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Mode-I Fracture Analysis of Thermally Aged of Glass and Glass-Carbon Hybrid Composites

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***Abstract:** Fibre reinforced polymer composites find application in domains leading from aerospace to sports gear manufacturing, however the influence of environmental factors such as temperature, and corrosion adversely affects their structural integrity. The objective of the research endeavour is to characterize the fracture toughness behaviour of glass/epoxy and glass-carbon hybrid fibre reinforced composites under detrimental thermal aging conditions. The tests were conducted to predict the mechanical behaviour of both normal and exposed specimens at different thermal aging conditions. The study focuses on the Mode-I Interlaminar Fracture Toughness in terms of strain energy release rate* G_I *of FRP composites under three different temperatures (-10°C,-20°C and room temperature) with three different aging periods of 150 hours, 300 hours and 500 hours. The energy release rate of material has reduced from room temperature to low temperature due to the catastrophic state of crack propagation. From the final test carried out after 500 hours of aging, the energy release rate of glass-epoxy aged specimens decreases to 10-15% to that of pristine specimens of same material at -20°C but for glass-carbon hybrid specimens the decrease in order of 5-10%. Hence more changes were observed in glass/epoxy specimen than that of hybrid due to an interfacial failure between fibres. The failure mechanism is initiated with matrix cracking at room temperature to fiber shrinkage and fiber breakage at low temperatures. The micro structural failure of pristine and thermally exposed specimens was studied by SEM image.*

***Keywords:** Glass-epoxy and Glass-Carbon hybrid composites, Mode-I interlaminar fracture toughness, Energy release rate, Thermal aging.*

I. INTRODUCTION

Polymer–matrix composites used in aerospace and other applications may be exposed to environments usually involving temperature and humidity. It is evident from the literature that both physical and mechanical properties of composites are strongly affected during hygrothermal conditioning which eventually reduces the overall composite performance [1–3]. Composite materials are nowadays used widely because of its high strength/Stiffness, light weight and corrosion resistance properties. It plays an inevitable role in the manufacture of component from chemical, marine, sports to aircraft components. Hence the knowledge of the damage behaviour and the transition of damage from a subcritical stage to a critical stage are of considerable interest in the case of composite materials [4-5].

Han Xiaoping et al.[2] described that the fracture toughness of glass-cloth/epoxy laminates has been determined under different temperatures and strain rates by means of the WEK fracture mode and it implies that different damages are formed in the laminates under different temperatures and strain rates. Dionysis E. Mouzakis et al. [6] studied that the failure of polymer matrix composites to investigate the combined action of temperature, humidity and UV radiation on polymers and composites, an environmental ageing with various matrix. Scanning electron microscopy studies performed before and after environmental chamber conditioning revealed that some microcracks had occurred on the surface of the specimens. R.D. Adams, M.M. Singh [7] found that longitudinal shear modulus and loss factor were measured over a range of temperature, from -150 to +20*C, both before and after conditioning in a hot, wet environment. Delamination between layers is an important problem in applications of fiber reinforced composite laminates and tests were carried out to determine the interlaminar fracture toughness of AS4/3501-6 (carbon/epoxy) composite laminates using mixed-mode bending tests. Analysis of the test specimens in terms of mode I and mode II energy release rates and detailed finite element analyses[8]. This paper examines the effect of plain stitching by untwisted fibre rovings in the in-plane mechanical properties and Mode I interlaminar fracture toughness of glass/polyester composites and it is observed that stitching increases the Mode I delamination toughness up to 20 times higher than that of unstitched specimen[9]. P. Hutapea [10] has studied high temperature Mode-I interlaminar test on IM7/LaRC-RP46 composite with various temperatures and strongly implies that the G_{Ic} values are increased near Tg and G_{Ic} values are decreased above Tg. The experimental design and testing methodology of Mode-I interlaminar fracture test for uni-directional polymer reinforced composites were being attributed [11, 12] .Environmental effects on composite materials were discussed in detail to the adverse environment conditions and its failure has been studied [13-15]. The mechanism behind the effect of temperature on fracture toughness is popularly attributed to factors such as fiber-matrix interface bond, microstructure and properties [16,17] of the matrix yet arguments are still prevalent about their credibility. degradation of composites due to environmental effects were well documented on fiber-reinforced polymer (FRP) composites for Aerospace Engineering The area between FRP composite sections and the adhesive layer was confirmed to be the most sensitive part to moisture effects. This research developed a step towards the prediction of long-term performance and life-time estimation of FRP-steel composite bridges [18].

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However it came into our notice that there are only a countable number of studies on the dynamic fracture behavior [2] of composites at medium strain rates and hence the study was focused on the effects of strain rates on fracture toughness of thermally aged composite materials. Comparing the fracture toughness of moisture absorbed specimen of different temperatures, the specimen exposed to a higher temperature exhibits a higher failure rate [1, 16]. V. Arumugam etal [21]. has studied the characterization of failure modes in GFRP Laminates Under Mode I Delamination by Acoustic Emission Technique where the failure mode of matrix cracking, delamination and fiber failure is studied by FFT and STFFT. At high temperature the mode of failures of fiber bridging, fiber breakage and matrix cracking were studied by SEM image[6,10].

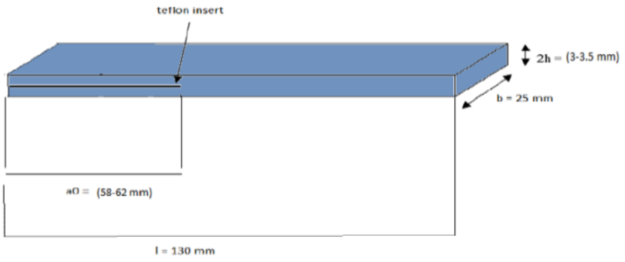
This study focuses to determine the interlaminar fracture toughness of Glass/epoxy and glass carbon hybrid composites when subjected to ageing at low temperatures of -20°C, -10°C [7] and room temperatures with various intervals. The exposure of 150 hours, 300 hours and 500hours specimens were employed in Mode-I (DCB) interlaminar fracture test to evaluate the fracture toughness of specimen under thermal conditions of above mentioned temperatures. The energy release rate G_I for the different conditions were determined and the outcomes were compared for glass-epoxy and glass-carbon hybrid composite. Microscopic analyses of thermally aged specimen were studied by SEM image and the corresponding failure mechanisms also have been studied.

II. EXPERIMENTAL WORK

A. Material geometry:

The fabrication of GFRP composite laminates were carried out by hand lay-up process followed by compression moulding where the laminate composed of 12 plies of unidirectional glass fibre with epoxy resin. The Teflon flim (<15µm) is act as delamination initiator of length 58mm was placed at the midplane of the composite laminate. According to ASTM D5528 the specimens of dimensions 130mm x 25mm x 3-3.5mm were cut from the laminate by diamond saw cutting tool. From the matrix digestion method (ASTM D3171), the weight fraction of fibre was measured as 54%.

As per the Double Cantilever Beam test, the piano hinges were attached on both contact surface of specimen through the length of Teflon flim as shown in fig 1a.



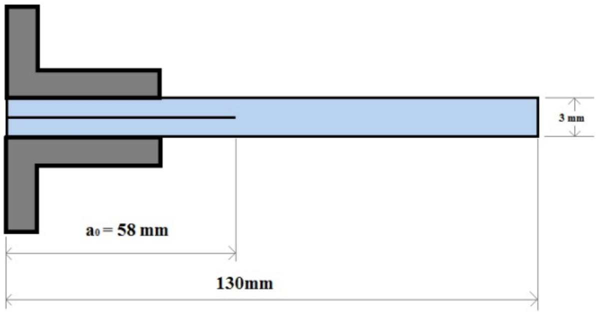


Fig 1a: Material geometry of FRP composite for DCB test

B. *Environmental conditions*:

Before the specimen was subjected to thermal ageing, a pre curing was carried out in order to drive out any moisture absorbed during the preparation of the specimens. The Specimens were placed in a freezer which is maintained at the temperature of -10°C and -20°C for the aging period of 150,300 and 500 hours.

C. *Mode -I fracture (DCB) Test*

The configuration of a double cantilever beam (DCB) specimen indicated by the ASTM standard D 5528-01 [8] was used to determine the mode I fracture toughness. Specimens with piano hinges were used, marks were made at every 5 mm from the tip of the delamination to observe the crack propagation and record the corresponding load point displacement. Five test specimens were used for the mode I fracture tests with various adverse temperature conditions. . The specimens were tested in a controlled displacement mode in 5 Ton capacity of Universal Testing Machine with a constant displacement rate of 2 mm/min.

The applied load vs opening displacement is recorded on a XY recorder in instantaneous delamination front locations are marked on the chart at intervals of delamination growth. The extension of the delamination front was observed and the crack opening displacement corresponding to every 5 mm extension was recorded.

Fig 1b: Crack propagation in glass-epoxy composite under DCB test

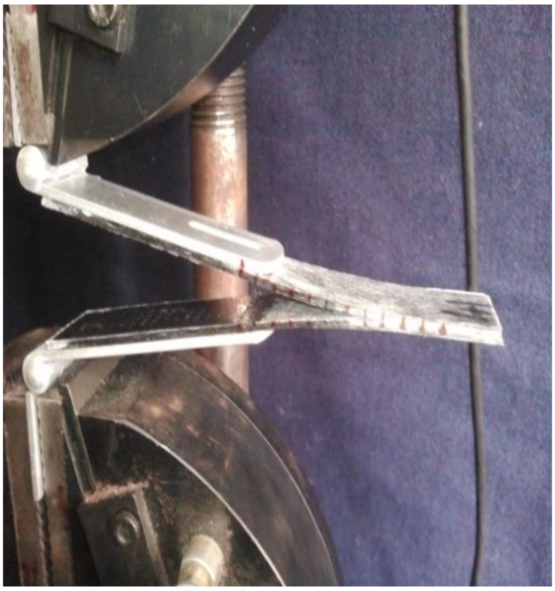


Fig 1c: Crack propagation in glass-carbon hybrid composite under DCB test

D. Fracture Toughness, G_{Ic}

The failure load for each case was selected as the highest load point of the linear section of the load displacement plot and used to determine the mode I critical energy release rate GIc [8].The mode-I interlaminar fracture toughness in terms of energy release rate (G_I) is calculated by using the modified beam theory.

Energy Release Rate, $G_I = \frac{3}{2} \times \frac{p}{b} \times \frac{\delta}{a}$ joules/m^2

Where P- load, □□ load point displacement, b-specimen width and a- delamination length which observed from the load vs displacement curve.

III. RESULT AND DISSCUSSION

The glass-epoxy composite and glass-carbon hybrid composite specimens were aged for a period of 150 hours , 300 hours and 500 hours at the temperature of -10℃ and -20℃. Due to cold temperature exposure the composite samples have become more brittle in nature when compared to that of un-aged specimens. Load v.s Displacement graphs for different aging conditions as shown below.

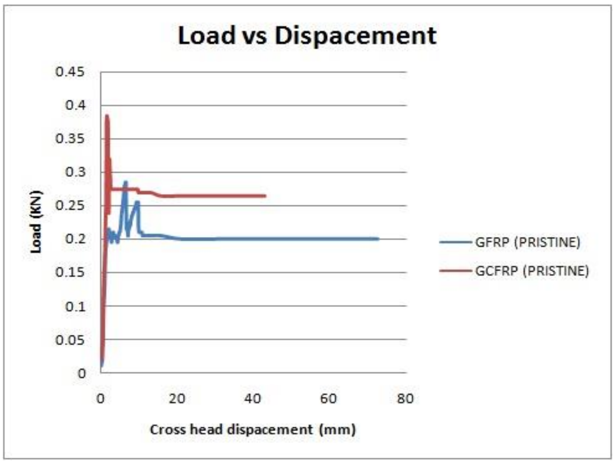


Fig 2a: Load v.s Displacement for glass-epoxy and glass-carbon hybrid composites.

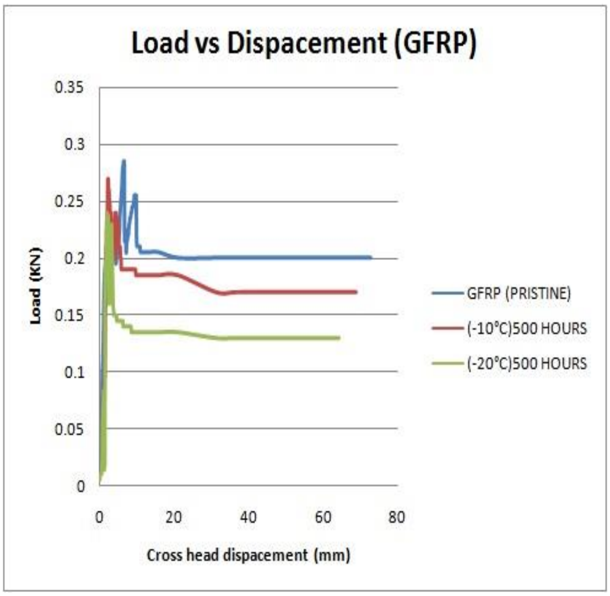


Fig 2b : Load v.s Displacement for glass-epoxy composites under different aging conditions.

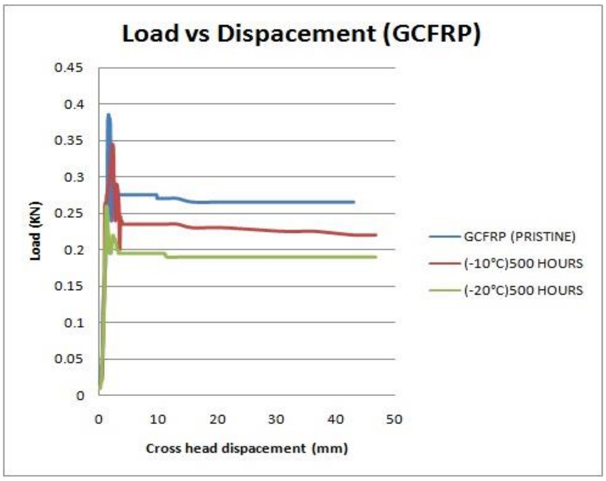


Fig 2c : Load v.s Displacement for glass-carbon hybrid composites under different aging conditions.

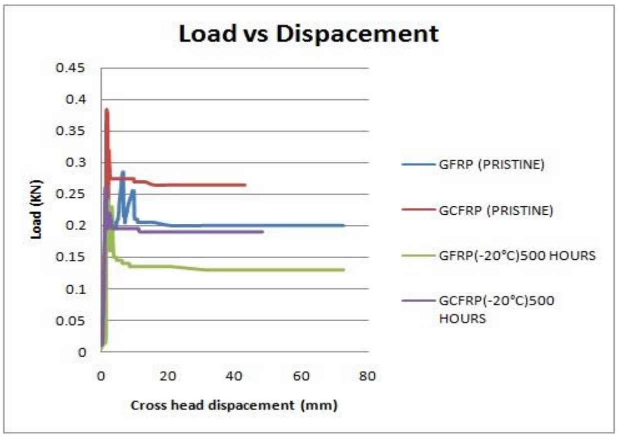


Fig 2d: Load v.s Displacement for glass-epoxy and glass-carbon hybrid composites at -20°C

The thermally exposed specimens of interlaminar shear strength have interpreted by Delamination Resistance (R-Curve). The R-curve drawn between G_I vs delamination length, inference of this curve the fracture toughness of the material at various conditions can be studied. The energy release rate (G_I) for pristine and various thermally aged specimens were calculated by the above formula and results were drawn in the following figures.

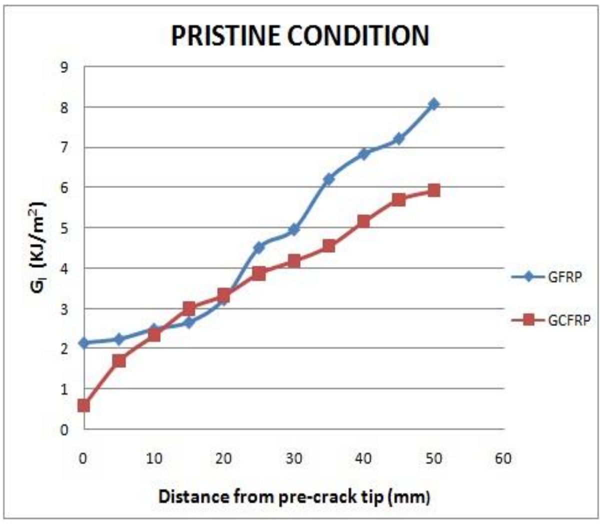


Fig 3: Energy release rate for both glass-epoxy and glass-carbon hybrid composites at pristine condition.

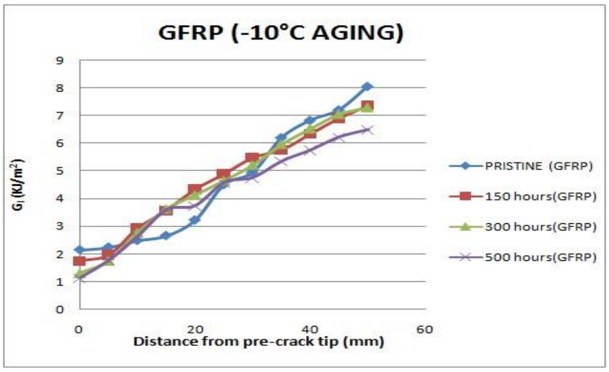


Fig 4: comparison of glass-epoxy composites at -10°C for various aging periods.

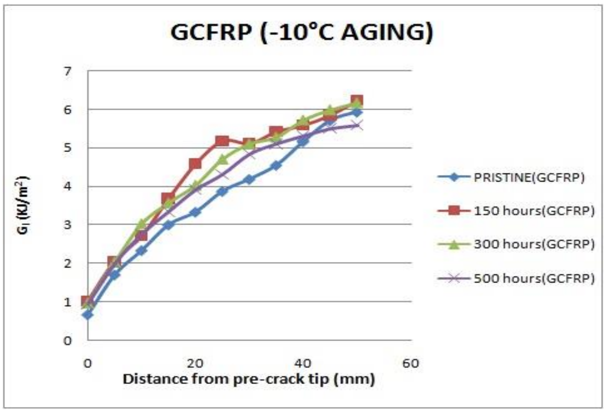


Fig 5: comparison of glass-carbon hybrid composites at -10°C for various aging periods.

From the R-curve, for both glass-epoxy and glass-carbon hybrid composites the energy release rate for aged specimen is found to be 5%-15% lesser than that of un-aged specimens.

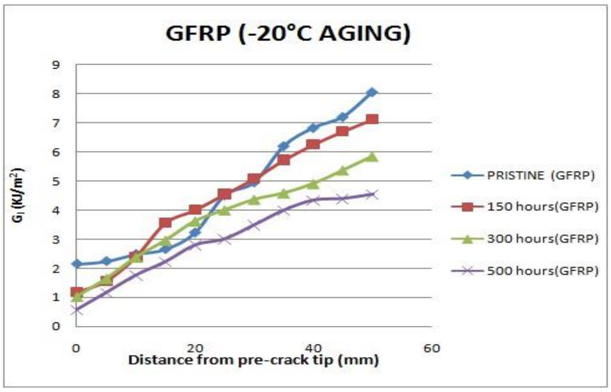


Fig 6: comparison of glass-epoxy composites at -20°C for various aging periods.

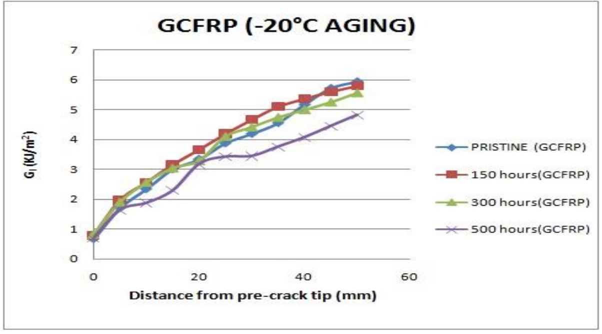


Fig 7: comparison of glass-carbon hybrid composites at -20°C for aging periods.

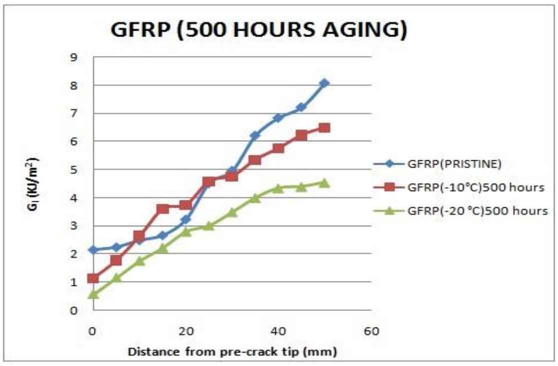


Fig 8: 500hours of aging of glass-epoxy composites with three different temperatures.

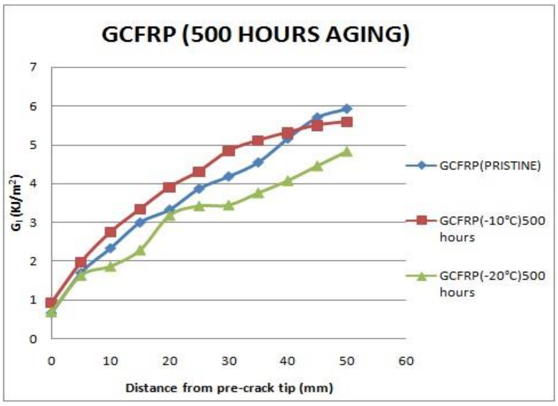


Fig 9: 500hours of aging of glass-carbon hybrid composites with three different temperatures.

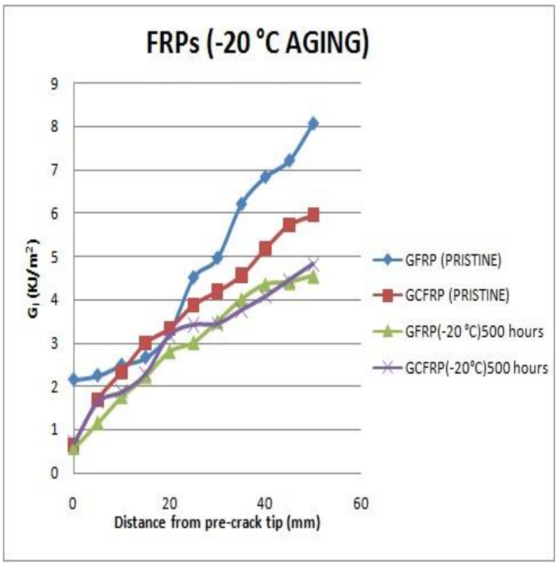


Fig 10: comparison of glass-epoxy composites and glass-carbon hybrid composites at pristine and 500 hours of aging.

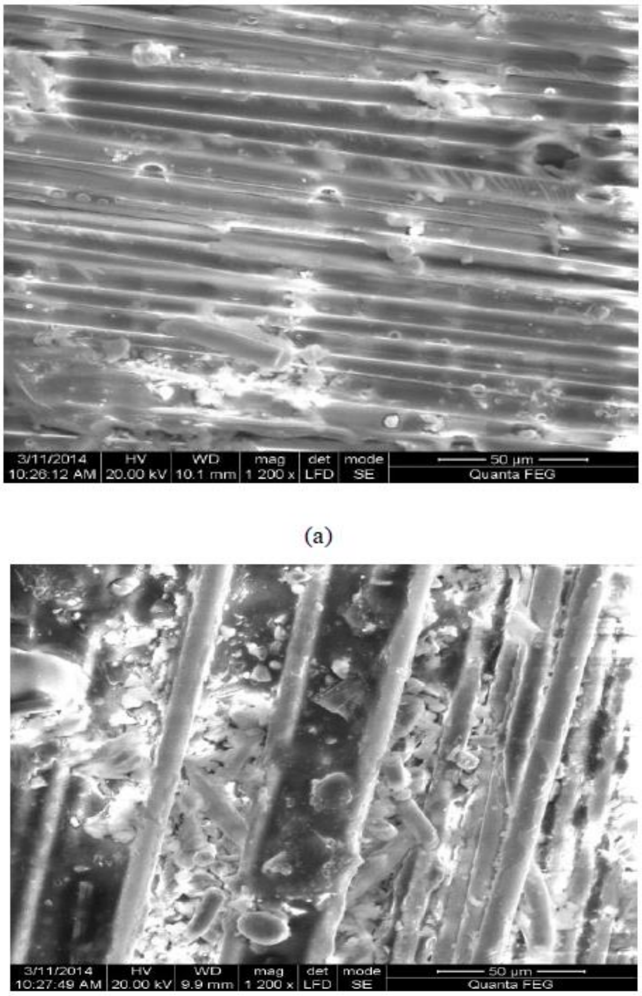
Compared in -10℃ and -20℃ ageing, the more changes were observed in -20℃ ageing condition owing to the increase in the brittle nature of the composite material as the temperature falls. Hence composite materials at -20℃ become more brittle than that of -10℃ aging; however a slight change of 3%-8% in the energy release rate of -10℃ aged specimens to that of un-aged specimen have been observed. The load absorbed by the specimen's decreases as the ageing period increases.

The energy release rate is dependent upon the ageing conditions, ageing period and also the material interfacial strength. Inference of the R-curve the DCB test was carried out for the two different types of materials and into study their nature at -20°C can be some common specified thermal ageing condition.

On comparing, delamination of glass-epoxy composite and glass-carbon hybrid composite the energy release rate is slightly more in glass-epoxy composite than in glass-carbon hybrid composite, because the percentage of elongation is significantly more in glass-epoxy composites than in of glass-carbon hybrid composite. The total cross-head displacement of the tested samples of glass-epoxy composite varies from 64mm-73mm but for glass-carbon hybrid composite the value varies from 42mm-48mm.Hence the energy release rate is more in glass-epoxy composite than that of glass-carbon hybrid composite.

A. SEM Analysis

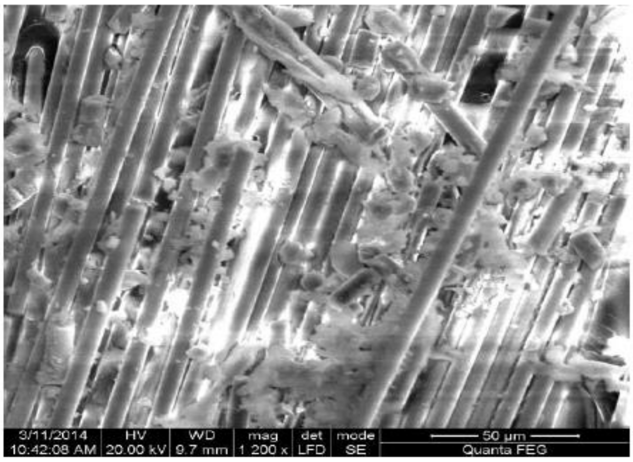
In Figs.12&13, SEM photographs were presented to compare the occurrence of fibre shrinkage, fiber breakage and microcracks between unaged and 500 hrs aged specimens. The material which exposed to low temperature with prolong endure tends to change the microstructure due to formation of fiber shrinkage, fiber breakage and spontaneously microcracks takes lead to loss of fracture toughness, GIc as shown in fig.10. Formation of microcracks in the 500 hrs aged specimen due to property mismatch between the fibres and matrix during the extended cold Temperature exposure can be seen in fig.13&14. From the Fig. 13 (a) & (b), the interlaminar failure revealed that the misalignment of glass/epoxy composites are more compared to that of glass-carbon composites. In summary, the low temperature exposed specimens were easily delaminating with rapid crack propagation due to the extensive microcrack and interfacial bonding failure between the adjacent fibers. The rate of crack propagation increases frequently decreases the integrity of the structure which is extrapolated by fig.14.



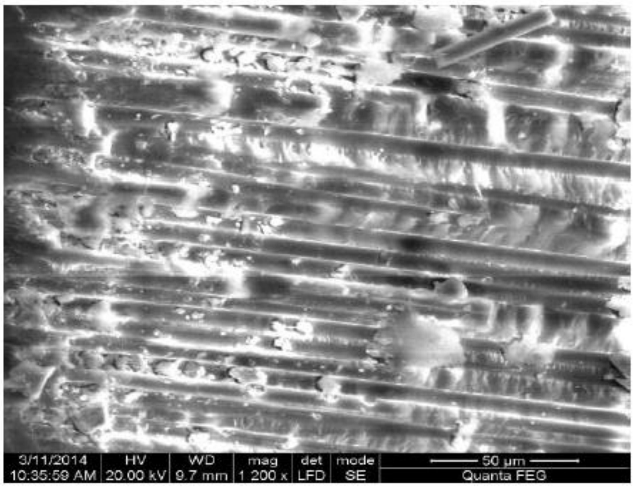
(a)

(b)

Fig.12 SEM fracture surface image of Glass/epoxy and Glass-Carbon Hybrid of pristine condition (Room Temperature)



(a)



(b)

Fig.13 SEM fracture surface image of (a) Glass-epoxy and (b) Glass-Carbon Hybrid of 500 hrs aged (-20°C) specimens

IV. CONCLUSION

Uni-directional glass-epoxy and carbon-epoxy composites were subjected to thermal aging with various intervals and temperature range and then tested on mode-I interlaminar fracture test to determine the energy release rate. Effect of temperature and aging period on fracture toughness was evaluated. The following conclusions from these experimental may be obtained:

1. The crack growth behaviour of aged and unaged DCB specimens at low temperature consisted of slowly subcritical growth and relatively fast crack propagation. Owing to the visco-elastic and visco-plastic behaviour of matrix, the material showed the non-linear load- displacement response with respect to temperature. As the temperature decreases interfacial behaviour of the composite materials increases irrespective of the material.

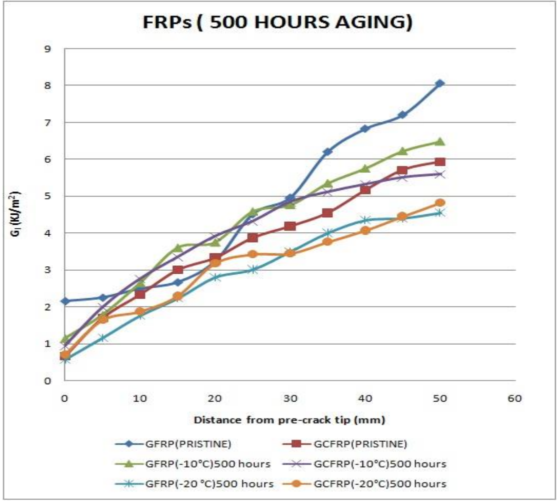


Fig 14: Comparison of FRPs composites pristine to that of 500 hours of aging at -10°C and -20°C

2. The energy release rate for un-aged glass epoxy is slightly higher than that of glass-carbon material owing to the material elongation property. The crack propagation of aged specimens was accelerated due to catastrophic state changes.
3. The energy release rate of glass-epoxy aged specimens decreases to 10%-15% to that of pristine specimens of same material but for glass-carbon hybrid specimens the decrease in percentage of 5%-10%.
4. Hence from final DCB test carried out after 500 hours of ageing at -20°C, the decreases in energy release rate for glass epoxy-composites are more compared to that of glass-carbon composites.
5. Microscopic analyses of thermally aged specimen were studied by SEM image and the corresponding failure mechanisms also have been studied.

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