Mechanical properties and water absorption profile of GFRP composites

5.1 Introduction:

The present investigation consists of two parts where the first part containing the investigation of the elastic property of polymer composite which is helpful in structural design and then application of this composite as in case of boat hulls and also in case of other automotive parts and aerospace industry which is generally facing different water condition during operation so here I have considered three water situation: seawater, acidic water, and distilled water. The effect of varying diameter and volume fraction on the property of composite have been presented using FEA (Abaqus) and Analytical methods which results in an improvement in the property by increasing the value of diameter and volume fraction. The main aim of this article is to relate the value of the analytical method with the computational results to obtain the best property. It seems to be GFRP composite is most effective if the load is acting along the direction of fiber. There is a good agreement between FEA and Analytical results. Nielsen elastic model showing large variation after 60% volume fraction. The water absorption effect on composites is studied. Different water conditions are as follows: seawater, acidic water, and distilled water. This test is done on room temperature and elevated temperature during the different time intervals. From the results found it was observed that the pattern of water absorption resembles non-Fickian. Maximum moisture content value (M_m) values are 11.855. Mostly, the application of this research is in the case of Boat hulls (flat, round, multi, vee, etc.) which generally faces these types of water. So the design of Boat hulls, automotive parts, aerospace vehicle parts etc should be based on acidic water.

5.2 Problem Description

The effect of varying diameter and volume fraction on the property of composite is presented with the help of RVE model. As an initial assumption, The model used is (a) cube of size 21.1μm and the volume fraction ranging from 10 to 75%. The fiber diameter is obtained with the help of volume fraction. The property of matrix and fiber are shown in Table 5.1 (a) and (b) (supplied by hindoostan composite solution).

5.3 Micromechanical Modeling

The main aim of this paper is to calculate the mechanical properties of glass fiber reinforced polymer (GFRP) composite. So micromechanical models are used to calculate their properties. The used models are Voigt model, Tsai Hahn's Equation, Halpin-Tsai, Micromechanics Model, Nielsen model, and Chamis method.

5.3.1 Rule of mixture:

This model is developed by Voigt and ruess [79,80]. Here the considered material is a fiber of continuous type and matrix. It is one of the easiest methods to calculate the elastic properties of a unidirectional composite. It represents a simple linear variation of longitudinal Young's modulus E_1 from E_m to E_f as V_f goes from 0 to 1.

Longitudinal properties,

$$E_1 = E_f V_f + E_m(1-V_f)$$

$$\nu_{12} = \nu_f V_f + \nu_m V_m$$

Where, V_f *and* V_m *are volume fractions.* (5.1)

Transverse properties,

$$E_2 = \frac{E_m E_f}{E_m V_f + E_f V_m}$$

$$\nu_{21} = \frac{\nu_{12}}{E_1} E_2$$

Shear properties,

$$G = \frac{E}{2(1+\nu)}$$

$$G_{12} = \frac{G_f G_m}{G_m V_f + G_f (1-V_f)}$$

5.3.2 Nielsen Elastic [175] Model

It is obtained by simply introducing maximum packing fraction ϕ_{max} and its value depends on model geometry. ϕ_{max}= 0.785 and 0.907 used in a square and hexagonal array of fibers.

$$\frac{P}{P_m} = \frac{1 + \zeta\eta V_f}{1 - \eta\psi V_f}$$

$$\eta = \frac{\left(\frac{P_f}{P_m}\right) - 1}{\left(\frac{P_f}{P_m}\right) + \zeta}$$

$$\psi = 1 + \frac{(1 - \phi_{max})}{\phi_{max}^2} V_f$$

5.3.3 The Halpin-Tsai [115] model

It tends to correct longitudinal shear modulus and the transversal

Young's modulus.

$$\frac{E_2}{E_m} = \frac{1 + \xi\eta\nu_f}{1 - \eta\nu_f}$$

$$\eta = \frac{\left(\frac{E_f}{E_m}\right) - 1}{\left(\frac{E_f}{E_m}\right) + \zeta}$$

ξ=curve fitting parameter

ξ=2 for E_2 of square array of circular fibers

ξ=1 for G_{12}

5.3.4 The Chamis micromechanical [176] model

It is the most used and trusted model which gives a formulation for all five independent elastic properties.

$$E_1 = E_f V_f + E_m V_m$$

$$E_2 = \frac{E_m}{1 - \left\{\sqrt{V_f}\left[1 - \left(\frac{E_m}{E_f}\right)\right]\right\}}$$

$$\nu_{12} = \nu_f V_f + \nu_m V_m$$

$$G_{12} = \frac{G_m}{1 - \left\{\sqrt{V_f}\left[1 - \left(\frac{G_m}{G_f}\right)\right]\right\}}$$

5.4 Finite Element Analysis Using Abaqus

This method is employed to calculate the property of GFRP composite material. It contains the E_{11}, E_{22}, μ_{12}, μ_{21}, G_{12}. The RVE (representative volume element) is observed as a clamped free arrangement and the load is axial displacement =1µm. And it is applied on the free edge as given in Figure 5.1

By applying Hook's law on the RVE following value is obtained:

$$\delta l = \frac{PL}{AE} \qquad E = \frac{PL}{A\delta l} \tag{5.2}$$

Where L =Preliminary length of RVE, E =Modulus of elasticity in the direction of displacement, A =Cross-section area, and F= force created at the nodes of section and can be evaluated by using this software.

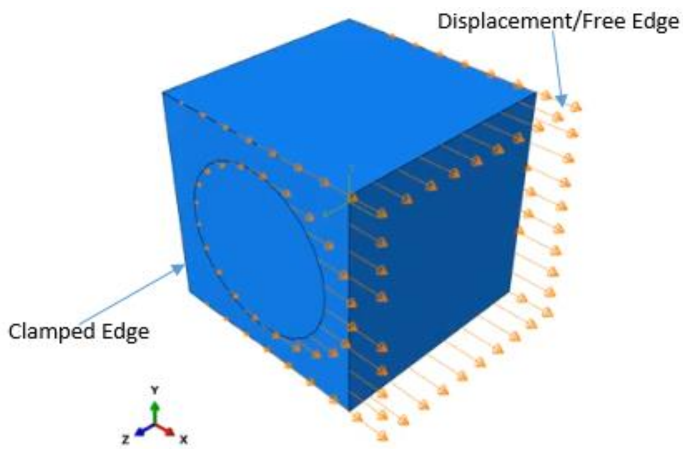


Figure 5.1. 3D RVE loading and boundary condition

So E can be calculated in that particular direction. Similarly E_{22}, E_{33} value is obtained. The Poisson's ratio can be calculated as:

$$\nu = -\frac{\varepsilon_{transverse}}{\varepsilon_{longitudinal}} \tag{5.3}$$

The shape and size of the mesh will affect the results. There is an improvement in results as we are decreasing the mesh size, By decreasing the mesh size the chances of getting an error increased so the calculation time is increased. So the resultant shape is reliant on geometry. So, according to geometry the best shape is selected. The most suitable mesh size is obtained using the Trial and error technique. Let us take a starting mesh size and FEA will calculate the result. The results will be recalculated based on the selected smaller mesh. This process is going to be continued up until the results are optimum. The meshes are triangular, square and many other shapes, while the triangular and square meshes are foremost common. In this Investigation, because of the Cube-shape geometry, the most suitable meshes are Hex-dom inated meshing. Here, after performing so many times trial and error practice the optimal mesh size obtained is 1 and the calculated values are converged and it is shown in Figure 5.2.

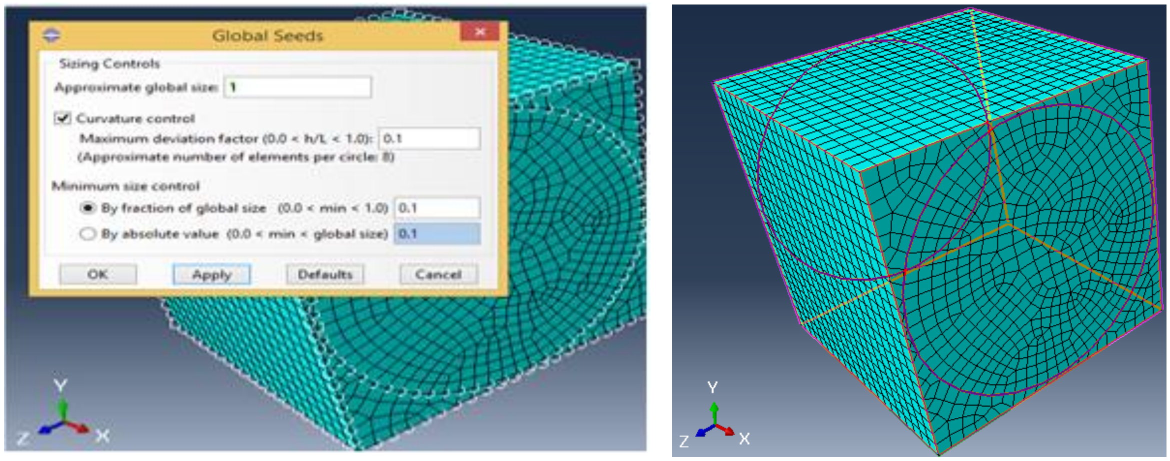


Figure 5.2. The final mesh of 3D RVE of Neat Composite

5.5 Computational Results and Discussion

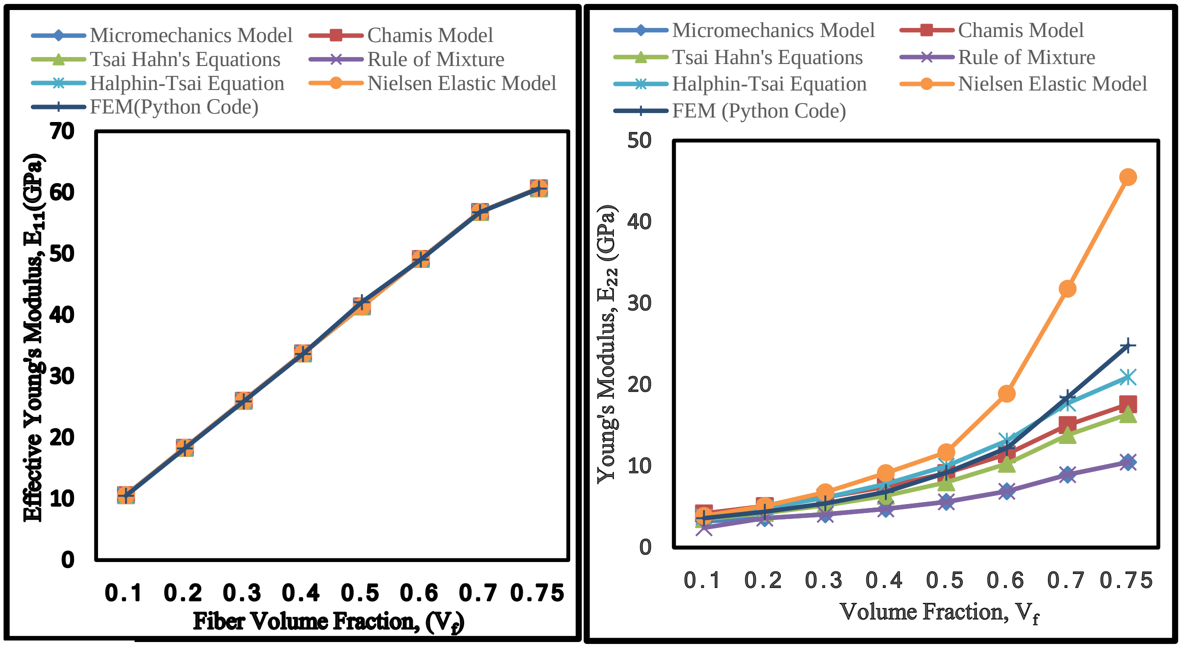
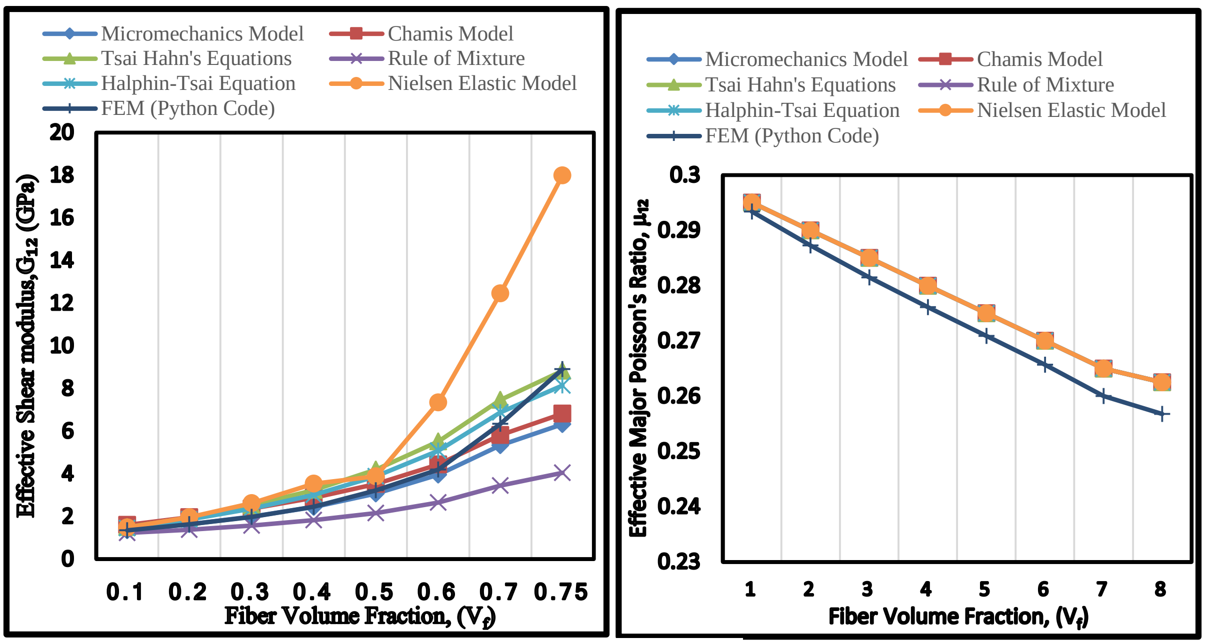


Figure 5.3. Variation of (a) longitudinal modulus and (b) Transverse modulus of elasticity versus fiber volume fraction

The calculated results such as various modulus and poisons ratio for various volume fraction with the help of RVE where the volume fraction range =10 to 75% is considered.

The results are presented in the form of the chart as shown in fig. 3 to 7. The FEA results and analytical results are compared. Analytical models used are Micromechanics Model, Tsai Hahn's equation, Nielsen method, etc. properly predict the effects of varying diameter and volume fraction on E_{11} , E_{22} , μ_{12} , μ_{21} , G_{12} of composites. As V_f increases E_{11} increases linearly is shown in Figure 5.3. The FEA values and analytical model give very good predictions in the case of E_{11} but there is a slight variation in E_{22} , μ_{12} , μ_{21} , G_{12} of the composite.



(a) (b)

Figure 5.4. Shear modulus (b) Poisson's ratio versus volume percent of fiber

In the composite system, a portion of the matrix is substituted by a fiber. As a result, fiber content increases which make composite stiffer and stiffer and give the higher value of modulus of elasticity. FEM also presents that behavior. With the help of contour results against V_f, a graph is generated and there is a non-linear plot between V_f and modulus of elasticity E_2 as shown in Figure 5.4 Halpin-Tsai and Chamis model overvalue the FEA results, while Voigt model gives good prediction with FEA value. There is large variation in result after 50% volume fraction. However, the Nielsen method also shows good prediction. The fiber percentage up to 40% approximately has shown very less effect on the E_2. With the help of contour results against V_f, a graph is generated and there is a non-linear plot between V_f and modulus of rigidity G_{12} as shown in Figure 5.4. There is a non-linear behaviour between G_{12} and V_f. By varying V_f the G_{12} value going to increase. Halpin-Tsai method and Chamis method over estimate the FEA result. The shear modulus increases gradually by increasing the fiber percentage. Hence there is maximum contribution of fiber to achieve best result for composite if the applied load is shear. The best result is obtained for highest value of V_f.

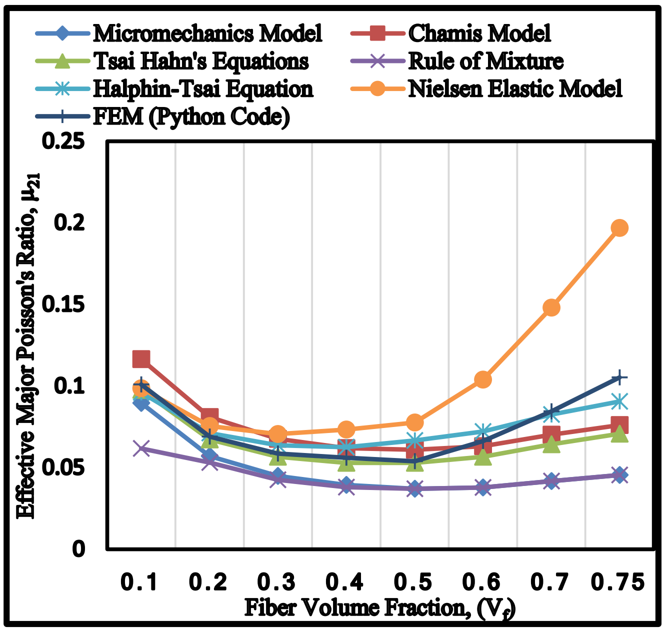


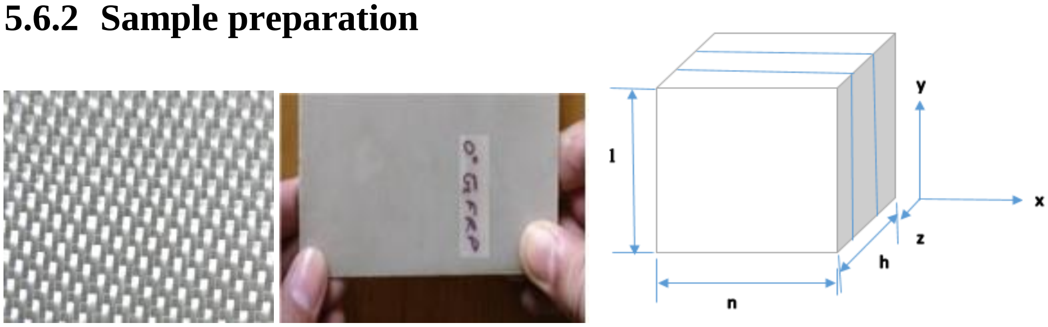
Figure 5.5. Poissons ratio variation against volume fraction of fiber

5.6 Experimental Details

5.6.1 Materials and Fabrication of composite

The GFRP composite was fabricated with the help of a hand layup method. According to the requirement of total number of specimens required for characterization of composite a composite plate is being manufactured having dimension 275 mm x 190 mm x 2.5 mm and having ply orientation of 0 degree and 90 degree respectively. Firstly, the required amount of Hin-preg®A45 epoxy resin and hardener mixed in an appropriate ratio of 10:3. After mixing resin and hardener in proper ratio mixture is stirred using magnetic stirre for half an hour for obtaining a uniform solution. As the mixture gets warmed up laminated composites are laid using layer deposition method to counter epoxy accumulation and to avoid dry patches a pressure of 10KPa is applied on the top surface. Perfect curing of composites occurs approximately after 22 hours. After complete curing, composites are cut into required sample dimensions for experimental testing.

5.6.2 Sample preparation



(a) (b) (c)

Figure 5.6. (a) Woven E-glass (b) Composite plate $(0^0,0^0,0^0,0^0)_S$ (c) Geometry of the test specimen [177]

Table 5.1. (a) Properties of the glass fiber

Properties	Value	Unit
E-modulus	80	GPa
Poisson's ratio	0.25	
Volume fraction	0.5	
Density	2.62	g/cm^3
Shear-modulus	32	GPa

(b) Properties of the Matrix (Epoxy)

Properties	Value	Unit
E-modulus	2.915	GPa
Poisson's ratio	0.3	
Volume fraction	0.5	
Density	1.15	g/cm^3
Shear-modulus	1.121	GPa

Prepared samples as per the required dimension are used for the water absorption test. The process of polishing samples is performed using different grades. Grades of the emery used include 50,200 and 600 numbers for obtaining proper geometry and perfect surface finish. The E- glass fiber and fabricated composite plate is shown in Figure 5.6 (a) and (b) respectively. For water absorption investigation, square samples were prepared having dimension 1cm×1cm from the composite plate as per condition h/l<1, h/n<1. Figure 5.6 provides an idea about the properties of Glass fibers and matrix.

5.7 Material characterization

The water absorption effect on composites is studied. Different water conditions are as follows: seawater, acidic water, and distilled water. This test is done on room temperature and elevated temperature during a different time intervals. During the measurement of water absorption, withdrawing the composite specimen during a different span of the time interval from the solution, and remove surface moisture with the help of tissue paper, and then weighted with the help of an electronic balance to monitor the weight gained.

Figure 5.7. The flask containing Acidic water, distilled water and seawater

The water absorption process of FRP composites is at first water absorption takes place lin early inside the polymer obeying Fick’s law and thereafter saturated nearly and finally stopped. Furthermore, it increases due to capillary action and digression of epoxy polymer and there is a penetration of water through micro-cracks. With the help of equation (5.4) the moistness content M (%) of the composite was calculated (ASTM D5229):

$$M(\%) = 100\left(\frac{M_1 - M_0}{M_0}\right) \qquad (5.4)$$

Where, M(%) = moisture content (%); M1(g) = wet sample weight at a particular time, and M0(g) =initial weight. Next to water absorption behavior is being analyzed by calculating diffusion coefficient (D) and to achieve these GFRP composite samples are dipped in different solutions. Diffusion coefficient (D) can be calculated as:

$$D = \left(\frac{kh}{4M_m}\right)^2 \qquad (5.5)$$

Where, Mm (%) = maximum weight gain (%); h (mm) = thickness of specimen; and k = initial slope can be calculated as:

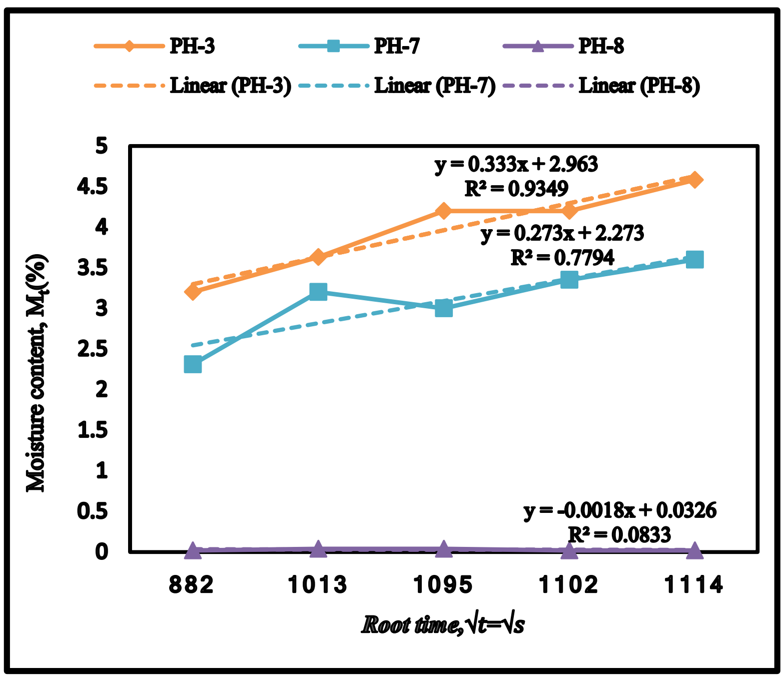


Figure 5.8. Neat composite having 90 Degree ply orientation

$$k = \left(\frac{M_2 - M_1}{\sqrt{T_2} - \sqrt{T_1}} \right)^2 \quad (5.6)$$

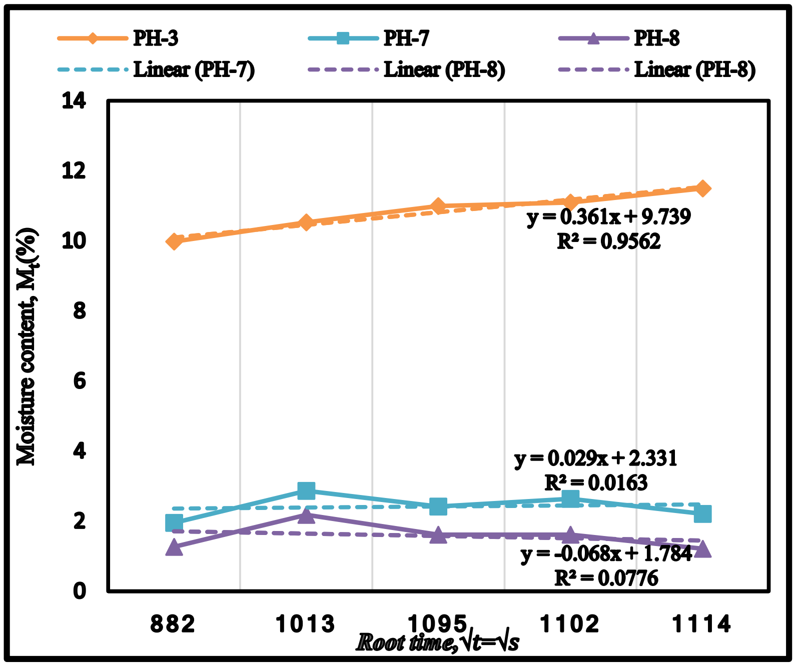


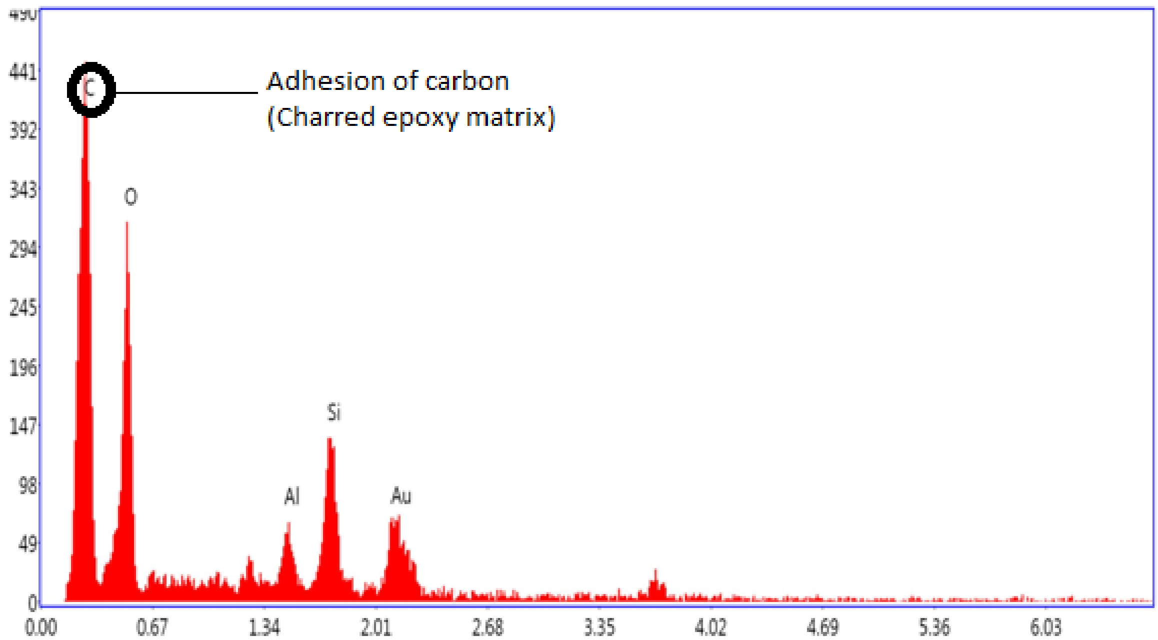
Figure 5.9. Neat composite having 0 Degree ply orientation

The first reading was taken before loading and then after loading of the water absorption process. Therefore, the difference in weight can be easily visible and recorded and this change took place linearly with root time, $\sqrt{t}=\sqrt{s}$. The resultant values are shown in Table 5.2

Table 5.2. The maximum moisture content, M_m (%) of GFRP composite.

Sample	Maximum moisture content, M_m (%)
Zero degree Ph-3	11.21
Ninty degree Ph-3	11.855
Zero degree Ph-7	2.87
Ninty degree Ph-7	3.33
Zero degree Ph-8	2.18
Ninty degree Ph-8	0.038

5.8 Energy-dispersive X-ray spectroscopy (EDS)



Element	Weight %	Atomic %	Net Int.	Error %
C K	49.63	65.16	115.94	8.47
O K	28.45	28.05	63.95	10.68
AlK	2.68	1.56	12.64	12.98
SiK	7.66	4.30	33.83	8.44
AuM	11.59	0.93	16.36	15.10

Figure 5.10. EDS elemental spectrum and quantification results.

EDS is a chemical microanalysis technique used in conjunction with scanning electron microscopy. To determine the elemental composition of the investigated volume, it recognises x-rays that the sample emits while being bombarded by an electron beam. Carbon adhesion is confirmed by EDS analysis on the composite face and is caused by the burned epoxy. The analysis is shown in Figure 5.10.

5.9 Microscopic Examination

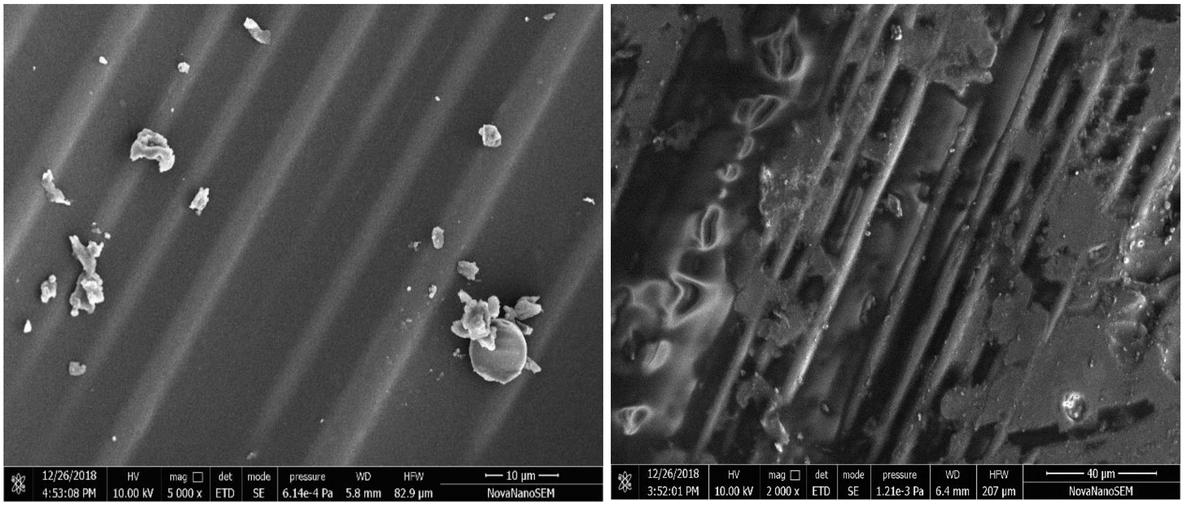


Figure 5.11. Cross sectional identical distribution of Glass fibers inside the epoxy matrix.

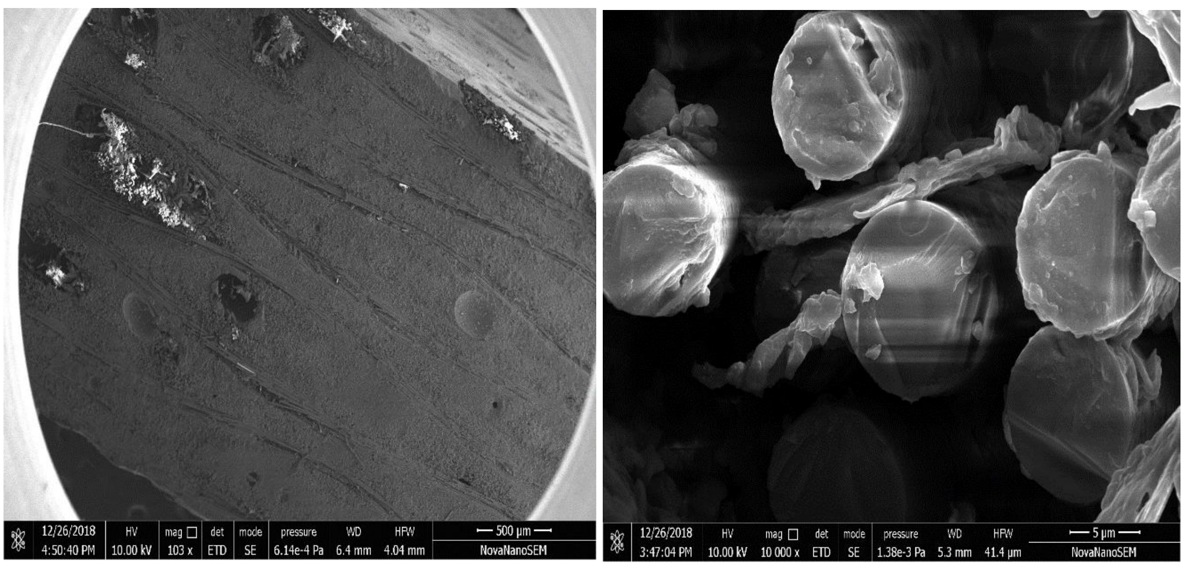


Figure 5.12. Longitudinal identical distribution of Glass fibers inside the epoxy matrix.

5.10 Results and Discussions

Water absorption behavior of GFRP composites samples, were immersed into three different aqueous environments, namely: an acidic solution (pH-3), seawater (pH-8), and distilled water (pH-7) which were at room temperature and at elevated temperature, for a period of 9 days, 12 days under room temperature and then 2 more days,16 hours and then 7 hours under elevated temperature. These solutions have been chosen because these solutions represent real-life situation and the solutions are applied on those samples. Those three solutions were also applied by the earlier researcher [5,6]. Water absorption profile, for 0^0 ply orientation composite specimen and 90^0 ply orientation composite specimens, as given in Figure 5.9 and Figure 5.8 respectively. From the water absorption curves, it is clear that with an increasing immersion time the absorbed water content increased. These findings were published earlier regarding the GFRP composites [5–7]. The pattern of water absorption resembles non-Fickian and showing increasing tendency and never attain equilibrium after the start. Similar findings were previously reported [5,6]. The moisture uptake never reaches equilibrium, and follow non-Fickian behavior. The maximum moisture content, Mm for GFRP composite are represented in Table 5.2. The highest value of moisture content, immersed in acidic solution, followed by a distilled water, and seawater. Further, the diffusion coefficient is calculated with the help of equation (5.5). Based on the diffusion coefficient value diffusion of water GFRP composite is more suitable in case of distilled water, than acidic water and lastly seawater due to the presence of huge salt molecules within the seawater which slows down the diffusion technique inside the matrix of a composite material, which results to lesser absorption kinetic factors.22 It is similar to the hydrolysis technique of cellulose inside the fiber. The hydrolysis is more noticeable in acidic water, compared with distilled water and lastly seawater.

5.11 Conclusion

The present investigation consists of two parts where the first part containing the investigation of the elastic property of polymer composite which is helpful in structural design and then application of this composite as in case of boat hulls and also in case of other automotive parts and aerospace industry which is generally facing different water condition during operation so here I have considered three water situation: seawater, acidic water, and distilled water. The Effective Elastic Moduli of polymer composite is being investigated using FEM methodology. There is a good agreement between FEA and Analytical results. There is a linear increment of E_{11} value whereas in case of E_{22} value there is non-linear increment as the V_f is going to increase from 0 to 75%. The μ_{12} and μ_{21} value given by FEA are closely agreed with the value given by the Analytical solution. There is a linear decrement in the value of μ_{12} and having a good agreement with Analytical value. On the other hand, there is a decrement in value of μ_{21} until reaching minimum value and then again there is an increment in value as V_f increases. Almost all methods showing good agreement up to 50% volume fraction and thereafter deviation is going to increase. Nielsen elastic method showing large variation after 50% volume fraction. There is an increment in the value of modulus of rigidity G12 by increasing V_f. Almost all methods showing good agreement. Further, it can be concluded that the rule of mixture showing negligible variation but Nielsen elastic method showing large and maximum deviation after 50%. Nielsen elastic model showing large variation after 50% volume fraction. The water absorption effect on composites is studied. Different water conditions are as follows: seawater, acidic water, and distilled water. This test is done on room temperature and elevated temperature during a different time intervals. From the results found it was observed that the pattern of water absorption resembles non-Fickian. Maximum moisture content value (Mm) and the highest diffusion coefficient (D) value has been recorded And found that The specimen is absorbing maximum acidic water than distilled water and lastly the seawater. Mostly, the application of this research is in the case of Boat hulls (flat, round, multi, vee, etc.) which generally faces these types of water. So the designer should be keeping in mind acidic water as a criterion during the design of Boat hulls, automotive parts, aerospace vehicle parts.