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Fracture behavior of glass fiber reinforced polymer composite

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Abstract

Chopped strand glass fiber reinforced particle-filled polymer composite beams with varying notch-to-depth ratios and different volume fractions of glass fibers were investigated in Mode I fracture using three-point bending tests. Effects of polyester resin content and glass fiber content on fracture behavior was also studied. Polyester resin contents were used 13.00%%, 14.75%, 16.50%, 18.00% and 19.50%, and glass fiber contents were 1% and 1.5% of the total weight of the polymer composite system. Flexural strength of the polymer composite increases with increase in polyester and fiber content. The critical stress intensity factor was determined by using several methods such as initial notch depth method, compliance method and *J*-integral method. The values of K_{IC} obtained from these methods were compared.

Keywords: Glass fibers; Fracture toughness; Aggregate; Polymers; Composite

1. Introduction

Particle-filled glass fiber reinforced polymer composite (PC) is formed by combining mineral aggregates and glass fiber with a resin system. Because of rapid setting and high-strength properties, polymer composites are being used in a variety of construction, rehabilitation and repair applications such as bridges, pipelines and other types of constructions [1–5]. To produce economical and high-strength particle-filled polymer composite systems, an optimum amount of polymer is used in composite formulation. Although some of the assumptions in linear elastic fracture mechanics and elastic-plastic fracture mechanics are incorrect for particle-filled polymer composites, cement concrete and mortar, many attempts have been made to characterize the crack behavior of these materials [6–13]. For determining the values of critical stress intensity factors, K_{IC},, different types of specimens and different approaches are being used such as critical values of *J*-integral, critical crack tip opening displacement, compliance technique and R-curve analysis [14,15].

In this study, Mode I fracture behavior and crack surface displacements of glass-fiber-reinforced polymer composite materials were investigated using single edge notch beams loaded three-point bending. The effects of polyester resin and glass fiber contents on the fracture behaviors of polymer composite were analyzed. Flexural strength, K_{IC} and J_{IC} of the glass fiber reinforced polymer composite were investigated. The values of K_{IC} that were determined from the initial crack depth method, compliance method and *J*-integral method were compared.

2. Experimental

2.1. Specimen preparation

The resin selected for this study was Neoxile 266, an isophthalic polyester resin which was cured using 1% of methyl ethyl ketone peroxide catalyst and 0.5% of cobalt–naphthanate accelerator. The sand fillers were used in three grades. Chemical analysis of the sand fillers is given in Table 1. Sieve analysis showed that 11% of the sand particles were in the range of 0.3–1.00 mm, 47% of the particles were in 0.1–0.3 mm and 42% of the sand size was between 0.05 and 0.1 mm. E-glass fibers, 10–12 mm in length, were produced by cutting from continuous fibers. Initially, the composite material was formulated by using only polyester resin and sand. The first type of bending specimens was produced without glass fiber reinforcement, their mechanical proper-

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Table 1
Chemical analysis of the sand used in polymer composite system

Chemical content	By weight (%)
SiO_2	97.14
Al_2O_3	1.12
Fe_2O_3	0.15
CaO	0.11
MgO	0.30
Clay	0.14
Others	1.04

ties and critical stress intensity factors were determined. The second type of specimens was produced using glass fibers, sand and polyester resin. The polyester resin content varied between 13.00%, 14.75%, 16.50%, 18.00% and 19.50%, and glass fiber contents were 1% and 1.5% by weight of the composite system.

The glass fibers, sand particulates and polyester resin were poured into a disposable container and mixed until the mixture became homogenous. The polymer composite mixture was cast in aluminum trays, 300 × 30 × 50 mm, with polyvinyl alcohol film coated to facilitate demoulding. The polymer composite in the trays was compressed and cured at room temperature for days. Postcuring was done at 80 °C for 24 h. The specimens were cut using a 2-mm-thick diamond saw to create notches between 18 and 38 mm deep. The notch tips of the specimens were sharpened with a surgery blade. Since the polymer composite specimens were brittle, there was no need to open a starter fatigue crack. The specimen configuration is shown in Fig. 1.

2.2. Fracture mechanics tests

Linear elastic fracture mechanics tests were carried out according to ASTM E 399. Three-point bending tests were performed, on five different a/b ratios (0.38, 0.50, 0.55, 0.60 and 0.76) of cracks were chosen, and cracks were opened perpendicular to the beam axes as shown in Fig. 1. The crosshead speed was 0.05 mm/min of the test machine. All beams were tested to maintain a constant rate of increase of crack mouth opening displacement (CMOD), which was measured by a clip gage, attached to the bottom of the beam. During the test, deflections of the beam were measured by a linear variable differential transformer (LVDT) located 5 mm from the notch under the centerline of the beam. To determine the mechanical properties of the polymer composite with and without glass fiber content, three-point bending tests were

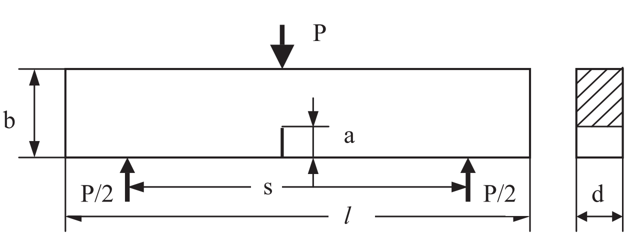

Fig. 1. Sketch of three-point bending specimen.

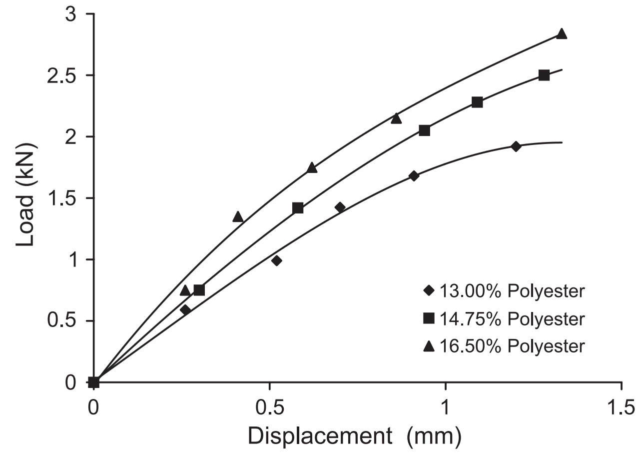

Fig. 2. Load–displacement curves for 1% fiber reinforced polymer composite system.

also performed for unnotched beams. Maximum bending load (P_{max}), maximum deflection (δ_{max}), Young modulus in bending (E_b) and flexural strength (σ_b) were determined. The average Poisson ratio (v) was found to be 0.20.

3. Numerical results

For evaluation of material constants the ratios of polyester resin contents were 13.00%, 14.75%, 16.50%, 18.00% and 19.50% and the ratios of chopped strand glass fiber content were 1% and 1.5% by weight of the polymer composites system. Three-point bending tests were conducted for every type of specimen at room temperature. Three replicate tests were performed for each type of specimen, and the average of the test results was used in the evaluation. Typical load versus deflection curves are shown in Figs. 2–4. All of the load deflection curves have an initially linear response, which becomes progressively nonlinear above displacements of 0.4 mm. The load carry-

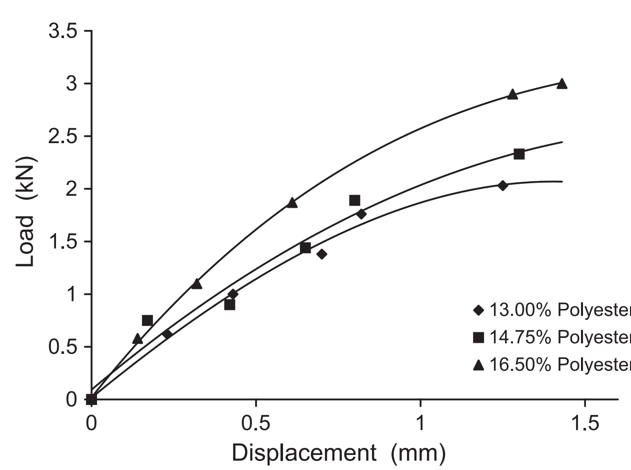

Fig. 3. Load–displacement curves for 1.5% fiber reinforced polymer composite system.

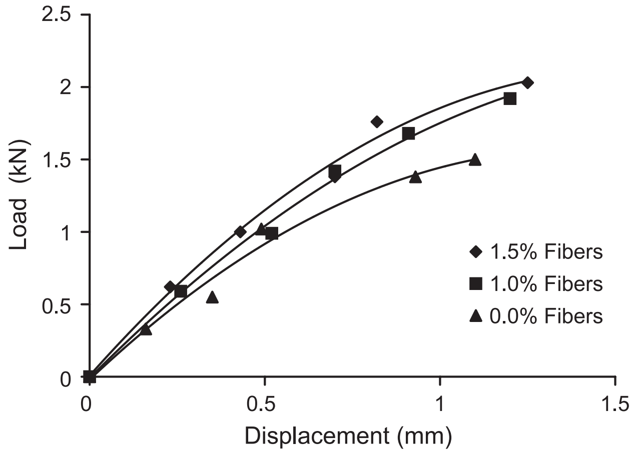

Fig. 4. Load–displacement curves for 13% polyester content polymer composite system.

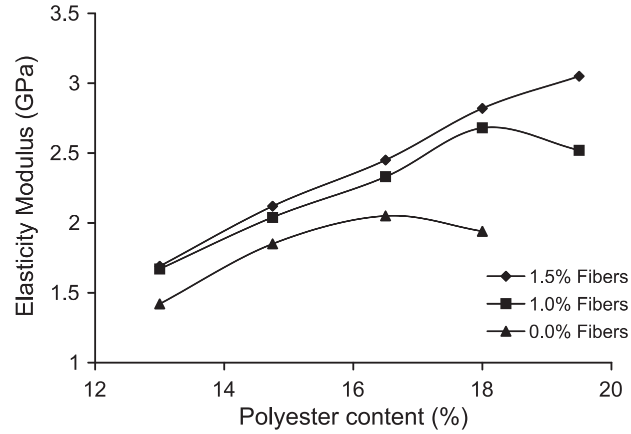

Fig. 6. Variation of flexural modulus versus with polyester content for polymer composite system.

ing capacity for 1% and 1.5% fiber-reinforced polymer composites increased with increasing polymer content.

At room temperature flexural strength of the polymer composite system with and without glass fiber content initially increased with increasing polyester resin content and, after reaching a maximum, decreased as shown in Fig. 5. For the composite system without reinforced, the maximum flexural strength was obtained for the 16.5% polyester resin ratio. For the 1% and 1.5% fiber reinforced composite systems, the maximum flexural strengths were obtained for the 18% and 19.5% polyester resin ratios, respectively. For further increases in polyester ratio, the flexural strengths decreased. In addition, as shown in Fig. 5, the glass fiber content can be seen to decrease brittleness of the polymer composite system. The 16.5% polyester and 1% glass-fiber-reinforced composite system had 19% higher strength than the corresponding polymer system without fibers. Also the 16.5% polyester and 1.5% fiber-reinforced composite system had 23% higher strength than the corresponding polymer system without glass fiber content.

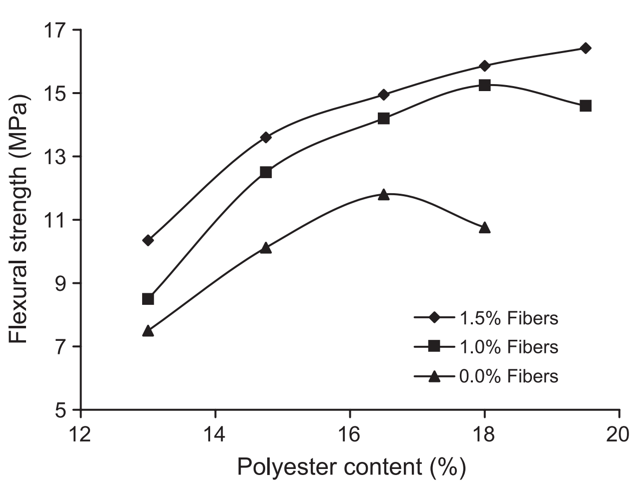

Fig. 5. Variation of flexural strength versus with polyester content for polymer composite system.

The flexural modulus was obtained from the linear portion of the stress–strain curve. The flexural modulus increased with increasing polyester resin and glass fiber content as shown in Fig. 6. After reaching a maximum value it decreases with further increases in polyester content. For the composite system without reinforcement, the maximum flexural modulus was obtained at the 16.5% polyester resin ratio as in flexural strength. For the 1% and 1.5% fiber-reinforced composite systems the maximum flexural modulus was obtained at the 18% and 19.5% polyester resin ratio, respectively. For 16.5% polyester and 1% glass-fiber-reinforced composite system has 15% higher modulus than the corresponding polymer system without fiber content. Additionally, the 18% polyester and 1.5% fiber-reinforced composite system has a 23% higher flexural modulus than the corresponding polymer system without glass fiber content.

4. Determination of critical stress intensity factor

There are several methods developed to determine critical stress intensity factor K_{IC}, initial notch depth method, compliance technique, crack mouth opening displacement method, etc. For this study linear elastic fracture mechanics tests were evaluated for K_{IC} according to the ASTM E 399. The critical load was determined from the load–deflection curves by secant line with a slope of 0.5 less than the initial tangent slope at room temperature. The load–deflection curves of the notched and unnotched specimens with 16.5% polyester resin and 1.5% glass-fiber-polymer composite system are shown in Fig. 7. The load versus crack mouth opening displacement curve for the same type of specimen and composite system is shown in Fig. 8.

4.1. Initial notch-depth method

Linear elastic fracture mechanics stress intensity factor for a beam under three-point bending was developed by Tada et al. [15] and Prokopski and Langier [16]. This

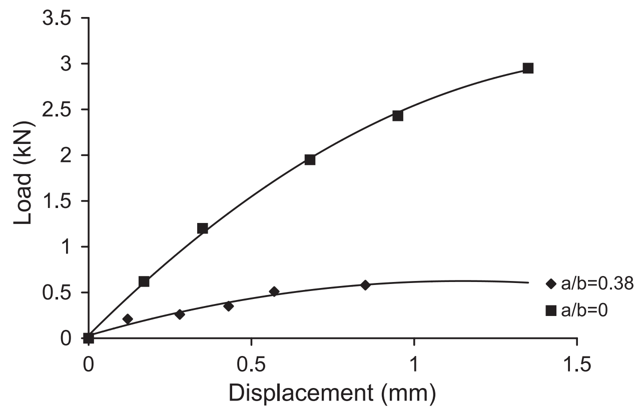

Fig. 7. Load–displacement curves for 16.5% polyester and 1.5% fiber for polymer composite system.

method was based on calculation of critical stress intensity factor by using initial notch-depth method. According to this method the equation of Mode I stress intensity factor is,

$$K_{IC} = \left(\frac{3Ps}{2b^{3/2}d}\right)F\left(\frac{a}{b}\right) \tag{1}$$

Where P is the required peak load for propagation of the crack, s is the beneath length of the beam, $b \times d$ is the cross section of the beam and a/b is notched to depth ratio as shown in Fig. 1. $F(a/b)$ is the correction factor, which depends on the finite size of the specimen.

$$F\left(\frac{a}{b}\right) = \frac{1}{\sqrt{\pi}}\frac{1.99 - A(1-A)(2.15 - 3.93A + 2.7A^2)}{(1+2A)(1-A)^{3/2}} \tag{2}$$

Where,

$$A = \frac{a}{b} \tag{3}$$

The Mode I critical stress intensity factors of 13.00%, 14.75%, 16.50% polyester resin and 1% and 1.5% glass-fiber-polymer composite system were calculated from the

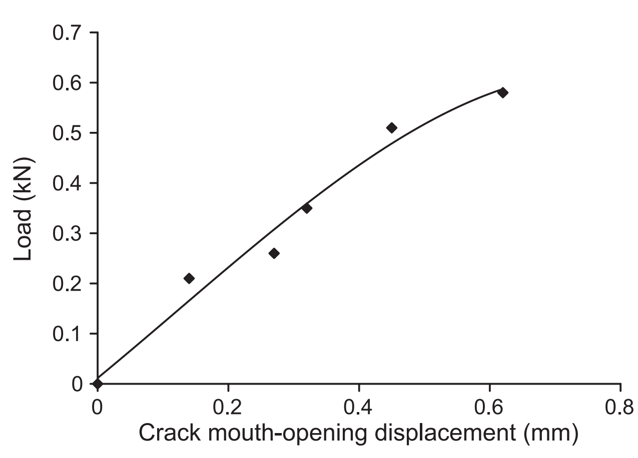

Fig. 8. Load–crack mouth opening displacement curve for 16.5% polyester and 1.5% fiber for polymer composite system.

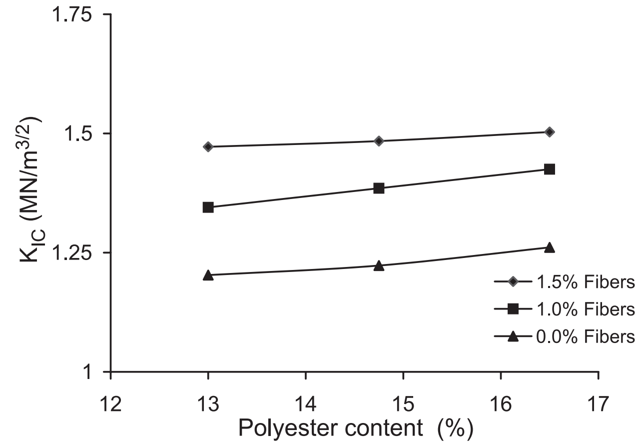

Fig. 9. Variation of K_{IC} with polyester content for initial notch depth method.

Eq. (1). The empirical Eq. (1) is applicable to any (a/b) ratio with 0.5% sensitivity [17].

Fig. 9 shows the variation of the critical stress intensity factors with polyester ratio according to initial notch-depth method. Fig. 9 also shows the effect of the glass fiber content on the K_{IC}. The critical stress intensity factors increased with increasing fiber content. The composite system without fiber content has the lower K_{IC} values than the system with fiber content. In 13.00% polyester composite system without fiber content, K_{IC} was found to be 1.20 MN/m$^{3/2}$, while 1% fiber content was 1.34 MN/m$^{3/2}$ and 1.5% fiber content was 1.47 MN/m$^{3/2}$. The K_{IC} of the polymer composite system with 1% fiber content is about 10% higher than the system without fiber content. The K_{IC} of the composite system with 1.5% fiber content was found to be 18% higher than the system without fiber content and 7% higher than with 1% fiber content.

4.2. Compliance method

The compliance method is an effective method for determining the fracture characteristics of brittle materials. Compliance can be calculated from a load–displacement curve or from a load–crack mouth-opening displacement curve. In the present study the load–crack mouth-opening displacement curve was preferred. Then, a third degree polynomial was obtained from compliance (C) versus (a/b) graph. Compliance equation for the a/b ratio between 0.38 and 0.76 was found as follows,

$$C = 18.31\left(\frac{a}{b}\right)^3 + 15.6\left(\frac{a}{b}\right)^2 - 19.2\left(\frac{a}{b}\right) + 3.52 \tag{4}$$

Critical stress intensity factors were obtained from the following equation for the plane strain case.

$$K_{IC} = \frac{E}{(1-\nu^2)}\frac{P}{2d}\frac{dC}{d\left(\frac{a}{b}\right)} \tag{5}$$

Where P is the peak load, which was, determined from the load–deflection curves by secant line with a slope of 0.5 less than the initial tangent slope. $(1-v^2)/E$ is valid for plane strain case. E is the flexural modulus and v is the Poisson ratio.

Fig. 10 shows the variation of the critical stress intensity factors with polyester content according to compliance method. In addition the Fig. 10 shows the effect of the glass fiber content on the K_{IC}. The critical stress intensity factors increased with increasing fiber content. The composite system without fiber content has the lower K_{IC} values than the system with fiber content.

The K_{IC} of the 14.75% polyester composite system with 1% fiber content is about 17% higher than the system without fiber content. The K_{IC} of the composite system with 1.5% fiber content is found 3% higher than the system with 1% fiber content and 13% higher than without fiber content.

4.3. J-integral method

J-integral method can be applied to find fracture toughness of a nonlinear elastic materials [18]. This method is based on determination of an energy, which expresses the change in potential energy when a crack extends. That is,

$$J = -\frac{1}{d}\frac{dU}{da} \quad (6)$$

Where, d is width of the specimen, U is the potential energy, a is the length of the crack.

There are several methods which developed to determine J-integral. Some of these methods are the initial notch depth samples method [19], deep crack sample technique [20] and notched versus unnotched sample technique [21]. Since the notched versus unnotched samples technique gives better results for fiber-reinforced composite materials [14], in this study this method was preferred to obtain the J-integral values. According to this method, J-integral was calculated by subtracting the elastic energy area under the load–displacement curve of the notched sample from the area under the load–displacement curve of the same type of unnotched sample.

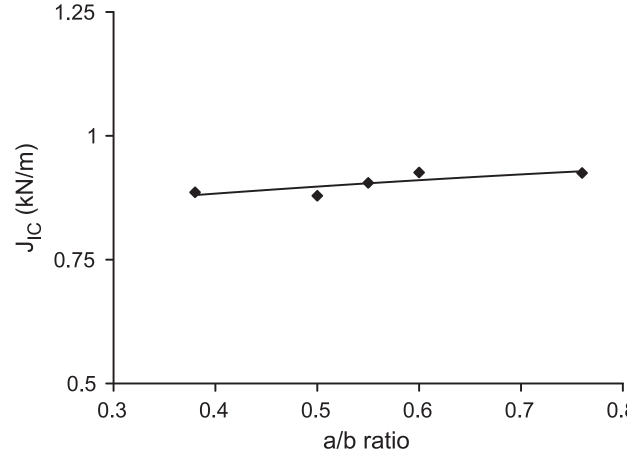

Fig. 11. Variation of J_{IC} with notch-to-depth ratio (a/b).

$$J_{Ic} = \frac{2(A_t - A_u)}{d(b-a)} \quad (7)$$

Where, A_t and A_u are the strain energy of the notched and unnotched sample, respectively as shown in Fig. 7.

Fig. 7 shows the load–deflection curves of the notched and unnotched specimens with 16.50% polyester resin and 1.5% glass fiber polymer composite system. The notch aspect ratio of 0.38 was chosen for this graph. A plan meter measured the area under the curves and the critical J-integral values were calculated from Eq. (7). Fig. 11 shows the variation of the critical J-integral (J_{IC}) with respect to a/b ratio. J_{IC} remains almost constant with increasing a/b ratios. To estimate the fracture toughness of a nonlinear elastic body, J_{IC} has been proposed when linear elastic behavior

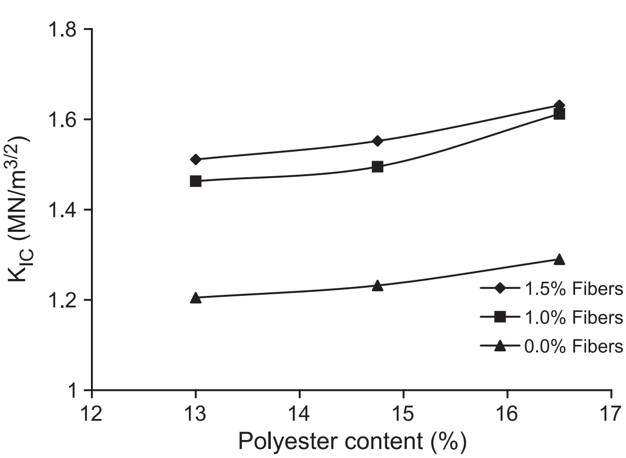

Fig. 10. Variation of K_{IC} with polyester content for compliance method.

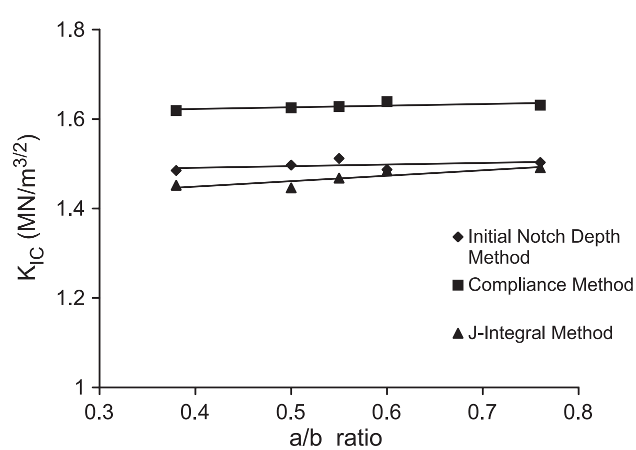

Fig. 12. Relationship between K_{IC} and notch-to-depth ratio (a/b) for polymer composite system.

predominates, J-integral is directly related to the K_{IC} through the following equation,

$$K_{IC}^2 = \left(\frac{E}{1-v^2}\right)J_{IC} \tag{8}$$

K_{IC} values were obtained from Eq. (8). Fig. 12 shows the variation of the critical stress intensity factors for 16.5% polyester and 1.5% composite system with respect to a/b ratios, according to compliance method, initial notch depth method and J-integral method. It can be said that critical stress intensity factor does not increase while (a/b) ratio increases. The same situation is also valid for critical J-integral.

5. Conclusion

In this study, the effect of chopped strand glass fiber content on fracture behavior of the polymer composites were investigated and the following conclusions were derived:

1. Both in fiber-reinforced and without reinforcement polymer composite systems flexural strength and flexural modulus increase with increasing polyester content from 13.00% to 19.50% in weight. After reaching some peak values both flexural strength and modulus decrease with further increasing polyester ratio. This occurred due to the properties of the polyester dominate in the composite system and the weak bonds occurred between sand particles. While fiber content increased from 1% to 1.5% in weight flexural strength and modulus also increased.
2. The critical stress intensity factors K_{IC} increased with increasing glass fiber ratio for all methods, that is the initial notch depth method, the compliance technique and the J-integral methods. The critical stress intensity factors did not also change by increasing the notch-to-depth ratio. This shows K_{IC} does not depend on (a/b) ratio. J_{IC} is also not depending on (a/b) ratio.

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