Experimental Investigation and Mathematical Modeling of Tensile Properties of Unsaturated Polyester Reinforced by Woven Glass Fibers

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Received on: 17/6 /2013 & Accepted on: 3/10 /2013

ABSTRACT

This research studied the tensile properties of glass fiber reinforced unsaturated polyester with different fiber volume fraction V_f, and angle of fibers for coarse and fine woven fibers reinforcement. The composite specimens were prepared by hand lay-up technique and cutting according to (ASTM D – 638) for tensile test to obtain modulus of elasticity, ultimate tensile strength and elongation percentage of the composite specimens. Mathematical models were done by using statistical analysis which shows the tensile properties of the composite specimens as a function of volume fraction and fiber angle.

The results show that the maximum value of the modulus of elasticity was (11.5 GPA) and the maximum value of ultimate tensile strength was (240 MPa) which happed at (11% V_F) for fine woven fibers and for ($0^{\circ}/90^{\circ}$) fibers angle, and vice versa for percentage elongation was (2.5%).

Keywords: - Polymer Composite, Glass Fiber, Tensile Test, Model.

التقصي العملي والنمذجه الرياضيه لخصائص الشد للبولي استر الغير مشبع المقوى بالياف الزجاج الحصيرية

الخلاصه

في هذا البحث تم دراسة خواص الشد للبولي استر غير مشبع مقوى بالياف الزجاج عند تغير كل من الكسر الحجمي وزاوية الليف لنوعين من التقوية الحصيرة الخشنه والناعمه. حضرت العينات المركبة بالطريقة اليدوية وقطعت وفق المواصفه (ASTM D – 638) لفحص الشد للحصول على معامل المرونة واقصى أجهاد شد والاستطالة النسبية لهذه العينات. تم عمل نماذج رياضية باستخدام التحليل الأحصائي الذي يبين خواص الشد كدالة لكسر الحجمي وزاوية الليف.

بينت النتائج بان اقصى قيمة لمعامل المرونة كانت (11.5 GPa) واقصى اجهاد شد كان (240 MPa) يحصلان عند الكسر حجمي (11%) عند التقوية بالحصيرة الناعمة ولزاوية ليف ($0^{o}/90^{o}$) والعكس بالعكس للاستطاله النسبية حيث كانت (2.5%).

https://doi.org/10.30684/etj.32.3A.8
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INTRODUCTION

During the past few decades, many polymer composites have been prepared and combined with various types of synthetic reinforcing fillers in order to improve the mechanical properties and obtain the characteristics demanded in actual applications [1].

Today, polymer composite materials are replacing many conventional materials. Fiber-reinforced composite polymers have several advantages over conventional materials, such as low weight, low cost, and ease of processing. Also good strength/stiffness ratio, good static and dynamic properties, as well as good resistance to corrosion [2].

Composite materials have a wide range of applications thanks to their good properties under loading conditions such as structure, ship, aerospace, aircraft, boat and car industries. The efficiency of the fiber-reinforced composites also depends on the manufacturing process that the ability to transfer stress from the matrix to fiber [3].

Fiber-reinforced composites with exceptionally high specific strengths and moduli have been produced that utilize low-density fiber and matrix materials [4].

Rot & et al. investigated the tensile strength of polyester reinforced by E-glass fiber. There studied the tensile strengths of the polyester laminates were determined as a measure of interfacial bond strength. In accordance with the principle of factorial design [5].

Araujo & et al. studied the mechanical properties and water sorption behavior of polyester /fiber glass composite of recycled fiber glass were prepared by compression molding and compared with polyester/virgin glass fiber composites. The results showed that fiber glass wastes are promising to be reused in polyester resin composites [6].

Rejab & et al. illustrated the mechanical properties of chopped E-glass fiber reinforced polyester resin with different fiber volume fraction by considering both analytical and experimental method. The experimental results show that the mechanical properties were improved when volume fraction is increased [7] **.**

Anbusagar & et al. studied analysis of fiber reinforced polymer using experimental and CLT approach. The fibers are used to prepare laminates are chopped strand mat (CSM), glass fiber (random orientation), woven roving mat (WRM) glass fiber (cross ply orientation of $0^{\circ}/90^{\circ}$) and unidirectional glass fiber (UDF) with polyester resin. This work presents a modified laminate structure from existing laminate structure and to produce the boat of 650 Kg in the fiber-reinforced polymer. It was found that a modified symmetric laminate is a suitable laminate for the manufacture of fishing boat [8].

Irawan & et al. studied tensile strength of ramie fiber (RE) reinforced epoxy resin to development of prosthesis with (RE) as an attempt to substitute socket prosthesis with fiber glass/polyester composite (FGP). The results showed that socket prosthesis made of RE has highest tensile and flexural strengths when compared to RE and FGP composite materials [9].

Jawad & et al. studied the tensile strength of unsaturated polyester (UPE)/polyvinal chloride (PVC) reinforced with random glass fiber. The results show increasing the values of maximum stress, yielding stress and modulus of elasticity for UPE/PVC blends with increasing the weight percentage of (PVC) [10].

Putic & et al. studied the effect of alkaline solutions on the tensile properties of glass polyester pipes. It was found that the alkaline solutions lead to adecrease the tensile properties [11].

The aim of this research was to study the influence of volume fraction and orientation of glass fibers on tensile properties of unsaturated polyester reinforced by woven fine and coarse fibers.

Theoretical Analysis

The modulus of elasticity for the composite material determined in term of the properties of the fibers and the matrix and in term of the relative volumes of fiber and matrix .The modulus of elasticity in the longitudinal direction is [12] :-

$$E_{c(II)} = E_f V_f + E_m V_m \qquad \dots (1)$$

Also the modulus of elasticity in the lateral direction is:-

$$E_{c(\perp)} = \frac{E_f E_m}{E_f V_m + E_m V_f} \qquad \dots (2)$$

Where:-

E_f & E_m =Young modulus for fiber and matrix respectively.

V_f & V_m = volume fraction for fiber and matrix respectively.

From tensile test the relationship between stress and strain can be expressed as:-

$$\sigma = E.\varepsilon \qquad \dots (3)$$

Tensile strength is calculated by dividing the load at break by the original minimum cross sectional area.

$$\text{Tensile strength} = \frac{(\text{load at break})}{(\text{original width})(\text{original thickness})}$$

The strain which is used in such stress –strain curve is a linear strain and can be expressed as:-

$$\varepsilon = \frac{\Delta L}{L_{\circ}} \qquad \dots (4)$$

Where:-

ΔL: $L - L_{\circ}$

L: The final length (m).

$L_{\circ}$: The original length (m).

MATHEMATICAL MODEL

Response surface method (RSM) is a collection of a mathematical and statistical technique that are useful for modeling, analysis and optimizing the process in which response of interest is influenced by several variables and the objective. In many engineering fields, there is a relationship between an output variable of interest "z" and a set of controllable variables {x, y ….., N_n}. In some systems, the nature of relationship between y and x values might be known. Then, a model can be written in the form [13] :-

$$z = f(x, y\dots N) + \mathcal{E} \qquad \dots (5)$$

The variables (*x*, *y* and N) are independent variables where the response (*z*) depends on them. The experimental error term, denoted as Ɛ.

In this study, multiple polynomial (least square fitting) regression analysis is used to establish a mathematical model among the experimentally obtained parameters. Multiple regression analysis techniques are applied to relate the volume fraction and angle of glass fibers for two type (fine and coarse fiber), the best form of the of the relationship between the property, volume fraction and angle of fiber parameters is chosen in the form of [14]:-

$$z = a_\circ + b * x + c * y + d * x^2 + e * y^2 + g * x * y \qquad \dots (6)$$

The analysis of variance (ANOVA) is also called coefficient of multiple determination referred to (R) measure the proportionate reduction of total variation in associated with use of the set of predictors in the model (is used to cheek the validity of the model) it is defined in terms of SST,SSR, and SSE as [15] :-

$$R^2 = \frac{SSR}{SST} = 1 - \frac{SSE}{SST} \qquad \dots (7)$$

Where:-

SSE:- the sum of squared error.

SSR:- the regression sum of squares.

SST:-the total correct sum of squares.

EXPERIMENTAL WORK

Basically two main tasks were carried out to achieve the objectives of study. The first task was the preparation of composite material by combining the unsaturated polyester and woven fiber glass (illustrated in Figure (1)) with different fibers volume fraction (0, 3, 5 & 8 % V_f) for coarse fibers and (0, 4, 7 & 11% V_f) for fine fibers, and with different angle of fiber ($0^\circ/90^\circ$) and ($45^\circ/-45^\circ$). Then it was continued by performing the tensile test carried out to determine the characteristics of the studied composite. The usage of unsaturated polyester resin as a matrix was chosen because it is the standard economic resin commonly used, preferred material in industry and besides, it yields highly rigid products with a low heat resistance property. The type of unsaturated polyester resin is provided from the Saudi Arabia Company in the form of transparent viscous liquid at room temperature. The resin was prepared by mixing unsaturated polyester with 2% hardener. The hardener type used is the Methyl Etheyl Keton Peroxide (MEKP). The mechanical properties of unsaturated polyester resin and glass fiber are given in Table (1).

PREPARATION OF COMPOSITES

The composite specimens were fabricated by using hand lay-up technique. Composites having different fibers content were prepared by varying the type, volume fraction, and angle of fibers for fine and coarse woven fibers. In the first process of preparing the composite specimens' preparation process is to set the percentage of fibers content in the composite. The amount of resin needed for each category of composite laminate was calculated after that. Then the resin was mixed uniformly with hardener, the mixture was poured carefully into the moulds and left in the mould for 24 hours. After the composites were fully dried, they were separated off from the moulds, and then put the specimens in oven at (55 $^{\circ}$C) for (1 hrs) [16].

Specimens are prepared after the composites are ready. The geometry of the specimens is set by referring to ASTM standard D- 638 as shown in Figure (2) [17].

Tensile test is done by using universal testing machine type (LARYEE) with capacity (50 KN) applied load and strain rate (0.5 mm/min).

RESULTS AND DISCUSSIONS

Tensile Test Results

Stress – Strain Curve

The stress- strain curve for composite specimen reinforced for both coarse and fine fiber is presented in figures (3, 4, 5& 6).

It was cleary evidented that characteristic stress- strain results are trend growing from linearty and eventually develops into nonlinear. The characteristic linear slope predominantly reflects the deformation of glass fibers, while the characteristic nonlinear is basically attributed to the deformation of the matrix resin [18].

It was found that the fiber in the arrangement ($0^{\circ}/90^{\circ}$) the load is applied in fiber direction and then increased gradually till the failure (fracture) of the specimens. While the specimen's with fiber direction ($45^{\circ}/-45^{\circ}$) the load is applied on the direction make angle (45°) with fiber direction. The test in 45° the matrix is dominated, without significant extension in fiber, until the final stages when the fibers eventually stretch and break [19& 20].

Also it is clearly evident that the stress increase with increase volume fraction of fiber, so that the tensile stress found to be maximum for composite with fine fiber was (240 MPa) at (11% V_f) and angle ($0^{\circ}/90^{\circ}$) while the maximum stress for composite with coarse fiber was (215 MPa) at (8 % V_f) and angle ($0^{\circ}/90^{\circ}$).

Modulus of Elasticity

The variation of the modulus of elasticity with the fiber volume fraction for both coarse and fine fibers which of composite specimen as shows in Figures (7 & 8).

It is clear from these Figures, the modulus of elasticity increase with increasing the fiber volume fraction. The maximum value of the modulus of elasticity was obtained for coarse fiber was (9 GPA) at (V_F =8%) and angle of fiber ($0^{\circ}/90^{\circ}$), while the maximum value of the modulus of elasticity was obtained for fine fiber was (11.5GPa) at ($V_{F=}$11%) and angle of fiber was ($0^{\circ}/90^{\circ}$). This shows the indication of the ability of glass fiber to impart greater stiffness to the unsaturated polyester. It is known that fibers which has a higher stiffness than the matrix and that lead to improvement the stiffness of the composites [21 & 22].

As fiber volume fraction increased, the possibility of fiber- matrix interaction which leads to an increased in the efficiency of stress transfer from the matrix phase to the fiber phase. It has been widely accepted that orientations of glass fibers in polymer composites have significant effects on mechanical properties of composite.

Also it is clear from these figure the modulus of elasticity of fiber in ($0^{\circ}/90^{\circ}$) direction higher than ($45^{\circ}/-45^{\circ}$) fiber direction this is because the direction of load fibers causes a homogenous stress distributed on the fibers and the base materials and that leads to distributing the internal stresses on the fibers and the matrix, also the fiber in this direction load achieved to reduce most of stress by the matrix and fibers [10].

Ultimate Tensile Strength

The variation of ultimate tensile strength of specimens composite with varying fiber volume fraction for both coarse and fine fiber is presented in figure (9& 10).

It can be seen that with increasing the fiber volume fraction, the ultimate tensile strength increasing. This is due to the fact that the addition of fibers has strengthen. The interface of resin matrix and fibers where it increase transferred from the matrix therefore, the composite can sustain higher load compared to the unreinforced polyester [23& 24].

As illustrated from figure (9) the maximum value of ultimate tensile strength for composite specimens reinforced with coarse fiber were (215 MPa) and (160 MPa) for ($0^{\circ}/90^{\circ}$) and ($45^{\circ}/-45^{\circ}$) respectively. Also from figure (10) the maximum value of ultimate tensile strength for composite specimens reinforced with fine fiber were (240 MPa) and (195 MPa) for ($0^{\circ}/90^{\circ}$) and ($45^{\circ}/-45^{\circ}$) respectively.

Percentage Elongation

The results of percentage elongation at break for both coarse and fine fibers reinforced unsaturated polyester as shown if figure (11 & 12).

It is show that the percentage elongation at break of the composite specimens, decreased with the increases the fiber volume fraction. This is because the presence of fiber imparts the stiffening effect within the matrix and thus imposed a mechanical restraint on the composite. Also decrease of elongation percentage on the interference that depends between fibers and matrix. Its value decrease this behavior may be attributed to the formation of strong structures [25 & 26].

The minimum value of percentage elongation was obtained for fine fiber was (2.5 %) at (V_f=11%) and angle of fiber is ($0^{\circ}/90^{\circ}$) and minimum value of percentage elongation was obtained for coarse fiber was (3%) at (V_f=8%) and angle of fiber is ($0^{\circ}/90^{\circ}$).

Mathematical Model Result

The experimental results are modeled using RSM. Table (2) shows the summary of models and coefficient multiple determinations (R^2) of the properties as function of (x= volume fraction of fiber) and (y=angle of fiber). It can be seen from these models that the volume fraction have greater effect than the angle of fiber on the properties.

CONCLUSIONS

The experimental investigations used for the analysis of tensile behavior of glass fiber reinforced unsaturated polyester lead to the following conclusions:-

1- The value of young's modulus and ultimate tensile strength of specimens increases with increase fiber volume fraction for two type of glass fiber.

2- Higher modulus of elasticity and ultimate tensile strength in ($0^{\circ}/90^{\circ}$) direction of fiber than ($45^{\circ}/-45^{\circ}$) direction of fiber for two type of fiber.

3- Percentage elongation value decreases with increase the volume fraction of fiber and also lower value of percentage elongation at ($0^{\circ}/90^{\circ}$) for two type of fiber.

4- Mathematical models represent the volume fraction have greater effect than the angle of fiber on the properties.

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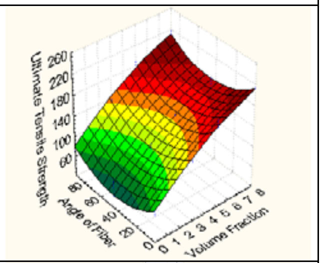
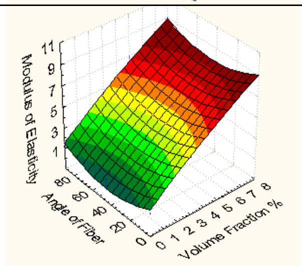
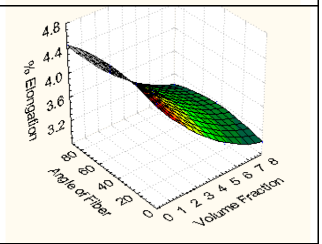
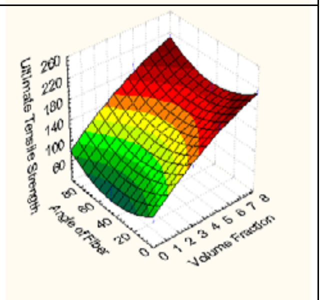
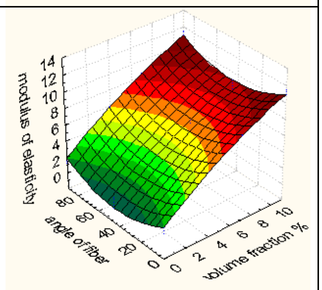
Table (1) Mechanical Properties of the Materials used [4].

Material	Density (gm/cm^3)	Young Modulus (Gpa)	Tensile Strength (Mpa)	Percentage Elongation	Poisson's Ratio
Unsaturated Polyester	1.04-1.46	2.06-4.41	41.4-89.7	< 2.6	0.33
Glass Fiber	2.58	72.5	3450	4.3	0.22

Table (2) Results for mathematical model.

property	Mathematical model and coefficient of multiple determination	Figure
Ultimate tensile strength for fine fiber	$Z=(80.6127)+(23.751)*x+(1.5888)*y+(0.933333)*x^2+(0.017654)*y^2+(5.10559e^{-10})*x*y$ $R^2 = 0.97252$	
Modulus of elasticity for fine fiber	$Z=(1.55686)+(1.09634)*x+(-0.05555)*y+(0.02111)*x^2+(0.0006173)*y^2+(1.26676e-15)*x*y$ $R^2 = 0.99004$	
Percentage elongation for fine fiber	$Z=(4.4549)+(0.295947)*x+(0.00667)*y+(0.01444)*x^2+(-0.000074)*y^2+(4.403417e-17)*x*y$ $R^2 = 0.99683$	
Ultimate tensile strength for coarse fiber	$Z=(81.14487)+(19.49963)*x+(1.544444)*y+(0.4761904)*x^2+(0.0171605)*y^2+(1.11568e-13)*x*y$ $R^2 = 0.98439$	
Modulus of elasticity for coarse fiber	$Z=(1.88666)+(1.11476)*x+(-0.088889)*y+(-0.02619)*x^2+(0.000987)*y^2+(9.35308e-15)*x*y$ $R^2 =0.98532$	

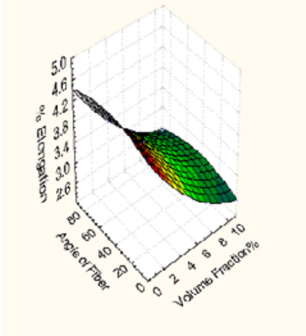
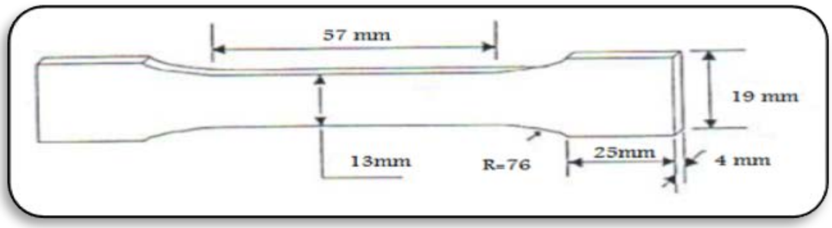
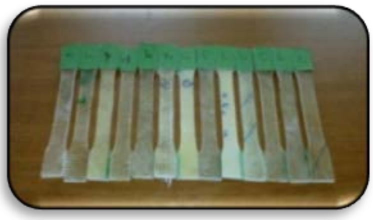
Percentage elongation for coarse fiber	$Z=(4.42269)+(-0.290916)*x+(0.01)*y+(0.010714)*x^2+(-0.00011)*y^2+(8.560813e-18)\ *x*y$ $R^2 = 0.99635$	

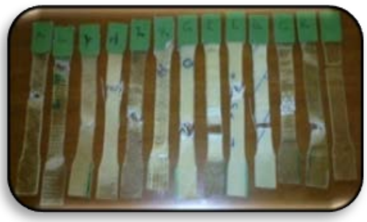
Figure (1) Glass fiber used in this research.



a) Tensile test standard specimen.



b) Before test



c) After test

Figure (2) Composite specimens of tensile test.

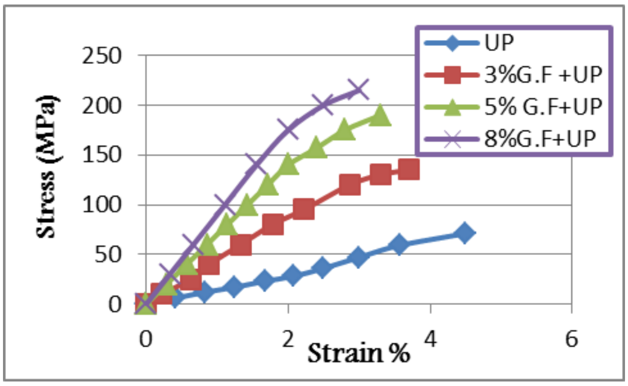


Figure (3) Stress – strain curve for coarse fiber at θ=(0°/90°).

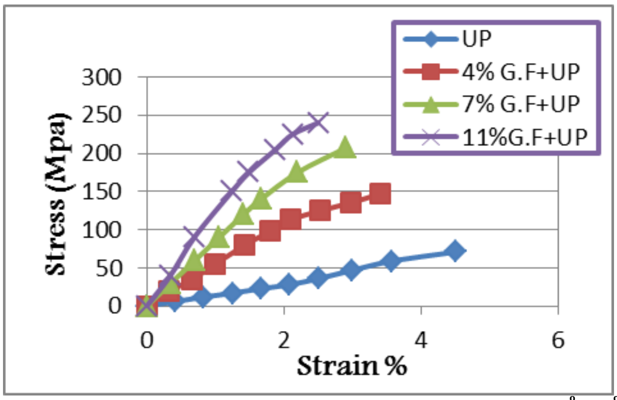


Figure (4) Stress – strain curve for fine fiber at θ=(0°/90°).

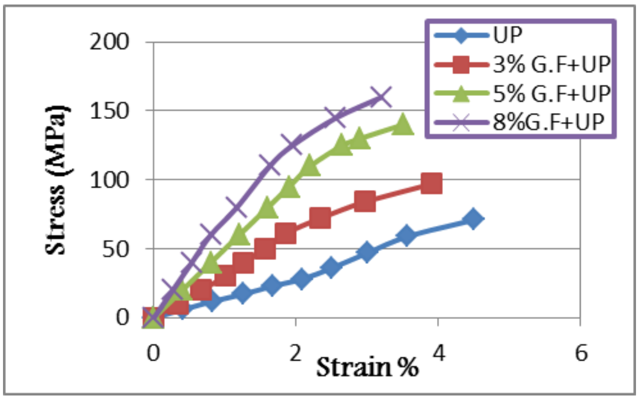


Figure (5) Stress – strain curve for coarse fiber at θ= (45°/- 45°).

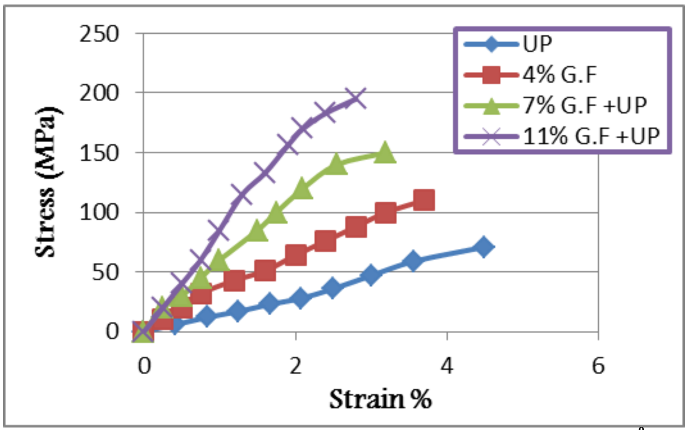


Figure (6) Stress – strain curve for fine fiber at θ= (45°/ -45°).

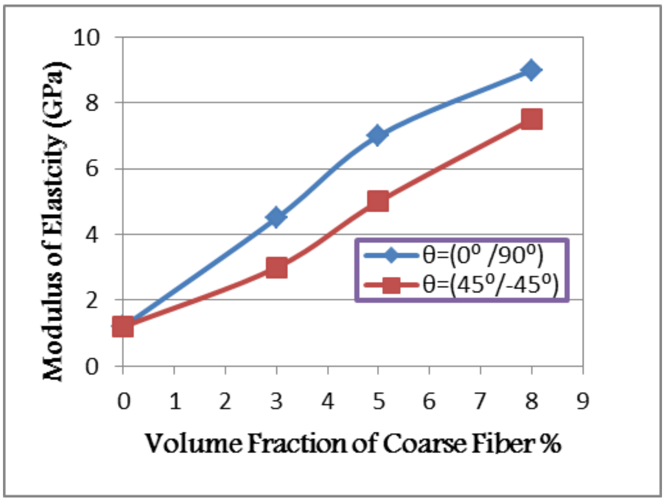


Figure (7) Plots between volume fraction of coarse fiber & modulus of elasticity.

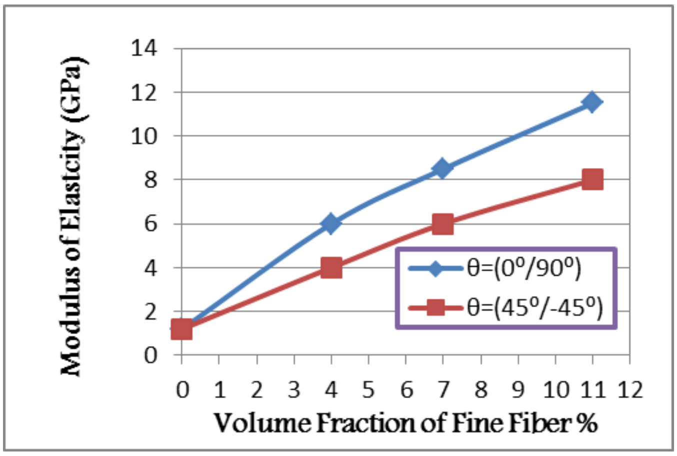


Figure (8) Plots between volume fractions of fine fiber & modulus of elasticity.

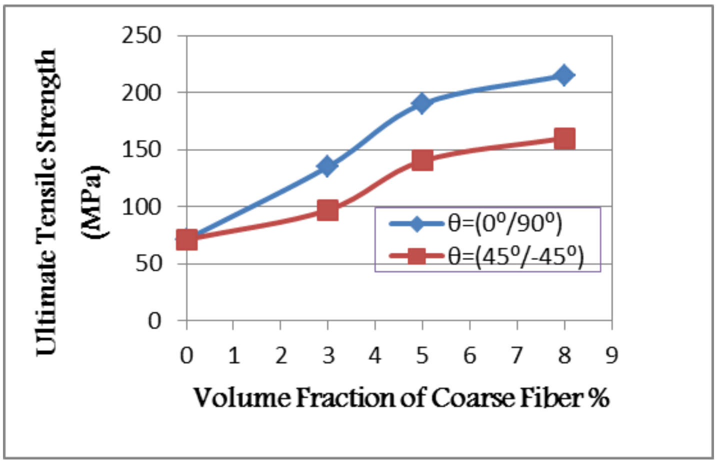


Figure (9) Plots between volume fraction of coarse fiber & ultimate tensile strength.

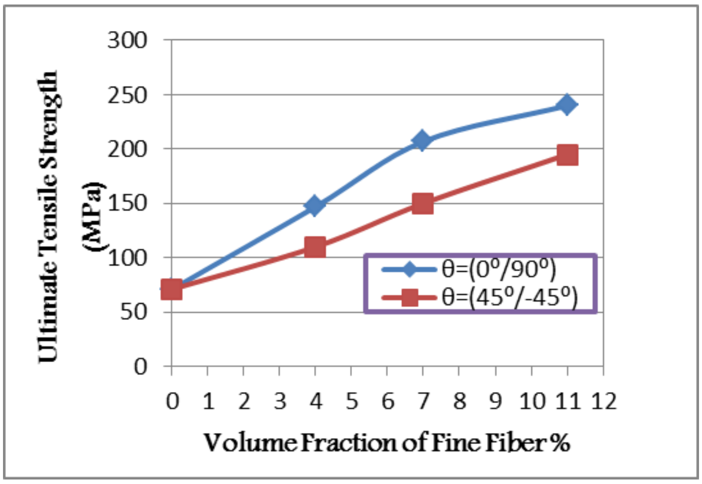


Figure (10) Plots between volume fractions of fine fiber & ultimate tensile strength.

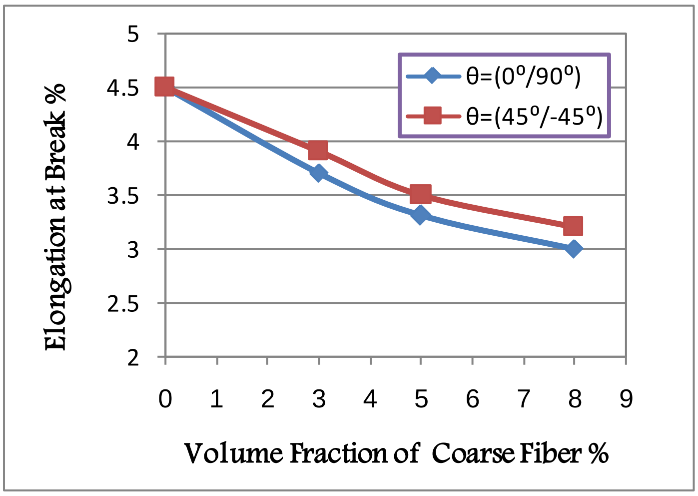


Figure (11) Plots between volume fraction of coarse fiber & elongation %.

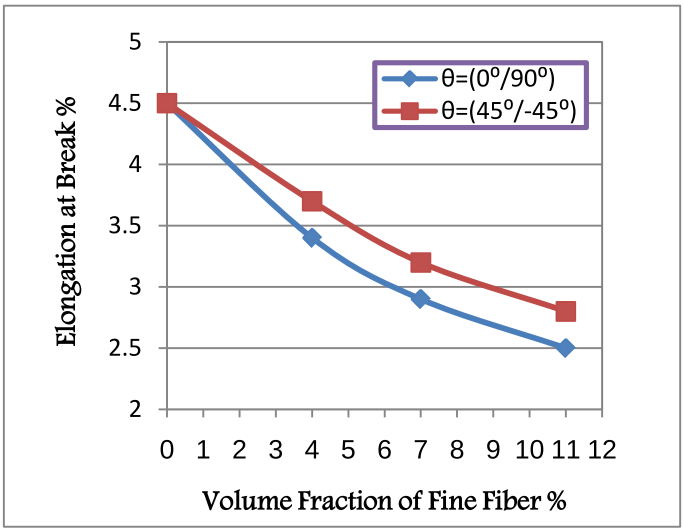


Figure (12) Plots between volume fraction of fine fiber & elongation %.