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Prediction of Mechanical Behaviour of Unidirectional Natural Fibre Reinforced Polymer Composite using Analytical Approach

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***Abstract* - The fibre-reinforced polymer composites are novel materials for the last few decades because material properties can be regulated easily by changing the fibre content in the matrix. The properties of these materials can be evaluated by any of the two methods i.e. experimentation method or analytical approach. The results obtained from analytical approach are very close to exact results and can be helpful for researchers to predict the performance of the composite. In this paper different natural fibres like jute, banana, coir, softwood kraft pulp and cotton are used as reinforcement and for the matrix phase, materials like epoxy resin and polyester resin are used. The volume fraction of the fibers in the resin varies from 0.1 to 0.7. The variation of elastic modulus is observed in the linear as well as in transverse directions for natural fibre with both epoxy and polyester resin by changing the volume fraction of fibre in resin. The main objective of this research paper is the implementation of an analytical proven model like the rule of mixture and inverse rule of mixture for predicting the performance of various natural fibres reinforced epoxy composites with varying fibre fraction. The database is also generated for predicting the performance of composites at various volume fractions. Fibres are assumed as unidirectional in the polymer matrix.**

Index Terms - Fibre composite, Rule of mixture, Natural fibre, Elastic modulus

INTRODUCTION

Natural fibre-reinforced polymer composites are used nowadays as a substitute for conventional materials in various applications. The natural fibre-reinforced material has a wide potential due to the property changing behaviour as per need. A lot of experimental and modelling work has been carried out in the field of synthetic fibres and their composites. Especially waste fibres like coir, jute, and banana, etc and their polymer composites are need a modelling approaches for easy and fast understating the behaviour of composite. Agricultural wastes fibres are produced in huge amounts in India. If these fibres can be tested for certain applications will give twin benefits to the environment and replacement of conventional material. To meet the challenges for utilising the natural fiber based composites analytical study are performed. The key motivating factor of writing this paper is highlighting the variation of mechanical properties of natural fibres with the polymers by applying proven modelling theory like the rule of mixture and inverse rule of mixture. The key challenges are to analyze natural fibres reinforced epoxy and polyester composites with the proven analytical theory of modelling and to observe the variation of elastic modulus of various natural fibres with both epoxy and polyester resin. It will also helpful for generation of the database for predicting the behaviour of natural fibre composite.

LITERATURE REVIEW

The natural fibre polymer composite materials are mostly used and it becomes a key material for various engineering applications. The material property can be varied as per fibre volume fraction hence various micromechanical models are discussed in the literature to easily approximate the behaviour of composite. The elastic modulus for two or more multiple phases is obtained by the approximation method and reported [1]. The analysis of composite materials by periodic microstructure is suggested and using Fourier series techniques. It is found that experimental results are matched with the Fourier series technique [2]. The Halpin-Tsai equation is derived from elastic calculations and shows the effect of volume fraction and packing geometry [3]. A particulate filled polymer is studied for thermal conductivity by using the finite element method. The values are compared with experimental results and empirical relations. The values proved that finite element methods can be used for analysis [4]. The finite element method is used for the analysis of composite by representative volume element approach and found good agreement with experimental results [5]. Many synthetic fibres with polymer resins are modelled but fewer attempts are made with natural fibres. Various mathematical models like the rule of mixture and inverse rule of mixture are reviewed with natural fibres. The advantages and disadvantages of each model are reported with flax-wood-polypropylene composite as an example [6]. The micromechanical model approach is not limited to synthetic fibres with thermosetting but applied successfully with natural fibre reinforced thermoplastics and found that these models can be used successfully with thermoplastics as do in thermosetting. A cluster parameter is discussed in the paper where the reduction in fibre stress surface area is a key parameter for strengthening the composite [7, 23]. Kenaf fibre with epoxy was tested for different volume fractions and found that experimental results are close with the rule of mixture results [8]. The elastic and thermal conductivity of unidirectional fibre composite is evaluated by micromechanical models and numerical approach i.e. finite element method. The finite element model is based on representative volume element code in ANSYS and results are compared. It is found that properties are affected by a cross-section of fibre, fibre geometry, and fibre volume fraction [9]. The key difficulties are discussed with transverse thermal conductivity variation in continuous fibers and possible suggestions are incorporated [33]. Finite element techniques are used for analysis of various complex problems. Particulates/fiber filled polymers composite are analysis by finite element techniques for thermal conductivity [30, 31]. Representative volume element based techniques used for modelling of composite with variation of fiber size [27, 29]. Representative volume element generation with intermixing of straight and curved fibres in finite element methods improves the volume fraction count and is used successfully for chopped fibres [10]. A mathematical relation is developed with an elliptical shape and hence its effect on thermal conductivity is also studied [24]. Natural fibres with epoxy resin are focused on predicting the performance of the composite. Pineapple fibre with epoxy resin is tested for various analytical models (MATLAB GUI) and results are compared with experimental [11]. A detailed review is presented in the literature for the tensile properties of natural fibre polymer composite with various micromechanical models and shows that natural fibre reinforced thermoplastic composite results are close with experimental results. It is also revived that Halpin-Tsai methods give most effective results than other models [12]. A comprehensive collection of Representative volume element techniques is reviewed for heterogeneous material with various important key factors [13]. Thermal conductivity is also a key property for a composite and it is investigated with various micromechanical techniques. Various models are reviewed and it was concluded that no one model is a perfect prediction of the composite but for solid-filled composite, Lewis and Nielsen's equations are best fitted [14]. The composite is analyzed as micro, mini, and macro principle (MMM) in which if crystal diameter or particle diameter are considered as the micro approach. If dimensions of representative volume element are considered then it is considered as mini scale and if dimensions of the whole composite are considered as a macro-scale concept [15]. For the analysis of nonlinear properties like tensile strength, a modified rule of the mixture model is used and modified Halpin-Tsai models are used for both micro and nanoparticles reinforced composites [16]. Transverse normal loading of unidirectional fibre composite is discussed in the literature for various cross-section shapes and various fibre and matrix properties [17]. The polypropylene and hemp fibres are analyzed with a modified rule of mixture model and it is concluded that for better performance the fibres should be axially aligned in loading direction [18]. Some author works on statistical approach for analysis of reinforced composite. Mechanical properties of polypropylene reinforced with natural fibre and short glass fibre are analyzed with a statistical approach. The results are verified with experimental techniques [19]. Jute and polypropylene composite is analyzed with modification and coupling agent spastically and experimentally and aging effect discussed [20]. The detailed discussion is reported with polypropylene and fibre composite for variation of fibre level. It is found that fibre composition influenced the higher stress region of the composite. It is also reported that from the finite element model that if fibre concentration is low at a particular region then less applied stress is shared [21]. Modelling methods can also use for the prediction of wear behaviour of high-stress wear under various operating conditions [22]. Study of wood plastic composite with micromechanical models is discussed and fiber orientation factors considered and verified with experimental data [25]. Thermoplastic polymers are also reinforced with sisal fiber with changing the volume fraction and their mechanical properties are discussed with various theoretical models. It is reported that adhesion between fibre and matrix plays an important role [26]. A detailed step by step rule of mixture analyzed and verified experimentally for modulus variation [28]. Rule of mixture with various affecting factors are discussed in the literature for more accuracy [32].

As per the observation recorded in various literature surveys, it is proven that analytical models are helpful for predicting the performance of the natural fibre reinforced polymer composite. During the literature survey, it is found that huge research is carried out for synthetic fibres and now researchers are working with natural fibres with analytical approaches.

MATERIALS AND METHODS

The natural fibres such as Jute, Banana, Coir, Cotton, Bamboo, and Softwood kraft pulp are used as reinforcement for analysis purposes. The thermosetting polymer epoxy resin and polyester resin are used as a matrix. The properties of the fibres and matrix are taken from the published literature [9, 12, 34, 35, 36, 37]. Fibres are assumed to be unidirectional and hence elastic moduli are evaluated in linear and transverse directions.

TABLE 1:
PROPERTIES OF FIBRES AND MATRIX [9, 12, 34, 35, 36, 37]

S. No.	Fibre / Resin	Property	
		Young's Modulus (GPa)	Density (g/cm^3)
1.	Jute	26.5	1.45
2.	Coir	6	1.15
3.	Cotton	12.6	1.6
4.	Bamboo	35.91	0.91
5.	Banana	17.85	1.35
6.	Softwood kraft pulp	40	1.5
7.	Polyester resin	2	1.2
8.	Epoxy	3	1.1

ANALYTICAL METHODS

Various theoretical models are revived in the literature for analytical analysis of fibre-reinforced polymer composites [14]. A well-known proven model i.e. Rule of the mixture is used for comparing the elastic modulus for natural fibre-reinforced polymer composite in a linear direction and inverse rule of mixture is used for variation of elastic modulus in the transverse direction. The rule of the mixture model is a very common model used for the evaluation of properties of the composite. Voigt's and Reuss's models are also known as the rule of the mixture and inverse rule of mixture model [6]. All the analytical models are taken as from reference [6, 9, 14].

Rule of mixture: $\boldsymbol{K_e = (1 - ø)K_c + øK_d}$

Inverse rule of mixture: $\frac{\boldsymbol{1}}{\boldsymbol{K_e}} = \frac{\boldsymbol{1-ø}}{\boldsymbol{K_c}} + \frac{\boldsymbol{ø}}{\boldsymbol{K_d}}$

Where:

$\boldsymbol{K_e}$ = Effective property of the composite

$\boldsymbol{K_c}$ = property of continuous phase (matrix phase)

$\boldsymbol{K_d}$ = property of discrete phase (fibre phase)

ø = Volume fraction of discrete phase

RESULTS AND DISCUSSION

The results are plotted for the variation of elastic modulus in a linear direction with the rule of the mixture for all the fibers (Jute, Banana, Coir, Cotton, Bamboo, and Softwood Kraft pulp) with epoxy resin in figure 1 and in transverse direction by the inverse rule of mixture in figure 2. The volume fractions of fibre in both the resins are varying from 0.1 to 0.7. It is observed from figure 1 that the elastic modulus of natural fibre reinforced polymer composite increases with increase in fibre volume content in the composite. The lowest elastic modulus is achieved at the lowest fibre volume fraction i.e. at 0.1 and the highest elastic modulus is achieved at the highest fibre volume fraction i.e. at 0.7 for each combination of natural fibre reinforced composite. The maximum elastic modulus value in the linear direction is observed for softwood kraft pulps with epoxy resin i.e. 28.9 GPa. Similarly the minimum elastic modulus value in the linear direction achieved for the combination of coir and polyester composite i.e. 2.4 GPa. Figure 3 and figure 4 plotted the variation of elastic modulus in linear and transverse direction for natural fibres and polyester resin respectively. The maximum elastic modulus value in the transverse direction is observed for softwood kraft pulps with epoxy resin i.e. 8.5 GPa. Similarly the minimum elastic modulus value in transverse direction is achieved for the combination of coir and polyester composite i.e. 2.1 GPa. It is also observed from the figure 1 and figure 3 that elastic modulus value showing a small variation for all the fibres with epoxy and polyester resin up to 0.2 fibre volume fraction and then deviates continuously up to 0.7 fibre volume fraction in linear nature. It is due to that as fibre content increases in the matrix the elastic modulus of composite shows significant variation. Similarly in transverse direction in figure 2 and figure 4, the elastic modulus shows close results up to 0.4 fibre volume fraction and then increases exponentially up to 0.7 fibre volume fraction for all the fibres with epoxy and polyester resin. These models are also successfully validated with various modelling techniques for the glass fibre epoxy composite in the literature [9].

FIG. 1:
VARIATION OF LONGITUDINAL MODULUS WITH VOLUME FRACTION FOR NATURAL FIBERS AND EPOXY RESIN

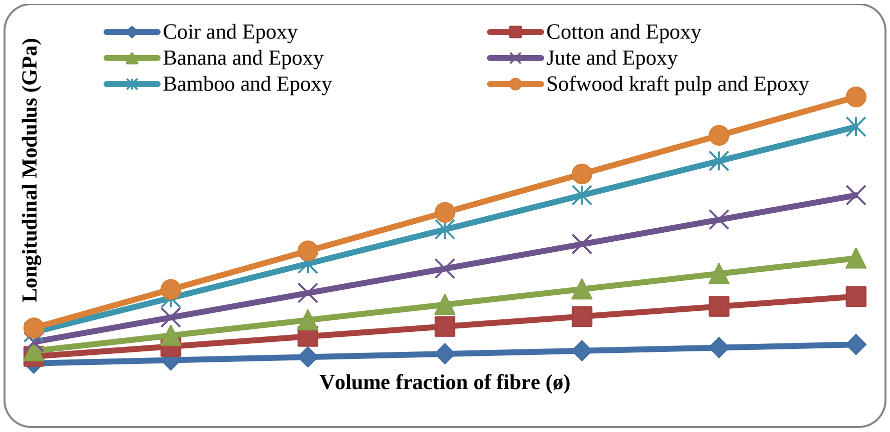


FIG. 2:
VARIATION OF TRANSVERSE MODULUS WITH VOLUME FRACTION FOR NATURAL FIBRES AND EPOXY RESIN

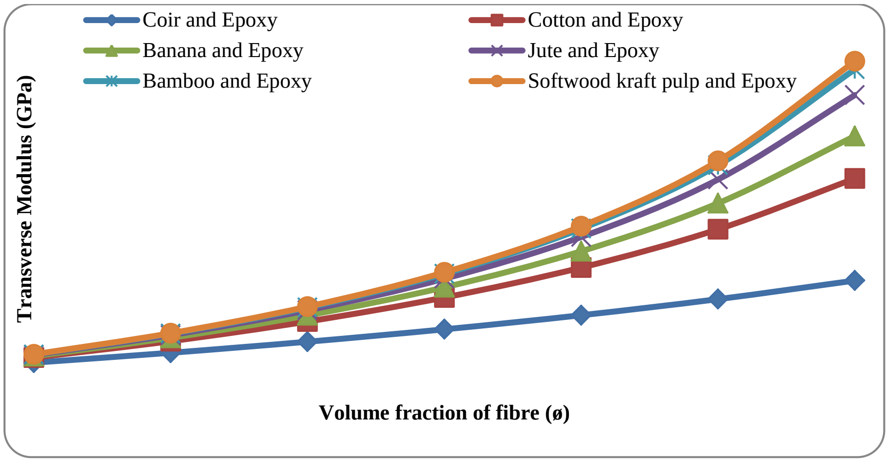


FIG. 3:
VARIATION OF LONGITUDINAL MODULUS WITH VOLUME FRACTION FOR NATURAL FIBERS AND POLYESTER RESIN

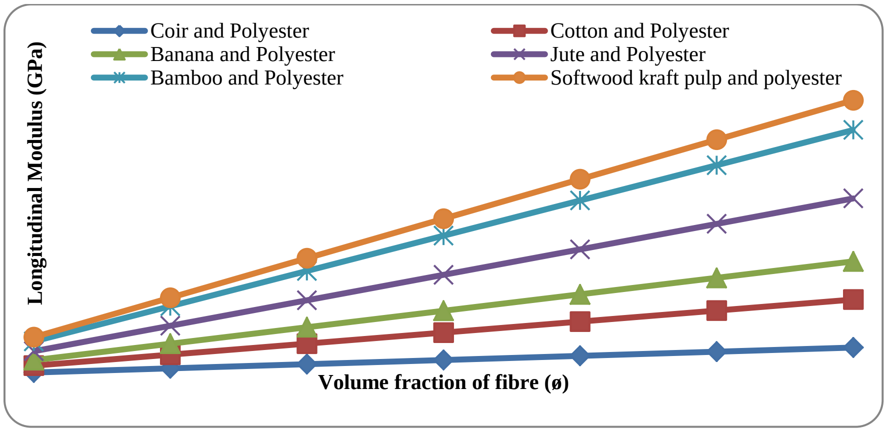
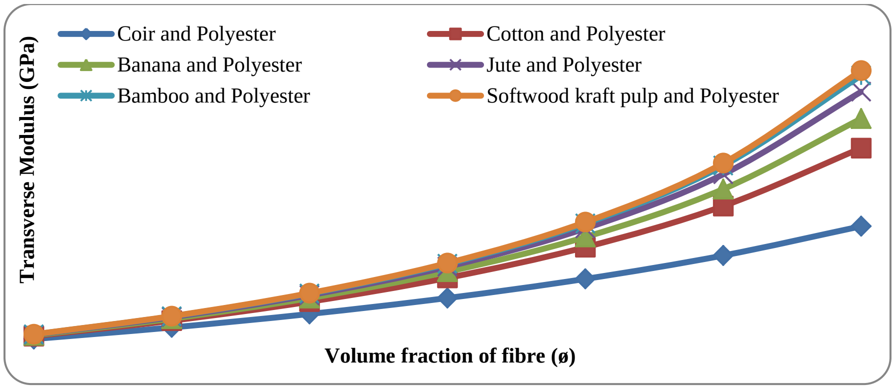


FIG. 4:
VARIATION OF TRANSVERSE MODULUS WITH VOLUME FRACTION FOR NATURAL FIBRES AND POLYESTER RESIN



Conclusion And Future Scope

The analytical proven models i.e. Rule of the mixture and inverse rule of mixture models are used for predicting the performance of natural fibre reinforced epoxy/polyester composites with varying fibre fraction. Fibres are considered as unidirectional in the epoxy resin and hence elastic modulus is evaluated in linear as well as in transverse directions. It is concluded that theoretical models shows good agreement with property variation in composites and it helps for predicting the performance of composite theoretically. The useful data predicted from theoretical models can give easy predictions to researchers for the behaviour of composites in the future. Experimental results may vary from theoretical models due to the involvement of various factors such as moisture absorption, fabrication techniques, void factors etc and should be considered for the exact behaviour of composite.

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