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The Reliability Level in Determining the Yield Strength of Glass Fibre-SiC Reinforced Epoxy Resin based on Input Volume Fractions of Glass Fibre and SiC

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ABSTRACT: *The reliability level in determining the yield strength of glass fibre-SiC reinforced epoxy resin based on input volume fractions of glass fibre and SiC has been established. The yield strength of the composite was predicted, using a derived empirical model;* $ϒ = Ђɤ_s - ßɤ_g + N$. *Analyses of generated results indicate that the validity of the derived model is strongly rooted on the core model structure;* $ϒ + ßɤ_g \approx Ђɤ_s + N$, *where both sides of the structure are correspondingly near equal. The model-predicted results are in agreement with previous research, considering the direct and inverse relationships between yield strength of the composite and input volume fractions of SiC and glass fibre respectively. The correlations evaluated using experimental and model-predicted results, between the yield strength and volume fractions of glass fibre & SiC were all > 0.99. The standard error involving model-predicted yield strength, relative to the experimental results was 1.89%. This translates to over 98% model confidence levels. The yield strengths of the composite per unit volume fractions of glass fibre & SiC were -5.1571, -4.8435 and -4.8509 MPa* $(\%)^{-1}$ *and 2.79, 2.6203 and 2.6243 MPa* $(\%)^{-1}$*, using experimental, derived model-predicted and regression model-predicted results respectively. The overall maximum deviation of the model-predicted tensile strength from experimental results was < 7%. The derived model will evaluate the yield strength of the glass fibre-SiC reinforced polyester, within the experimental results range, on substituting into the model, volume fractions of glass fibre and SiC, providing the boundary conditions are considered.*

KEYWORDS: *Yield strength, Glass Fibre-SiC, Epoxy Resin, Hand Lay-Up, Input Volume Fraction.*

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1. INTRODUCTION

Glass Fiber-Reinforced Plastic matrices are known as GFRPs. These materials consist of a glass fiber-reinforced plastic matrix. E-glass's exceptional qualities—which include being strong, lightweight, and durable—have led to a wide range of applications in several industries. According to Report [1], the exceptional qualities of E-glass have made it suitable for use in a variety of structural applications, such as those in the automotive, defense, aerospace, sports, and transportation industries (for example, pistons, cylinder liners, and bearings).

According to research [2], adding more reinforcement element resulted in improved mechanical qualities including impact toughness and hardness. Tensile strength of polymers reinforcing with SiC-P exhibits a distinct pattern; it rises with SiC-P reinforcement up to 10% and then falls with additional SiC-P reinforcement up to 15%. Research on how the addition of glass fiber affected mechanical attributes like impact, bending, and tensile strength revealed notable increases in those attributes [3]. In this work, aluminum oxide, silicon carbide, and glass fiber reinforced polymer (GFRP) are used to fabricate epoxy and polyester resin composites. Research has demonstrated [4] that composites made of epoxy resin exhibit greater strength than those made of polyester resin.

The effects of glass content, composite thickness, reinforcement geometry, and type of fabrication on the damage developed during flexural tests for continuous random glass-polyester composites, fabricated using Resin Transfer Molding (RTM) and Hand Lay-Up (HLU) have been investigated [5]. Results of the investigation show that the flexural strength and modulus of composites containing 20% and 30% continuous random fibers gave mean values; 84 MPa and 7 GPa and 110 MPa and 10 GPa respectively, for the Hand lay-up composites.
Metal Matrix Composite (MMC) material has been widely used [6] as a result of its excellent properties, which includes high strength, hardness, stiffness, wear, and corrosion resistance. An example of MMC is Aluminum matrix reinforced with silicon carbide particles (SiC-P).

Results of previous investigation [7] indicate that the yield strength of the glass fibre-SiC reinforced epoxy resin is function of the input volume fractions of glass fibre and SiC. However, no existing mathematical expression or model has evaluated the yield strength of the composite based on the input concentration ratio of the highlighted constituents. This formed the basis for the present work to fill in the gap.

The present work aims at deriving an empirical model which will emphasize a reliable dependence of yield strength of the composite on the inbuilt glass fibre and SiC contents. It is therefore very instructive to state that if the model is successfully derived, the yield strength of the glass fibre-SiC reinforced epoxy resin will be predicted within the experimental result range, by just substituting into the model, the input volume fractions of glass fibre and SiC, providing the input parameters are within the boundary conditions.

II. MATERIALS AND METHODS

A. Materials

E-glass fibers used in this work [7] were produced by extruding thin strands of silica glass. The glass was considered because it is ideal for composites, being extremely strong, lightweight, and robust. Moreover, the bulk strength and weight properties of this material are very favorable, and it is easily molded. Epoxy of density: 1.44 g/cm^3 was used because it is easy to incorporate into composite laminates, as a result of its high density and high adhesion between fibers. LY 556 epoxy resin and hardener (HY 951) were used at room temperature to increase composite strength and interfacial adhesion. Polyester (PE): a viscous liquid, transparent and thermosetting polymer type used. The liquid converts to solid on adding hardener additives such as Methyl-Ethyl-Ketone-Peroxide (MEKP). Silicon carbide was produced in an Acheson graphite electric resistance furnace, by combining silica sand and carbon at high temperatures. Under an inert atmosphere at low temperatures, it can also be prepared by the thermal decomposition of a polymer. Furthermore, it has a low density, high strength, high hardness, high thermal conductivity, and excellent thermal shock resistance. In composite production, silicon carbide is one of the best filler materials.

B. Preparation of Composite Specimens by Hand Lay-Up Technique

A hand lay-up technique was adopted [7] to fabricate two laminates using epoxy and polyester resins. Initially, to facilitate the removal of the laminates, a releasing agent was applied over the mold. E-glass fibers of dimension; 300 mm long by 300 mm wide were laid in a normal direction after a thin layer of resin mixed with SiC was applied to the mold. To remove any air bubbles, a weight of 5 kg was placed undisturbed for 3 hours over the fiber. On the surface of the first layer, the resin mixed with SiC was applied and rolled with rollers to achieve a homogeneous structure. The resin was again spread over and rolled, after the third layer was laid on top. This process was repeated until eight layers were formed. A weight of 10 kg was applied to the entire setup, to remove the air bubbles, after which it was then left for 24 hours to cure. The same procedure was repeated for all compositions containing SiC.

C. Mechanical Testing

a. Tensile Test

The fabricated hybrid composite material was prepared [7] for mechanical testing by cutting it, using a saw cutter and then giving the edges fine finishing with emery paper. The sample dimension for the tensile test was 2 cm wide and 15 cm long. During tensile tests, specimens were mounted on the machines, and tension was applied until it fractured in the testing machine. As the gauge length increases, the tensile force increases as well. The gauge section was measured with the applied force as tension was applied. This same procedures were carried out on all the specimen and results outlined [7].

D. Reliability Model for Yield Strength Dependence on glass fibre-SiC contents

a. Model Derivation

Table 1: Variation of yield strength of glass fibre-SiC reinforced epoxy resin with volume fractions of glass fibre and silicon carbide [7]

(ϒ)	(ɤg)	(ɤs)
25.10	43.88	0
35.42	41.98	3
42.30	40.71	5
50.70	38.97	8
56.30	37.81	10
61.01	36.25	13
64.14	35.21	15
74.20	33.92	18
80.90	33.06	20

Computational analysis of the experimental results shown in Table 1, resulted to Table 2 which indicate that;

$$\Upsilon + ß_{ɤg} \approx ƀɤ_s + N \quad (1)$$

$$\Upsilon = ƀɤ_s - ß_{ɤg} + N \quad (2)$$

The expression (2) predicts the yield strength of glass fibre-SiC reinforced epoxy resin, at known input volume fractions of glass fibre and silicon carbide. The empirical model is the sum of two linear functions. Table 1 and Table 2 indicate that ϒ, $ɤ_s$ and $ɤ_g$ are the yield strength of glass fibre-SiC reinforced epoxy resin (MPa), volume fraction of silicon carbide (%) and volume fraction of fibre glass (%) respectively. The model is referred to as Nwoye`s Model for yield strength of glass fibre-SiC-epoxy resin composite or Nwoye`s Y-GLAFISEC Model. The equalizing constants; ß, ƀ and N are 2.418, 1.3122 and 132.868 respectively. These constants were generated by a soft ware [8]. Interaction between the variables and these constants ensures that both sides of *9.43.2* are of the same units.

The yield strength of materials is calculated from Hall-Petch equation given as:

$$\sigma_y = \sigma_i + Kd^{-1/2} \quad (3)$$

Equation (3) shows that σ_y , σ_i, K and D are the yield stress (N/mm^2), friction stress (N/mm^2), locking parameter and grain diameter respectively. This is quite different from Hollomon`s equation for yield strength calculation, given as:

$$\sigma_t = K\varepsilon_t^m \quad (4)$$

where σ_t and ε_t are true stress of composite (MPa) and true strain (%), while K and m are constants which depend on the material in service.

The yield strength from equations (3) and (4) where calculated using conventional formulae, following determination from the experiment and substitution of associated variables into the highlighted mathematical expressions. The derived model in (2) can be detailed as (5) and (6) by substituting equations (3) and (4) into (2) respectively, providing the numerical differential between each expression is zero or negligible. This becomes:

$$\sigma_i + Kd^{-1/2} = ƀɤ_s - ß_{ɤg} + N \quad (5)$$

$$K\varepsilon_t^m = ƀɤ_s - ß_{ɤg} + N \quad (6)$$

This implies that $\Upsilon = \sigma_y = \sigma_t$. Therefore, any variable or constant can be evaluated if other values are known.

IV. RESULTS AND DISCUSSION

A. Boundary and Initial Conditions

Consider filler materials; glass fibre and SiC particles, interacting with epoxy resin which is the matrix. The yield strength of the composite is affected by the input concentrations of the fillers. The considered range of yield strength, glass fibre and SiC content are 25.10 - 80.9MPa, 33.06 - 43.88% and 0-20% respectively.

Table 2: Variation of $\Upsilon + ßɤ_g$ with $ђɤ_s + N$

$\Upsilon + ßɤ_g$	$ђɤ_s + N$	Differentials
131.2018	132.8680	1.6662
136.9276	136.8046	-0.1230
140.7368	139.4290	-1.3078
144.9295	143.3656	-1.5639
147.7246	145.9900	-1.7346
148.6625	149.9266	1.2641
149.2778	152.5510	3.2732
156.2186	156.4872	0.2686
160.8391	159.1120	-1.7271

B. Model Validity

The validity of the derived model in (2), is rooted on the core model structure $\Upsilon + ßɤ_g \approx ђɤ_s + N$ in (1), both sides of which are almost equal. Proximate values of model structure components in Table 2, computed from experimental results in Table 1, indicate the basis for the derivation, functionality and acceptability of the model.

The derived model was also validated by comparing the predicted results with the experimental, through graphical, statistical and deviation analysis.

a. Graphical Analysis

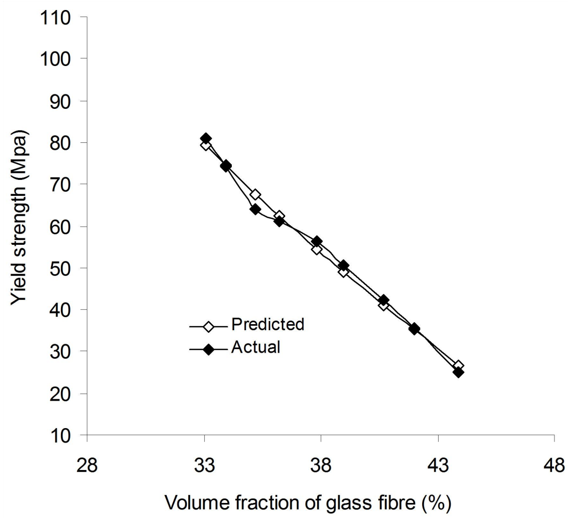

Fig.1: Comparison of the yield strengths of glass fibre-SiC reinforced epoxy resin (relative to input volume fraction of glass fibre) from actual and model-prediction.

Graphical analysis of Fig.1 and Fig.2 shows highly fitted and aligned curves of yield strengths of glass fibre-SiC reinforced epoxy resin (relative to volume fraction of glass fibre), representing experimental & derived model-predicted results and experimental, model-predicted & regression model-predicted results respectively. Curves from each figure show very similar spread & trend of results point distribution, and also very close corresponding point values. Furthermore, the curves in both figures are oriented in the negative plane, and so will prompt negative slopes, following the inverse variation of the yield strength of the composite with input volume fraction of glass fibre.

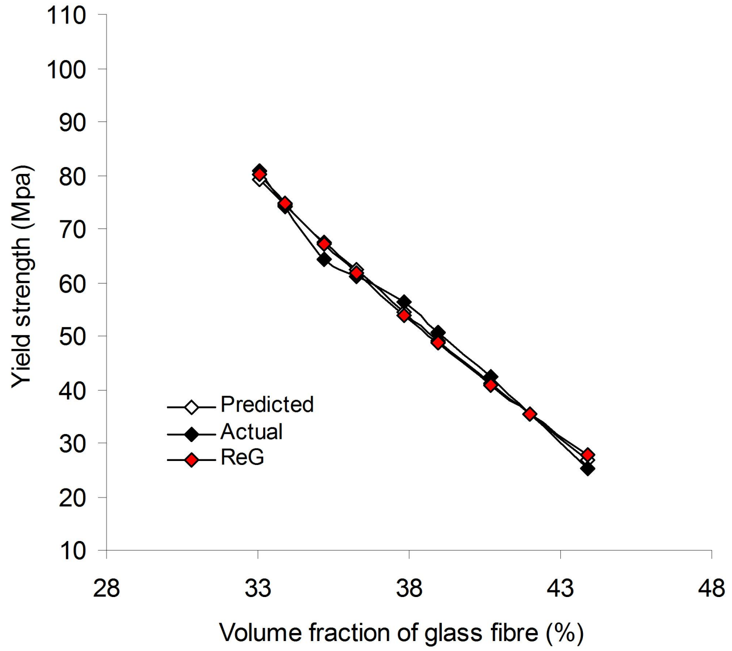

Fig.2: Comparison of the yield strengths of glass fibre-SiC reinforced epoxy resin (relative to input volume fraction of glass fibre) from actual, derived and regression model

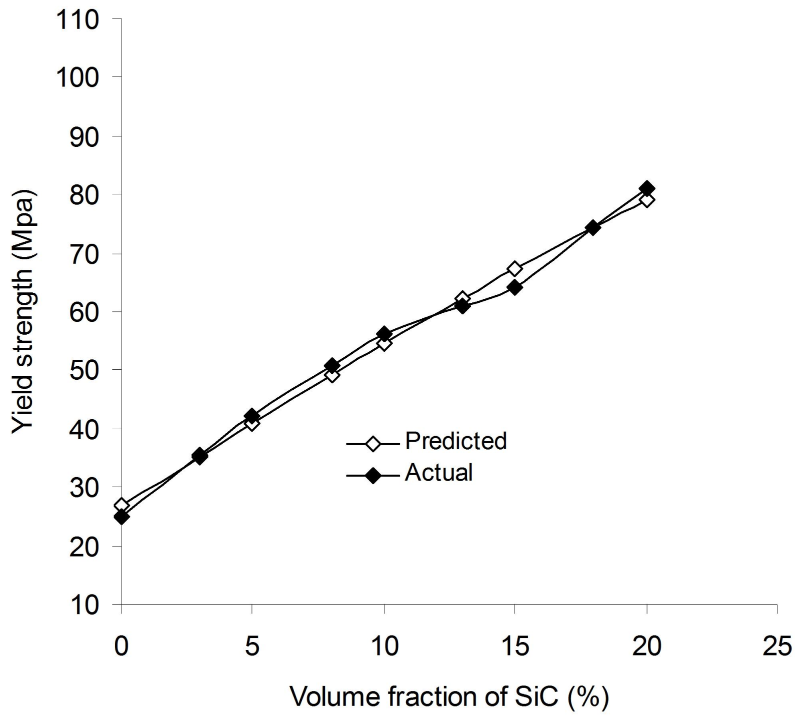

Fig.3: Comparison of the yield strengths of glass fibre-SiC reinforced epoxy resin (relative to input volume fraction of SiC) from actual and model-prediction

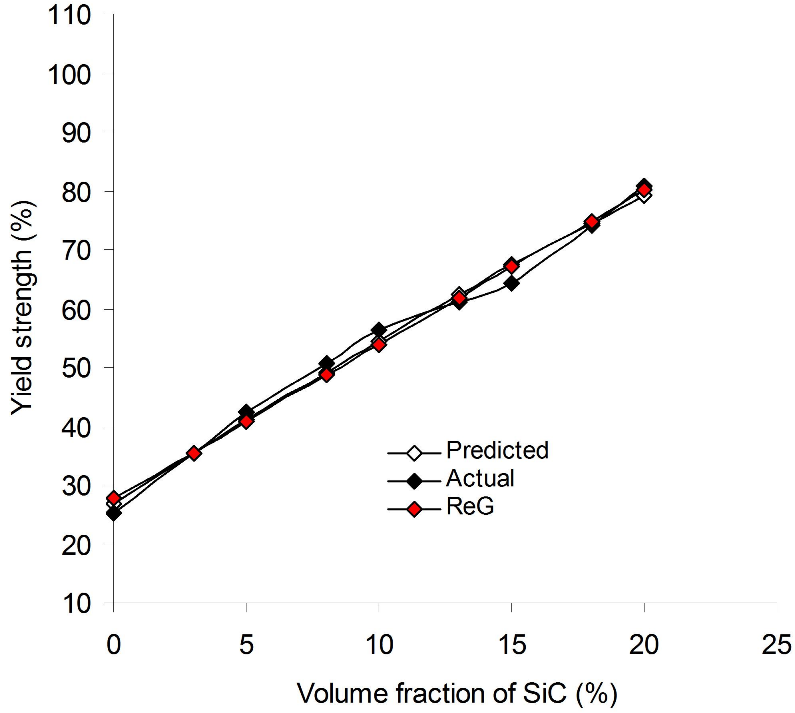

Fig. 4: Comparison of the yield strengths of glass fibre-SiC reinforced epoxy resin (relative to input volume fraction of SiC) from actual, derived and regression model.

Contrary to Fig.1 and Fig.2, curves from Fig.3 and Fig.4 will give positive slopes, since the curves are oriented in the positive plane, following the direct variation of yield strength of the composite with input volume fraction of SiC. The later figures also show highly fitted and aligned curves, designating yield strengths of the composite, but relative to input volume fraction of SiC. These curves also represent experimental & derived model-predicted results and experimental, model-predicted & regression model-predicted results respectively. Considering the level at which these curves are fitted and aligned, they share similarities, not only in terms of the trend & spread of results points, but also among the corresponding result values.

b. Statistical Analysis

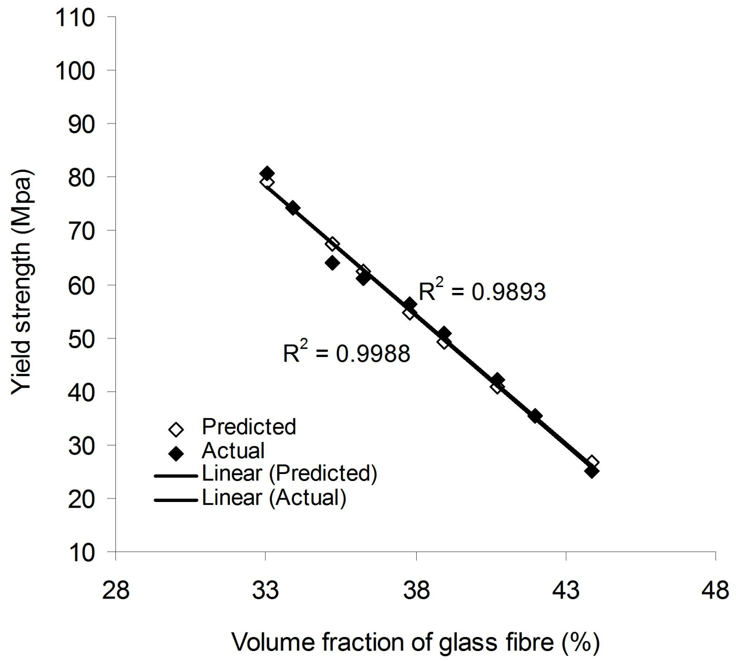

Fig.5: Coefficient of determination between yield strength and volume fraction of glass fibre as evaluated from actual results and derived model.

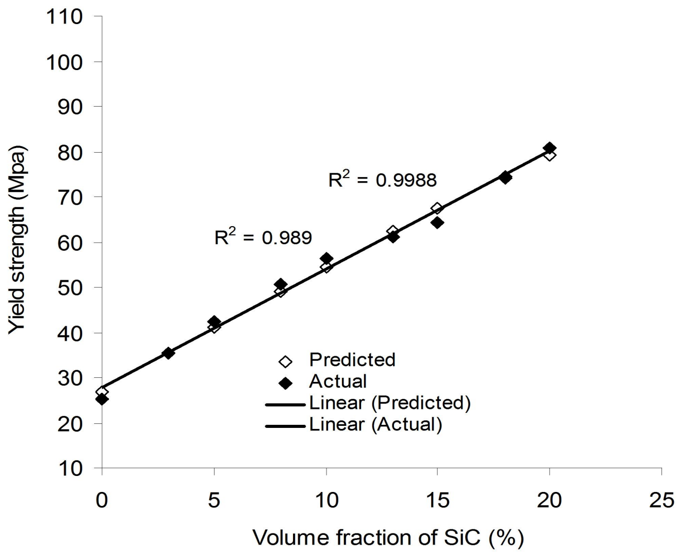

Fig.6: Coefficient of determination between yield strength and volume fraction of SiC as evaluated from actual results and derived model.

The correlations between yield strength and volume fractions of glass fibre & SiC were evaluated from the coefficients of determination R^2 shown in Fig.5 & Fig.6 as 0.9994 and 0.9946 & 0.9994 and 0.9945, using model-predicted and experimental results respectively. Comparative analyses of these results indicate that data points distribution from model prediction show greater alignment and better fitted lines than those from the experiment. However, on pairing both results, they show very close alignment.

Statistical analysis of generated results emphasizes that the overall standard error, associating model prediction of the composite yield strength (relative to experimental values) is 1.89%, for every change in the input volume fractions of glass fibre and SiC. This translates into a model confidence level above 98%.

c. Deviation Analysis

Table 3: Differential between experimentally determined and model-predicted yield strength Υ_ε and Υ_M respectively.

Υ_ε	$\Delta\Upsilon = \Upsilon_M - \Upsilon_\varepsilon$
25.10	1.6662
35.42	-0.1230
42.30	-1.3078
50.70	-1.5639
56.30	-1.7346
61.01	1.2641
64.14	3.2732
74.20	0.2686
80.90	-1.7271

Table 3 shows the differential between experimentally determined yield strength and model prediction. The evaluated differentials are within 3 unit value, considering the magnitude of the yield strengths. This indicates that the derived model predicted values are almost the same as corresponding experiment results. The positive and negative differentials show increased and decreased model-predicted values respectively, relative to the corresponding experimental result. The differentials evaluated from both sides of the core model structure as shown in Table 2, and those from experimental and model-predicted results in Table 3 are equal. This affirms the validity of the derived model.

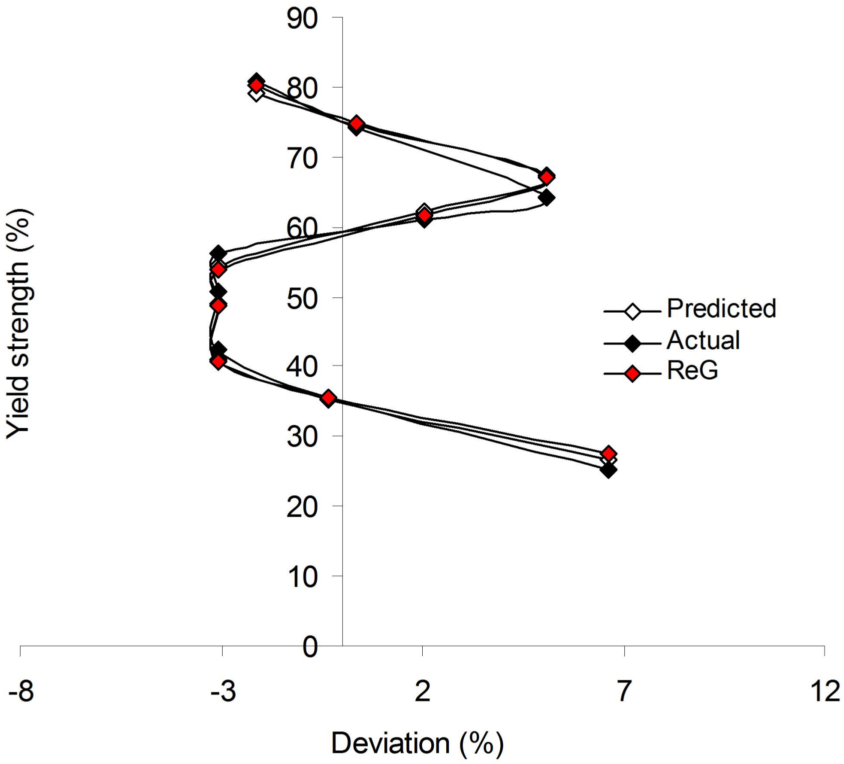

Fig.7: Variation of model-predicted yield strength of glass fibre-SiC reinforced epoxy resin with its corresponding deviation from experimental results

Fig.7 indicates that the overall maximum deviation of model-predicted yield strength of the composite (from corresponding experimental results) is < 7%. This translates into over 93% operational model confidence level. The figure emphasizes at each set of points, the discrepancy (in percent), between the experimental and model-predicted yield strength of the composite, and also between the derived and the standard model (regression model) predicted results. The figure also indicates that the least and highest deviations of the model-predicted yield strength are -0.35 and 6.64% respectively. These deviations correspond to the yield strengths: 35.297 & 26.7662Mpa, input volume fraction of glass fibre: 41.98 & 43.88% and input volume fraction of SiC: 3 & 0% respectively. It is therefore strongly believed that the overall model confidence level places between 93 and 99%, following evaluations as standard error, correlations and maximum deviation.

The deviation Dv, of model-predicted yield strength from the corresponding experimental result was evaluated from the expression.

$$D_v = \left(\frac{\Upsilon_m - \Upsilon_\varepsilon}{\Upsilon_\varepsilon}\right) \times 100 \qquad (7)$$

Where

Υ_ε and Υ_m are yield strengths of the composite evaluated from experiment and model-predicted results respectively.

Fig.7 indicates that the overall maximum deviation of model-predicted yield strength of the composite (from corresponding experimental results) is < 7%. This translates into over 93% operational model confidence level. The figure emphasizes at each set of points, the discrepancy (in percent), between the experimental and model-predicted yield strength of the composite, and also between the derived and the standard model (regression model) predicted results. The figure also indicates that the least and highest deviations of the model-predicted yield strength are -0.35 and 6.64% respectively. These deviations correspond to the yield strengths: 35.297 & 26.7662Mpa, input volume fraction of glass fibre: 41.98 & 43.88% and input volume fraction of SiC: 3 & 0% respectively. It is therefore strongly believed that the overall model confidence level places between 93 and 99%, following evaluations as standard error, correlations and maximum deviation.

Correction factor which overcomes the deviation is calculated as the negative of equation (7)

$$C_f = -\left(\frac{\Upsilon_m - \Upsilon_\varepsilon}{\Upsilon_\varepsilon}\right) \times 100 \quad (8)$$

Yield strength of glass fibre-SiC reinforced epoxy resin per unit input volume fraction of glass fibre Υ_g MPa $(\%)^{-1}$ was calculated from the expression;

$$\Upsilon_g = \Upsilon / \gamma_g \quad (9)$$

Re-written as

$$\Upsilon_g = \Delta\Upsilon / \Delta\gamma_g \quad (10)$$

The expression (10), is detailed as

$$\Upsilon_g = \Upsilon_2 - \Upsilon_1 / \gamma_{g2} - \gamma_{g1} \quad (11)$$

Where

$\Delta\Upsilon$ = Change in the yield strengths of the composite Υ_2, Υ_1 at two input volume fractions of glass fibre $\gamma_{g\,2}$, $\gamma_{g\,1}$.

A plot of points (43.88, 25.1) & (33.06, 80.9), (43.88, 26.7662) & (33.06, 79.1729) and (43.88, 27.6256) & (33.06, 80.1124) as shown in Fig.2, designated as ($\gamma_{g\,1}$, Υ_1) and ($\gamma_{g\,2}$, Υ_2) for experimental, derived model and regression model-predicted results, and substituting them into the expression (11), gives the slopes: -5.1571, -4.8435 and -4.8509 MPa $(\%)^{-1}$, as their respective yield strength of glass fibre-SiC reinforced epoxy resin per unit volume fraction of glass fibre.

The negative sign preceding the numerical values of the evaluated slopes is just an indication that an inverse relationship, exists between the yield strength of the composite and the input volume fraction of glass fibre as shown in Fig. 2. The real slopes are the magnitudes of the evaluated results.

Yield strength of glass fibre-SiC reinforced epoxy resin per unit input volume fraction of SiC Υ_s MPa $(\%)^{-1}$ was calculated from the expression;

$$\Upsilon_s = \Upsilon / \gamma_s \quad (12)$$

Re-written as

$$\Upsilon_s = \Delta\Upsilon / \Delta\gamma_s \quad (13)$$

The expression (13), is detailed as

$$\Upsilon_s = \Upsilon_2 - \Upsilon_1 / \gamma_{s2} - \gamma_{s1} \quad (14)$$

Where

$\Delta\Upsilon$ = Change in the yield strengths of the composite Υ_2, Υ_1 at two input volume fractions of SiC $\gamma_{s\,2}$, $\gamma_{s\,1}$.

Similarly, a plot of points (0, 25.1) & (20, 80.9), (0, 26.7662) & (20, 79.1729) and (0, 27.6256) & (20, 80.1124) as shown in Fig.4, designated as ($\gamma_{s\,1}$, Υ_1) and ($\gamma_{s\,2}$, Υ_2) for experimental, derived model and regression model-predicted results, and substituting them into the expression (14), gives the slopes: 2.79, 2.6203 and 2.6243 MPa $(\%)^{-1}$, as their respective yield strength of glass fibre-SiC reinforced epoxy resin per unit percent volume fraction of SiC.

IV. CONCLUSION

The reliability level in determining the yield strength of glass fibre-SiC reinforced epoxy resin based on input volume fractions of glass fibre and SiC has been established, using a derived empirical model; $ϒ = Ꜧɤ_s - ẞɤ_g + N$. Analyses of generated results indicate that the validity of the derived model is strongly rooted on the core model structure; $ϒ + ẞɤ_g \approx Ꜧɤ_s + N$, where both sides of the structure are correspondingly near equal. The model-predicted results are in agreement with previous research, considering the direct and inverse relationships between yield strength of the composite and input volume fractions of SiC and glass fibre respectively. The correlations evaluated using experimental and model-predicted results, between the yield strength and volume fractions of glass fibre and SiC were all > 0.99. The standard error involving model-predicted yield strength, relative to the experimental results was 1.89%. This translates to over 98% model confidence levels. The yield strengths of the composite per unit volume fractions of glass fibre and SiC were -5.1571, -4.8435 and -4.8509 MPa $(\%)^{-1}$ and 2.79, 2.6203 and 2.6243 MPa $(\%)^{-1}$, using experimental, derived model-predicted and regression model-predicted results respectively. The overall maximum deviation of the model-predicted tensile strength from experimental results was < 7%. The derived model will evaluate the yield strength of the glass fibre-SiC reinforced polyester, within the experimental results range, on substituting into the model, volume fractions of glass fibre and SiC, providing the boundary conditions are considered.

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