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The Influence of Moisture and Pressure on the Mechanical Properties of a Glass-Epoxy Matrix Composite and a Graphite-Epoxy Matrix Composite

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U. S. Department of Commerce
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Substantial reductions in the yield stress and ultimate strength were observed in the wet condition for the glass-epoxy samples at both pressures, while the strength of the graphite-epoxy composite was found to be insensitive to the water exposure. The wet strength of the glass-epoxy composite was found to be independent (CONTINUED)

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Abstract

The influence of exposure to water at ambient pressure and at elevated pressure was evaluated on the mechanical properties of a glass fiber-epoxy matrix composite and a graphite fiber-epoxy matrix composite. The mechanical properties of three different fiber orientations for each material were measured in the dry condition, after exposure to water at ambient pressure and after exposure to water at 5.9 MPa. In order to determine if the observed degradation was permanent, the mechanical properties were also measured after the absorbed water was removed. During exposure, the rate and extent of water absorption and desorption was evaluated by measuring the weight change at periodic intervals.

Substantial reductions in the yield stress and ultimate strength were observed in the wet condition for the glass-epoxy samples at both pressures, while the strength of the graphite-epoxy composite was found to be insensitive to the water exposure. The wet strength of the glass-epoxy composite was found to be independent of water pressure during absorption and upon desorption, complete recovery of the dry strength was demonstrated. Evidence of compression-induced failure was observed for the graphite-epoxy composite in the wet condition.

Key Terms: composite, environmental degradation, mechanical properties, pressure, water, immersion, glass, graphite, epoxy

Introduction

Polymer matrix composites (PMC's) are being utilized for increasingly more demanding applications because of their capability to resist aggressive environments and some of the applications currently under consideration involve exposure to combinations of water and extreme pressure (e.g. deep water submersibles). While the question of how these materials perform under extreme pressure conditions has been the subject of research, many uncertainties remain as to what effects absorbed water may have on the mechanical properties of a PMC and whether or not these effects are aggravated by pressure.[1]

Absorbed water generally has a plasticizing effect on polymeric resins which may be the cause of significant reductions in their strength and it has been postulated that water present in the matrix phase is responsible for a similar reduction in the mechanical strength of some PMC's.[1-5] This reduction in strength has been attributed to a combination of several effects specific to the components of the composite— some of which are reversible and others irreversible. Effects such as a decrease in the glass transition temperature of the resin, and increases in internal stresses resulting from swelling of the matrix, are examples of physical changes that are generally reversible on removal of the absorbed water.[3] However, in some PMC systems, these physical changes induce irreversible, mechanical damage such as blistering. Other forms of irreversible damage result from chemical changes such as hydrolysis of the atomic bonds or the products of degradation reactions between the absorbed water and the components of the composite.[1-3]

The exact nature of the influence of absorbed water on the mechanical performance of a PMC is not entirely understood, but in general, the observed effects are centered on a reduction in the strength of the bond between the fiber and the matrix.[6,7,2] The total strength of a composite is obtained from a combination of the three primary constituent phases: the matrix, the reinforcement and the reinforcement-matrix interface.[7] Since the modulus of the reinforcing fibers is substantially greater than that of the matrix, the fibers are the principal load-bearing elements in the system. The primary role of the interface region in a composite system is to transfer stress from the matrix to the reinforcement.[2,7] It is, therefore, essential for the resin to adhere to the reinforcing elements since the ultimate strength of the composite is directly dependent on the efficiency of the stress transfer.[2] The plasticizing nature of absorbed water is believed to affect the interfacial bond strength by causing a reduction in the matrix stiffness which then lowers the resistance to the shear stresses produced during stress transfer at the fiber matrix interface.[7,2] This reduction in the ability to resist shear stress may be compounded if the reinforcing fibers undergo a degradation reaction with the absorbed water. This then results in a reduction in the effective cross sections of the fibers which in turn diminishes their capacity to support load.[2]

Water absorption in PMC systems has been shown to occur by two basic processes: diffusion through the resin phase, and transport through defects such as cracks and holes. However, it is also believed that the interface between the fiber and the matrix plays an important role in the absorption process because of capillary action in the region.[2,3,5] Research has shown that at room temperature, saturation of a PMC is reached at least one order of magnitude more rapidly than saturation of the polymer resin alone[2,3] and that diffusion is not directly effected by changes in pressure.[3,4,8] It has also been observed that the rate of water transport into the composite varies significantly with fiber orientation such that transport in the direction along the fiber axis can be at least five times greater than the transport in the perpendicular direction.[5] This is believed to be of great importance–particularly in composite systems where the fibers do not absorb water.[9,5] Therefore, the primary mechanism of water absorption for a PMC is now generally believed to be a combination of permeation through the cracks and holes at the surface and capillary action in the region of the fiber/matrix interface, not bulk diffusion through the matrix[1] and it has been demonstrated that the absorption characteristics for any composite system are directly affected by the void and the resin contents. Therefore, the sensitivity to water in most composite systems can be substantially controlled with a low the void content.[2,10]

The results of an experiment in 1989 suggested that the exposure of a PMC to water under conditions of high pressure could increase the rate of water transport into the voids, thereby leading to a significant acceleration in the overall water uptake of the composite.[11] Although the bulk of the existing literature shows that water absorption in PMC systems is essentially insensitive to hydrostatic pressure, the results of this experiment indicated that an exposure to natural seawater at a pressure equivalent to a 2000 foot submersion (5.9 MPa) resulted in a significant increase in the water absorbed as compared to a similar exposure at atmospheric pressure.[11] These results also showed a greater reduction in the mechanical properties generated by the increased moisture content, with no significant difference found in the diffusion coefficient at the two pressures. Based on the assumption that vapor pressure is relatively unaffected by pressure over the range examined, it was concluded that the observed increase in the water absorption must have been due to an increase in the number of residence sites which developed as a result of damage induced during exposure to the high pressure. Since no evidence of blistering was found, it was also concluded that increased osmotic pressure and blister growth could not be the cause of this pressure effect and that "mechanical damage to preexisting voids and defects in the composite" must be responsible for the increased water uptake and strength decrease at the higher pressure.[11] Since this hypothesized degradation mechanism only requires hydrostatic pressure and voids in the PMC, then it should not be limited to the PMC system investigated. That is, if this degradation mechanism is indeed operable, then other PMC systems should exhibit similar degradations on exposure to similar conditions and since the observed degradation is hypothesized to be the result of mechanical damage, it should not be reversible upon removal of the absorbed water.

To test the hypothesis that exposure of a PMC to water under high hydrostatic pressure results in an increase in the degradation of the mechanical properties by this mechanism, a series of experiments was designed to examine the sensitivity of mechanical properties to absorbed water and hydrostatic pressure. These experiments were also designed to determine whether the effect (if any) is reversible upon complete removal of the absorbed water. The two PMC systems chosen for this evaluation, a glass fiber reinforced-epoxy (GFRP) and a graphite fiber reinforced-epoxy (CFRP), have similar matrix phases but different reinforcements and they are representative of the PMC systems presently under consideration for many marine applications. Since distilled water has been shown to be more aggressive to these PMC systems than salt water, distilled water was used for these exposures instead of sea water or salt water.[9,12,13]

Experimental

The experiments were performed in two stages. The material selected for the first study was a commercially produced, epoxy matrix composite reinforced with woven E-glass (borosilicate) fibers (G-10*). The nominal composition and physical properties for a typical borosilicate glass fiber reinforced-epoxy matrix composite are given in Table 1. The mechanical properties and the water absorption characteristics of this material have been well characterized (ASTM D-709). Samples were cut from a sheet with a thickness of 2.4 mm (3/32 inches) in accordance with ASTM Standard D-790. The orientations, designated as 0°, 90° and 45°, are with respect to the warp or primary fiber direction of the cloth (the secondary fiber direction, the woof, is perpendicular to the warp). To ensure a fully dry initial condition, all samples were stored in a desiccator at ambient temperature and pressure for a period of six months prior to testing. Baseline characterization of the properties of the G-10 was done by analyzing a portion of the dried samples in four-point bend mode on a screw-driven tensile machine under ambient laboratory conditions. Samples were then immersed in double-distilled water at room temperature either at ambient pressure or under a pressure of 5.9 MPa. The samples were removed periodically during exposure, lightly dried to remove excess surface moisture, and weighed on an analytical balance. After an exposure period of approximately 70 days, half of the samples were removed and tested in four point bend while the other half were again placed in a desiccator to remove the absorbed water. The weight of the samples was also measured periodically during the desorption process. The mechanical properties were evaluated after 200 days (approximately 90% removal of the absorbed water) and after a period of one year (complete desorption). The fracture surfaces generated during mechanical testing were then sputter coated with gold for examination in a scanning electron microscope (SEM).

The material selected for the second study was a woven graphite fiber-epoxy matrix composite, also commercially available. The exact composition and properties for each component are shown in Table 2. The format for the analysis of the graphite-epoxy material, which is still in progress, is essentially the same as that for the glass-epoxy, except for longer immersion times due to the differences in diffusivity.

Results and Discussion

The data presented in Tables 3 and 4 are the results of the mechanical testing on the glass-epoxy and the graphite-epoxy materials, respectively. The values in each table correspond to a mean value and the standard deviation for three individual experiments, except for those values denoted with an asterisk (*) which represent singular data points.

As expected, the absorbed water in the glass composite produced a reduction in the mechanical properties in all three fiber orientations tested. These effects are clearly demonstrated in the yield stress data (determined by the 0.2% offset

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*Westinghouse Electric Corporation, Hampton, SC method described in ASTM Standard D-709). Initially, the values of the yield stress for the G-10 in the 0° and 90° orientations were 296 MPa and 321 MPa respectively, but after a water weight gain of approximately 0.5%, the yield stress for the 0° orientation was reduced by approximately 25% (227 MPa) and by approximately 20% for the 90° orientation (269 MPa). The fact that the reduction observed in yield strength for the samples exposed at ambient pressure was essentially the same as the reduction observed in the samples exposed at the elevated pressure (15%) indicates that either the increased pressure had no significant influence on the mechanical properties or the influence was masked by the more dominant effects of the absorbed water.

If the influence of the absorbed water on the mechanical properties is assumed to be solely caused by the plasticizing effects of the water on the polymer resin, then all of the initial properties should be restored upon complete desorption of the water, since this is a completely reversible process.[2] As shown in Table 3, approximately 96% and 100% (for the 0 and 90° orientations respectively) of the original magnitudes of the yield stress for the samples tested at ambient pressure was recovered after a 200 day desorption period while the samples tested at 5.9 MPa demonstrated a 95% recovery (for both 0 and 90° orientations). Unlike the yield strength, the ultimate strength was not recovered after the same desorption period. However, after removal of the remaining absorbed water, the ultimate strength did regain the initial values. This demonstrated that the original strength of this composite could be restored with sufficient drying time.

The area under the force-displacement curve was measured in order to give an indication of the energy required to induce failure as a function of water content— these values are also given in Table 3. In general, the fracture energy did not demonstrate large changes in magnitude, but, a minor decrease from the initial value was observed after a 90% desorption. The magnitude of the energy then surpassed the initial value upon the completion of the desorption process, which could possibly reflect a change in the behavior of the composite. Additional analysis is required to determine the exact nature of the cause of this change in energy.

The strength of the graphite-epoxy composite was found to be less sensitive to absorbed water than the glass-epoxy composite. Only the ultimate strength and energy values are presented in Table 4 because the high stiffness of the graphite fibers (240 GPa) produced near linear, brittle behavior for the entire mechanical test. Error values in the mechanical data for these materials ranging from 20 to 60% are commonly reported in the literature, but, the average standard deviation value for this graphite-epoxy composite (for the 0° and 90° fiber orientations) was 130 MPa which indicates reasonable reproducibility.[6]

The samples were tested after an approximate water weight gain of 1% and no significant change in the magnitude of the ultimate strength from the dry condition was observed. This supports observations by Shen and Springer that since the graphite fibers generally do not absorb water, absorptions below a threshold value determined by the fiber and void contents (approximately 1.2%) have no significant influence on the mechanical properties in a graphite composite system (the solubility limit of the matrix is believed to be about 1.5%).[6] As in the case of the G-10, no significant effect of pressure was observed on the strength. This again indicates that compared to the results at ambient pressure, increased pressure did not enhance the degradation of the mechanical properties for the graphite composite.

No significant change was exhibited in the energy values for this material from the dry to the wet conditions. This indicates that for small water contents, the high stiffness of the graphite fibers results in a threshold energy value which must be overcome prior to the occurrence of fracture regardless of the presence of water in the matrix.

Figures 1 through 4 are optical micrographs showing the general fracture behavior of the two composite materials in the fully dry and wet conditions. These figures are representative failures which were mounted in cross section so that the 90° fibers are in plane with the page, the 0° fibers are perpendicular to the page plane and the darker areas are matrix material. The polished surfaces revealed the delamination effects which occurred during the four point bend tests. There was no real difference in the general fracture characteristics between the ambient soaked and the pressure soaked conditions for either material, therefore, samples exposed at ambient pressure were used to represent the wet condition for both materials.

Figure 1 shows the brittle-like behavior of the matrix observed in the G-10 in the fully dry condition. In this figure, several large secondary cracks perpendicular to the fracture surface are shown in the following locations: along the interface between the 0° fiber bundles and the matrix, along the interface between the 90° fiber bundles and the interface, through the 0° fiber bundles, and through the matrix rich regions. It is important to note that there appears to be no tendency for the crack to propagate in any particular region. This indicates good stress transfer from the bulk to the reinforcement until sample failure—a result of strong fiber/matrix bonding. Cracks can be seen in the matrix-rich regions, possibly reflecting a more brittle behavior in the matrix, but, the majority of the cracks away from the fracture surface observed in this condition appear to be located in the regions of a fiber bundle/matrix interface. This tends to support the hypothesis of an inherent weakness in the interfacial region as compared to either the fibers or the pure matrix.[7]

The features in the wet condition, shown in Figure 2, suggest a change from the fracture behavior observed in the dry condition. The secondary cracks present in the micrograph are located primarily along the interface regions between the 0° fiber tows and the matrix, but unlike the dry condition, the fracture surface of the wet condition does not show cracks running either along the 90° fiber bundle/matrix interface or through the 0° fiber bundles. Some cracks can be seen running through the matrix-rich regions for a short distance, however, they either arrest in the matrix or at a fiber bundle/matrix interface. The observed differences in crack location are believed to be the result of one or more of three possibilities: plasiticizing of the matrix by the absorbed water made crack propagation through the matrix region more difficult, swelling of the matrix as a result of the absorbed water increased the stress at the matrix/ fiber interface which in turn made crack propagation easier in that region, and lastly, the absorbed water was responsible for a degradation in the interfacial strength.

Micrograph 3 shows the fracture behavior of the graphite-epoxy material in the dry condition. Secondary cracks can be seen running along the fiber/matrix interface regions, perpendicular to the fracture surface. But, more noticeable in this figure, is a series of cracks located on the tension side of the sample running parallel to the fracture surface. Note that in this material, the transition from tension to compression loading can be more easily distinguished which allows for easier interpretation of the overall failure. These cracks appear to have separated the 0° fibers within a single tow and although it is obvious that the lay-up of the graphite-epoxy is very different from that of the G-10, it is uncertain as to how this difference in the lay-up influences the fracture process. It does, however, appear that the 0° fiber/fiber interface region is weaker than the remainder of the composite. It is important to note that in this material, the majority of the secondary cracking appears to be situated at the 0° fiber/fiber interface region which may indicate that initially, the preferred mode of failure in this material is separation of the individual graphite fibers within a tow rather than delamination. This would then imply a very good fiber-matrix interlaminate bond in the dry condition.

The behavior of the graphite composite in the wet condition is shown in Figure 4. In general, there is little or no secondary cracking on the tension side of the sample and the principal type of cracking shown on the fracture surface of this sample is of the 0° fiber/fiber interfacial type, similar to that demonstrated in the dry condition. This supports the assumption that the interface weakness seems to be further enhanced by the absorbed water. While there is a small amount of secondary cracking and delamination near the neutral axis region, the major difference between the two conditions lies on the compression side. It can be assumed that if sufficient bonding exists between a fiber and the matrix, a compression type failure, e.g. buckling, would not be expected to occur because of the restraining effects imposed on the fibers by the stiffness of the matrix, but, if that stiffness was degraded by the plasticizing effects of absorbed water, then the resulting decline in the restraint could permit the occurrence of a buckling type failure. An example of this type of failure can be seen on the wet graphite sample (inset, Figure 4). While no significant change in the mechanical strength was observed in the wet condition, the presence of fiber buckling seems to indicate a slight shift in the behavior of the matrix as a result of the water present. This type of failure was not observed in any of the wet G-10 samples probably because of the great difference in stiffnesses between the graphite and the glass fibers.

Figures 5 and 6 are scanning electron micrographs showing the general fracture behavior of the G-10 in the fully dry condition. The principal features of the fracture surface represented in Figure 5, a low magnification overview, are exposed fiber bundles surrounded by large regions of fractured matrix. Overall, the matrix appears to reflect a brittle texture with many regions showing a river pattern. These regions are more clearly depicted in Figure 6, a close-up of a typical resin-rich region near the tensile surface. Like the optical micrographs, Figures 5 and 6 also reflect the characteristics expected of good fiber matrix bonding in the dry condition, but, a preference for matrix cracking does appear to be present in this view of the surface.

The general fracture characteristics of the G-10 in the wet condition, shown in Figure 7, are clearly not the same as seen in Figure 6. The primary features observed in this condition are inter-fiber debonding and fiber pullout, not the pure matrix zone cracking as observed in the dry condition, indicating a change in the fracture behavior in the composite. The plasticizing effects of absorbed water can be better observed in Figure 8, a close-up of a wet matrix-rich region. In this figure, the matrix shows signs of flow lines and fiber debonding, not brittle cracking as was observed in dry condition. This appears to correlate with the observed change in the strength of the composite.

Figures 9, and 10 are scanning electron micrographs of the graphite composite in the fully dry condition. The predominate features, shown in the low magnification view of Figure 9, are mostly 0° inter-fiber cracks (similar to those observed in the cross section views) and fiber pullout resulting from the tensile forces, and effects such as delamination produced by the compression loading. In general, a brittle-like texture in the matrix-rich regions and good fiber/matrix bonding were observed throughout the entire surface of the sample. An example of the fiber/matrix bonding observed in the dry condition is shown in Figure 10 where two fibers exposed during fracture can be seen with a large quantity of clinging matrix.

The low magnification overview in Micrograph 11 displays the dramatic change in the fracture surface morphology of the wet graphite sample as compared the dry condition. In general, an increase in the amount of fiber pullout can be seen in the tension areas along with some of the characteristic 0° fiber/fiber cracking, but again, the major difference in the wet condition lies in the compression region. In this region, several fractured fiber tows can be seen lying in the same plane. This type of morphology, sometimes referred to as "fiber chopping",[14] appears to correspond to the buckling failures observed in the cross section views. A higher magnification view, as shown in Micrograph 12, reveals a mass of fibers within a single tow and a substantial amount of in-plane cracking in the surrounding matrix. Also noticeable in this fractograph are remanents of shattered graphite fibers scattered over the surface, a result of the buckling failures, which reflect the high amount of energy required to induce a compression failure in this material.

Based on these results, it can be said that the presence of absorbed water in the glass-epoxy composite resulted in a reduction in the mechanical properties, but this reduction was shown to be completely reversible given sufficient drying time. The effect of the absorbed water was also shown to be independent of pressure since no significant difference in the behavior was observed between the two pressures. It can also be said that the influence of absorbed water on the mechanical properties for the graphite-epoxy composite was negligible, but, the absorbed water did appear to decrease the stiffness of the matrix. This effect was shown by the presence of compression related failures in the wet condition. Like the G-10, no differences were observed in mechanical behavior between the two pressures. Therefore, compared to the results at ambient pressure, it was determined that pressure did not enhance the degradation of either material.

The results of this evaluation clearly demonstrate that the degradation mechanism hypothesized in the 1989 experiments is not operable in either of the PMC systems tested. All of the observed effects which resulted from exposure to water were shown to be completely reversible given sufficient drying time. It was also clearly demonstrated that the observed effects were not enhanced by an increase in hydrostatic pressure. Therefore, the hypothesized damage mechanism, believed to induce permanent mechanical damage by affecting preexisting voids in the composite, cannot be generic to all PMC systems. It should be noted, however, that the composite material tested in the 1989 experiments could have had a significantly higher void content than the materials used in this evaluation, the fibers may have had different surface treatments, and that natural seawater was also used during the exposures. The biologicals contained in the natural seawater may indeed be responsible for the difference in results since they may exert a different influence on the behavior of the composite which could then have been exaggerated by the increased pressure.

Conclusions

The effects of absorbed water and pressure were evaluated on the mechanical properties of two composite systems each having similar epoxy matrix materials, one reinforced with glass fibers and the other with graphite fibers. Both materials were exposed to water at ambient and elevated pressures and tested in four point bend.

On exposure to water, the glass reinforced composite demonstrated an average of 20% reductions in both the yield stress and ultimate strength with respect to the dry condition. Complete recovery was shown in the yield stress after a desorption period of 200 days, but, the ultimate strength required one year to produce a similar restoration thereby demonstrating the strong influence of absorbed water on the strength of the glass composite. The graphite composite showed no significant change in the mechanical properties with water absorption. In both materials, the effect of the pressure under which the composites were exposed to water was found to have no influence on the measured mechanical properties. Fractography revealed a change in the fracture behavior and a general increase in matrix plasticity for both materials as a result of the absorbed water.

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Table 1. Composition and Properties of a Glass-Epoxy Composite [15,16]

Borosilicate Glass Fibers	
Nominal Composition (wt %):	SiO_2 54%, CaO 17.5%, Al_2O_3 14% B_2O_3 10%, MgO 4.5%
Tensile Strength:	3.45 GPa (500 ksi)
Tensile Modulus:	72.4 GPa (10×10^6 psi)
Specific Gravity:	2.58 g/cc
Epoxy Resin (Typical)	
Tensile Strength:	90-110 MPa (13-16 ksi)
Tensile Modulus:	3.0-5.0 GPa (435-725 ksi)
Specific Gravity:	1.30 g/cc
Composite	
% Glass by Weight:	65-80%
% Epoxy by Weight:	20-35%
Specific Gravity: (rule of mixtures)	2.13-2.32 g/cc

Table 2. Composition and Properties of Graphite-Epoxy Composite[*]

Graphite Fabric	
Trade name:	Celion-BASF 630500 Carbon/Graphite 613
Tensile Strength:	3.79 GPa (550 ksi)
Tensile Modulus:	235 GPa (34 $\times 10^{6}$ psi)
Surface Treatment:	Sized with compatible epoxy resin
Epoxy Resin	
Trade Name:	Hexcel Epoxy F455
Tensile Strength:	80 MPa (11.6 ksi)
Tensile Modulus:	3.25 GPa (470 ksi)
Composite	
% Graphite by Weight:	63%
% Epoxy by Weight:	37%
Specific Gravity:	1.5 g/cc

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[*] Stevens Products, Inc., East Orange, NJ

Table 3 Mechanical Properties of Glass-Epoxy Composite

Testing Condition	Fiber Orientation	Ultimate Strength (MPa)	Yield Stress (MPa)	Energy (N•m)
Fully Dry	0°	353 ±13	296 ±10	2 ±0.1
	90°	406 ±1	321 ±5	3 ±0.1
	45°	276 ±10	164 ±6	3 ±0.1
Saturated at 0.1 MPa	0°	342 ±8	227 ±9	2 ±0.1
	90°	380 ±5	269 ±8	3 ±0.1
	45°	253 ±3	102 ±7	3 ±0.0
Saturated at 5.9 MPa	0°	344 ±5	252 ±9	2 ±0.2
	90°	386 ±2	270 ±6	3 ±0.1
	45°	256 ±4	107 ±9	3 ±0.0
Saturated at 0.1 MPa Desorbed 200 Days	0°	323* n/a	283* n/a	2* n/a
	90°	388* n/a	335* n/a	3* n/a
	45°	174* n/a	155* n/a	3* n/a
Saturated at 5.9 MPa Desorbed 200 Days	0°	333 ±8	291 ±14	2 ±0.2
	90°	381 ±1	334 ±6	3 ±0.2
	45°	182 ±1	160 ±8	3 ±0.1
Saturated at 0.1 MPa Desorbed 365 Days	0°	363* n/a	320* n/a	2* n/a
	90°	418* n/a	352* n/a	3* n/a
	45°	220* n/a	182* n/a	4* n/a
Saturated at 5.9 MPa Desorbed 365 Days	0°	368 ±8	314 ±12	2 ±0.1
	90°	422 ±6	359 ±9	4 ±0.6
	45°	221 ±0	190 ±3	4 ±0.1

Table 4. Mechanical Properties of Graphite-Epoxy Composite

Testing Condition	Fiber Orientation	Ultimate Strength (MPa)	Energy (N•m)
Fully Dry	0°	982 ±172	5 ±0.9
	90°	821 ±145	5 ±2.3
	45°	224 ±12	4 ±0.4
Saturated at 0.1 MPa	0°	1003 ±136	5 ±1.3
	90°	945 ±21	4 ±0.6
	45°	227 ±2	4 ±0.0
Saturated at 5.9 MPa	0°	878 ±70	5±0.2
	90°	939 ±210	4 ±1.0
	45°	222 ±14	4 ±0.2

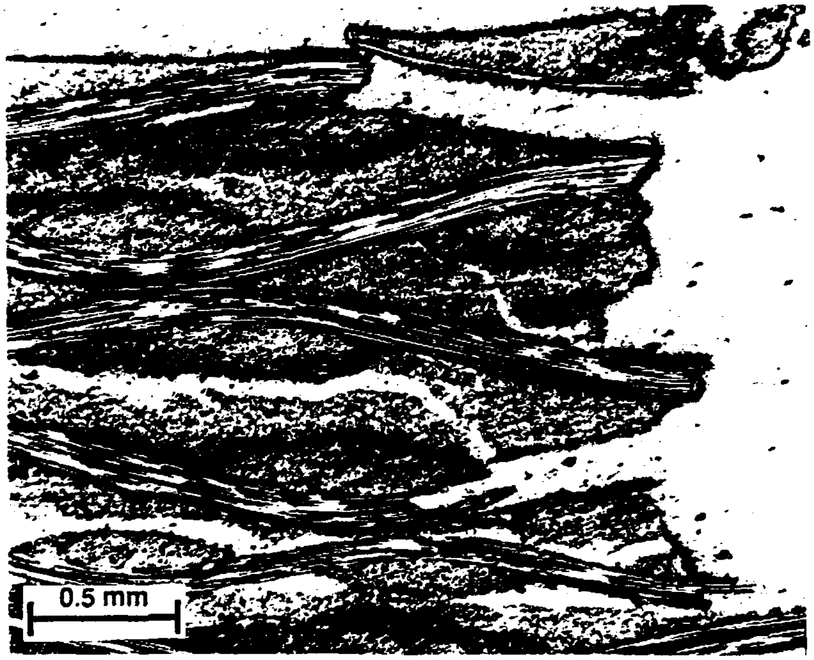

Figure 1 Optical micrograph of dry glass-epoxy composite fracture surface mounted in cross-section.

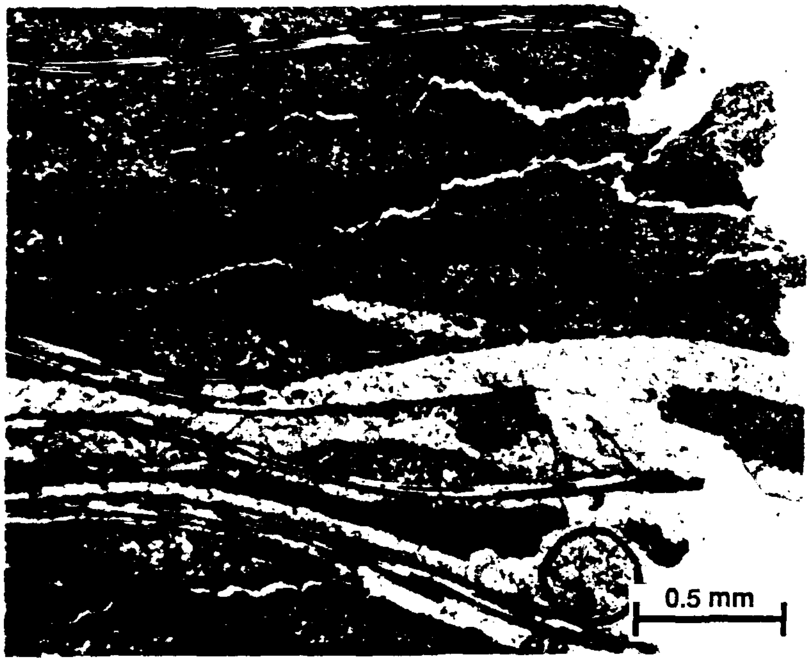

Figure 2 Optical micrograph of wet glass-epoxy composite fracture surface mounted in cross-section.

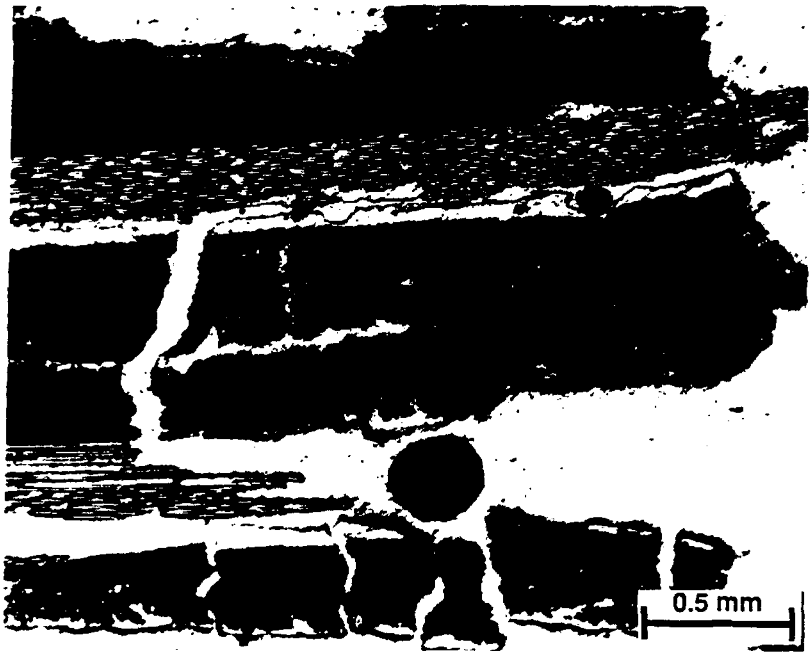

Figure 3 Optical micrograph of dry graphite-epoxy composite fracture surface mounted in cross-section.

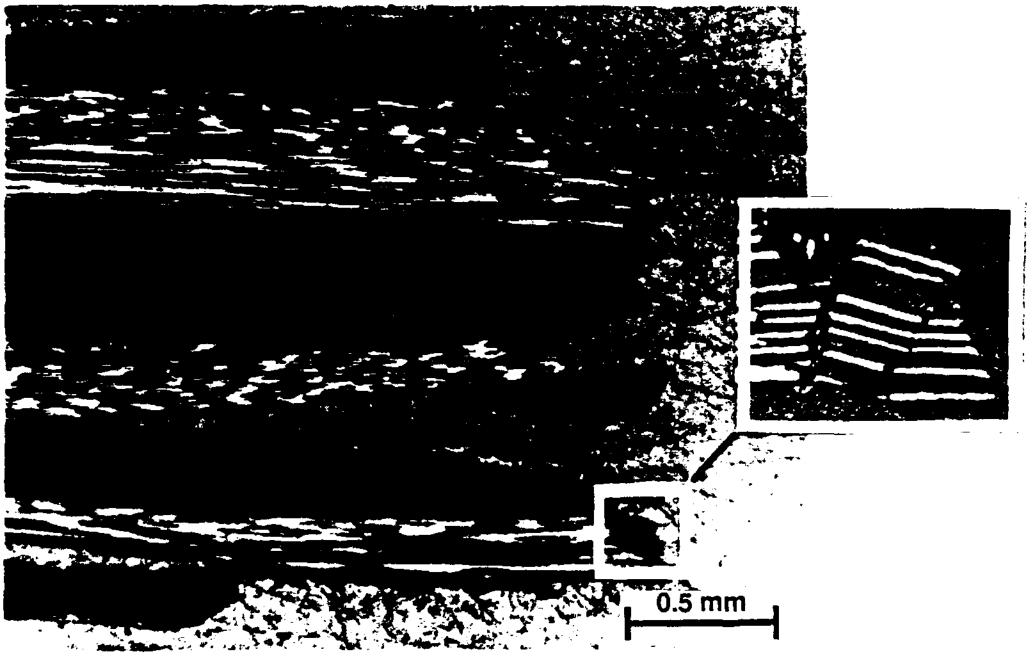

Figure 4 Optical micrograph of wet graphite-epoxy composite fracture surface mounted in cross-section.
Inset: Higher magnification of buckled fibers

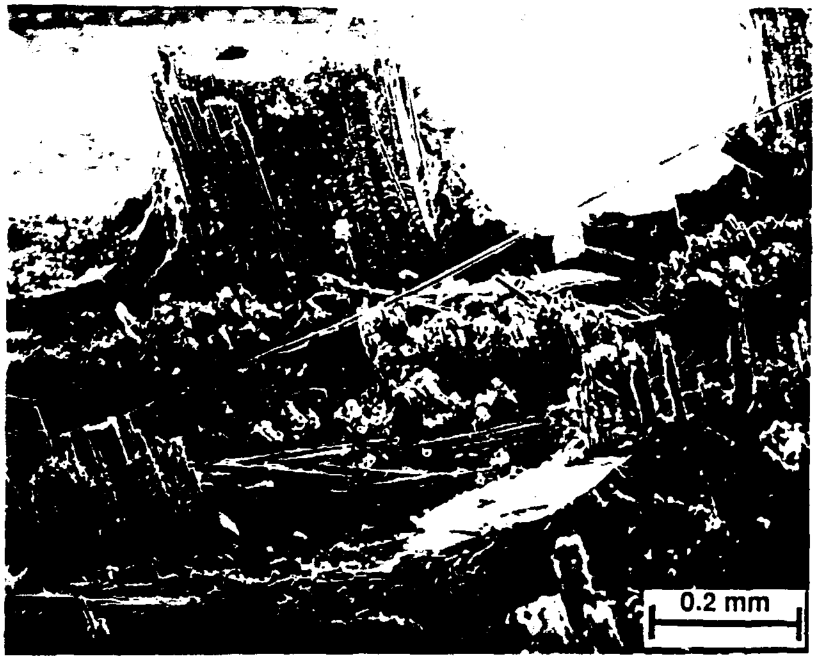

Figure 5 Low magnification scanning electron micrograph of glass-epoxy composite fracture surface in dry condition.

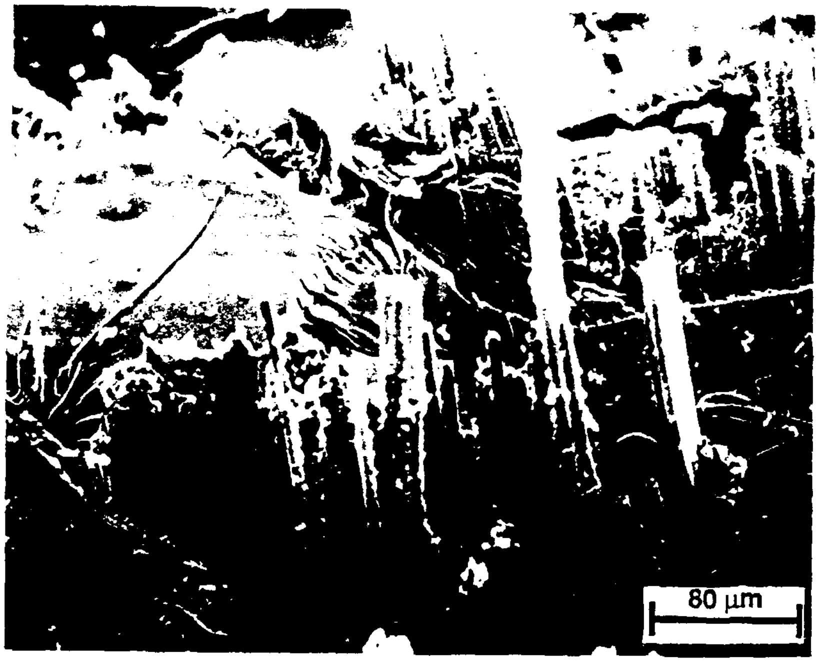

Figure 6 High magnification scanning electron micrograph of glass-epoxy composite fracture surface in dry condition.

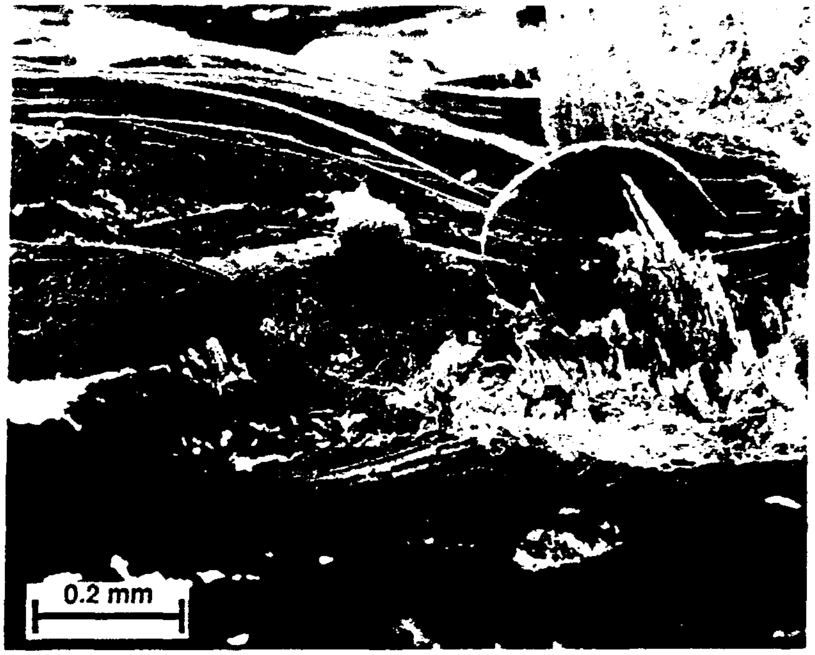

Figure 7 Low magnification scanning electron micrograph of glass-epoxy composite fracture surface in wet condition.

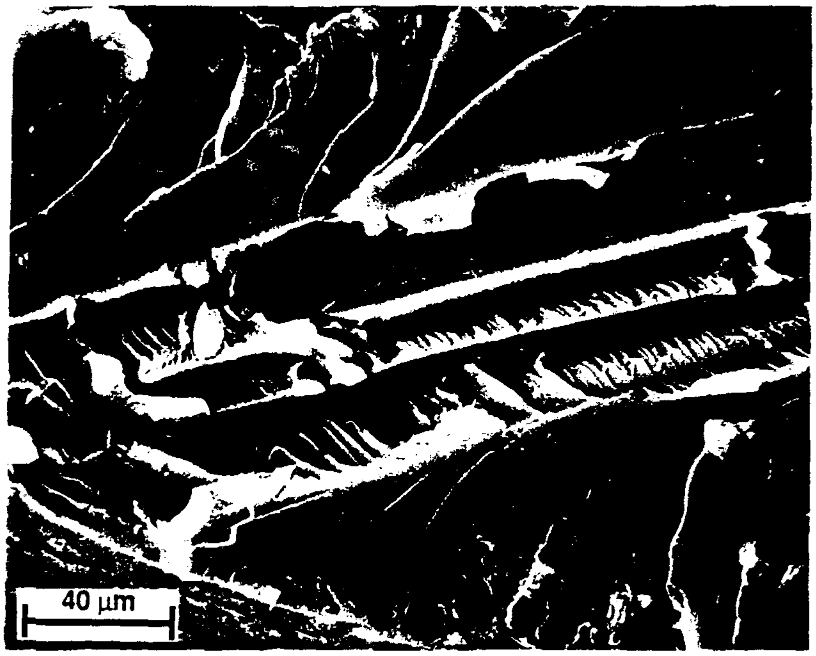

Figure 8 High magnification scanning electron micrograph of glass-epoxy composite fracture surface in wet condition.

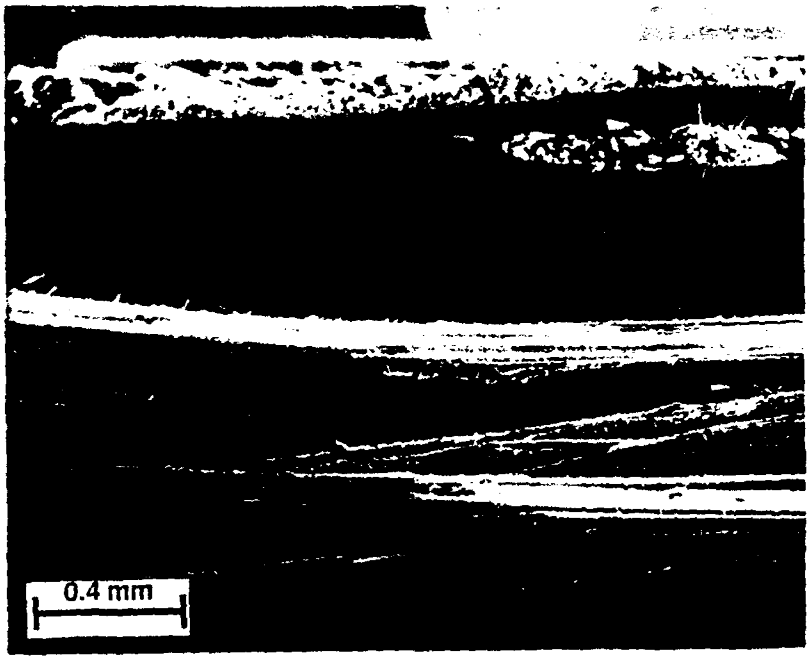

Figure 9 Low magnification scanning electron micrograph of graphite-epoxy composite fracture surface in dry condition. (tension side at top)

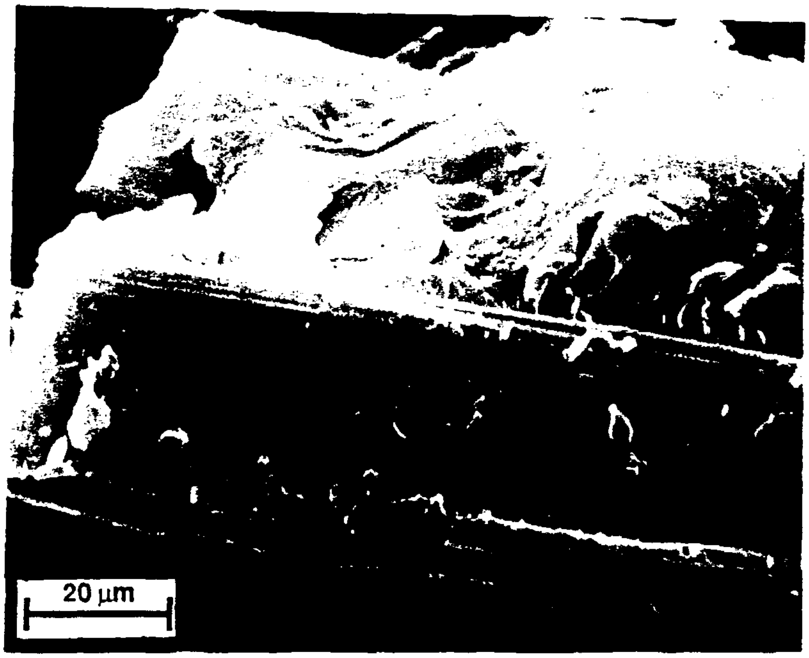

Figure 10 High magnification scanning electron micrograph of graphite-epoxy composite fracture surface in dry condition.

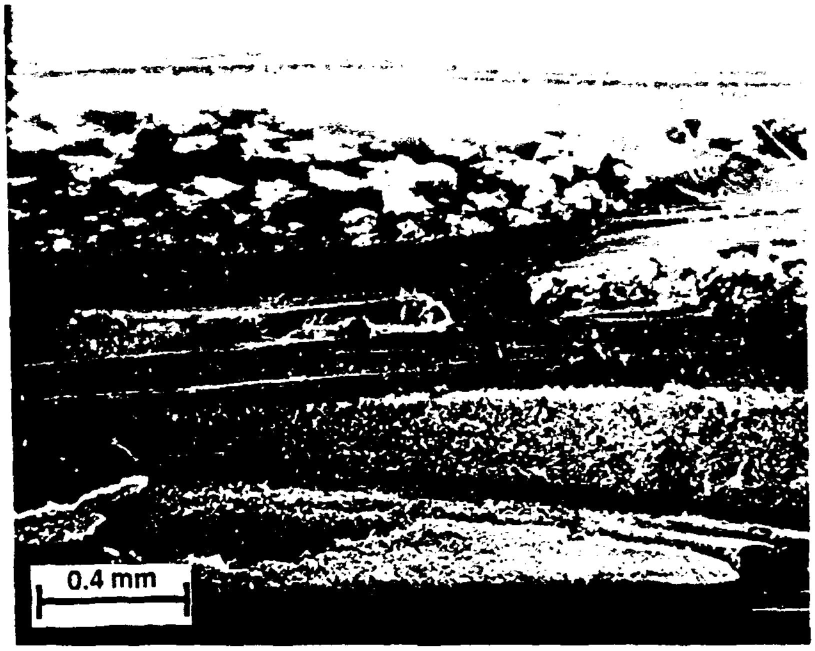

Figure 11 Low magnification scanning electron micrograph of graphite-epoxy composite fracture surface in wet condition. (tension side at top)

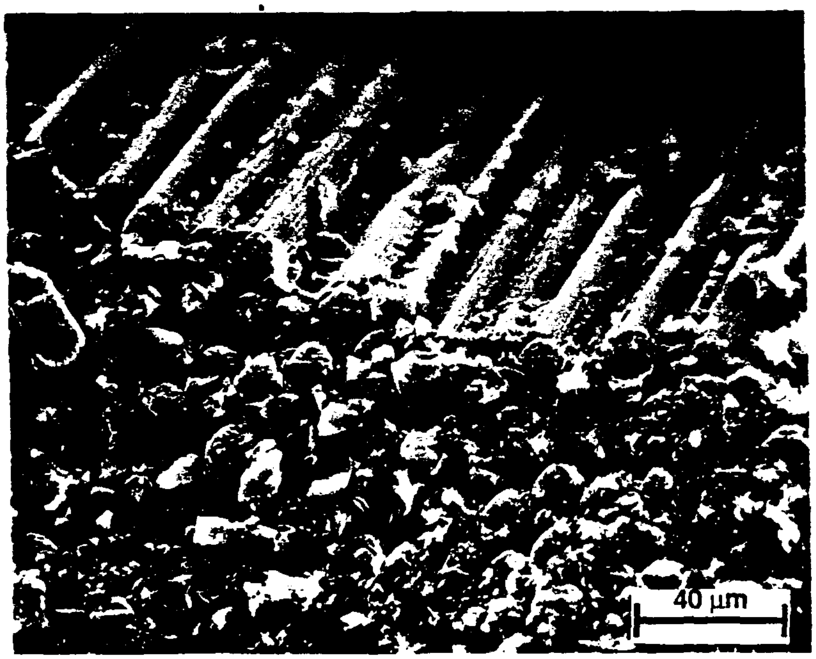

Figure 12 High magnification scanning electron micrograph of graphite-epoxy composite fracture surface in wet condition.