EFFECTS OF ENVIRONMENT ON FRACTURE TOUGHNESS OF GLASS FIBER/POLYESTER COMPOSITE

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Abstract: The resistance of a material to crack propagation is greatly influenced by the fracture toughness of that material. Many parameters are responsible for the fracture and damage process of a material. In this work, an experimental investigation has been carried out on the fracture toughness of chopped strand mat glass fiber reinforced composite after exposing to various adverse environments, like, water, saline water, acidic water, organic fuel, ice temperature and hot air, for different durations using single edge notched (SEN) specimens. The sharp notch of different length sizes, namely, 2 mm, 4 mm, 6 mm (approximate), were cut in different specimens. It has been drawn a number of important inferences from this work. Fracture toughness is independent of crack size. There is a sizeable effect of environments on fracture toughness. A relationship between fracture toughness and duration of exposure under these adverse environments has been established. The fracture toughness has been found to decrease gradually with increased duration of environmental exposure, whereas the fracture toughness has been found to be independent of pre-crack/notch length.

Keywords: Fracture Toughness, Composite, Tensile loading.

1. INTRODUCTION

Ships, aircrafts and rockets are extremely complex engineering systems with many thousands of components. In the construction of such systems, it is impossible to completely avoid the presence of flaws such as cracks and these systems often faces a wide range of environmental exposures. Understanding the strength of materials in the presence of cracks and under adverse environmental impacts is thus key to developing reliable aerospace and ocean engineering hardware. The fracture toughness can be used to characterize the fracture behavior of composite materials under varied conditions.

Fracture in all materials, brittle or ductile, homogeneous or composites, is governed more or less by microscopic discontinuities and imperfections, such as, cracks, inclusions or dispersed phases. The strength of a material may be correlated with its fracture energy, elastic modulus, and the size of the crack initiating the fracture. In this domain, the fracture toughness of the material has a major role in the determination of the fracture behaviour and resistance of the material to crack propagation under the influence of an external load. The material cannot be used without analyzing the fracture toughness. Central to the process is the determination of stress intensity factor, which is a function of the geometry of the structure and the character of the load. The advent of fracture mechanics has accelerated the methods for determination of crack growth rate and maximum allowable damage at limit load conditions[1, 2]. In that line, the degradation of strength of composite materials in presence of micro cracks must be understood precisely under any situation for their wider application. The glass fibre reinforced composites are finding wide applications in primary structures of the aircrafts, space crafts, ocean vehicles, automotive industries as well as other cladding situations. These applications sometimes face a wide range of environmental exposure like low temperature, acidic water, high temperature, organic fuel, water, saline water, etc. Thus the understanding of the fracture behaviour and prediction of fracture toughness of composite materials after different environmental exposure have assumed greater importance.

The importance of estimating the fracture load of notched plates has more or less been established and the influence of related parameters like width and thickness of specimen, notch geometry, notch angle, notch root radius, and notch depth have widely been studied[3-5]. Thus, the determination of stress intensity factor has become mandatory for reliability of composite structure. However, the fracture strength of the composites after exposure to adverse environmental condition is yet to be substantially established. In this context, an extensive experimental investigation of fracture toughness after different environmental exposure has been carried out in the present study.

2. THEORY OF FRACTURE TOUGHNESS

Many researchers[6-9] have used the linear elastic fracture mechanics (*LEFM*) approach for studying the crack growth resistance of fiber-reinforced composite materials. The *LEFM* approach[10], originally developed for metallic materials, is valid for crack growth with little or no plastic deformation at the crack tip. It utilizes the concept of stress intensity factor K_I, which is defined as

$$K_I = \sigma Y \sqrt{\pi C} \qquad (1)$$

Where, K_I= mode *I* stress intensity factor, σ = applied stress, C= crack length and Y= geometric function that depends on the crack length, crack location and mode of loading. Here, mode *I* refers to the opening mode of crack propagation due to an applied tensile stress normal to the crack plane.

Equation (1) shows that the stress intensity factor increases with both applied stress and crack length. An existing crack in a material may propagate rapidly in an

unstable manner (i.e., with little or no plastic deformation) when the K value reaches a critical level. The critical stress intensity factor, also called the fracture toughness, indicates the resistance of the material to unstable crack growth.

From Eq. (1), K_I provides the severity of the crack tip environment, and it is logical to characterize resistance to fracture by a critical value, that is, K_C. Generally, K_C is determined by laboratory tests of material.

By simplifying the stress field in the local direction, normal to the axis of the main crack, the stress on the i-th ligament from the original crack tip with the main crack located at the edge of the j-th ligament can be assumed as σ_{ij}. For the case of precut notch with no prior crack extension, the stress at the notch tip is σ_{11} and it can be determined by using the failure stress (σ_f), the stress intensity factor K_I and the critical stress intensity factor (K_C) can be expressed as

$$\sigma_{11} = \sigma_f \left(\frac{K_1}{K_c} \right) \tag{2}$$

The crack tip extends gradually under increasing load before main crack extension occurs and its extension diminishes the local stress σ_{11}. Equation (2) is equivalent to the assumption of a stress concentration at the crack tip and can be written as

$$\frac{\sigma_{11}}{\sigma} = \frac{\sigma_f Y \sqrt{C}}{K_c} \tag{3}$$

From classical fracture mechanics relationship, Eq. (3) in the form of stress intensity factor can be expressed as

$$K_I = \sigma Y \sqrt{C} \tag{4}$$

The K_I calculated through Eq. (4) is also called as the fracture toughness of the material. For a pre-crack length 'C' and maximum applied stress σ, the parameter 'Y'is a geometrical factor, which accounts for proximity effects of boundaries or other cracks, orientation of the crack, shape of the crack and the restraints on the structure containing the crack, and is usually determined by a simple relationship[11] as shown below

$$Y = 1.99 - 0.41\left(\frac{C}{W}\right) + 18.70\left(\frac{C}{W}\right)^2 - 38.48\left(\frac{C}{W}\right)^3 + 53.85\left(\frac{C}{W}\right)^4 \tag{5}$$

Where, W is the width of the specimen

3. EXPERIMENTAL

3.1. Composite Fabrication

This work has been carried out on a Polyester resin (268BQTN: a product of SHCP) and a hardener (Methyl Ethyl Ketone Per Oxide, commercially known as Butanox-50) reinforced by Chopped strand mat Glass fiber (CSM 501-300: a product of KCC). The composite specimens with two layers of embedded ply were fabricated in the laboratory at room temperature in the shape of a rectangular plate by Hand Lay UP (HLU) technique. Ample precaution was taken to minimize voids in the material and maintain homogeneity. The plates were post-cured at 80°C for 4 hours after 24 hours curing at room temperature. The Glass Fiber Reinforced Composite (GFRC) plate was found to have a thickness of 2.5 mm (±0.5%) and fiber volume fraction of 35% (±0.5%).

3.2. Specimen Preparation

The specimens with ASTM Standard (D-3039) dimensions, as shown in Fig. 1, were prepared from the fabricated Glass fiber reinforced composite plate. The

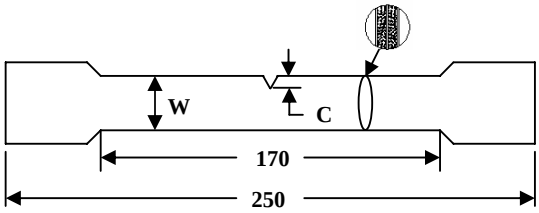

Figure 1. Dimension of the Specimen (Dimensions are in mm)

specimens were finally cut according to the sizes by a powered disc cutter. The sharp notch of different length sizes, namely, 2 mm, 4 mm, 6 mm (approximately) were cut in different specimens by the help of Surgical Blades (Size 22, Huaiyin Medical Instruments Co., Ltd., China). Microscopic examination has been carried out to measure the exact length of notches. The required number of specimens with single edge sharp notch was made in the same way.

3.3. Environment Selection

In accordance to exposure of aerospace and ocean vehicles structures, the following six types of environment have been selected for the present investigation:

- Water: Pure distilled water has been used.
- Saline water: A mass of 200 mg of NaCl has been mixed in 1000 ml of distilled water to prepare the saline water.
- Acidic water: Sulphuric acid of strength 0.01N has been taken as acidic water. Here, distilled water has been used to prepare 0.01N strength from concentrated H_2SO_4 (80%).
- Organic fuel: Commercially available kerosene oil has been used.
- Low temperature: Ice temperature has been considered as the low temperature environment.
- High temperature: Specimens have been kept in a closed oven and the temperature has been monitored by a thermocouple. The temperature was recorded as 60±5°C.

3.4. Environmental Exposure

The pre-notched specimens were exposed in six different environments for a fixed duration, such as 100 hours, 200 hours, 300 hours and 400 hours. The rate of environmental effect has been calculated for each exposed specimen in the form of percentage of weight gain (or loss) by using the following equation

$$\text{Weight gain (\%)} = \frac{M_f - M_i}{M_i} \times 100 \tag{6}$$

Where, M_f = Final mass of the specimen and M_i= Initial mass of the specimen.

3.5. Fracture Toughness Test

The fracture toughness test on the specimens exposed to various environments has been carried out by applying tensile loading on a servo-hydraulic tensile testing machine (Universal Testing Machine, MIDDLE SENSTAR) for the specimen having a single edge sharp notch. The specimens were clamped in pin-loaded grips and subjected to monotonic uniaxial tension at a displacement rate of 1.50 mm/min. The load, at which the complete fracture of the specimens occurred, has been accepted as the critical load.

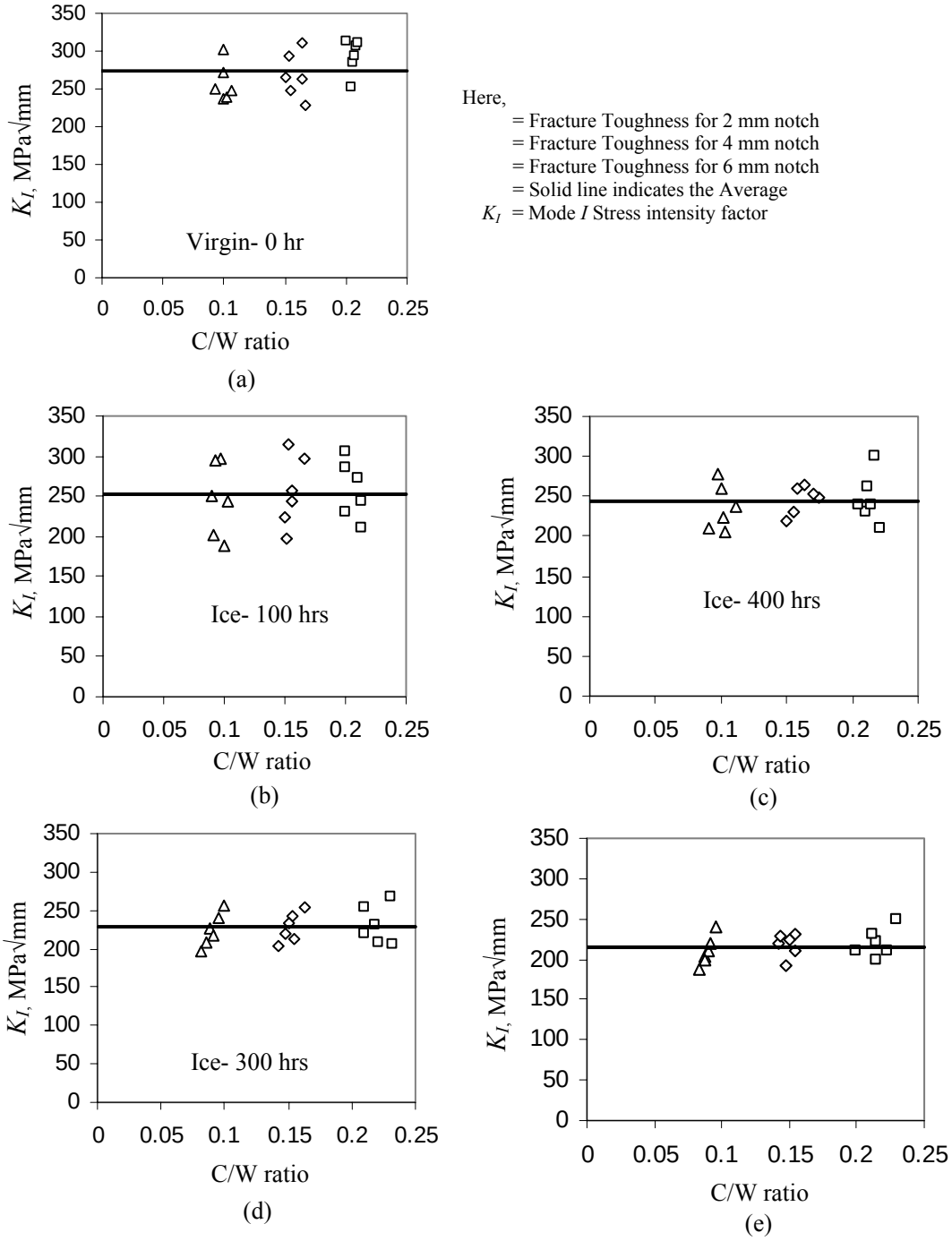

Figure 2. Fracture Toughness for different notch lengths exposed to low temperature (or, ice temperature) for (a) Virgin or 0 hour (b) 100 hours (c) 200 hours (d) 300 hours and (e) 400 hours.

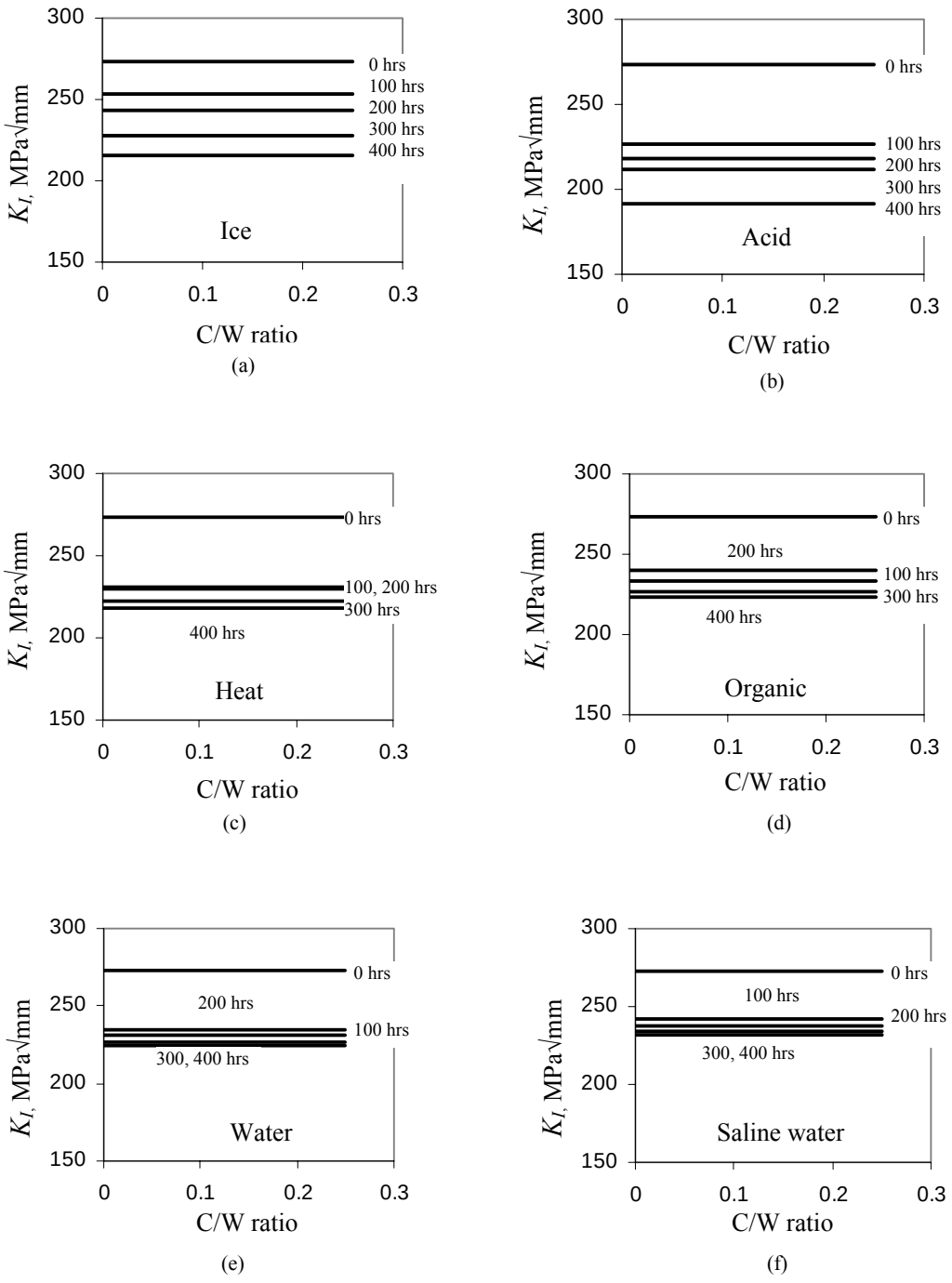

Figure 3. Average Fracture Toughness for different durations for (a) low temperature (or, ice temperature) (b) Acidic water (c) high temperature (d) organic fuel (e) water and (f) saline water environments.

4. RESULTS AND DISCUSSION

4.1. Fracture Toughness after Environmental Exposure

In the present investigation, studies have been carried out to find the fracture toughness of chopped strand mat glass fiber reinforced composite and the extent of its degradation by exposure to the six different environments up to 400 hours. Fig. 2 shows the data of fracture toughness of the composite for different notch lengths exposed to low temperature (or, ice temperature).

Fig. 2(a) shows the data of unexposed specimen. That is why it has been mentioned as virgin specimen. Fig. 2(b) to Fig. 2(e) show the data of fracture toughness obtained after exposing to low temperature (or, ice temperature) for 100hrs, 200 hrs, 300 hrs and 400 hrs respectively. It is observed from Fig. 2(a) to Fig. 2(e) that the fracture toughness is more or less independent of any of the notch lengths for each of the environmental exposure. Thus from the data, it has been assumed that the fracture toughness is

Table 1. Test results of average fracture toughness after various environmental exposures for different durations of exposure.

Duration of Exposure	Environment wise Fracture Toughness						
	Virgin, MPa $\sqrt{mm}$	Low Temp. MPa $\sqrt{mm}$	Acidic Water MPa $\sqrt{mm}$	High Temp. MPa $\sqrt{mm}$	Organic Fuel, MPa $\sqrt{mm}$	Water, MPa $\sqrt{mm}$	Saline Water MPa $\sqrt{mm}$
100 hours	273.20	253.10	226.84	230.40	240.42	234.92	242.38
200 hours	273.20	242.86	218.59	229.44	233.30	231.21	237.27
300 hours	273.20	227.65	211.44	221.85	226.61	226.54	234.09
400 hours	273.20	216.03	191.90	218.07	222.91	224.74	231.78

Table 2. Percentage variation of Fracture Toughness after exposure into various environments.

Types of Environments	Fracture Toughness, %			
	100 hours	200 hours	300 hours	400 hours
Virgin	100	100	100	100
Low Temperature	92.64	88.89	83.33	79.07
Acidic Water	83.03	80.01	77.39	70.24
High Temperature	83.98	84.33	81.20	79.82
Organic Fuel	88.00	85.40	82.95	81.59
Water	85.99	84.63	82.92	82.26
Saline Water	88.72	86.85	85.68	84.84

Table 3. Percentage of Weight Gain after various environmental exposures for different durations of exposure.

Duration of Exposure	Environments					
	Low Temperature %	Acidic Water %	High Temperature %	Organic Fuel %	Water %	Saline Water %
100 hours	1.18	0.35	-0.02	0.05	1.66	0.43
200 hours	1.87	0.62	-0.05	0.09	1.95	0.68
300 hours	2.48	0.84	-0.16	0.13	2.22	0.73
400 hours	2.94	1.05	-0.29	0.17	2.36	0.74

independent of notch lengths. Therefore, a firm line has been drawn at the average value of all data of specimens of 2 mm, 4 mm and 6 mm notch lengths in Fig. 2(a) to Fig. 2(e).

Fig. 3(a) shows the average values of fracture toughness of virgin specimen and of low temperature (or, ice temperature) exposure for different durations. Similarly, Fig. 3(b) to Fig. 3(f) show the average values of fracture toughness for acidic water, high temperature, organic fuel, water and saline water exposure for different durations respectively.

It is again observed from Fig. 3 that the resultant curves representing the average fracture toughness for different durations are independent of notch lengths but decreasing their values with the time exposed for all the different environments.

These average values of fracture toughness for each environment at different duration of exposure are summarized in Table 1 and Table 2 shows the percentage variation of fracture toughness after exposing to various environments.

Percentage of weight gain after various environmental exposures for different durations has been calculated by using Eq. 6 and shown in Table 3. The negative values in Table 3 indicate the loss of weight.

4.2. Effects of Notch Size on Fracture Toughness

The fracture toughness of sharply, pre-cut, and single edge notched specimen of chopped strand mat glass fiber/ polyester composite has been shown in Fig. 3 for various notch sizes exposed to various environments. It is observed that the fracture toughness remains constant, irrespective of notch size.

The failure of specimen can be attributed to the generation and propagation of the crack. While the size of the notch would generate tensile stress of varying magnitude, the specimens were found to exhibit almost equal fracture toughness. The geometric factor, *Y*, also varies with the size of the notch, and this is responsible for the observed constant fracture toughness results.

4.3. Effects of Environment on Fracture Toughness

The highest amount of degradation in fracture toughness has been recorded in acidic water (29.76% after 400 hours) and then in acidic water (22.61% after 300 hours) followed by low temperature (20.93% after 400 hours), high temperature (20.18% after 400 hours), acidic water (19.99% after 200 hours), organic fuel (18.41% after 400 hours) and water (17.74% after 400 hours).

The highest amount of weight gain has been recorded in low temperature (2.94% after 400 hours) and then again in low temperature (2.48% after 300 hours) followed by water (2.36% after 400 hours), water (2.22% after 300 hours), acidic water, saline water and organic fuel. Weight loss of 0.29% has been recorded after exposing into high temperature for 400 hours. For first two hundred hours of exposure, water exposed specimens gained more weight (1.95%) than specimens exposed into low temperature (1.87%) and specimens exposed into saline water gained more weight (0.68%) than specimens exposed into acidic water (0.62%). For the next two hundred hours of exposure, specimens exposed into low temperature gained

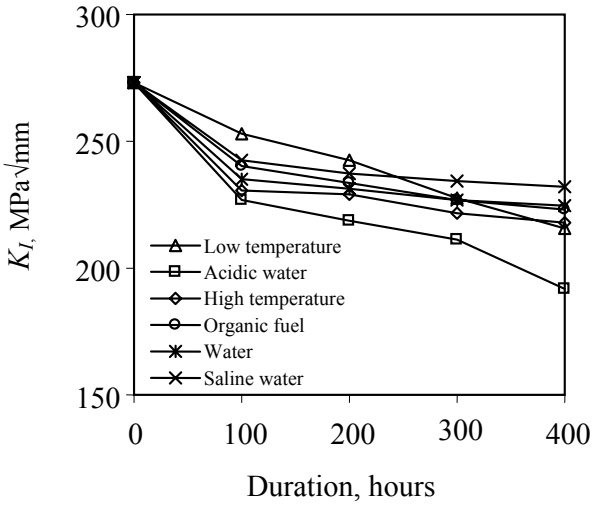

Figure 4. Comparison of average fracture toughness after exposure to various environments

more weight (2.94%) than water exposed specimens (2.36%).

The results of fracture toughness after different durations of environmental exposure and percentage weight gain in same period by the composite in different environments are shown in Fig. 4 and Fig. 5.

For the water-exposed specimens for exposure of 400 hours, it has been observed that there is 17.74% degradation in fracture toughness, while a weight gain of 2.36% has been recorded in the same duration. The penetration of water molecules in the interface region through the voids of the composite may be the reason of weight gain. The osmotic pressure of the water molecule might have facilitated the entrance of water molecules into matrix phase, and may have expanded its boundary in due course. As a result, the bond strength of the fiber and matrix has been weakened and load-bearing strength of the composite has been reduced, and this caused the reduction in fracture toughness.

When the specimens are exposed to saline water, only 0.74% weight gain has been recorded after 400 hours duration of exposure. The higher density of the liquid may be responsible for lower penetration of the saline water as compared to water. The reduction in fracture toughness has been found to be at a lower value of 15.16% as compared to 17.74% for the case of water in the same duration, although the liquid penetration is almost less than one third. The reduction in fracture toughness should be taken as a simultaneous effect of corrosivity of saline water and liquid penetration into the material in this case.

The investigation has been carried out in two groups of temperatures–one is lower value of environmental temperature and the other at a higher value. At the lower value of temperature, that is, ice temperature, a notable reduction in the fracture toughness has been observed and it is about 20.93% after 400 hours duration of exposure, while 2.94% of weight gain has been recorded in same duration. In ice, the water is in state of transition phase and temperature is about 0°C. The low temperature of the environment has caused the shrinkage of the constituent phases of the chopped strand mat glass fiber/polyester composite and transition pressure has caused a higher order of water absorption. This is mainly due to dissimilar contraction of matrix and fiber in low temperature. In consequence, detachment has been observed at the fiber and matrix interface and development of microcrack, debonding and delamination in the interface region of fiber and matrix. The process is further aggravated by formation of more cracks and more detachment at the interface when there is a prolonged exposure. Therefore, the fracture toughness has been reduced significantly.

When the specimens are exposed to hot temperature of 60°C, only 0.29% weight loss has been recorded after 400 hours duration of exposure. High temperature may be held responsible for dissociation of matrix and weight loss of the specimens. The reduction in fracture toughness has been found to be at a little lower value of 20.18% as compared to 20.93% for the case of low temperature in the same duration. The matrix behavior has been changed due to prolong exposure to hot temperature (60°C), and has ablated a fraction of matrix from the specimen. In addition, under high temperature the dissimilarity in the thermal coefficient behavior of matrix and fiber causes different expansion and contraction characteristics, resulting microcracks, debonding and delamination at the interface region similar to low temperature environment. The ablation of matrix may be increased as temperature rises, or time increases and thermal stress produced over the specimen, which results the micro buckling of fiber. It is resulted to the lower value of fracture toughness. In the present case, the environmental temperature was kept quite below than the melting temperature of matrix. So less reduction in fracture toughness has been anticipated in comparison to quite high temperature (above than ablation temperature of matrix).

When the specimens are exposed to organic fuel, only 0.17% weight gain has been recorded after 400 hours duration of exposure. The reduction in fracture toughness has been found to be at a value of 18.41% for this duration. The absorption of aromatic constituents of liquid fuel may be taken to cause a marginal weight gain. The apparent cause of fracture toughness degradation may be due to fuel absorption through the voids, which corrode the fiber exposed to it. Loosely bonded carbon particles may be detached from fiber by chemical reaction resulting in a rough surface. Thus, there is a considerable reduction in fiber strength and in fracture toughness.

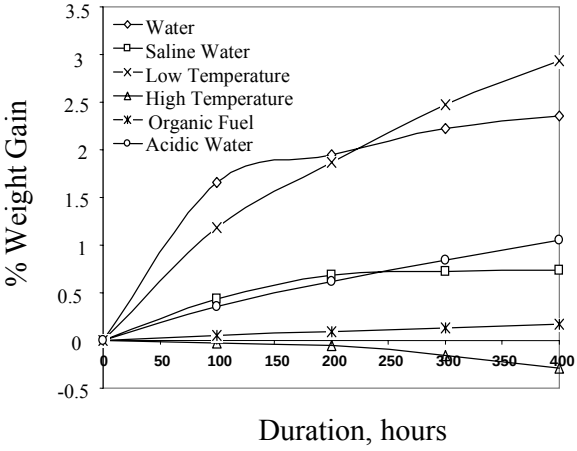

Figure 5. Comparison of percentage weight gain after exposure into various environments

When the specimens are exposed to acidic water, only 1.05% weight gain has been recorded after 400 hours duration of exposure. The reduction in fracture toughness has been found to be at a higher value of 29.76% as compared to all the previous cases in the same duration, although the liquid penetration is less than water, ice and more than saline water and organic fuel. This high value of degradation on fracture toughness is mainly attributed to the reaction of acid on composite. Concentrated H_2SO_4 acid would digest the binder material and debond the fibers from the matrix. When the concentration decreases to 0.01N, these effects would substantially decrease. However, prolonged exposure of composite may be taken to cause a slow reaction of acid and matrix, and developed debonding, delamination and micro-cracking in composite phases. Thus, there is a high amount of fracture toughness degradation.

The overall results obtained from various adverse environments have shown the rate of reduction of fracture toughness, which depend on reaction of constituent phases towards the exposed environments, duration of exposure and type of environment. Highest amount of fracture toughness strength reduction is noticed for acidic water and followed by low temperature and high temperature.

5. CONCLUSION

The fracture toughness can be used to characterize the fracture behavior of composite materials under varied conditions. The test and analysis methods presented in this work provide the tool to collect data necessary for design with above mentioned environmental effects. A significant amount of data was collected to assess the impact of environment on this composite. In this work, as the fabricated specimens do not show any R-curve behavior, attention should be given on environmental effects for this range of crack length. This study will help select a particular duration of environmental exposure as well as particular environment for this class of composite materials according to the design limits.

Based on the experimental results found for various environmental exposed specimens with different sizes of pre notches, and with diverse duration of environmental exposure, the following important conclusions can be drawn.

- Fracture toughness is independent of crack size.
- The highest amount of degradation in fracture toughness was found after exposure into acidic water and then in low temperature followed by high temperature, organic fuel, water, and saline water for the same duration of exposures.
- Among six environments specimens exposed in saline water showed lower values of degradation of fracture toughness. So, the fabricated glass fiber/polyester composite may be suitable for use in this environment.
- There is a sizeable effect of environments on fracture toughness. The environmental effects depend on the type of environment, hostility, corrosivity and constituent ingredients.
- It has been observed that the temperature has reduced the original strength in greater margin.
- In case of liquid environment, the density of the medium has significant influence over the rate of diffusion of moisture into material. It depends on the constituent particles of the liquid; its osmotic pressure and number of voids in material.

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