Hygrothermal Effects on Durability and Moisture Kinetics of Fiber-Reinforced Polymer Composites

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ABSTRACT

Various processes of degradation, both reversible and irreversible, are induced in composite materials on exposure to moisture. The durability characteristics of unidirectional E-glass-Vinylester composites under the influence of relative humidity and immersion in water at different temperatures are studied. The correlation between tensile and flexural strength data is investigated using statistical models. This research attempts to analyze the behavior of FRP composites exposed to the aforementioned environments and theoretically model their effects on the mechanical properties- Tensile strength, Tensile modulus, Flexural strength and Short beam shear strength- of the FRP composites, for purposes of long-term life prediction. This study attempts to develop an initial correlation between effects due to immersion in deionized water with those due to exposure to humidity in an attempt to further develop techniques for prediction of longer-term durability of these materials under field conditions.

INTRODUCTION

Recent years have witnessed a substantial increase in the use of Fiber-Reinforced Polymer (FRP) Composites in the form of reinforcing elements such as rebar, tendons and cables [1] as well as externally bonded reinforcement for strengthening and seismic retrofit [2]. However, the use of FRP to its fullest potential has been hampered by the fact that there is concern about their reliability and performance over long periods of time.

Exposure to humidity, water, alkalis, elevated temperatures and other harsh environments can induce physical and chemical changes in polymer composites. For example, on exposure to water or moisture, FRP composites have been reported to show reduction in strength [3,4], plasticization of the matrix [5,6,7] and also degradation of the fiber/matrix interface [8,9]. Environmental exposure can induce various chemical and physical processes of degradation in FRP composites. Therefore, a better understanding of the behavior of the FRP composites under these environments is absolutely essential to aid in the optimal design and the prediction of service-life of the structural components. Polymer composites are invariably exposed to moisture or humid air in their applications.

The primary objective of the research reported in this paper is to develop a fundamental understanding of the effects of hygrothermal exposure (related to both immersion and humidity based conditioning) on durability of E-glass/Vinylester composites. In addition to the goals of developing an understanding of moisture kinetics and deteriorative mechanisms, this study attempts to develop an initial correlation between effects due to immersion in deionized water with those due to exposure to humidity in an attempt to further develop techniques for prediction of longer-term durability of these materials under field conditions.

MATERIALS AND TEST METHODS

The composite system used in the study is a unidirectional E-glass/Vinylester composite with volume fraction 50-55 % manufactured by Resin Infusion Process with Dow Derakane 411-350 vinylester resin. The composites were subjected to 4 different sets of exposure environments, namely

1. Ambient conditions at 23 ^{o}C and 30 % Relative Humidity
2. Immersion in deionized water at 23 ^{o}C, 45 ^{o}C, 60 ^{o}C, 80 ^{o}C, 95 ^{o}C
3. Exposure to humid air with 0-5%, 45%, 60%, 75%, 98% relative humidity at 23 ^{o}C
4. Exposure to humid air with 0-5%, 45%, 60%, 75%, 98% relative humidity at 95 ^{o}C

After periods of exposure the specimen response was characterized through tensile strength (ASTM D3039M), flexural strength (ASTM D790), and short-beam shear strength tests (ASTM D 2344).

MOISTURE ABSORPTION RESULTS

Figures 1, 2 and 3 show the results of the moisture absorption experiments. The moisture absorption data was analyzed with the Fickian [6] and Langmuir [10] diffusion models and results are listed in Tables 1 and 2, respectively.

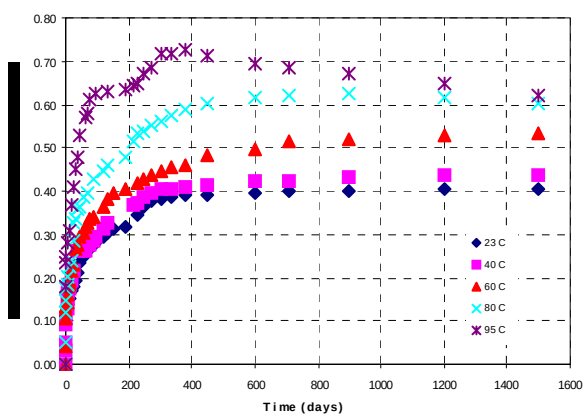

Fig. 1. Moisture absorption profiles of E-glass/Vinylester specimens immersed in deionized water at temperatures of 23 ^{o}C, 40 ^{o}C, 60 ^{o}C, 80 ^{o}C and 95 ^{o}C.

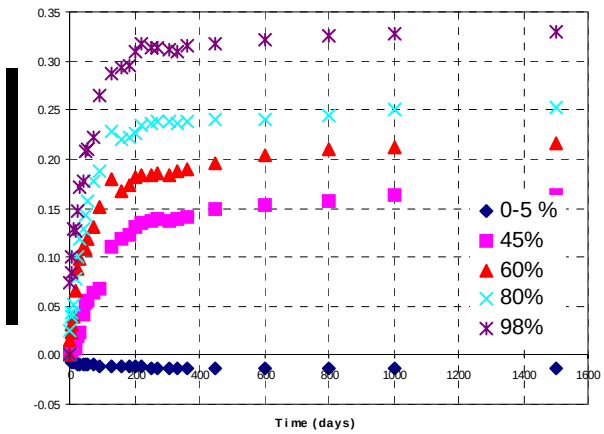

Fig. 2 Moisture absorption profiles of E-glass/Vinylester specimens exposed to relative humidity levels of 0-5 %, 45 %, 60 %, 80 % and 98 % at a constant temperature of 23 ^{o}C.

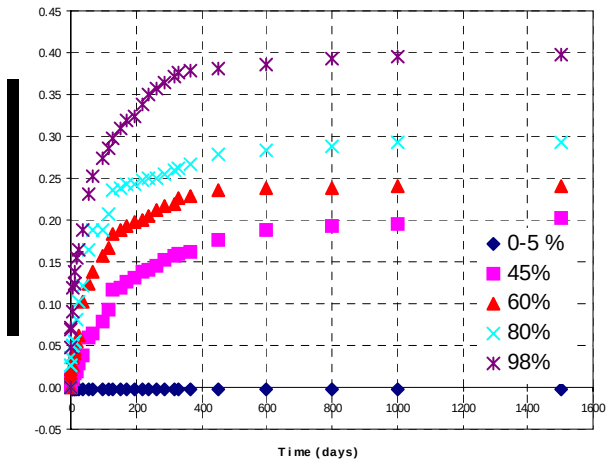

Fig. 3 Moisture absorption profiles of E-glass/Vinylester specimens exposed to relative humidity levels of 0-5 %, 45 %, 60 %, 80 % and 98 % at a constant temperature of 95 ^{o}C.

Table 1 Maximum moisture contents and Diffusion coefficients obtained from Fickian Diffusion Model for specimens immersed in water

Temp (^{0}C)	M_m %	Diffusion Coefficient (mm^2/sec)	
		Fickian Diffusion Model	Corrected for Edge Effects
23	0.405	1.304×10^{-7}	9.056×10^{-8}
40	0.438	1.969×10^{-7}	1.367×10^{-7}
60	0.533	2.139×10^{-7}	1.485×10^{-7}
80	0.624[a]	2.175×10^{-7}	1.510×10^{-7}
95	0.728[b]	2.414×10^{-7}	1.676×10^{-7}

[a] M_m at t = 900 days, followed by weight loss to M_m = 0.601 % at t =1500 days
[b] M_m at t = 380 days, followed by weight loss to M_m = 0.621 % at t =1500 days

Table 2 Maximum moisture contents and Diffusion coefficients obtained from Langmuir Diffusion Model for specimens immersed in water

Temp (^{0}C)	M_m %	Diffusion Coefficient (mm^2/s)		α	β
		Langmuir Diffusion Model	Corrected for edge effects		
23	0.405	8.945×10^{-8}	6.212×10^{-8}	1.761×10^{-4}	2.104×10^{-4}
40	0.438	1.048×10^{-7}	7.278×10^{-8}	1.530×10^{-4}	1.797×10^{-4}
60	0.533	1.257×10^{-7}	8.729×10^{-8}	3.300×10^{-4}	3.930×10^{-4}
80	0.624[a]	2.166×10^{-7}	1.504×10^{-7}	3.848×10^{-4}	5.177×10^{-3}
95	0.728[b]	2.384×10^{-7}	1.656×10^{-7}	3.540×10^{-4}	1.060×10^{-3}

[a] M_m at t = 900 days, followed by weight loss to M_m = 0.601 % at t =1500 days
[b] M_m at t = 380 days, followed by weight loss to M_m = 0.621 % at t =1500 days

CHARACTERIZATION Of MECHANICAL PROPERTIES

The decrease in tensile, flexural and short-beam shear strength properties due to immersion in deionized water are summarized in figures 4, 5 and 6, respectively. Figures 7 and 8 represent the decrease in short-beam shear strength of the specimens exposed to humid air at 23 ^{o}C and 95 ^{o}C.

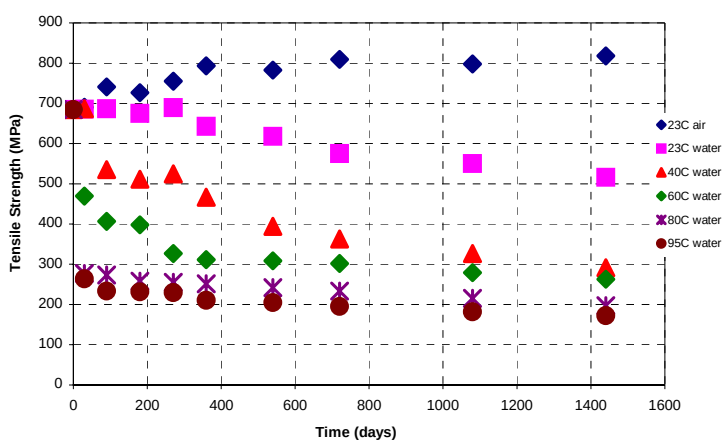

Fig. 4 Tensile strength profiles of E-glass/Vinylester composite specimens immersed in deionized water at temperatures of 23 ^{o}C, 40 ^{o}C, 60 ^{o}C, 80 ^{o}C and 95 ^{o}C and humid air (30 % RH) at 23°C.

Tensile strength data is a significant criterion in materials selection and preliminary design of composite laminates. Flexure tests are easy to run and relatively inexpensive. Therefore, establishing a correlation between standard tensile test and flexure test would provide a basis for the use of flexure test data for design purposes [11]. A two parameter Weibull distribution model was used to predict flexural strength from the tensile test data and results are compared in Figure 9.

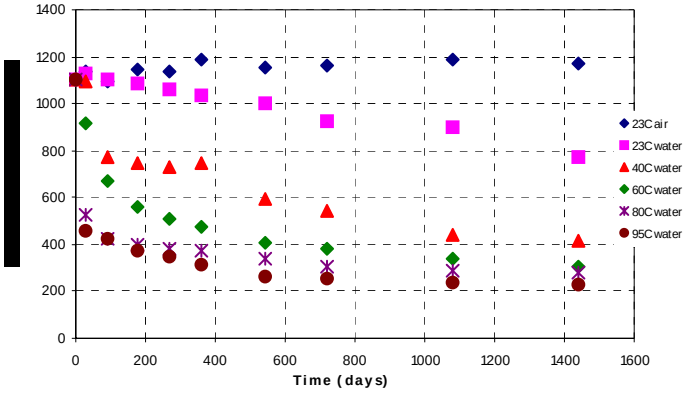

Fig. 5 Flexural strength profiles of specimens immersed in deionized water at temperatures of 23 °C, 40 °C, 60 °C, 80 °C and 95 °C and humid air (30 % RH) at 23 °C.

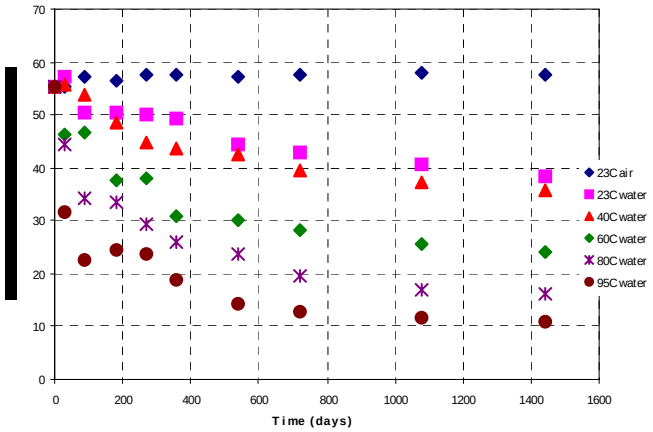

Fig. 6 Short beam shear strength profiles of specimens immersed in deionized water at temperatures of 23 °C, 40 °C, 60 °C, 80 °C and 95 °C and humid air (30 % RH) at 23 °C.

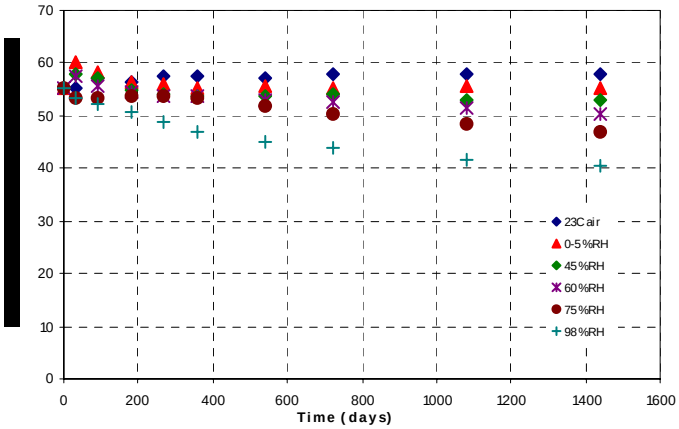

Fig.7 Short beam shear strength profiles of specimens exposed to relative humidity levels of 0-5 %, 45 %, 60 %, 80 % and 98 % at a constant temperature 23 °C

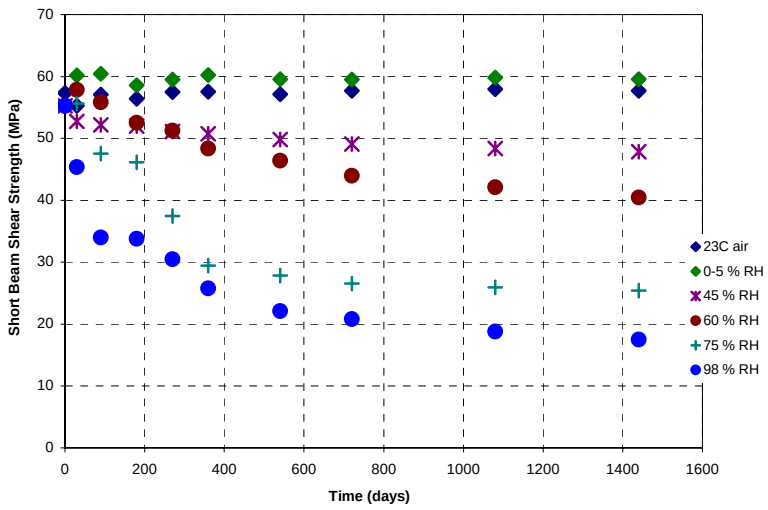

Fig. 8 Short beam shear strength profiles of E-glass/Vinylester composite specimens exposed to relative humidity levels of 0-5 %, 45 %, 60 %, 80 % and 98 % at a constant temperature 95 °C

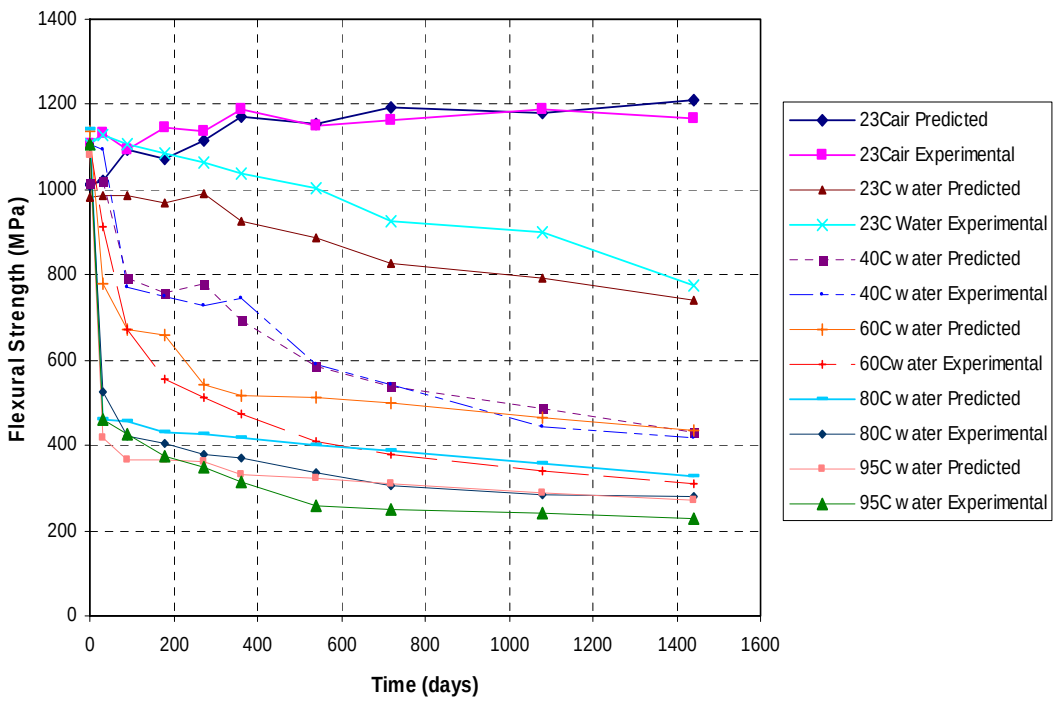

Fig. 9 Values of flexural strength predicted from tensile test data

PERFORMANCE PREDICTION

For the purposes of this investigation two life prediction models are used – the Arrhenius Rate relationship Model [12] and the Phani and Bose Model [13] wherein

the rate constant is assumed to follow the Arrhenius equation [14] and the Time and Temperature Superposition principle (TTSP) [15,16] is maintained. Predictive equations following these two models are given in Tables 3 and 4 and it is noted that they correlate well with experimental results.

Table 3. Arrhenius Equations for prediction of properties of E-glass Vinylester composites immersed in deionized water
*** t = time in days**

Property	Temperature of Immersion °C	Arrhenius Equation*
Tensile Strength	23	y(t) = -6.9588 ln (t) + 103.52
	45	y(t) = -8.5942 ln (t) + 104.30
	60	y(t) = -10.304 ln (t)+ 105.11
	80	y(t) = -11.821 ln (t) + 105.84
	95	y(t) = -12.850 ln (t) + 106.33
Tensile Modulus	23	y(t) = -1.1257 ln (t) + 100.56
	45	y(t) = -1.6668 ln (t) + 100.83
	60	y(t) = -2.2328 ln (t) + 101.11
	80	y(t) = -2.7346 ln (t) + 101.36
	95	y(t) = -3.0752 ln (t) + 101.53
Flexural Strength	23	y(t) = -10.217 ln (t) + 112.57
	45	y(t) = -10.855 ln (t) + 109.75
	60	y(t) = -11.523 ln (t) + 106.81
	80	y(t) = -12.115 ln (t) + 104.20
	95	y(t) = -12.517 ln (t) + 102.43
Short Beam Shear Strength	23	y(t) = -9.3715 ln (t) + 117.27
	45	y(t) = -9.1098 ln (t) + 113.02
	60	y(t) = -8.8361 ln (t) + 108.57
	80	y(t) = -10.250 ln (t) + 104.95
	95	y(t) = -12.104 ln (t) + 105.84

Table 4 Phani and Bose equations for tensile strength predictions at different temperatures * t = time in days

Property	Temperature of Immersion ^{o}C	Phani and Bose Equation*
Tensile Strength	23	$\sigma_{23C} = 275.03 \exp(-3.277 \times 10^{-4} t) + 172.02$
	45	$\sigma_{40C} = 275.03 \exp(-5.141 \times 10^{-4} t) + 172.02$
	60	$\sigma_{60C} = 275.03 \exp(-8.232 \times 10^{-4} t) + 172.02$
	80	$\sigma_{80C} = 275.03 \exp(-1.250 \times 10^{-3} t) + 172.02$
	95	$\sigma_{95C} = 275.03 \exp(-1.269 \times 10^{-3} t) + 172.02$
Tensile Modulus	23	$E_{23C} = 7.657 \exp(-1.021 \times 10^{-4} t) + 31.23$
	45	$E_{40C} = 7.657 \exp(-2.3123 \times 10^{-4} t) + 31.23$
	60	$E_{60C} = 7.657 \exp(-5.4337 \times 10^{-4} t) + 31.23$
	80	$E_{80C} = 7.657 \exp(-1.1591 \times 10^{-3} t) + 31.23$
	95	$E_{95C} = 7.657 \exp(-1.9382 \times 10^{-3} t) + 31.23$
Flexural Strength	23	$\sigma_{23C} = 474.898 \exp(-3.823 \times 10^{-4} t) + 226.98$
	45	$\sigma_{40C} = 474.898 \exp(-6.777 \times 10^{-4} t) + 226.98$
	60	$\sigma_{60C} = 474.898 \exp(-1.234 \times 10^{-3} t) + 226.98$
	80	$\sigma_{80C} = 474.898 \exp(-2.098 \times 10^{-3} t) + 226.98$
	95	$\sigma_{95C} = 474.898 \exp(-3.008 \times 10^{-3} t) + 226.98$
Short Beam Shear Strength	23	$\sigma_{23C} = 41.84 \exp(-2.809 \times 10^{-4} t) + 10.96$
	45	$\sigma_{40C} = 41.84 \exp(-6.013 \times 10^{-4} t) + 10.96$
	60	$\sigma_{60C} = 41.84 \exp(-1.332 \times 10^{-3} t) + 10.96$
	80	$\sigma_{80C} = 41.84 \exp(-2.698 \times 10^{-3} t) + 10.96$
	95	$\sigma_{95C} = 41.84 \exp(-4.356 \times 10^{-3} t) + 10.96$

SUMMARY

The research provides an extensive database of properties and changes thereof due to moisture and humidity. Initial attempts at modeling show good correlation and it is also shown that the use of Weibull theory enables prediction of characteristics from just a single test type. This provides a potential means for reducing the overall level of required testing.

REFERENCES

1) Carol L. Schutte, "Environmental Durability of Glass-fiber Composites", *Materials Science and Engineering*, 1994, Vol. R13, 265-324.
2) Wolff E.G., "Moisture Effects on Polymer Matrix Composites", *SAMPE Journal*, 1993, Vol. 29-3, 11-19.
3) Shen C. and Springer G.S., "Moisture Absorption and Desorption of Composite Materials", Environmental effects on Composite Materials, 1988, Ed., Springer G S, Vol. 3, 15-34.

4) Ghorbel I. and Valentin D., "Hydrothermal Effects on the Physico-Chemical Properties of Pure and Glass Fiber Reinforced Polyester and Vinylester Resins", *Polymer Composites*, 1993, Vol. 14-4, 324-334.
5) Karbhari V.M. and Zhang S., "E-glass/Vinylester Composites in Aqueous Environments – I: Experimental Results", *Applied Composite Materials*, 2003, Vol. 10, 19-48.
6) Crank J., Park G.S., Diffusion in Polymers, Academic Press, New York, 1968.
7) Marom G., "The Role of Water Transport in Composite Materials", Polymer Permeability, Comyn J, Ed., Elsevier, New York, 1975, 341-374.
8) Weitsman J., "Effect of Fluids on Polymeric Composites-A Review", Report to Office of Naval Research, Mechanical and Aerospace Engineering and Engineering Science, University of Tennessee, Report MAES98-5.0-CM, 1998.
9) Hopfenberg H.B. and Stannett V.T., "The Diffusion and Sorption of Gases and Vapors in Glassy Polymers", The Physics of Glassy Polymers, Ed., Haward R N, Applied Science Publishers, London, 1973, 504.
10) Carter H.G. and Kibler K.G., "Langmuir Type Model for Anomalous Moisture Diffusion In Composite Resins", *Journal of Composite Materials*, 1978, Vol.12, 118-131.
11) Whitney J.M. and Knight M., "The Relationship between Tensile Strength and Flexure Strength in Fiber-reinforced Composites", *(Journal Paper) Experimental Mechanics,* 1980, Vol.20-6, 211-216.
12) Reliasoft Corporation, Website, www.reliasoft.com
13) Phani K.K. and Bose N.R., "Hydrothermal Ageing of CSM- Laminate During Water Immersion- An Acousto-Ultrasonic Study", *Journal of Materials Science*, October 1986, Vol. 21-10, 3633-3637.
14) Phani K.K. and Bose N.R., "Temperature Dependence of Hydrothermal Ageing of CSM-Laminate During Water Immersion", *Composites Science and Technology*, 1987, Vol. 29-2, 79-87.