$

(1)

where $\sigma_r = 6M/bD^2$ in which $M$ is the applied moment, $a$ is the crack length, $b$ is the width, $d$ is the height of the specimen, and $f_1$ is a correction factor for four-point pure bending which depends on the relative crack length ($a/d$).
The fracture energy release rate can be calculated as

$$G = \frac{K_I^2}{E_1} = \frac{f_b \sigma_r^2 a}{E_1}$$  \hspace{1cm} (2)

Since for mode-I, the loading angle is zero. However, because of mismatch material the phase angle is not equal to zero. The shift is in the range of 0 to 15 degrees which is small and so the specimen can be considered to be essentially in mode-I with phase angle ($\psi$) equals zero.

Next, the four-point shear specimen shown in Fig. 2 is considered. This specimen has been rigorously analyzed for mixed mode fracture testing [8]. For four-point shear specimen, the apparent stress intensity factors related to the loads and specimen geometry are given by

$$K_I = \frac{M}{b d^{1/2}} f_b \left( \frac{a}{d} \right)$$  \hspace{1cm} (3)

$$K_{II} = \frac{Q}{b d^{1/2}} f_s \left( \frac{a}{d} \right)$$  \hspace{1cm} (4)

where $f_b$ and $f_s$ are correction factors depending on the ratio $a/d$, $M$ and $Q$ and the applied moment and shear force at the crack location respectively, and $b_1$, $b_2$ and $d$ are geometric quantities defined in Fig. 2. The corresponding energy release rate can be calculated as

$$G = \frac{K_I^2 + K_{II}^2}{E_1}$$  \hspace{1cm} (5)

To determine the loading angle ($\phi$) for the four-point shear test, the following equation can be used:

$$\phi = \tan^{-1} \left( \frac{f_s f_b c}{f_b} \right)$$

However, the exact phase angle depends is not the same as the loading angle because the phase angle ($\psi$) also depends on the material combinations. In this study, a shift of 11 degrees was taken into account.

### 2.2 Testing of Sandwich Specimens

To generate the fracture toughness for both mode-I and mixed mode conditions, the two types of sandwich specimens presented in the preceding section were tested. The cross sectional dimensions of both sandwiched specimen were 76.2 mm (height) $\times$ 38.1 mm (thickness). The thickness of the epoxy layer, $h$, was 2.54 mm for both specimens. The relative crack size ($a/d$) was 0.5 for all the specimens. In this study, $l = 228.6$ mm and $s = 114.3$ mm (see Fig. 1); while $b_1 = 139.7$ mm in, $b_2 = 88.9$ mm, $c = 5$ mm (see Fig. 2). Concrete with an average 28-day compressive strength of 37.9 MPa and one type of epoxy were used. The epoxy used in this study is well adopted in the
construction industry which is called Concressive LPL. To make sure a sharp precrack, a notch plate made of thin plastic with the thickness of 0.1 mm was attached to one side of the epoxy layer.

All specimens were cured for 28 days before conditioning. After 28 days curing, all the specimens were dried for 30 days in order to ensure that the moisture content of all specimens was 0% before any conditioning. After these preparations, all the specimens were treated under three different moisture durations, namely, 0-week, 2-week and 4 week; and two temperatures, namely, 23°C and 50°C. For each moisture and temperature condition, 3 specimens were tested. The relationship between the Young’s modulus and moisture content for both concrete and epoxy are plotted in Fig. 3. Dundur’s parameters $\alpha$ and $\beta$, oscillation index $\epsilon$, and shift angle in a sandwich specimen $\omega$ for the biomaterial combination are then computed based on the material properties corresponding to certain moisture level. Here, the Poisson’s ratio of concrete and epoxy were taken as 0.2 and 0.35 respectively for the calculation process. It is noticed that $\beta$ is quite small in which it is smaller than 0.2 in all cases. Hence, in order to simplify the calculation, $\beta$ is taken as zero and hence all the equations stated in section 2.1 can be used.

Four-point bending and shear tests on the sandwiched beam specimens were performed using an Instron machine with a displacement control. Loading rate was 0.00167 mm/min. The phase angle ($\psi$) of the bending specimen was treated 0°, while the phase angle ($\psi$) of the shear specimen was adjusted to be 60° in order to achieve the mixed-mode loading condition.

The load versus load-line displacement curve for both sandwiched bending and shear specimens were very brittle. Little microcracking was detected, and cracks advanced very rapidly. The variation of fracture toughness when subjected to different moisture durations and temperatures are shown in Figs. 4(a) and 4(b). The fracture toughness at each condition, which is shown on these graphs, was the average among 3 tested specimens. It is observed that there was a decrease in both mode-I and mixed mode fracture toughness with increasing moisture duration. For mode-I fracture toughness, there was a substantial decrease in fracture energy release rate with a complex phenomenon which involves a distinctive dry-to-wet debonding mode shift from material decohesion (concrete delamination) to interface separation. Such a great deterioration occurred after 4-week moisture conditioning at 23°C while it occurred after 2-week moisture condition at 50°C. It reveals that the combined effect of moisture and high temperature produce a more severe deterioration. Fig. 5(a) shows the failure mode of the dry sandwiched bending specimen at 23°C. Fig. 5(b) shows the failure mode of the wet sandwiched bending specimen with 4-week moisture duration at 50°C. For mixed mode fracture toughness, there was a gradual decrease with increasing moisture duration. However, the failure modes of all sandwiched shear specimens were similar to each other. Fig. 6 shows the typical observed failure mode of the sandwiched shear specimen.
3 CONCLUSIONS

The following conclusions are deduced from the experimental results:

- Deterioration of the concrete/epoxy interface under moisture is observed through investigation of the fracture toughness of such interface.
- Mode-I fracture toughness decreases substantially when involves a distinctive dry-to-wet debonding mode shift from material decohesion (concrete delamination) to interface separation.
- Mixed mode fracture toughness decrease gradually with increasing moisture duration.
- The combined effect of high temperature and prolonged moisture duration severely deteriorate the concrete/epoxy interface.

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