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AN EXPERIMENTAL INVESTIGATION OF MOISTURE EFFECT ON FATIGUE BEHAVIOR OF COMPOSITE MATERIALS

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ABSTRACT: *In this study the effect of moisture content on the fatigue behavior of the composite materials is investigated. Samples of random and woven fibers with polyester resin are used in this study. The samples are immersed in water for different period's .The moisture content is measured .The results Showed that the moisture content has a significant effect on the fatigue life of the composite materials. The fatigue life decreases as the moisture content increase.*

KEYWORDS: Material, Composite, Moisture Effect, Fatigue Behavior.

INTRODUCTION

Composite materials are engineered materials made from two or more constituent materials with significantly different physical or chemical properties which remain separate and distinct on a macroscopic level within the finished structure [1]. Composites are made up of individual materials referred to as constituent materials. There are two categories of constituent materials: **matrix and reinforcement.** At least one portion of each type is required.

Uses of Composite Materials

1. Space technology and production tails, wings etc.
2. Sport goods e.g. racing car bodies and bicycle frames etc.
3. Fuel efficient transport vehicles.
4. Carbon composite is used in solar panel substrates, antenna reflectors and yokes of spacecraft and heat shields of launch vehicles.

Advantages of Using Composites over Metals [2]

- Very high strength and low weight.
- Complex shape parts can be simple produced.
- High degree of integration possible.
- Excellent fatigue endurance concerning number of load cycles (many times higher than with metals) and residual fatigue strength.
- Excellent chemical resistance against acids, chemicals etc.
- Excellent weather/water resistance.

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- Composites have excellent RAM features (Radar absorbing material); radar and sonar transparent.
- Excellent impact habits.
- Excellent electrical (isolation and dielectric) habits, RF transparency and reflecting.
- Great thermal isolation, fire retardant habits, and high temperature performance.

Classification of composite materials [1]

(Based on reinforcing material structure)

Particulate Composites

a. Random orientation.

b. Preferred orientation.

Fibrous Composites

(1) **Short-fiber reinforced (length< 100 diameter).**

a. Random orientation.

b. Preferred orientation**.**

(2) Long-fiber reinforced

Long-fiber reinforced consists of a matrix reinforced by a dispersed phase in form of continuous fibers.

a. Unidirectional orientation.

b. Bidirectional orientation (woven).

c. Laminate (Fig. 1-1).

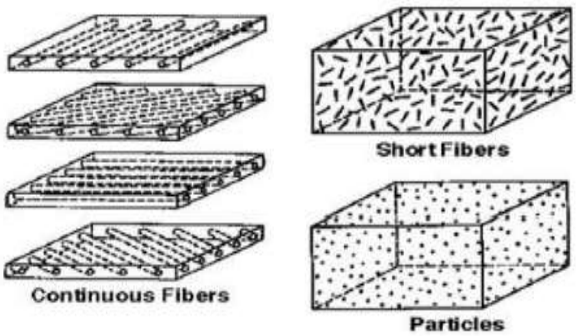

Fig.1-1: Types of composites [1]

Fiber Reinforced Polymers (FRP)

It is also called fiber-reinforced plastic. It is a made of a polymer matrix reinforced with fibers. The fibers are usually fiberglass, carbon or aramid, while the polymer is usually an epoxy, vinyl ester or polyester thermosetting plastic.

FRPs are commonly used in the aerospace, automotive, marine, and construction industries.

According to orientation of fiber (Fig.1-2) they can be categorized as:

1. Unidirectional
2. Bidirectional
- Cross Ply
- Angle Ply

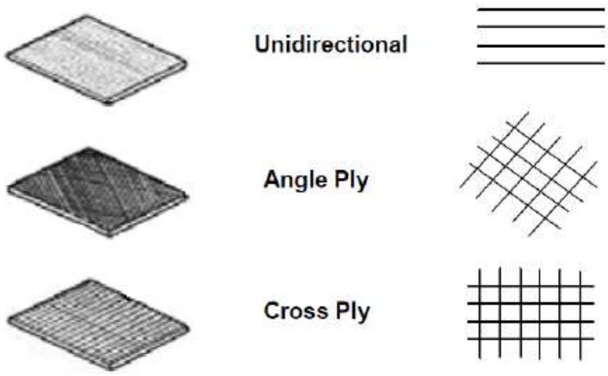

Fig.1-2: Fiber orientation types [1]

Advantages of FRP:

1. High strength to weight ratio.
2. Corrosion resistant.
3. Can be tailored for the application.
4. FRP has a low cost considering other materials.

Types of Fiber

a. Carbon Fiber

They are created when polyacrylonitrile fibers (PAN), Pitch resins, or Rayon are carbonized through oxidation and thermal pyrolysis at high temperatures. Carbon fibers are manufactured in diameters analogous to glass fibers with diameters ranging from 9 to 17 μm (Fig.1-3).

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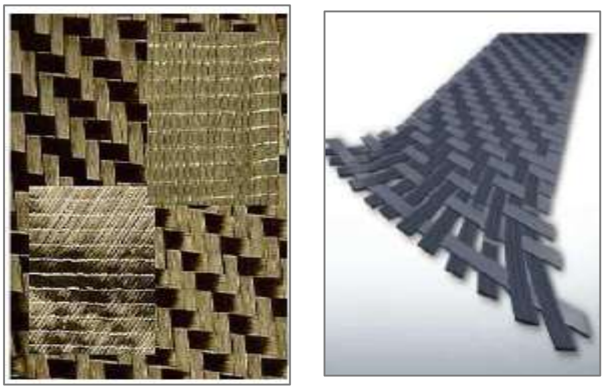

Fig. 1-3: Different types of matted carbon fibers [1].

b. Glass Fiber

FRP plastics use textile glass fibers; textile fibers are different from other forms of glass fibers used for insulating applications. Textile glass fibers begin as varying combinations of SiO_2, Al_2O_3, B_2O_3, CaO, or MgO in powder form. These mixtures are then heated through a direct melt process to temperatures around 1300 degrees Celsius, after which dies are used to extrude filaments of glass fiber in diameter ranging from 9 to 17 µm (Fig.1-4).

Fig. 1-4: Commercially available glass fibers [1].

Glass fiber is available in the following forms as shown in Fig.1.5:

a. Continuous Fiber.
b. Chopped strands.
c. Woven Fabric.

Continuous Fiber   Chopped strands   Woven Fabric

Fig. 1-5: Types of glass fiber [1].

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c. Aramid (Kevlar) Fiber:

It is a man-made organic polymer (an aromatic polyamide) produced by spinning a solid fiber from a liquid chemical blend. The bright golden yellow filaments produced have low density giving very high specific strength.

Environmental Effect on Fiber Composites:

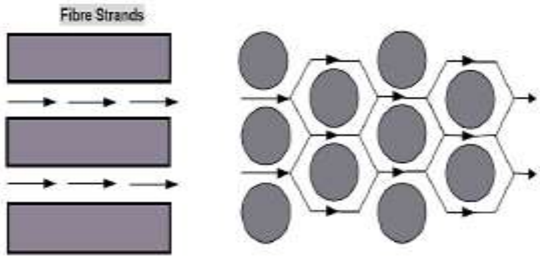

Fig. 1-6: Diffusion path of moisture into composite laminate in the thickness direction [7].

Improved properties of fibrous composites have led to expand its use in different important applications. These composites are affected by heat and moisture during operation under severe environmental conditions. They absorb moisture and expanded gradually with time. These will in turn reduce the failure time. Since the composites contain epoxy matrix and fibrous material, the most of moisture are absorbed by epoxy, and no moisture will be absorbed by fibers as shown in figure (1-6). So the volumetric expansion takes place in matrix will localize both stresses and strains inside it. In addition the moisture absorption will make changes in the thermal physical, mechanical and chemical properties of epoxy matrix because of plasticization and hydrolysis, which will reduce both elastic modulus and glass transition temperature. The moisture propagation in the interface between fiber and matrix will destroy the bond, resulting in loss of microstructure. After exposure to moisture absorption a clear decrease appear in the matrix-dominated characteristics (compressive, inter-laminar shear strength, fatigue resistance and impact tolerance). If the humidity condition is combined with electromagnetic solar wave then a harmful eroding on epoxy matrix presents. The eroding will decrease transverse strength and inter-laminar toughness. If transient moisture diffusion imposed under environmental conditions, it is called as Fickian process. In non-composite materials, the moisture diffusion is depending on maximum content of moisture and diffusivity factor. Maximum moisture content is defined as the ratio of increased weight due to moisture to dry weight of same material at saturation point. To get the saturation point a time limit has to be reached as follows:

$$\mathrm{W}_{r} = \frac{\mathrm{W_t} - \mathrm{W_0}}{\mathrm{W_0}}$$

Where: W_r is the relative weight gain, $\mathrm{W_t}$ is the weight at time t and $\mathrm{W_0}$ is the dry weight. The maximum moisture content is reached at infinite time. This content has a direct proportion to relative humidity of environment. The time required for maximum moisture content is a period to get the steady state equilibrium. This will take several months. Diffusivity is a measure of moisture diffusion, which in turn is related to ambient temperature but not related to relative humidity. The diffusion process is related to diffusivities of matrix and fibrous material, their arrangement in composite material. The effective diffusivity can be estimated either by mixing methods or numerically, although the mixing approach does not perform the entire structure of composite fiber reinforcement. Then effective diffusivity will be used to predict the moisture

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content, but in transient condition the value of effective diffusivity will not be accurate for this prediction. The exposure to hygrothermal environment under mechanical loads will make a change in the material properties due to irreversible degradation, see figure (1-7).

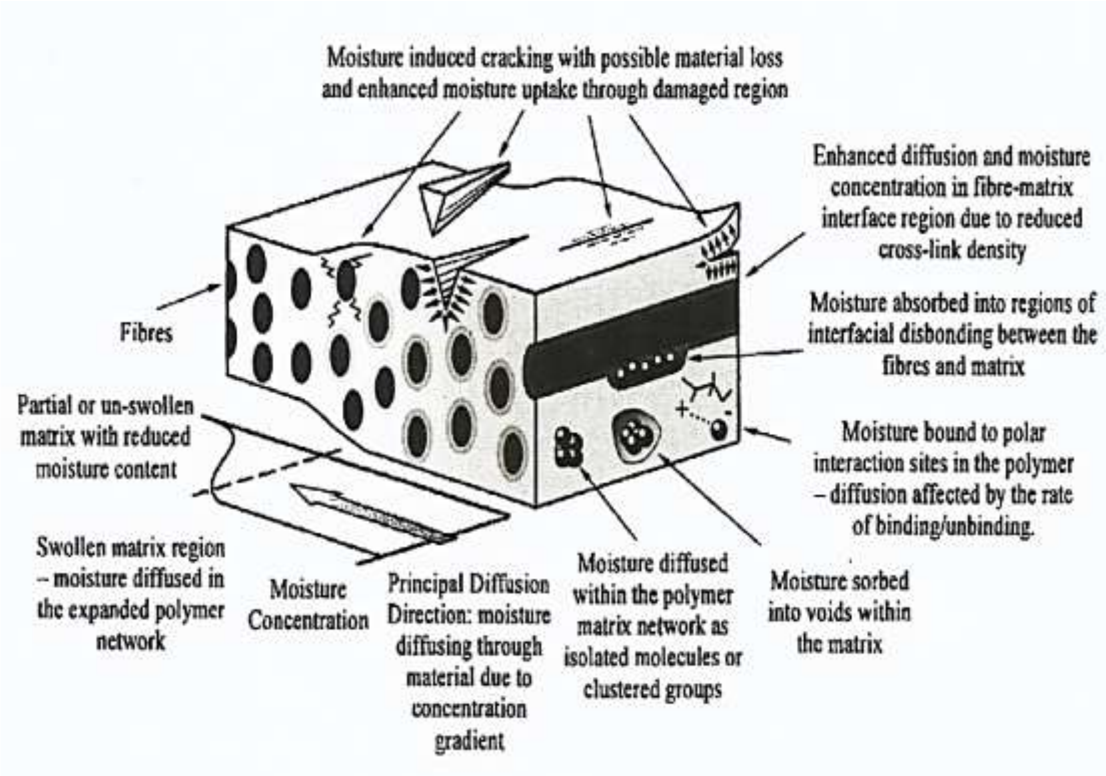

Fig. 1-7: Deteriorated fiber specimen under moist environmental condition [7].

Moisture will relax and oxidize of matrix material. While cyclic moisture will bond breaking fibers from matrix followed by initiation of continuous cracks, transverse cracks and fiber fracture. All these factors will affect elastic modulus, hygrothermal expansion coefficients and diffusion coefficient. The acceleration of moisture absorption will increase its diffusion. The undamaged material under moisture absorption is called well-accepted transportation models like Fickian and Langmuir diffusions. These models will no longer work with initial cracked materials at whole layers but work locally. The scope of present study is to examine and compare experimentally the effect of transient moisture under different environmental conditions (different temperature and relative humidity) on two types of composites: woven and random fiber glass subjected to different cyclic fatigue loads.

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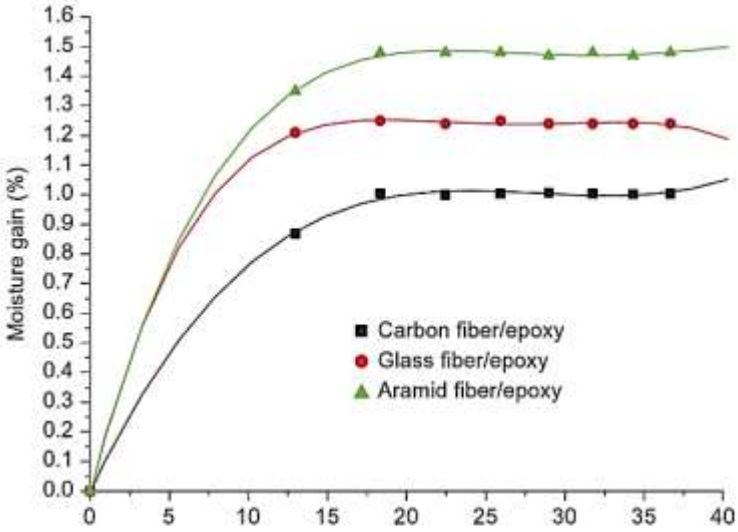
Description of the Different Stages in Moisture Absorption kinetics

Figure (1-8) shows the different stages in moisture absorption kinetics:



Square root of conditioning time (h)

Fig. 1-8: Moisture absorption kinetics [14].

- Stage 1: Moisture absorption is Fickian.
- Stage 2: There is a deviation from linearity with the time axis (reaching saturation, so decrease in slope).
- Stage 3: Total non-Fickian pattern (there is a development of micro cracks which enable rapid moisture diffusion, so rapid increase in percentage of moisture).

LITERATURE REVIEW

Paepegem and Degrieck [3] had investigated the bending fatigue. The materials used are plain woven glass/epoxy specimens in two configurations: [#0º] and [#45º]. Experiments show that these two specimen types, although being made of the same material, have a quite different damage behavior and that the stiffness degradation follows a different path. Next a numerical model is presented which allows one to describe the degradation behavior of the composite specimen during its fatigue life. This model has been implemented in a mathematical software package and proves to be a useful tool to study the fatigue degradation behavior of composite materials.

Paepegem and Degrieck [4] presented the fatigue behavior of plain woven glass/epoxy composites. Bending fatigue tests were used to yield the experimental data. With the aid of an advanced phase-shift shadow Moiré technique, an out-of-plane displacement profile during fatigue life of the composite specimens was recorded at a number of intervals, as well as the bending force history. A residual stiffness model which describes the fatigue damage behavior of the composite material was adopted. Next a new finite element approach was developed to implement the fatigue damage model in a commercial finite element code that proves to be capable of simulating the observed experimental results.

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Paepegem et al., [5] presented a phenomenological residual stiffness model which predicts the stiffness degradation as well as final failure of the composite component. The reserve to failure has been evaluated by means of a modified use of the Tsai-Wu static failure criterion. The fatigue damage model has been applied to displacement-controlled bending fatigue experiments of plain woven glass/epoxy specimens. The damage and stress (re)distribution, as well as the force-cycle history have been simulated and compared to experimental results. Due to the consistent integration of continuum damage mechanics and the residual stiffness approach, the implementation of the fatigue model in a commercial finite element code has been possible, which allows for an accurate simulation of the successive damage states during fatigue life.

Paepegem and Degrieck [6] presented a phenomenological residual stiffness model that predicts the stiffness degradation and (possible) permanent strain in fiber-reinforced polymers under in-plane fatigue loading. The model takes into account the actual stress state in each material point and does not make any assumptions about geometry or boundary conditions of the fatigue loaded specimen. As the presented model has been developed within a larger research programmed, the emphasis in this paper lies on the theoretical modelling framework, rather than on an in-depth validation of the model which would require much more detail about the close feedback between experimental data and finite element simulations. Therefore the development of the stress-strain-damage relationships and the damage growth rate equations is explained thoroughly and a few finite element results are presented for plain woven glass/epoxy composites.

Ganapathi et al., [8] studied static and dynamic characteristics of thick composite laminates exposed to hygrothermal environment, which was studied using a realistic higher-order theory developed recently. The formulation accounts for the nonlinear variation of the in-plane and transverse displacements through the thickness, and abrupt discontinuity in slope of the in-plane displacements at any interface. The analysis is carried out employing a C0 QUAD-8 isoperimetric higher-order finite element. It is shown that the shear deformation theory without accounting for the thickness-stretching effect and slope discontinuity in the in-plane displacements may not be adequate for the analysis of fairly thick composite laminates exposed to hygrothermal loading. The significance of retaining various higher-order terms in the present model, in evaluating the deflection, buckling and natural frequency for composite laminates at different moisture concentration and temperature, is brought out through parametric study.

Chakraverty et al., [9] tested E-Glass reinforced epoxy composites, which first exposed to an environment laden with moisture (hygrothermal; 600℃, 95% humidity) and then to up and down-thermal shocks for different lengths of time. A 3-point bend test using INSTRON-1195 is carried out to estimate inter laminar shear strength (ILSS) values of the shock treated and untreated samples (after hygrothermal exposure) separately. Low temperature DSC is carried out to record the deviation in Tg, the glass transition temperature. Hygrothermal conditioning without thermal shock reveals a general trend of lowering of ILSS values with varied exposure times. Up and down-thermal shocks are seen to affect the ILSS values

Differently, the lowest Tg being recorded for samples exposed to up-thermal shock after hygrothermal conditioning. Scanning electron micrographs reveal the mode of failure which includes fiber fragmentation, fiber pull-out and fiber matrix debonding.

Papanicolaou et al., [10] aimed to investigate the effect of damage due to hygrothermal fatigue on the mechanical behavior of CFRP (Carbon Fiber Reinforced Polymer) laminates as well as

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on the skin-core interfacial stress field in sandwich structures having CFRP laminates as core material and aluminum as skin. The above behavior was both experimentally and analytically studied using a model recently developed by the CMG group at University of Patras.

S. K. Singh [11] developed an efficient C0 FE model based on Refined Higher Order shear deformation Theory (RHSDT) for hygrothermal analysis of laminated composite plates. The improved C0 FE model based on refined higher order plate theory satisfies the inter-laminar shear stress continuity at the interfaces and zero transverse shear stress conditions at plate top and bottom. In this model the first derivatives of transverse displacement have been treated as independent variables to overcome the problem of C1 continuity associated with the plate theory. In the present theory the above mentioned C0 continuity of the present element is compensated in the stiffness matrix calculations by adding suitable term to the stiffness matrix. In order to avoid stress oscillations observed in the displacement based finite element models, the stress field derived from temperature fields (initial strains) must be consistent with total strain field interpolations used in the finite element formulation. Special steps are introduced (e.g. sampling at gauss points) to compensate this problem. A nine nodded C0 continuous isoparametric element is used to model the proposed theory. Numerical results and comparison with other existing solutions show the present C0 finite element is efficient, accurate and free of locking.

Naceri [12] studied the effect of hygrothermal conditioning on the moisture diffusion properties of the fabric composite (glass fiber/epoxy resin) was investigated. The water uptake of the specimens conditioned in humid environment at different relative humidity's (0, 60 and 96 % r.h.) at constant temperature (60°C) was evaluated by weight gain measurements. The moisture diffusion properties of the fabric composite (glass fiber/epoxy resin) were determined using standard weight gain method. The weight gain experiments were performed to determine the equilibrium moisture content Mm of the fabric composite as a function of relative humidity (r.h.). The measured weight gain is then fit to the solution to the diffusion equation (Fick's law) to determine the diffusivity D. The comparison carried out between the values obtained of the characteristic parameters: diffusivity and maximum weight gain (D and Mm) of the kinetics of water absorption by the hygrothermal test of conditioning carried out into the laboratory and those given by Loos and Springer confirms the following principal remarks clearly: the diffusion coefficient D and the maximum weight gain Mm depend not only on the nature of material but also of the environmental conditions (hygrothermal conditioning). The maximum concentration of water (matrix interface) obtained from calculations based on measured values, where a homogeneous diffusion phenomenon is assumed inside the material (D=0), shows clearly that the presence of fibers in a polymeric matrix reduces the water up-take of the matrix by about 4 times.

Levon Minnetyan [13] investigated the influence of hygrothermal environmental conditions on the load carrying ability and response of composite structures via computational simulation. An integrated computer code is utilized for the simulation of composite structural degradation under loading. Damage initiation, damage growth, fracture progression, and global structural fracture are included in the simulation. Results demonstrate the significance of hygro-thermal effects on composite structural response, toughness, and durability.

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EXPERIMENTAL WORK

Apparatus

Fatigue test rig

Figure (3-1a to 3-1c) shows the details of the fatigue machine, it consists of the following components:

- Strain measurements system: This consists of two strain gauges one for tensile and the other for compression. The strain gauges are connected by a Whetstone bridge .The output of this circuit is feeding to the strain meter which is calibrated to measure the stress. The strain gauges are glued to a polished steel plate to which one of the specimen grips is connected.
- Connecting rod with adjustable length to adjust the displacement ratio (R). This rod is connect at one end to cam system which is attached to shaft connected to electric motor by an open belt drive system. The other end is connected to the specimen grip.
- Digital Counter to record the number of cycles.
- Automatic stop switch.

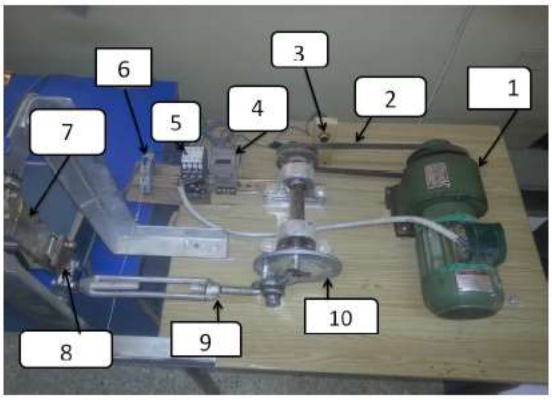

Fig 3.1a: Fatigue machine components.

(1) Electric Motor. (2) Belt Drive. (3) Revolution pointer. (4) Counter. (5) Circuit breaker. (6) Stopper. (7) Specimen. (8) Specimen gripper. (9) Connecting rod. (10) Cam.

Fig 3.1b: Fatigue machine Strain meter component.

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(c)

Figure 3.1c: Fatigue machine strain gauge.

Fabrication of Specimen

The composite specimens are manufactured from woven and random fiber glass and polyester as a matrix with volume fraction (33%) by hand layup method. Figures (3-2a to 3-2f) show the various steps of preparing the specimens and the dimensions of the tested specimens.

Fig 3-2a

Fig 3-2b

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Fig 3-2c

Fig 3-2d

Fig 3-2e

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Fig 3-2f

Fiber volume fraction and its calculations:

Fiber volume fraction means the amount of fiber present in the composite material and can be calculated from the following equation.

$$V_f = \frac{\rho_m W_f}{\rho_f W_m + \rho_m W_f}$$

Where:

V_f: Volume fraction of fibers.

W_f: Weight of fibers.

W_m: Weight of matrix.

ρ_f: Density of fibers.

ρ_m: Density of matrix.

Test Procedure

- Place the specimens in container filled with water for different periods. The water temperature is controlled by a thermostat sensor inside water and connected to cooler/ heater mounted in a closed water cycle with the pan. A digital time counter (solar/ battery) powered displays time in hours and days.
- Connect the specimen to the grips of the fatigue test machine.
- Adjust the displacement ratio and running the machine.
- After specific time such as I hour, the number of cycles and the strain meter reading are recorded.

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RESULTS AND DISCUSSION

Figures (4-1 to 4-4)) show typical force –cycle histories for woven composite. The abscissa contains the number of cycles: the ordinate axis shows the force (Newton), which is measured by strain gauges during the fatigue test s at constant bending displacement. The woven specimens degrade gradually and their stiffness is reduced significantly after 20000 cycles.

Figure (4-5) show the comparison between the specimens for different periods. This figure indicates that the moisture has a significant effect on composite stiffness, i.e. the moisture reduces the composite stiffness.

Figures (4-6 to 4-9) show typical force–cycle histories for random composite. The abscissa contains the number of cycles: the ordinate axis shows the force (Newton), which is measured by strain gauges during the fatigue test s at constant bending displacement. The random specimens degrade gradually and their stiffness is reduced significantly after 20000 cycles.

Figure (4-10) shows the comparison between the specimens for different periods. This figure indicates that the moisture has a significant effect on composite stiffness, i.e. the moisture reduces the composite stiffness. From the results it can be seen that the initial force on the woven composite is smaller, because their stiffness is lower than random type.

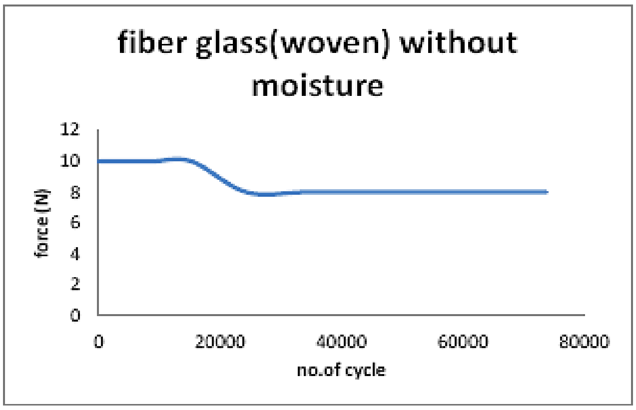

Fig 4-1: Bending fatigue behavior of woven composite materials without aging.

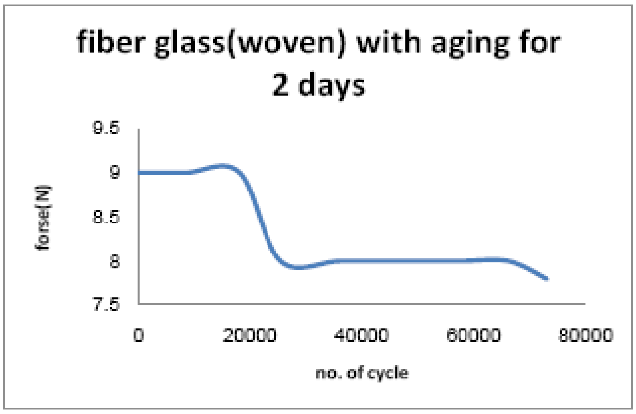

Fig 4-2: Bending fatigue behavior of woven composite materials with aging for 2 days (0.00598).

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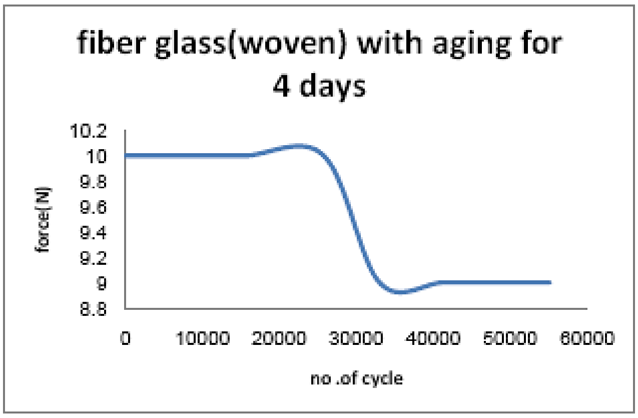

Fig 4-3: Bending fatigue behavior of woven composite materials with aging for 4 days (0.023).

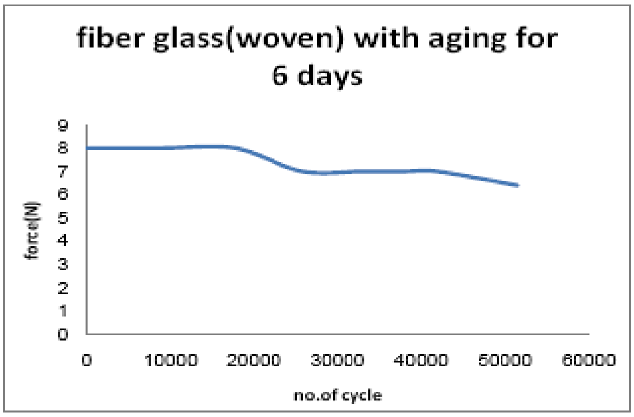

Fig 4-4: Bending fatigue behavior of woven composite materials with aging for 6 days (0.052).

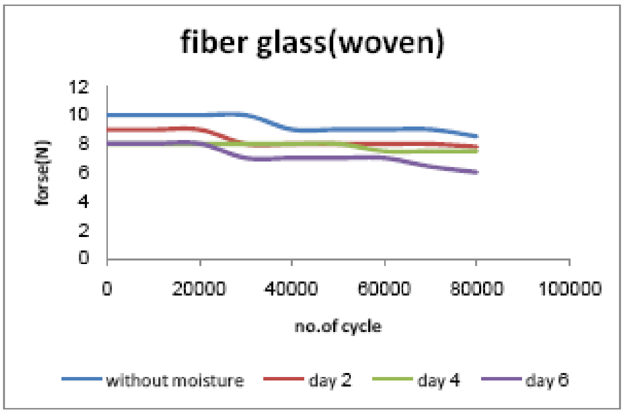

Fig 4-5: Comparison of Bending fatigue behavior of woven composite materials for different periods.

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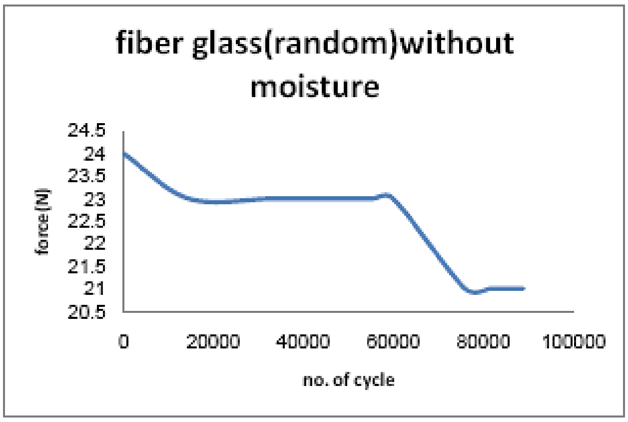

Fig 4-6: Bending fatigue behavior of Random composite materials without aging.

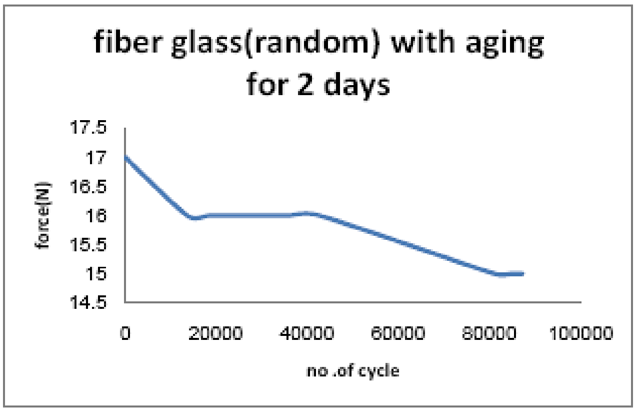

Fig 4-7: Bending fatigue behavior of random composite materials with aging for 2 days (0.00818).

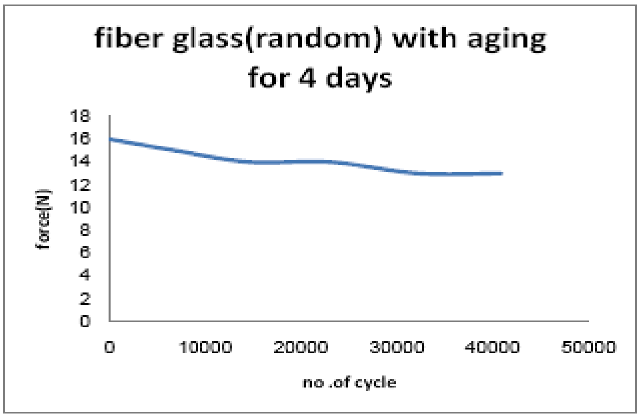

Fig 4-8: Bending fatigue behavior of random composite materials with aging for 4 days (0.019).

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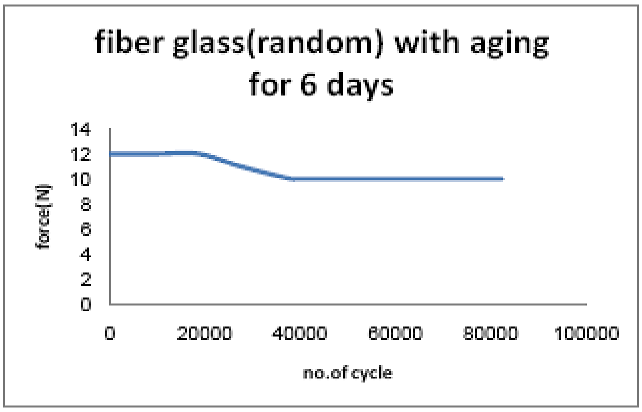

Fig 4-9: Bending fatigue behavior of random composite materials with aging for 6 days (0.041).

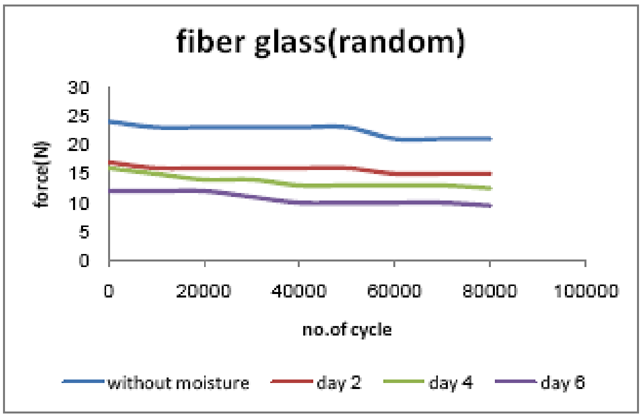

Fig 4-10: Bending fatigue behavior of random composite materials with aging for different periods.

CONCLUSIONS

The moisture content has a significant effect on the composite stiffness.
The random composite have higher stiffness than woven composite.
The stiffness reduced after 20000 cycles.

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