# Hygrothermal Characterization and Diffusion Studies on Carbon/Epoxy Composites

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**ABSTRACT:** Hygrothermal studies were carried out on unidirectional (UD) carbon fiber epoxy (LY 5052) composites at $V_f = 0.5$ and have been carried out for three different cases viz. 45°C/85% RH, 45°C/95% RH and 45°C/immersion (100% RH) till saturation is reached. In all cases composite specimens of different test configurations [Longitudinal Tensile (LT), Transverse Tensile (TT), Longitudinal Compression (LC), and Transverse Compression (TC)] were subjected to the above conditions and their diffusion behaviour studied. Generally, the specimens under the above conditions exhibited Fickian diffusion behavior.

## INTRODUCTION

GRAPHITE/EPOXY COMPOSITES ARE widely accepted for use as primary aircraft components and in other structural applications due to their high performance characteristics. Studies on carbon composites are plentiful due to their extensive use in the aerospace industry. When used to reinforce polymer matrices, carbon composites do absorb moisture by a diffusion process [1,2], and it is essential to understand their behavior under varied environmental conditions of which the hygrothermal factor is of vital importance.

A common material used in the aerospace industry uses oriented carbon filaments reinforcing an epoxy matrix. Springer [1] reported the diffusivity of a carbon/epoxy at 74°C and 90% relative humidity as $2.6 \times 10^{-7}$ mm²/sec. Rao et al. [3] reported the diffusion coefficient of carbon/epoxy system at 70°C and 85% RH in the range of $2 \times 10^{-7}$ mm²/sec to $2.5 \times 10^{-7}$ mm²/sec. Often following standard

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test procedures, large test data for different hygrothermal exposures are generated for carbon composites [4].

Long term exposures to moisture of carbon/epoxy laminates were conducted to determine diffusion coefficients and have been reported by Blikstad et al. [5]. The use of accelerated moisture conditioning of graphite/epoxy composite and the comparison with regular conditioning was discussed by Ciriscioli et al. [6]. The diffusion coefficient values in the present work also agree with those of the literature.

## EXPERIMENTAL DETAILS

### Material and Specimen Preparation

UD carbon (C-160, Anchor Reinforcement Ltd., USA)/epoxy (LY 5052 of Ciba Geigy) test specimens were used in the present work. The specimens were cut from oven cured laminate fabricated out of stackings (0°–0°) of pre-impregnated layers cured under a standard room temperature vacuum bag molding (RTVBM) procedure, inhouse developed. The fiber weight fraction of all the laminates was 65 ± 3% (or 0.5 $V_f$). Test specimens for Longitudinal Tension, Transverse Tension, Longitudinal Compression and Transverse Compression tests were cut from the laminates, the thickness of each specimen being 2 mm. The tensile test specimens were of dimensions 250 mm × 25 mm × 2 mm and the compressive test specimens were of dimensions 120 mm × 12.6 mm × 2 mm.

A large number of specimens were chosen to comply with the acceptance requirements of this type of composition for use in certain classes of aircraft. A total of 72 specimens classified as LT, TT, LC and TC were used for environmental conditioning. Three sets of six specimens for each type of test were subjected to exposure at three different conditions viz. 45°C/85% RH, 45°C/95% RH and 45°C/immersion.

## RESULTS AND DISCUSSIONS

### Determination of Diffusion Parameters $M_m$, $D_c$

Figure 1 to Figure 3 show plots of % moisture absorption vs. Sq. root of Time in hours for LT, TT, LC, TC, and IPS test specimens of glass/epoxy conditioned at 45°C/85% RH, 45°C/95% RH and 45°C/immersion. The nature of the curves indicate Fickian diffusion pattern with an initial linear portion and thereafter remaining a concave to time axis until maximum moisture content ($M_m$) is reached.

The $D_c$ values for all specimens were calculated, using the equation

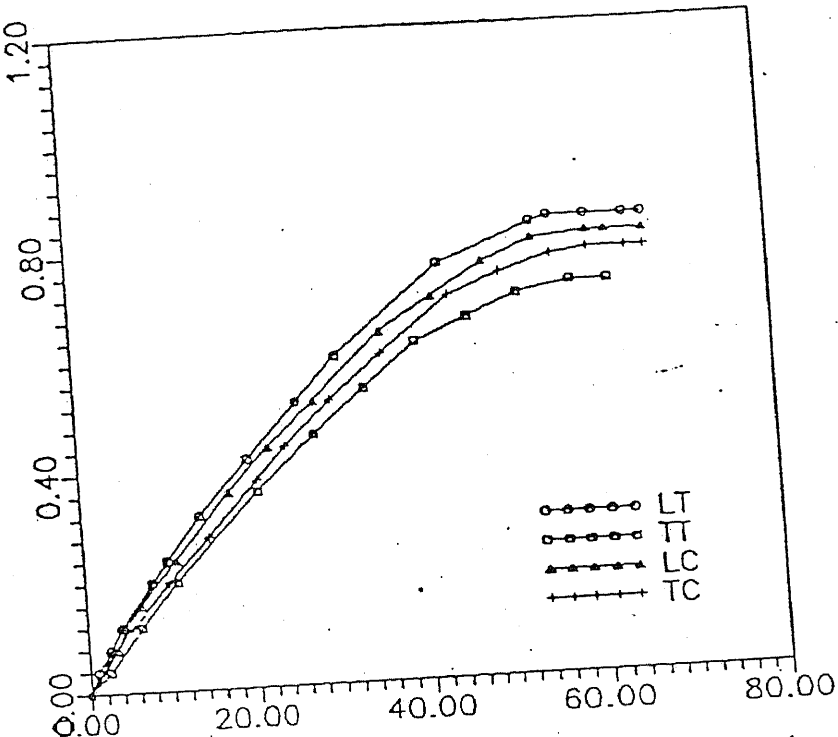


Figure 1. Moisture absorption curves for carbon/epoxy test specimens conditioned at 45°C/85% RH—x-axis: sq. root of time in hrs. and y-axis: % moisture gain.

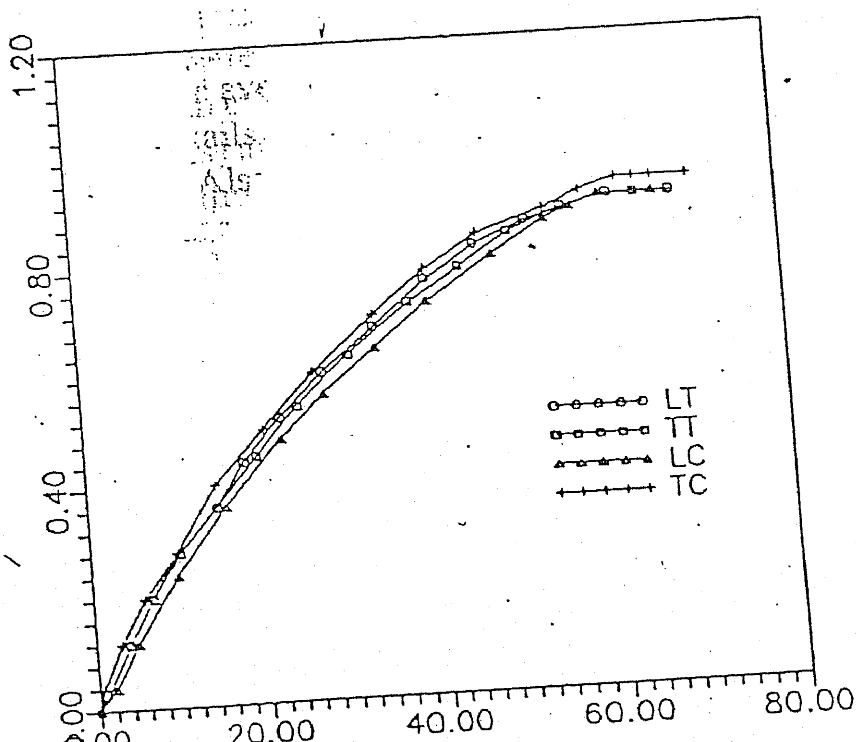


Figure 2. Moisture absorption curves for carbon/epoxy test specimens conditioned at 45°C/95% RH—x-axis: sq. root of time in hrs. and y-axis: % moisture gain.

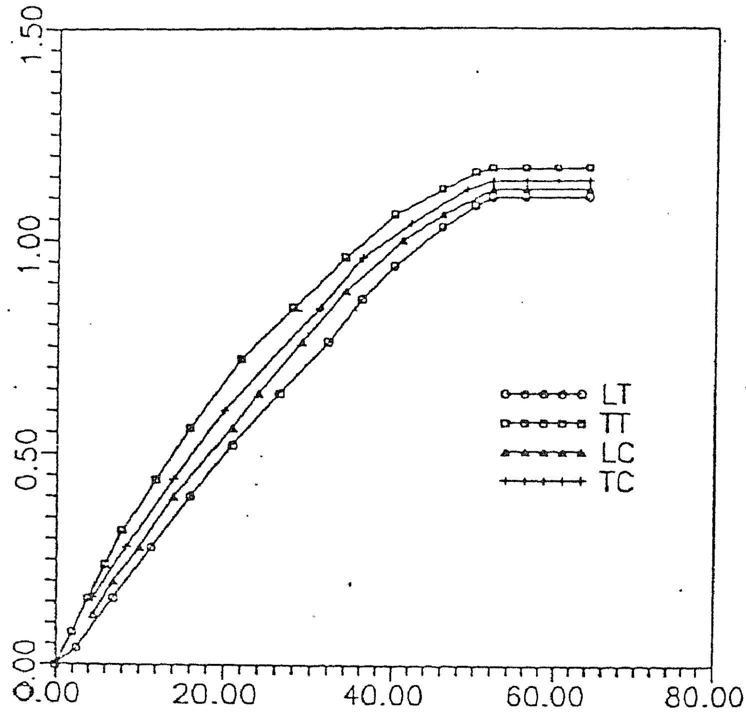


*Figure 3. Moisture absorption curves for carbon/epoxy test specimens conditioned at 45°C/immersion—x-axis: sq. root of time in hrs. and y-axis: % moisture gain.*

$$D_c = \pi[h/4M_m]^2 \quad \left[(M_2 - M_1)/\left(\sqrt{t_2} - \sqrt{t_1}\right)\right]^2$$

were

The averaged $D_c$ values for a given type of test specimen were also obtained. The details of results for the test specimens conditioned are given in Table 1.

Also for the same thickness (i.e., same number of layers) and for different test specimens of the same laminate under one set of test conditions, a small variation in the diffusivity values is noticeable. For a given material there are variations in the diffusivity values reported from one investigator to the other. The likely reason for these variations is the differences in the curing processes used in the different laboratories. It is very evident that even slight, unintentional differences in the curing process may alter the value of $D_c$ significantly [7].

*Table 1. Comparison of diffusion parameters for different carbon/epoxy test specimens conditioned at 45°C/85% RH, 45°C/95% RH, and 45°C/immersion.*

| Test Specimen | (%) $M_m$ at | | | $D_c \times 10^{-7}$ mm²/sec | | |
|---|---|---|---|---|---|---|
| | 85% RH | 95% RH | Immersion | 85% RH | 95% RH | Immersion |
| LT | 0.82 | 0.90 | 1.10 | 1.57 | 2.42 | 2.84 |
| TT | 0.72 | 0.90 | 1.17 | 2.63 | 3.78 | 3.98 |
| LC | 0.81 | 0.90 | 1.12 | 2.25 | 2.75 | 3.21 |
| TC | 0.78 | 0.93 | 1.14 | 2.81 | 3.76 | 3.55 |

Table 2. Comparison of analytical and experimental values obtained for carbon/epoxy specimens conditioned at 45°C/95% RH.

| Test Specimen | $D_c \times 10^{-7}$ mm²/sec | | $T_m$ (in days) | | % $M_m$ |
|---|---|---|---|---|---|
| | Analytical* | Experimental | Analytical | Experimental | |
| LT | 2.54 | 2.42 | 85 | 78 | 0.90 |
| TT | 3.81 | 3.78 | 90 | 84 | 0.90 |
| LC | 2.92 | 2.75 | 75 | 82 | 0.90 |
| TC | 3.70 | 3.76 | 83 | 78 | 0.93 |

*Values obtained using M8 gain of Springer [8,9].

The M8 gain [8,9] of Springer was applied for 45°C/95% RH conditioning case and found to yield $M_m$, $T_m$ and $D_c$ values comparable to experimental values obtained (Table 2).

## Fickian Correlation Curves

Figure 4 to Figure 6 show the correlation curves for the three conditions studied and clearly indicate a good correlation between the analytical and experimental values.

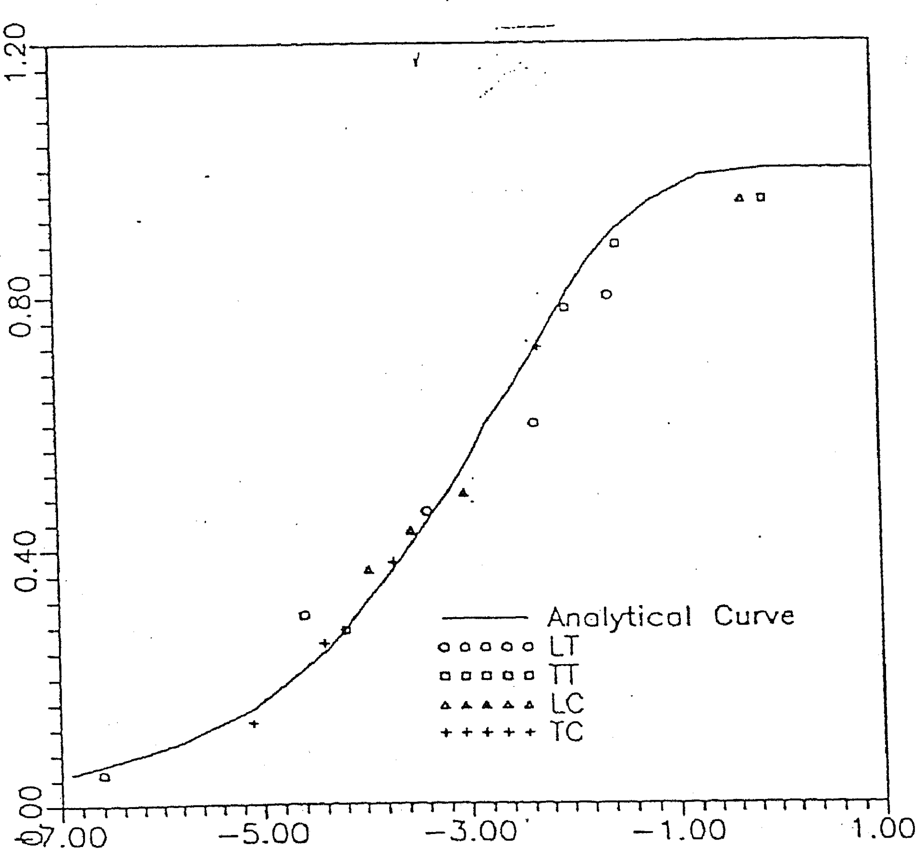


Figure 4. Comparison of analytical and experimental values for carbon/epoxy test specimens conditioned at 45°C/85% RH—x-axis: ln ($D_c t/h^2$) and y-axis: G = ($M_t/M_m$).

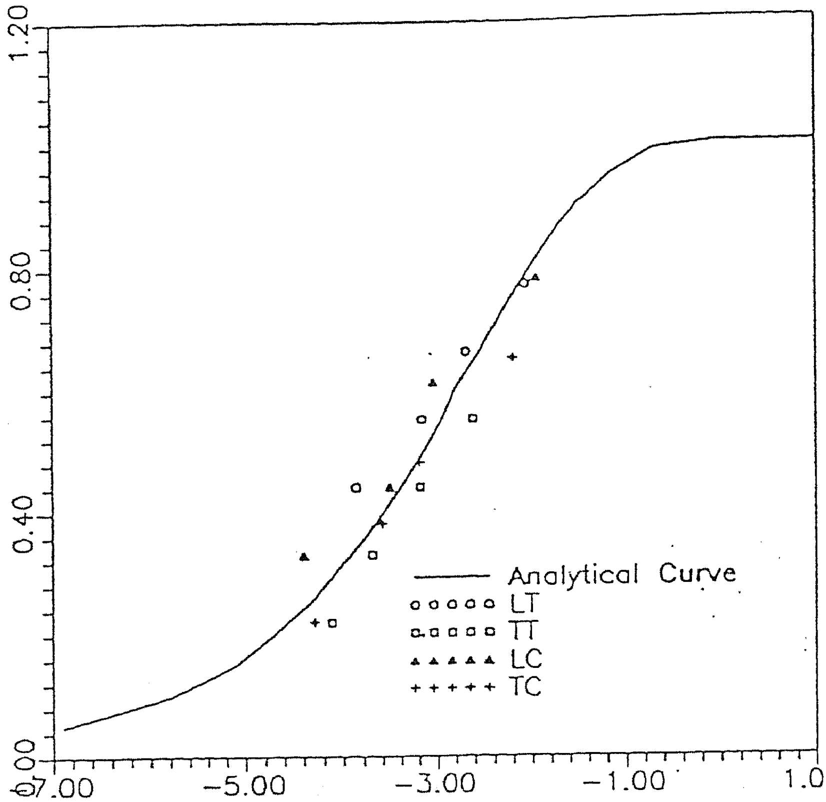


*Figure 5. Comparison of analytical and experimental values for carbon/epoxy test specimens conditioned at 45°C/95% RH—x-axis: ln ($D_c$ t/$h^2$) and y-axis: G = ($M_t$/$M_m$).*

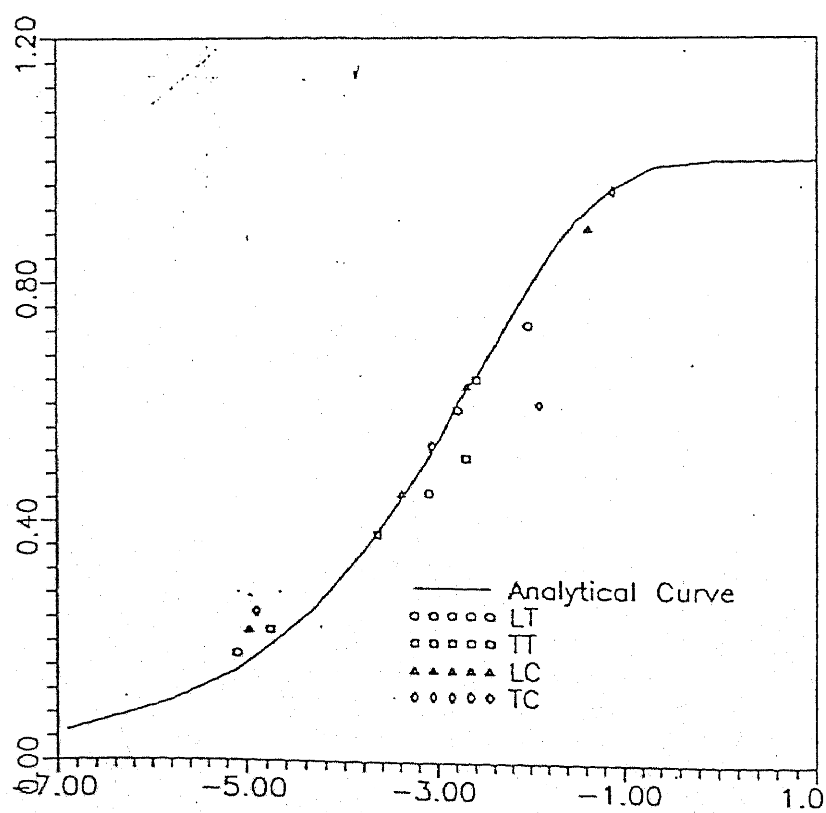


*Figure 6. Comparison of analytical and experimental values for carbon/epoxy test specimens conditioned at 45°C/immersion—x-axis: ln ($D_c$ t/$h^2$) and y-axis: G = ($M_t$/$M_m$).*

## Variation of Maximum Moisture with % RH

It is well known that the maximum moisture content is a strong function of RH of the ambient. For a material immersed in liquid $M_m$ is a constant.

$$M_m = \text{constant (liquid)}$$

For a material exposed to humid air $M_m$ depends on the relative humidity ($\phi$), according to the relationship

$$M_m = a(\phi)^b \text{ (humid air)}$$

$$\log M_m = \log a + b \log(\phi)$$

From the data obtained at two different conditions viz. 45°C/85% RH and 45°C/95% RH, $a$ and $b$ were evaluated for the above equation as $a = 0.972$ and $b = 1.33$.

Figure 7 shows the variation of $M_m$ with % RH at constant temperature in general for a carbon/epoxy system.

Also, Figure 8 to Figure 11 show the variation of %$M_m$ with percentage relative humidity for LT, TT, LC and TC specimens individually.

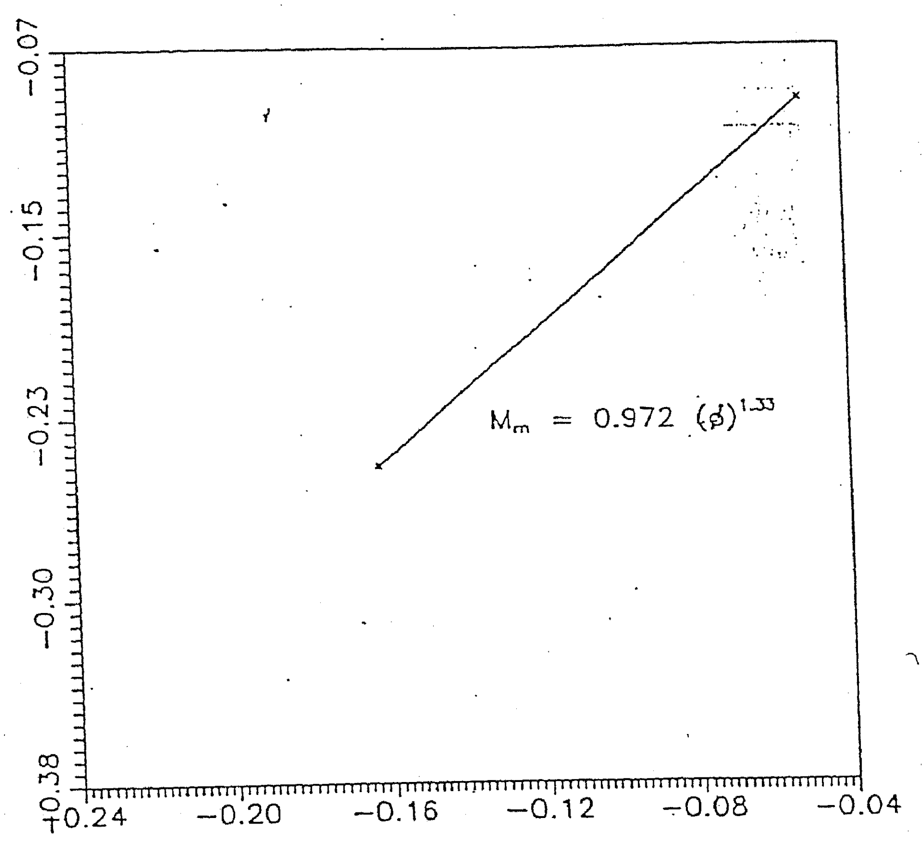


*Figure 7: Variation of maximum moisture content with % relative humidity for carbon/epox system.*

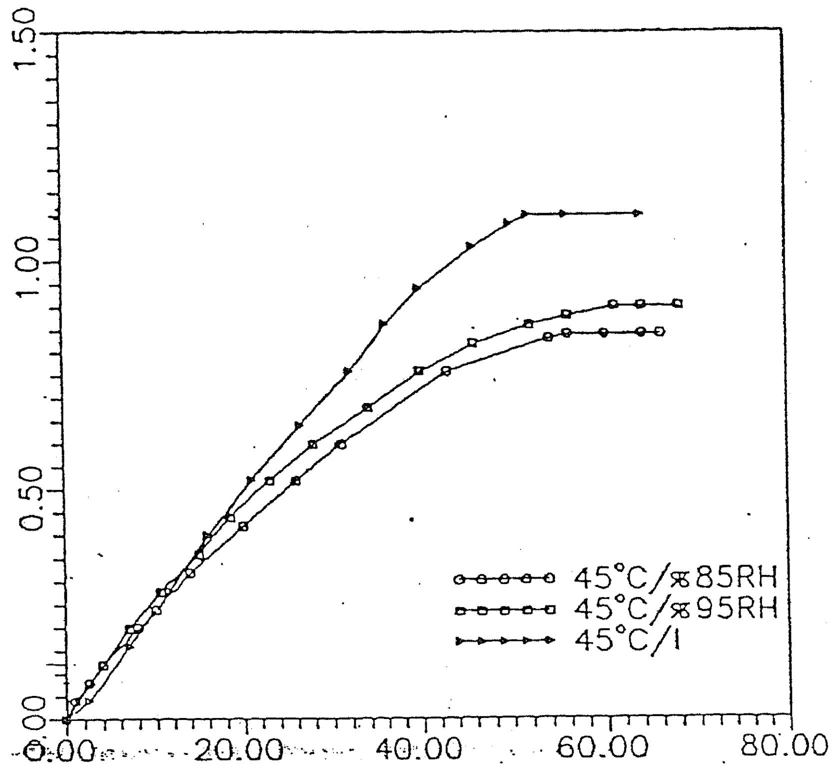


*Figure 8. Variation of maximum moisture with relative humidity for LT specimens of carbon/epoxy.*

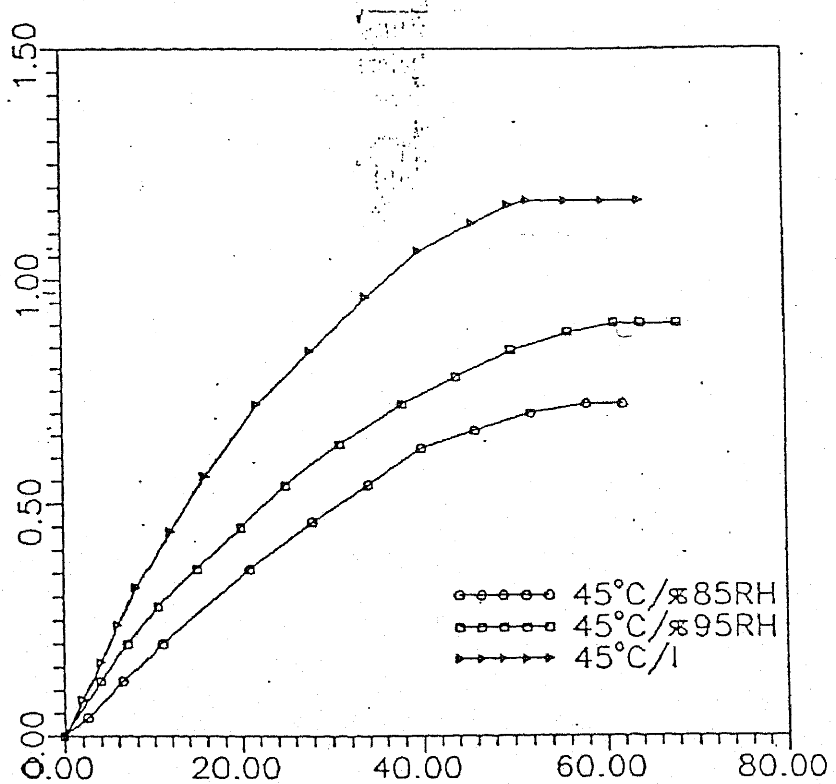


*Figure 9. Variation of maximum moisture with relative humidity for TT specimens of carbon/epoxy.*

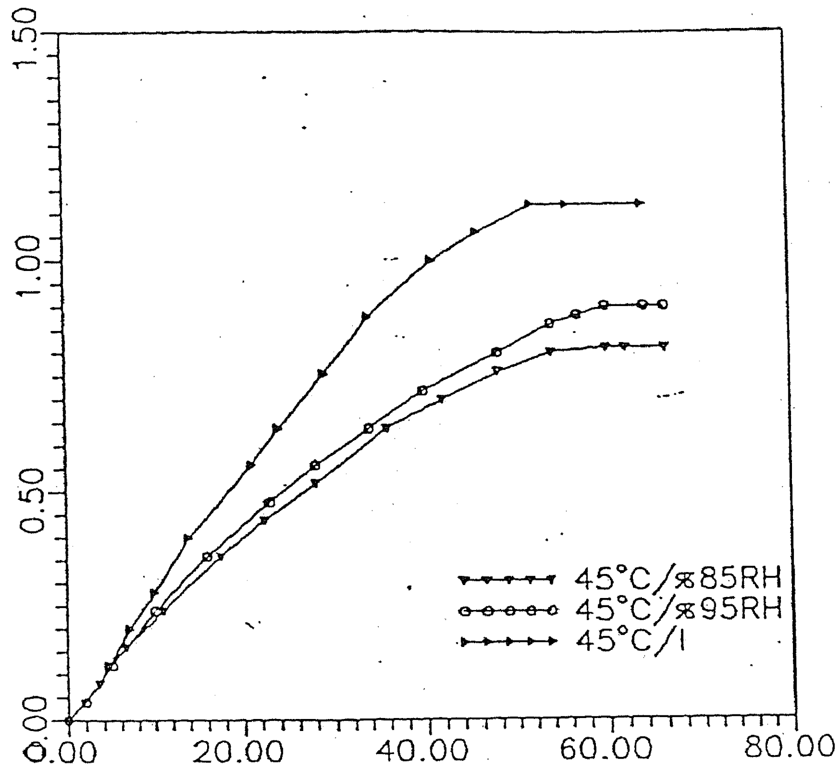


*Figure 10. Variation of maximum moisture content with relative humidity for LC specimens of carbon/epoxy.*

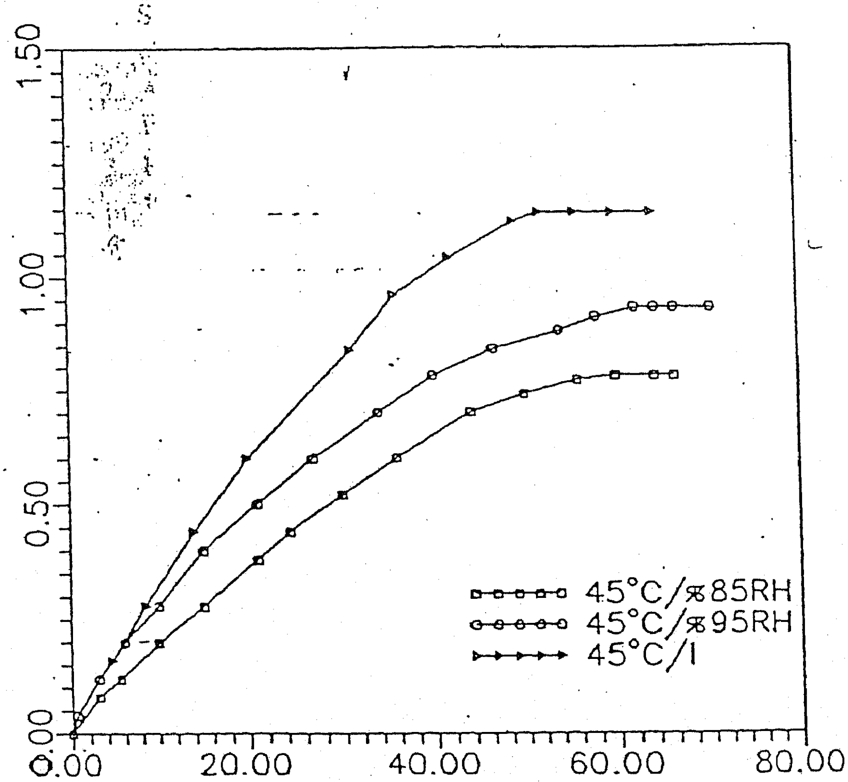


*Figure 11. Variation of maximum moisture content with relative humidity for TC specimens of carbon/epoxy.*

## CONCLUSIONS

- The unidirectional carbon/epoxy specimens exhibited the Fickian behavior at different hygrothermal conditions studied.
- The maximum moisture content increased with the increase in relative humidity.
- The $D_c$ values remain practically the same for all hygrothermal conditions considered.

Also, the experimentally obtained and analytically predicted $D_c$ and $T_m$ values are in good agreement.

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