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Hybrid-modelling of Mechanical Properties and Thermo-mechanical Behaviour of Chopped Strand Mat Reinforced Thermoset Composites

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Author's contribution

The sole author designed, analysed, interpreted and prepared the manuscript.

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ABSTRACT

The concern of this paper is to develop simple workshop application models for predicting the mechanical properties and the evaluation of the thermo-mechanical behaviour of chopped strand fibre-mat reinforced thermoset composites. A hybrid of empirical and strength of materials approach was used at macro- and micro-mechanics levels to model the random fibres which were treated as simple bars within the mat preform and the resulting composite material. The model was validated experimentally by testing wet lay-up produced samples with varying fibre volume fractions and they were found to agree well. The toughness modulus of the composite was also modeled using the secant modulus obtained from the sample's stress – strain curves of uniform material composites produced at different temperature histories. The toughness modulus determined using the new model was compared with that obtained using the area under the same stress – strain curve computed by Simpson's rule and the results agreed very well.

Keywords: Thermoset composites; chopped strand mat; mechanical properties, thermo-mechanical behaviour; hybrid-modelling.

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1. INTRODUCTION

Chopped strand mat composites have found favour in many design and construction industries as alternative structural and nonstructural materials. In automobile and boat construction, random mat fiber composites have extensively replaced the traditional steel sheets and wood boards in the construction of vehicle bodies and boat hulls [1]. In plumbing works, it is now the material of choice in the fabrication of bath tubs, water vats, sewers, channels and pipe lines. These are due to their excellent strength to weight ratio, resistance to corrosion and ease of fabrication into rounded aesthetic curvatures. Other applications include bullet proofing, motor cycle parts, house doors and acoustic enclosures. These are due to their additional damping and excellent impact energy absorption capabilities.

Fibres are obtained from the market as either, weaved, nonwoven or matted while the thermosets which form the matrix are obtained as viscous liquids. Generally, mats are sheets of chopped fibres randomly distributed in a plane supplied in the form of powder matted or emulsion matted continuous flat sheet or ply rolled on drums or reels. Composite materials are produced by placing together a mixture of fibres and matrix with the matrix in mouldable form and with or without heat and pressure depending on the type of resin and manufacturing procedure, and allowed to cure. The matrix or resin acts as a vehicle for subtending the fibres in composites. It also serves to transfer any load between the fibres [2], acts as a mechanical support for the fibers and protects the fibers from the environment.

The orientation and arrangement of the fibres relative to one another, their distribution and the fibre concentration significantly affect the strength and other properties of the fibre-reinforced composites [3]. Usually, continuous fibres are aligned, while discontinuous or short fibres may be aligned, randomly oriented or partially oriented. Unidirectional arranged fibres gives the highest strength in the longitudinal direction and gives the weakest in the transverse direction. Fibers usually lie in the laminate plane and stresses perpendicular to the laminate plane are carried by matrix and fiber/matrix interface. Therefore, such weaknesses have to be avoided. As stated in Advanced Manufacturing Technology Strategy (AMTS) Standard Workshop Practice, laminates with plies in only one direction are susceptible to crack propagation [4]. With the random nature of the fibres, it is expected that chopped strand mat laminates will exhibit excellent fatigue life due to the bridging of the fibers across cracks which significantly hinders its propagation. Normally, when the fibre distribution is uniform, superior overall composite properties can be obtained. Laminates are produced applying different ply fibre orientations and ply stacking sequence according to requirements. The fibre orientation and stacking sequence affect the interlaminar fracture toughness and the specific energy absorption of composites positively [1]. The higher the fiber volume content, the higher the strength of the laminae provided the matrix coats the fibres completely. The rule of mixture is used to predict the stiffness and strength of composites but it has been found wanting in predicting the stiffness and strength of random mat fiber composites. The rule of mixture for composite stiffness, E_c and ultimate strength, σ_{cu} are given as

$$E_c = V_f E_f + V_m E_m \tag{1}$$

and

$$\sigma_{cu} = V_f \sigma_{fu} + V_m \sigma_m \tag{2}$$

where *V, E* and σ represent volume fraction, Young's modulus and strength respectively. Subscripts *c, f* and *m* stand for composite, fiber and matrix respectively. For unidirectional fibre reinforced composites, the elastic constants can be obtained as [1,5]

$$E_{11} = V_f E_f + V_m E_m \tag{3}$$

$$\upsilon_{12} = V_f \upsilon_f + V_m \upsilon_m \tag{4}$$

The representation of the composite transverse modulus, E_{22}, and shear modulus, G_{12} is given by the Halpin-Tsai equation [6]

$$E_{22} = E_m \left[\frac{E_f(1 + \zeta_E V_f) + \zeta_E E_m (1 - V_f)}{E_f(1 - V_f) + E_m(\zeta_E + V_f)} \right] \tag{5}$$

$$G_{12} = G_m \left[\frac{G_f(1 + \zeta_G V_f) + \zeta_G G_m (1 - V_f)}{G_f(1 - V_f) + G_m(\zeta_G + V_f)} \right] \tag{6}$$

In all these equations *E* is the Young's modulus of elasticity, *G* is the shear modulus, υ is the Poisson's ratio, *V* is the volume fraction and the subscripts *f* and *m* are for fiber and matrix respectively. ζ_E and ζ_G are the adjustment factors with typical values of *2* and *1* respectively for elastic composites.

Chopped strand mat is composed of cut fibers randomly distributed in a plane, this results in a quasi isotropic inplane macroscopic behaviour. Locally the behaviour is very anisotropic, depending on the fibre length, aspect ratio, local fibre content, spatial distribution and the quality of the fibre/matrix interface. The microstructure is thus complex and heterogeneous. The material can be characterized on either a macroscopic or a microscopic scale. Unlike the unidirectional and angle ply composites, chopped strand mat composites have received less attention towards its mathematical modeling despite its ubiquitous application. This paper, therefore, contributes to redress the imbalance.

2. LITERATURE

As noted there are only a few discussions on the microstructure evaluation of fibre mat composites. Nonetheless, Ionita and Weitsman [7] used the laminate theory to investigate the aspects of the mechanical behaviour of a random array of chopped carbon-fiber strands embedded in a urethane resin and accounted for the random distributions of various strands and scatter in their mechanical properties been dependent on the sample size. To account for undulations of chopped strands at their cross-over points, 82.5% of the reduced stiffness element Q_{11} of the unidirectionally reinforced ply equivalent was used for computations. They also observed that the fringe patterns corresponded to noticeable levels of shear strains which should have been absent for an ideally isotropic material. In a subsequent article, Ionita and Weitsman [8] developed a model which simulates the random geometry of the randomly reinforced chopped carbon fiber-strand/urethane composite based on mechanics model and ideas of composite laminate theory to predict material properties and failure. In the two studies urethane was used which is a thermoplastic material. Ghasemnejad et al. sought the effect of fiber orientation and stacking sequence on the composite crash box design by studying their effects on the interlaminar fracture toughness using glass fiber/epoxy laminate from different layups. They reported that the interlaminar fracture toughness of glass fiber/epoxy affects the frond bending resistance due to the main central interwall crack in a progressive crushing failure and consequently specific energy absorption [9]. Aboudi developed a first order continuum theory with microstructure for aligned short fiber composites. The fibrous material is modeled by a triply periodic array of rectangular parallelepiped elastic fibers which were embedded in an elastic matrix [10]. Reduction of the theory, by which the microstructure variables were eliminated, yielded the effective modulus of the short fiber composite. Eleiche et al. used the single-shear tests to study the effect of fiber orientation in multidirectional glass fiber reinforced polyester laminates of different stacking sequence. They reported that the experimental shear modulus of elasticity was independent of plies stacking sequence in the laminate, while the ultimate shear stress was highly affected by it [11]. Fukuda and Chou [12] used a probabilistic approach to study the effects of fibre length and orientation distribution on the strength of unidirectional short fibre composites with uniform fibre length, unidirectional short fibre composites with fibre length distribution, random short fibre composites with uniform fibre length and partially-aligned short fibre composites with uniform fibre length. Nevertheless, chopped strand mat sold in the market today have both fibre length distribution and random orientation distribution. Serrano et al. [13] evaluated the stiffening abilities of old newspaper fibers compounded with polypropylene and back calculated the value of the intrinsic Young's modulus by means of micromechanics models. They established the Hirsch model as a valid tool to estimate the intrinsic modulus of the reinforcement while the Cox and Krenchel modified rule of mixtures was used as the basis for defining a fiber tensile modulus factor which gives the contribution of the reinforcement to the Young's modulus of the composite, as a function of the fiber volume fraction. The random fiber mat composite stiffness is given by Gay, et al. [1]

$$E_{mat} = \frac{[2(\overline{E_L} + \overline{E_T}) + 4\nu_{TL}\overline{E_L}][\overline{E_L} + \overline{E_T} - 2\nu_{TL}\overline{E_L} + 4G_{LT}]}{4[\frac{3}{2}(\overline{E_L} + \overline{E_T}) + \nu_{TL}\overline{E_L} + 2G_{LT}]} \quad (7)$$

Where

$$\overline{E_L} = \frac{E_L}{1 - \nu_{LT}\nu_{TL}}$$

$$\overline{E_T} = \frac{E_T}{1 - \nu_{LT}\nu_{TL}}$$

While the unidirectional longitudinal modulus E_L can be fairly accurately obtained through the rule of mixtures as

$$E_{L=}V_f E_f + (1 - V_f)E_m$$

The unidirectional transverse modulus is obtained by Chamis model as

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

with E_m = the elastic modulus of the polyester resin

E_f = the elastic modulus of the glass fibers

V_f = the fiber volume fraction

In the prediction of Young's modulus for natural fibre reinforced composites, many researchers employed the Cox and Krenchel model [14,15,16,17]. This may not be unconnected with the inherent shortness of natural fibres and the difficulty associated with their alignment. Chopped strand mat share this same characteristics and hence similar models could as well be developed along that line. Summerscales et al. [18] reviewed recent statistical models which have been applied to natural fiber reinforcements for composite systems. The rule of mixture was extended to include the effects of porosity, fibre diameter and yarn twist. Fiber correction factor was introduced to correct for the over-estimation of fiber cross-section which occurs when an apparent cross-sectional area is calculated from the diameter measured normal to the fiber axis.

Garkhail et al. [19] studied the mechanical properties of natural-fibre-mat reinforced thermoplastics. The influence of fibre length and fibre content on stiffness, strength and impact strength of these natural fibre composites is reported and compared with data for glass-mat-reinforced thermoplastics. They deployed Cox-Krenchel modified rule of mixtures equation, for predicting stiffness of short fibre reinforced composites, given as

$$E_C = \eta_O \eta_{LE} V_f E_f + (1-V_f)E_m \qquad (8)$$

where η_{LE} is Cox fiber length efficiency factor which takes care of the ineffective loading of fibres over their stress transfer length and is given as

$$\eta_{LE} = \left[1-\frac{\tanh(\beta L/2)}{\beta L/2}\right]$$

Where

$$\beta = \frac{2}{D}\left[\frac{2G_m}{E_f ln(\sqrt{\pi}/X_i V_f)}\right]^{1/2}$$

G_m is the shear modulus of the matrix, X_i depends on the geometrical packing arrangement of the fibres and D is the fibre diameter.

η_O is Krenchel orientation factor which allows for the introduction of a fibre orientation distribution, and neglecting transverse deformations, it is given as

$$\eta_O = \sum_n a_n Cos^4\phi_n$$

where a_n is the fraction of fibres with orientation angle ϕ_n with respect to the loading axis. η_O takes the values of 3/8 and 1/5 for two and three dimensional random fibre orientations respectively.

Similarly, the strength of discontinuous fibre composites as given by Kelly and Tyson is

$$\sigma_{uc} = \eta_O \eta_{LS} V_f \sigma_f + (1-V_f)\sigma_m \qquad (9)$$

where η_{LS} is the fibre length efficiency factor and η_O is the fibre orientation factor similar to the Cox-Krenchel model, to account for off-axis fibre orientation.

Fu and Lauke [20] also studied the effects of fiber length and fiber orientation distributions on the tensile strength of injection moulded short-fiber-reinforced thermoplastics adopting a probabilistic approach. They presented a modified rule of mixture for predicting the ultimate strength of the composite as follows:

$$\sigma_{cu} = X_1 X_2 V_f \sigma_{fu} + V_m \sigma_m \qquad (10)$$

where X_1 and X_2 are the fiber orientation and fiber length factors respectively and the product of X_1 and X_2 is the fiber efficiency factor for the strength of the composite.

It is apparently clear from the foregoing that few studies existed in literatures in the area of chopped strand mat thermoset composites as a structural material. There is need for a more practicable approach to the design of the fibre mat thermoset composites as the use gains more and more preeminence by the day. The models developed before now for predicting the mechanical properties of random fibre mat composites look too involving. An alternative approach is therefore suggested here. The study therefore seeks to develop appropriate mathematical models, which is easy and simple, for predicting the strengths of the fibre mat composites. This will enable the efficient utilization of time and the selection of the composite design parameters which will lead to stronger, stiffer and more durable composite components while taking the economy into consideration.

3. STUDY MODELLING

Given the stress tensor for a particular point based on some reference coordinates *x, y, z* as shown in Fig. 1 the components of the stress vector on any oblique plane whose normal has direction cosines, $Cos\theta_x = l$, $Cos\theta_y = m$, $Cos\theta_z = n$

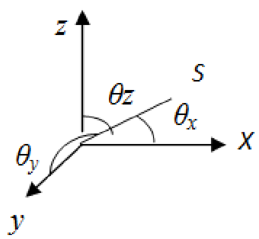

Fig. 1. Directional cosines of an arbitrary plane

are given by $\begin{Bmatrix} S_x \\ S_y \\ S_z \end{Bmatrix} = \begin{bmatrix} \sigma_{xx} & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_{yy} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_{zz} \end{bmatrix} \begin{Bmatrix} l \\ m \\ n \end{Bmatrix}$

the normal component of the resulting stress is

$$\sigma_n = S_x l + S_y m + S_z n$$
$$= \sigma_x l^2 + \sigma_y m^2 + \sigma_z n^2 + 2(\tau_{xy} lm + \tau_{yz} mn + \tau_{zx} nl)$$

$$S^2 = \sigma_n{}^2 + \tau_{nt}{}^2 = S_x{}^2 + S_y{}^2 + S_z{}^2 \qquad (11)$$

where τ_{nt} is the shear stress on the plane.

The conventional way of matting the fibers makes the fibers lie parallel to the x-y plane or 1-2 plane and, the 3 and *z*-axis coincide with little matrix constraint in the *z*-direction, thus enabling plane stress analysis to suffice.

Consider now a random fibre mat composite with specific fiber volume content and fairly distributed in different directions, the fibre strands can be visualized (Fig. 2) and the relevant equations have been formulated.

The fibres have been assumed to align themselves fairly at equal angles and overlapping along their joining length thus forming equivalent continuous strands bound by the resin; the length to diameter aspect ratio of the fibres being in the order of thousands as obtained in chopped strand e-glass mat. Because in a preliminary tensile test the specimen fail by brittle fracture without substantive fibre pull-out it seems then that the overlap joints were even better reinforced with double fibers "tied" by matrix. The fibre length factor can then be taken as unity. Hence for an equivalent single fiber arbitrarily oriented within the plane, we have the modified rule of mixture composite strength in the rectangular laminate Cartesian axis as

$$S_c = \eta_O \eta_{LS} V_f S_f + (1 - V_f) S_m$$

with $\eta_{LE} = 1$ and for a single fibre

$$S_c = V_f S_f Cos\theta + (1 - V_f) S_m$$

where V_f is the fiber volume fraction, S_f is the fiber strength and S_m is the matrix strength.

If it is presumed that the fibers are equally oriented in all directions (ie 360°) then resolving each fiber into the laminate horizontal x-axis will

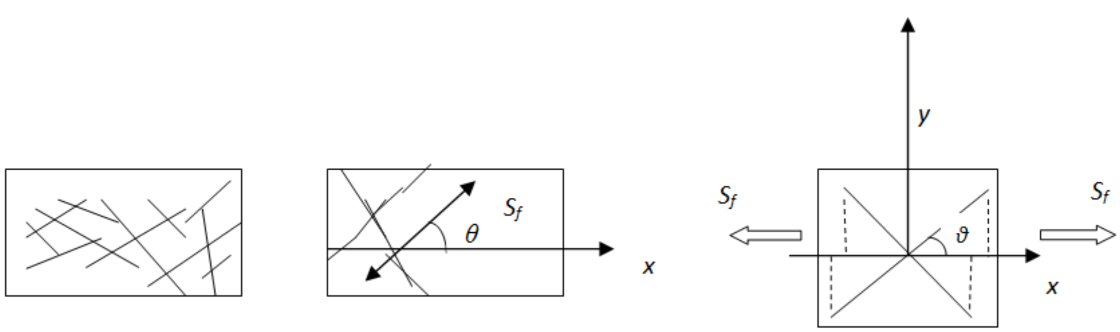

Fig. 2. Random fiber mat in a ply

entail adding the individual fibres directional cosine contributions from all directions

$$Cos(-90) + Cos(-89) \ldots Cos(0) + Cos(1) + Cos(2) + Cos(3) \ldots Cos(90) = \sum_{-90}^{90} cos\theta$$

For randomly oriented and fairly distributed fibers having a quasi isotropic property, a modified equation of the rule of mixtures can therefore be written as

$$S_c = \frac{1}{2\pi} V_f S_f \int_{-\pi/2}^{\pi/2} cos\theta + (1 - V_f) S_m$$

$$S_c \cong \frac{1}{3} V_f S_f + (1 - V_f) S_m \quad (12)$$

Corollary to the strength, the stiffness can be approximated as

$$E_c \cong \frac{1}{3} V_f E_f + (1 - V_f) E_m \quad (13)$$

The volume fraction of fibre can be obtained from the mass balance of fibres before and after lamination as follows:

Mass of fibres in the specimen = mass of fibres used

$$V_f \times \rho_f \times V_s = \rho_{Af} \times A_s \times N$$

where V_f is the fibre volume fraction, ρ_{Af} is the area density of fibre mat, N is the number of plies, ρ_f is the volume density of fibre, A_s is the inplane area of specimen, V_s is the volume of specimen

therefore

$$V_f = \frac{\rho_{Af} \times A_s \times N}{\rho_f \times V_s}$$

$$V_f = \frac{\rho_{Af} \times A_s \times N}{\rho_f \times A_s \times t_h}$$

$$V_f = \frac{\rho_{Af} \times N}{\rho_f \times t_h} \quad (14)$$

t_h is the composite specimen thickness

Equation (12) and (13) are simplified new models for random fibre mat composite strength and stiffness evaluation. The equation suffices as far as the fibres are fully coated with the resin and within the usual 30% volume fraction for wet lay-up. The constant factor in the first term on the right reflects the fibres control of the composite strength.

4. MATERIALS AND METHODS

4.1 Materials

E-glass chopped strand mat formed as a continuous flat sheet and rolled on hard cardboard paper spool was used as reinforcement. The fibre length ranges between 48 - 50 mm according to measurement (see Fig. 3). The diameter is within 9 – 15 µm [21]. The fibers were fairly evenly distributed and randomly evenly oriented, and were held together in a powdered binder. It is presumably quasi isotropic in the inplane directions as the fibers lie in a plane parallel to the 1-2 plane coinciding with the major dimensions of the length by width. Area density: 450 g/m^2; Grade: A-Level; Net Weight: 45.5 kg/Roll; made in Taiwan and marketed in Nigeria by NYCIL Limited.

Resin composition of the commercial unsaturated polyester used is given in Table 1. What constituted the additives/pigments still remains proprietary to the manufacturers as these were not given explicitly in the label. This is presented in tins, gallons and Gerry cans as a low viscous liquid. They are cheaper and easier to process compared to epoxy, hence a good choice for low stress components manufacturing.

Table 1. Polyester resin composition

Unsaturated polyester resin		**Producer: Blue Sea Resin Industries Limited, Taiwan Marketed in Nigeria by: Atlantic Fibre Industrial Limited**
Composition		**Percentage (%)**
1	Propylene Glycol	23
2	Phthalic Anhydride	21
3	Maleic Anhydride	16
4	Styrene Monomer	38
5	Additives/Pigment Paste	2
	Total	100

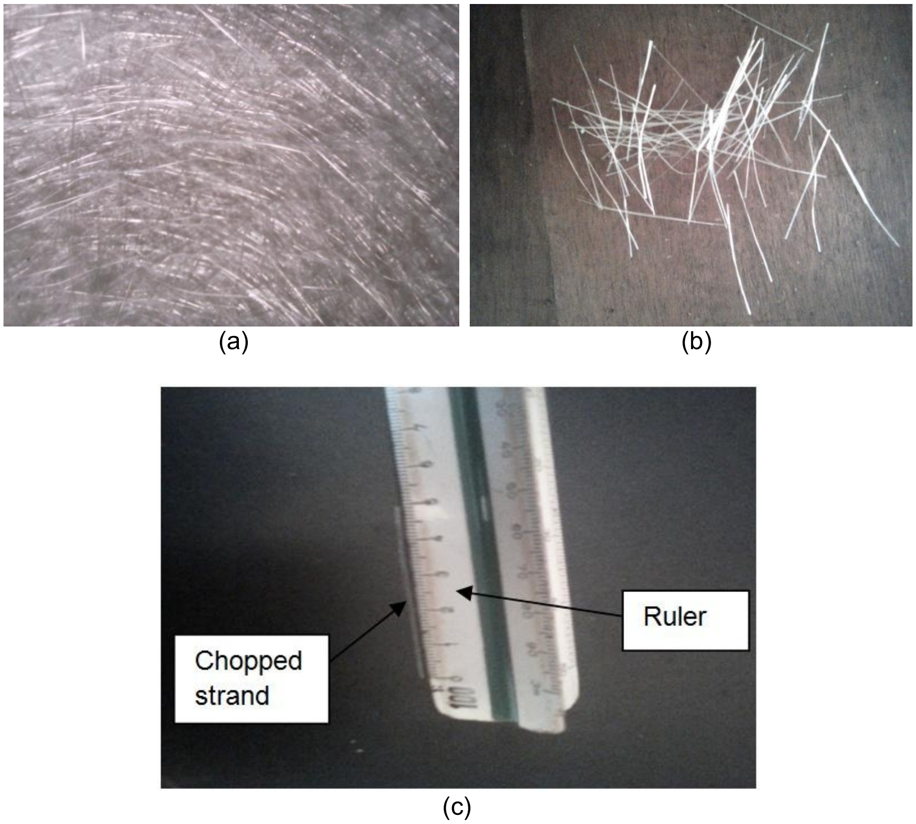

Fig. 3. (a) Fibre mat (b) extracted chopped fibre strands from mat (c) single chopped strand measured approximately 50 mm

Catalyst: butanox HBO-50 Methyl ethyl ketone peroxide (MEKP), solution in dimethyl phthalate is used to initiate free radical polymerization of the styrenated polyester resin. It is produced and marketed as UN3105 Organic peroxide, Type D, Liquid (methyl ethyl ketone peroxide), in 5 kg gallon by AKZO Nobel Polymer Chemicals, Belgium. Accelerator: Cobalt octoate derivative; this is a solution of cobalt salts diluted in styrene and white spirit. It is employed to quicken the decomposition of the initiator at low temperatures. This is presented in the market as a purple liquid chemical. The resin formulation used is 400:2:1 of polyester, catalyst and accelerator respectively.

4.2 Study Design

Because the fibre volume fraction affects the physical and mechanical behaviour as shown by equations (13) and (14) it is necessary to ascertain the fiber volume fraction of the laminate; experiments were then carried-out using different principles. Firstly, the fibre volume fraction of the glass fibre reinforced composite was determined by the resin burn-off method. This is particularly suitable because glass is resistant to oxidation at elevated temperatures [1]. A 3-ply laminate coupon was produced and measured with a vernier caliper, given nominal values as 322 x19 x 4 mm and weighed with a digital kitchen scale to get 34 g. The coupon was then set up in flame to burn off the resin matrix. The fiber residue was washed dried and weighed to get 10 g. The weight was subsequently divided by the density of E-glass fiber (2540 kg/m^3) as quoted in the literatures to get the fiber volume. The fiber volume so obtained was divided by the laminate coupon volume to get the volume fraction of fiber as 16%. The test closely followed ASTM D 3171 standard. Perturbed by the abysmal low value of fiber volume fraction obtained, a second method involving volume of water displaced on immersion as opined by Archimedes was employed. Two composite samples were weighed, and then completely immersed in a beaker of water by which the volume of water displaced was obtained. The samples were subsequently burnt to remove the lower temperature combustible resin and the glass fibres residue immersed in the beaker of water to establish the fibre volume content. The volume of fibre so obtained was then divided by the composite sample volume earlier measured. By this method laminate produced was found to contain 18% glass fibers. Thirdly, the area density approach derived in eq. (14) was employed whereby cut samples of the E- glass random mat reinforcement were weighed and their inplane dimensions of length and width measured, from which the area was calculated. By dividing the weight by the area, the area density was obtained. By measuring the inplane area of the produced composite sample and multiplying by the area density of the E-glass fibre mat and multiplying by the number of plies within the laminate, the total weight of fibres was established. Dividing the weight so established by the density of E-glass fibres gave the volume of fibres in the sample. The thickness of the sample was measured and multiplied by the area to obtain the sample volume. The volume of the fibres was then divided by the sample volume to determine the fibre volume fraction. In its strict sense only the thickness of the laminate need measured. For area density of 0.450 kg/m^2, glass density of 2540 kg/m^3, 3 plies and 3 mm thickness laminate, the volume fraction computed was 17.7%. The latter technique did not account for the powder binding material used to mat the fibres. However, it was adjudged negligible as sample mats cut from the roll were weighed, and then burnt and reweighed, did not show any significant change in weight [22]. Details of the 1st and 2nd volume fraction determinations were as presented in Table 2.

4.3 Determination of the Density of Cured Neat Resin

To help confirm the property of the polyester vis-a-vis the quality, the density of the resin was sought. A cured neat resin was produced and weighed. The neat resin sample piece weighed 41 g. From the vernier caliper measurements, the volume was calculated based on the length, width and thickness as 34375.5 mm^3. The mass was divided by the volume to get 1192.71 kg/m^3 as the density. Variously the volume was obtained through the water displaced as 34 ml in accordance with the Archimedes principles. This gave, upon evaluation, the value of 1205.89 kg/m^3 as the density[1]. This was perceived to be more correct as it took care of the irregularities in the coupon shape.

In the laminate production wet lay-up method was adopted [21]. Tensile test coupons cut measured 160 x 19 x 3 mm by length, width and thickness respectively. Tensile test was conducted using Hounsfield (Monsanto) Tensometer, Manufactured by Tensometer Limited, made in England, accuracy 0.01 N. The test followed the ASTM D 638 standard for tensile properties of plastics [23].

Table 2. Volume fraction determination of the random mat reinforced composite

Parameter	Fiber Mat	Neat Resin coupon (1)	Neat Resin coupon(2)	3-ply laminate (1)	3-ply laminate (2)
Volume from vernier caliper measurements (length x width x thickness) mm^3			34375.5	22604.4	24472
Mass before burn-off (g)	10	36	41	31	34
Volume of water displaced (ml)	4		34		25
Density (kg/m^3)[caliper]			1193	1371	1389
Density (kg/m^3)*	2500		1206		1360
Mass after burn-off (g)	10	2(charred residue)		10	10
Volume of water displaced (ml)	4				4
Fiber weight fraction (%)	100			32.3	29.4
Fiber volume fraction (%)	100				16
Resin volume fraction (%)		100	100	77.03	79.6
Fiber volume fraction (%)				22.97	20.4

Density calculated from water displaced

5. RESULTS AND DISCUSSION

Figs. 4(a) – (e) show the engineering stress-strain curve behavior of composite laminates containing 1-ply, 2-ply, 3-ply 4-ply and 5-ply respectively. It is observed that the curve for 1-ply is most linear, followed by the curve for 2-ply whiles the curve for 5- ply is the least. It appears that the higher the fiber volume fraction the more the curve deviates from linearity. The character may not be unconnected with the random orientation and undulated structure of the fibres in the chopped strand mat which tends to align and straighten out before been fully put under tension during tensile test.

The more the fiber volume content the rougher the cut surface morphology. There was however no substantial fibre pull-out during the tensile failure, it was a brittle failure with cutting of the fibres across the loading direction. This indicates strong interfacial adhesion between the fiber and the resin matrix.

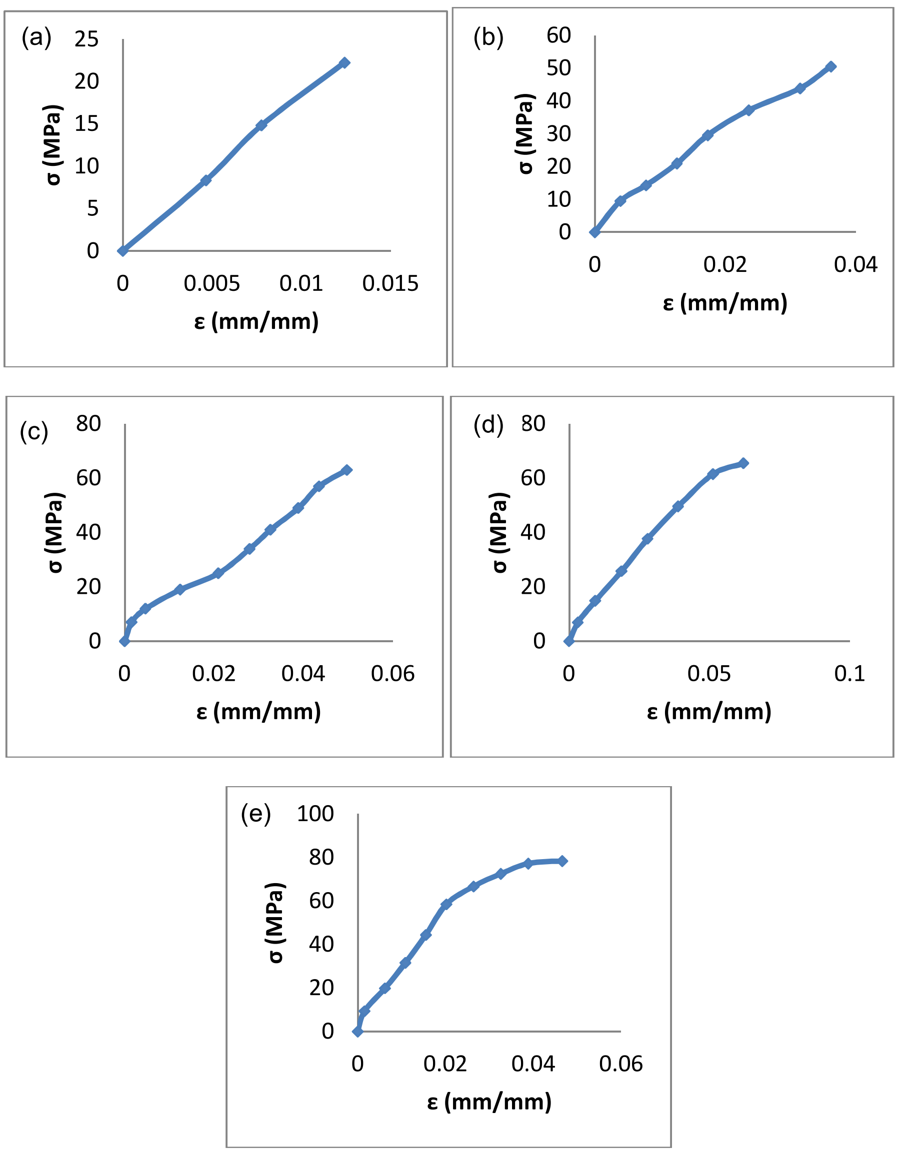

Fig. 4. Stress-Strain curve behavior: (a) composite containing 1-ply, (b) composite laminate containing 2-ply, (c) composite laminate containing 3-ply, (d) composite laminate containing 4-ply, (e) composite laminate containing 5-ply

Figs. 5 and 6 show the predicted and experimental effects of fiber volume fraction on the mechanical properties of the E-glass fiber chopped strand (random) mat reinforced polyester resin composite using the Gay's model, Rule of mixture model, the newly developed model and validating the same with the experimental result. The value of E-glass fibre ultimate stress is given in the literature as 3450 MPa and the Young's modulus as 72.4 GPa [24]. The matrix ultimate strength and Young's modulus were obtained by the author experimentally as 11.23 MPa and 1.88 GPa respectively. The models evaluation gave linear relationships between the fibre volume fraction and the material modulus and strength while the experiment gave undulating trend. The undulation might probably be due to the randomness in the fibre arrangement, fibres not being all straight and unequal fibre distribution on the mat plane. However the new model was able to give an idealized moving average trend which fits the experiment better than others. The rule of mixtures overestimates the modulus and also the strength and therefore does not predict the mechanical properties of random mat composites accurately. From literature reviews the rule of mixtures is good for uniaxially tested unidirectional reinforced laminates. Gay's model is quite complex and also did not actually capture the mechanical characteristics of this very formulation of glass/polyester composite.

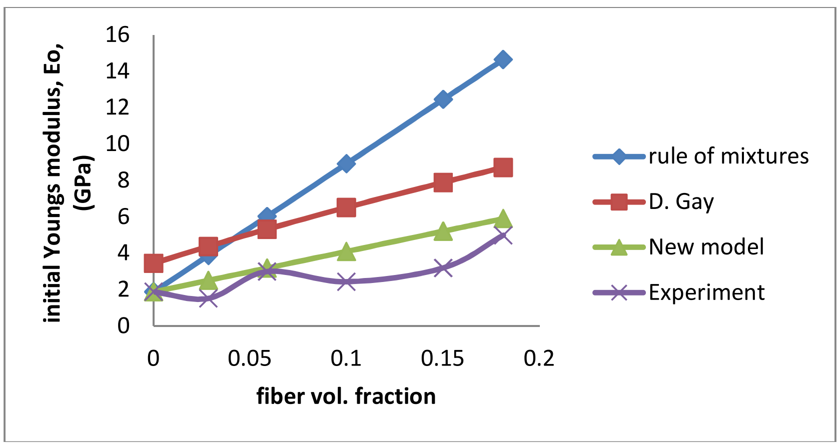

Fig. 5. Effect of volume fraction on initial Young's modulus

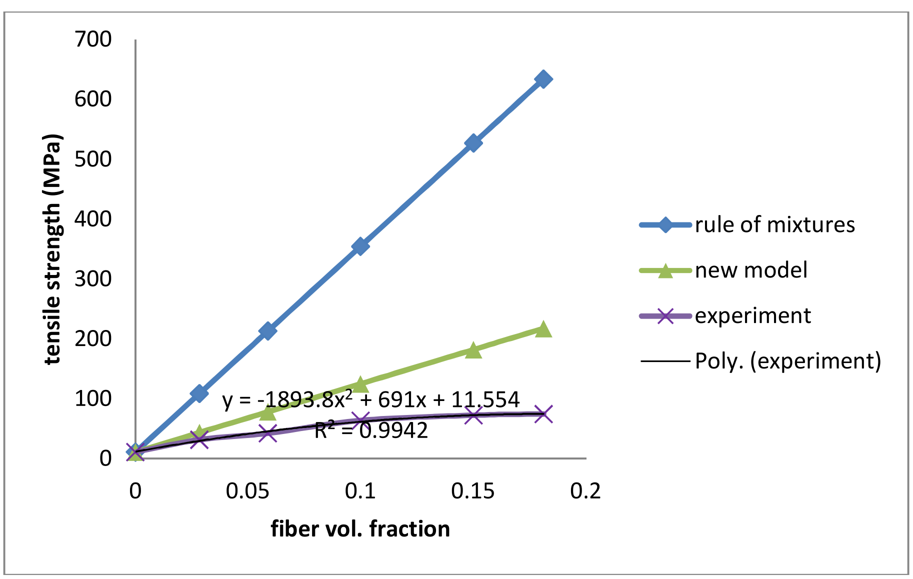

Fig. 6. Effect of volume fraction on random mat laminate tensile strength

The new model suffices at low fibre volume fractions typically obtained in hand lay–up composite applications. Unlike the situation with continuous long fibres where the modulus and strength increases monotonically with fibre volume ratio, it was observed that the strength and the modulus of chopped strand mat drops off at above 20% fibre volume content. This may be due to insufficient resin binder.

A polynomial fit of the experimental data suggests an empirical equation of the form

$$S_c = -1893V_f^{\,2} + 691V_f + (1 - V_f)S_m$$

This is normalized to obtain the strength of the composite with respect to the constituents, fibre and matrix.

$$S_c = -0.55V_f^{\,2}S_f + 0.018V_fS_fS_m + (1 - V_f)S_m \qquad (15)$$

This equation ensures that the strength and by extension the modulus decays above 20% fiber volume content which is characteristic of a chopped strand mat/matrix composite relationship.

5.1 Determination of Toughness of the Material from Stress-Strain Curve

Fig. 7 shows the engineering stress-strain curve of the sample with a linear fit forming the secant. With this trend, the ultimate stress can be assumed to equal the yield stress. This is true when Secant Young's modulus rather than initial Young's modulus is sought.

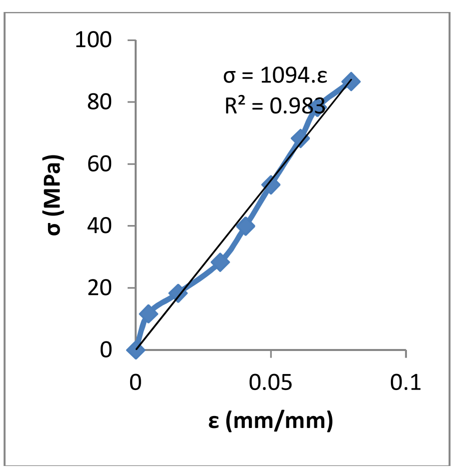

Fig. 7. Typical engineering stress-strain curve with secant modulus determination

The total capacity of the material to absorb energy without fracture is taken as the toughness, and the energy absorbed per unit volume of the material, called the modulus of toughness, T_m, is obtained as the area under the stress/strain curve. This is given as

$$T_m = \int_0^{\varepsilon_f} \sigma d\varepsilon$$

With the secant modulus already defined as in Fig. 7, the positive and negative errors tend to cancel out within the integration limit (i.e. areas above and below the straight line fitting from the experimental data line being approximately equal). Hence

$$T_m = \int_0^{\varepsilon_f} E_s \varepsilon d\varepsilon = E_s \int_0^{\varepsilon_f} \varepsilon d\varepsilon$$

$$T_m = \frac{1}{2} E_s \varepsilon_f^{\,2} \qquad (16)$$

where E_s is the secant modulus and ε_f is the failure strain. The values obtained from the above model were compared with that obtained from Simpson's integration rule as shown in Table 3. The developed secant model average modulus value is less by 3% compared to the Simpson's rule average modulus value of 2.67 MJ/m^3. The percentage difference can be neglected in the present applications of the fibre mat composites and still achieve the economic advantage of the new developed model.

To show that Simpson's rule and the new secant model agree to a very good extent an analysis of variance (ANOVA) is constructed to test the hypothesis, Null hypothesis, H_0: Secant values = Simpson's values and Alternative hypothesis, H_1: Secant values ≠ Simpson's values using F-ratio (see Table 4).

Since 0.234 is less than 4.20 at (1, 28) degrees of freedom in an *F*- distribution the null hypothesis is therefore not rejected. The values obtained from Simpson's rule and that from the new secant model are therefore essentially the same at a significance level of 5%.

A graphical representation of the toughness modulus obtained by computing the area under the stress-strain curves of laminates produced under different cure cycles, using the Simpson's numerical integration rule and the new secant model approach eq. (15) show that the computed values agreed well as indicated in Fig. 8.

Table 3. Toughness modulus determinations

Toughness modulus comparison										
	Simpson's numerical integration					secant modulus model				
Cure Temperature, T_c (°C)	**modulus MJ/m^3**	**Av. Mod., MJ/m^3**	**deviation**	**Variance**	**Std Dev.**	**modulus MJ/m^3**	**Av. Mod., MJ/m^3**	**deviation**	**Variance**	**Std Dev.**
30°C	2.44	2.67	-0.23	0.24	0.49	2.35	2.58	-0.23	0.23	0.48
40°C	3.28		0.61			3.20		0.62		
50°C	3.23		0.56			3.06		0.48		
60°C	2.96		0.29			2.38		-0.21		
70°C	1.87		-0.80			1.76		-0.82		
70 to 30°C step -10	2.50		-0.17			2.50		-0.08		
70 to 30°C step -13	3.32		0.65			3.41		0.83		
70 to 30°C step -20	2.69		0.02			2.64		0.06		
70 to 30°C step -13°C plus fan	3.27		0.60			3.05		0.46		
85°C	2.34		-0.33			2.45		-0.14		
105°C	2.69		0.02			2.64		0.06		
130°C	2.57		-0.10			2.52		-0.06		
150°C	1.73		-0.94			1.65		-0.93		
Fan cooled	2.75		0.08			2.74		0.16		
FRIDGE COOLED	2.39		-0.27			2.38		-0.21		

Table 4. ANOVA Table (one way)

ANOVA Table				
S. V.	***df***	***SS***	***MS***	***F-ratio***
Treatment	1	0.055243	0.055243	0.234031
Error	28	6.609362	0.236049	
Total	29	6.664604		
	$F_{1,28}(0.05)$ = 4.20			

Where SV = source of variation, df = degree of freedom, SS = sum of squares, MS = mean squares and F-ratio = test statistic

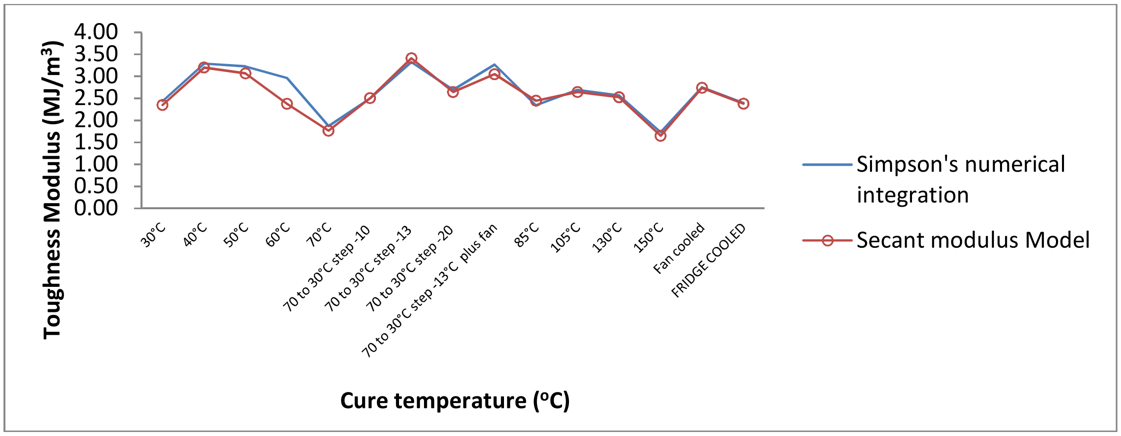

Fig. 8. Toughness modulus determined from Simpson's rule and the Secant modulus model approximation

6. CONCLUSION

Models have been developed to predict the tensile strength and modulus of chopped strand mat composites. The strength of the random mat composite based on micromechanics was modeled using the strength of materials approach and validated with the experimental results. There was no substantial fiber pull-out in the direction of the tensile loading which confirms the assumption of an inseparable overlap of the fibres within the inplane facilitated by the strong interfacial adhesion between the fibers and the matrix.

The rule of mixtures was found to overestimate the strength of the composite by well over 100%. The rule of mixtures works well with uniaxial, unidirectional fibre reinforced composites. A model based on the fibre mat area density and the thickness of the laminate composite was found to predict the volume fraction of the composite laminate very well. For the 3 plies, 450 g/m^2 and 3 mm thickness composite the volume fraction was found to be 18% which agrees with the value obtained experimentally, applying Archimedes immersion principles.

The toughness modulus and secant modulus of short fiber mat composites were also modeled and experimentally validated using chopped strand mat composites cured and cooled down through various cool-down paths. The toughness modulus was determined using a new hybridized secant modulus model. The values obtained from this method were compared to that obtained from the Simpson's rule by integration of the area under the curve. The two methods were found to agree very well within 95% confidence interval.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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