Experimental Investigation and Micro Mechanics Assessment for Longitudinal Elastic Modulus in Unidirectional Cotton-Polyester Composites

Piyush P. Gohil [#1], A.A. Shaikh [*2]

[#] *Department of Mechanical Engineering, Faculty of Technology and Engineering*
Charotar University of Science and Technology, College Campus, Changa-388 421, (Gujarat-India)

[*] *Department of Mechanical Engineering, S.V. National Institute of Technology*
College Campus, Ichchhanath, Surat -395 007, (Gujarat-India)

***Abstract*— Several billion tons of fillers and reinforcements are used annually in the plastics industry, and there is a huge potential market for recyclable, energy efficient and more environmentally friendly composite materials. The use of medium strength and low strength fiber available in nature are having enough potential for other application where high strength are not critical but it can provide a feasible range of alternative materials to suitable conventional material. The systematic experimental study using developed mould-punch set up and testing aids was carried out for the effect of volume fraction of reinforcement on longitudinal elastic modulus of unidirectional cotton fiber reinforced polyester composites. The testing was carried out as per ASTM D3039/D3039M-08. The micro mechanics assessment of obtained experimental results with models available in literature for longitudinal elastic modulus forms an equally important constituent of present work.**

Keywords—Cotton fibers; unidirectional composites; testing, experimental study, micro mechanics.

I. INTRODUCTION

A composite is a heterogeneous combination of two or more materials i.e. reinforcing agents and matrix [1], differing in form or composition on a macro scale. The combination results in a material that maximizes specific performance properties. The constituents do not dissolve or merge completely and therefore normally exhibit an interface between one another. In this form, both reinforcing agents and matrix retain their physical and chemical identities, yet they produce a combination of properties that cannot be achieved with either of the constituents acting alone. Commercial and industrial applications of fiber-reinforced composites are diverse and varied. Some of these applications are ship and submarines, aircrafts and spacecrafts, trucks and rail vehicles, automobiles, robots, civil engineering structures and prosthetic devices. The use of natural fiber composites starts gaining popularity in engineering applications. This is due to the fact that this material possesses characteristics that are comparable to conventional materials. Properties like light weight, low material cost, renewable and environmentally friendly are among the most important selling points of this material. In the past various studies have been carried out on natural fiber composites [2]. Natural fibers are based on renewable materials and depending upon the source can be subdivided mainly into two major groups: plant fibers (based on agricultural resources) and animal fibers (based on resources derived from animals). The group of plant fibers can be subdivided into several classes: straw, seed, bast, leaf and wood fibers as depicted in Fig. 1.

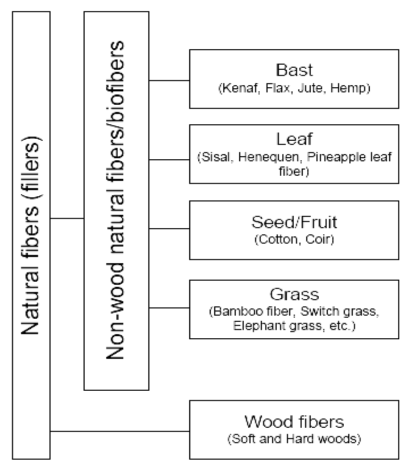

Fig. 1. Classification of natural fibers derived from plants [3]

The attempts made for jute and other repeatedly used natural fiber, of course provides data but there is paucity for experimental data for other seldom natural fiber like cotton, banana, pineapple leaf, and other. Hence there is a need to carry out systematic experimental research in this area.

II. LITERATURE REVIEW

India, endowed with an abundant availability of natural fibers such as jute, coir, sisal, pineapple, ramie, cotton, bamboo, banana etc., has focused on the development of natural fiber composites primarily to explore value-added application avenues. Such natural fiber composites are well suited as wood substitutes in the housing and construction sector. The development of natural fiber composites in India is based on a two-pronged strategy of preventing depletion of forest resources as well as ensuring good economic returns for the cultivation of natural fibers .

During the 1970s and 1980s natural fibers were partially replaced by petrochemical polymers because of their optimized properties and their faster manufacturing processes. In the mid 80s it was thought that the use of natural fiber reinforced composites could offer an interesting alternative to these plastics due to their technical, economic and ecological advantages and social benefits [4].

According to Karus et al. [5] in 2003 approximately 45,000 tons of domestic cotton fibers were used in the German automotive industry for interior applications, which results in 79,000 tons of composite parts and about 8 kg of cotton-fiber composites in a German car. Reclaimed cotton is mainly used as low cost fiber in composites used as interior parts for automotive devices. Since the late 1980s publications can be found dealing with finding the limits and advantages of using cotton as an adequate reinforcement fiber.

Muller et al. [6] reported that natural fibers like ramie, hemp, flax, jute or cotton are well suited for reinforcing polymers. They focused their work on the evaluation of the acoustical properties of natural fiber reinforced thermoplastics. The acoustical properties of these natural fibers reinforced materials are comparable to sandwich parts which were built out of glass fiber composites and PU-foam.

Jiang and Hinrichsen [7, 8] in their work combined a biodegradable polymer and natural fibers. Biodegradable composites consisted of flax and cotton fibers in combination with polyester amide films which were hot pressed using the film stacking process. The aim of their work was to determine the degree and rate of biodegradability of composites with natural fibers depending on the thickness of the samples.

Stanojlovic-Davidovic et al. [9] developed composites based on starch foam reinforced with natural fibers such as cellulose, hemp, cotton linters and wheat straw. Fibers were used to improve mechanical properties of starch foam formulations and to increase water resistance. The functional properties of the developed starch foams were comparable with those of polystyrene foams.

Foulk et al. [10] reported on the possibilities to create composites with cotton and flax-containing commercial fabrics and recycled high-density polyethylene (HDPE). According to their work additional research is needed to improve composite binding characteristics by allowing the stronger flax fibers in fabric to carry the composites load.

The cotton-polymer composite system made contributions to the war effort during 1941- 1946. [11-12] as fiber reinforced plastics; it was first used by the military for radar domes on aircraft.

Gohil and Shaikh [13] develop cotton-polyester cylinders of varying thickness using filament winding technique with cotton fiber and polyester resin. They modify the lathe machine to fabricate the filament wound cylinders. The cylinders of 3mm, 5mm and 7 mm thickness were fabricated as shown in Fig. 2 and the hydro test was conducted and some weight study was also carried out. The objective of the study was to make the people aware with the opportunity and advantageous of filament wound composite shell of cotton polyester composite to replace some of the available conventional shell in daily as well as industry use purposes which can be replaced by natural fiber composite.

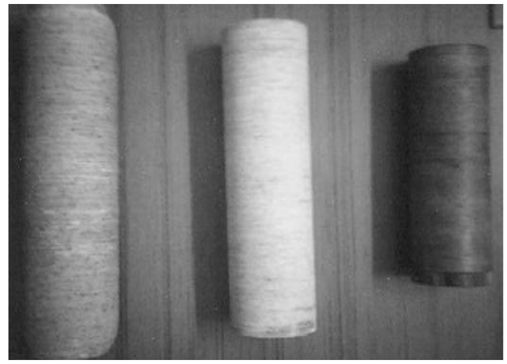

Fig. 2. Cotton-Polyester cylinders

III. Procurement of Materials

Composite requires reinforcement and a resin system to bind things together. There are many types of materials that can be used in this process. The choice of materials depends more upon the weight limitations and the strength performance requirements. Following sections elaborates the details of reinforcement and matrix material selection for the development of composites.

As revealed from the literature lot of work is done for high strength fibers and data base for experimental value for high strength fiber composite is available in literature. Looking to the inadequate data availability for natural fiber composites the area need to be focused with in depth study.

Therefore, it is decided to procure different types of natural fiber; as these fibers are not easily available in the required form which can be used for preparing the natural fiber composite specimen. Cotton fiber was procured from local market. Fig. 3. shows the photographs of procured cotton fiber.

Fig3. Cotton fiber sample

The resin/matrix that holds everything together provides the load transfer mechanism between the fibers. In addition to binding the composite structure together, the resin matrix serves to provide the corrosion resistance, protects the fibers from external damage, and contributes to the overall composite toughness from surface impacts, cuts, abrasion, and rough handling. Resin systems come in a variety of chemical families, each designed to provide certain structural performance, cost, environmental, and environmental resistance.

Four major types of matrices have been reported: Polymeric, Metallic, Ceramic and Carbon. Most of the composites used in the industry today are based on polymer matrices.

The reinforcement of polyesters with cellulosic fibers has been widely reported. polyester-jute [14, 15], polyester-sisal [16], polyester-coir [17] polyester-banana-cotton [18], polyester-straw [19], polyester-pineapple leaf [20], and polyester- cotton-kapok [21], are some of the promising systems.

Looking to the relative merits and qualities of polyester resin [22] and ease of availability in nearby market vicinity polyester have been selected. It is purchased from GIDC Odhav, Ahmedabad.

IV. Measurement of Constituent's Property

This section describes the measurements for of constituent's property for density and structural property.

A. Density Measurement

The use of Archimedes law is recommended by Morton [23] for density measurement. So, here it is decided to carry out the density measurement of procured cotton fiber. In this method, the sample of fiber resin is selected and its mass is measured on digital weight balance with a resolution of 0.001 gm. The volume of this fixed mass fiber is measured using standard displacement technique. In this technique weighted fiber sample is immerged in 100 ml measuring cylinder filled with water. The displaced volume is measured with micro pipette having L.C. of 0.02 ml. as shown in Fig. 4. Total 25 samples of cotton fiber were used.

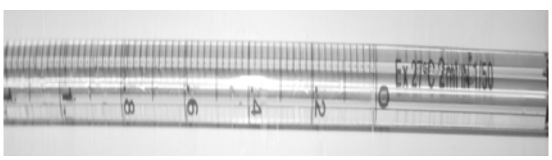

Fig. 4. Micro Pipette with L.C. of 0.02 ml

The density polyester is also measured based on principle of Archimedes. For this purpose, the cast plate of polyester resin with a size of. 30 cm X 18 cm was prepared as shown in Fig. 5.

From this prepared plate total 25 rectangular pieces of 4cm x 2cm size were cut. The cutting operation carried out using CNC laser engraver LaserPro Mercury II.

The mass of these casted pieces was measured by digital weight balance having L.C. of 0.001 gm. The volume of pieces was measured with standard displacement technique with the help of 100 ml measuring cylinder and 0.02 ml micro pipette.

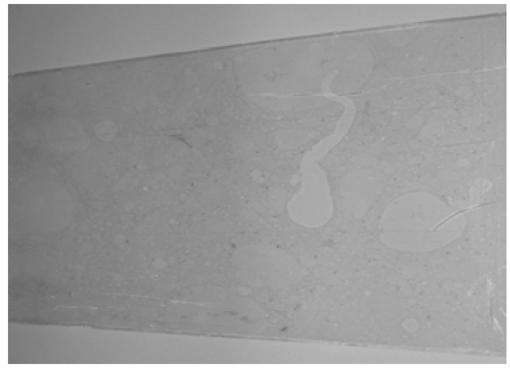

Fig. 5. Prepared resin plate

The statistical parameters for cotton fiber and polyester resin density measurement are depicted in Table I.

The inbuilt descriptive statistics analysis tool of Microsoft excel was used to generate a report of statistics for input range data which provides information about the central tendency and variability of the experimental data.

TABLE I
DESCRIPTIVE STATISTICS FOR DENSITY MEASUREMENT

Statistical Parameter	**Cotton Fiber**	**Polyester Resin**
Mean	1.48082	1.2203
Standard Error	0.01675	0.0026
Median	1.46714	1.2171
Mode	1.55000	1.2108
Standard Deviation	0.08379	0.0128
Standard Deviation (%)	5.65882	1.0527
Sample Variance	0.00702	0.0002
Kurtosis	-0.81613	-0.1022
Skewness	0.191249	0.8120
Range	0.31750	0.0465
Minimum	1.32000	1.2022
Maximum	1.63750	1.2487
Sum	37.02055	30.5068
Count	25	25.0000
Largest(1)	1.63750	1.2487
Smallest(1)	1.32000	1.2022
Confidence Level (95.0%)	0.03459	0.0053

The final experimental values for density observed by measurement for constituents and by performing the descriptive statistics are depicted in Table II.

TABLE II
DENSITY OF CONSTITUENTS (EXPERIMENTAL VALUE)

Sr. No.	**Name of Constituent**	**Density (g/cm^3)**
1	Cotton fiber	1.48 ± 0.083
2	Polyester resin	1.22 ± 0.012

B. Structural Property Measurement

The following section describes the property measured for the procured cotton fiber and polyester resin.

1) Cotton Fiber: The testing of cotton fiber was carried out at MANTRA (Man Made Textile Research Association, Surat under the ministry of textile. Govt. of India) which is a premier research association of this region in the area of fiber related research. Table III shows the strength and elastic modulus experimental value for procured cotton fiber reinforcement.

TABLE III
COTTON FIBER STRUCTURAL PROPERTY

Strength	Elastic Modulus
200 MPa	8.20 GPa

2) Polyester Resin: The measurement for the strength of casted neat polyester resin was carried out as per ASTM D 638-90 [24]. The casted specimens of polyester resin were made in specially prepared wooden mould with same proportions of initiator and accelerator. The specimen plate was cured for 24 hrs within the mould only. After curing the specimen were cut down as per dimension requirement of ASTM D 638-90 [24] using CO2 laser engraving machine. The dimensional detail of casted specimen dimension is given in Fig. 6 and Fig. 7. shows the cut specimen as per ASTM 638-90 [24].

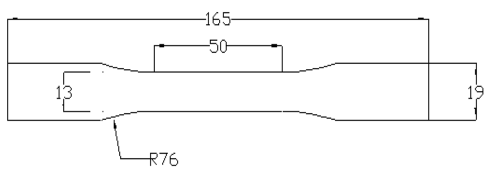

Fig. 6. Dimensional detail of casted specimen as per ASTM 638-90

Fig. 7. Developed neat polyester resin specimen as per ASTM 638-90

The strength was measured using computerized tensometer (Make: Kudale Instruments L.C. of 1 kg,) and cross sectional area is measured based on geometrical measurement using digital vernier (Make: Mitutoyo, having L.C. of 0.01 mm. Table IV shows the measured property for the polyester resin.

TABLE IV
POLYESTER RESIN STRUCTURAL PROPERTY

Strength	Elastic Modulus
20 MPa	2.31 GPa

V. COMPOSITE SPECIMEN PREPARATION

To prepare the composite specimen for testing purpose, appropriate mould punch setup is required, which can ensure the good quality of the specimens for the testing. Different options were thought for the mould punch setup by developing 3D CAD model using Pro Engineer Wildfire 3.0. The cavity of 280 x 200 x 20 was decided considering dimensions of testing specimen specified by various testing standards. Based on this cavity dimension all other parts of mould punch setup were finalized. It is possible to have multiple specimens i.e. 7 specimens for longitudinal case for testing from the prepared composite plate and the average value is to used for depicting the final answer. Fig 8. shows the assembly drawing of mould and punch set up.

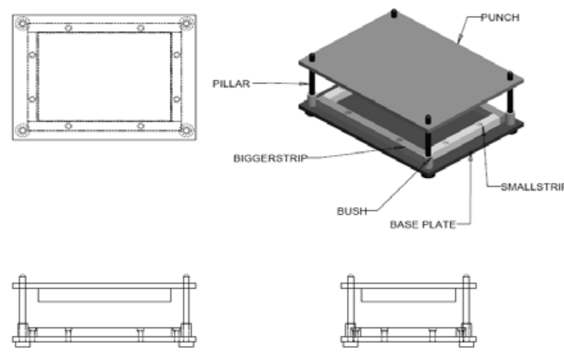

Fig. 8. Assembly drawing of mould and punch setup

The cavities of mould and punch were treated with SAE oil in order to facilitate easy removal of specimen. A 20 micron PVC film was used in cavities at all mating surfaces of mould and punch so as to avoid any penetration of resin in these surfaces as well as to enhance the easy removal of plate. With this care the specially prepared preform on textile warping machine are placed in mould cavity.

The mass of preform was measured using digital weight balance having L.C. of 0.001 gm and then measured volume of resin is poured into mould. In order to accelerate the curing process the accelerator was added with initiator in a proportion of 1.5% on volume base. The curing for composite specimen plate was carried out at room temperature and was allowed to cure for 24 hours within the mould. Fig. 9 shows the prepared composite plate of cotton polyester composite. Total five unidirectional cotton polyester composite plates with different fiber volume fraction were preaped.

Fig. 9. Prepared cotton-polyester composite plate

Table V shows the measured fiber volume fraction of all five plates.

TABLE V
FIBER VOLUME FRACTION

Plate No.	Fiber Volume Fraction v_f
1	0.1041
2	0.1955
3	0.2431
4	0.2717

5	0.3527

ASTM allows using the mild steel tab for specimens, which is easier to handle and fix with flat specimens therefore; it is decided to adopt the ASTM D3039/3039M-08 [25] standard for the geometrical dimension. As per the dimensions of the prepared composite plates it is possible to have 7 specimens of same fiber volume fraction. Fig. 10 shows the photographs of prepared specimens of unidirectional cotton-polyester composite for testing.

Fig. 10. Prepared cotton-polyester composite specimen for testing

VI. EXPERIMENTATION

All the specimens were prepared and made ready for the tensile testing. It is decided to evaluate the composite strength and composite elastic modulus for the prepared specimens. The computerized Tensometer (Make: Kudale Instruments L.C. of 1 kg) was used for tensile testing.

The load and displacement readings are observed through inbuilt software with available facilities of storing data as tabulated readings and graphs. The software is based on windows XP.

Tensometer was used to measure the peak load while the cross sectional area is evaluated based on geometrical measurement using digital vernier of L.C. 0.001 mm for the width and thickness of the specimen.

The measured parameters were given as input in the inbuilt software. The ratio of peak load to cross sectional area gives the strength of composite. Once, the data for strength and strain is available the elastic modulus can be determine by taking the ratio of strength to strain.

VII. MICRO MECHANICS ASSESSMENT

Varieties of predictive models in the literature available are either derived theoretically based on parametric constraints or semi empirically based on experimental studies.

Whitney [26] described that the static equilibrium requires the total resultant force on the element must be equal to the sum of forces acting on the fiber and matrix. Combining the static equilibrium condition leads to formation of rule of mixture as shown in equation 1.

$$E_c = E_f v_f + E_m v_m \quad \ldots\ldots\ldots\ldots (1)$$

Puck [26] also proposes the model as shown in equation 2 which is based on the concept of approximation considering the properties of longitudinal equation.

$$E_c = E_m (3.92 v_f + 0.89) \quad \ldots\ldots\ldots\ldots (2)$$

Madson [27] has modified the rule of mixture and proposed two porosity components i.e. a processed governed component and structurally governed component. A modified rule of mixture supplemented with these two parameters of composite porosity content was given as:

$$E_c = \left(v_f E_f + \left(1 - v_f\right) * E_m\right) * \left(1 - V_p^2\right) \quad \ldots .(3)$$

$$V_p = V_{p(Processing)} + V_{p(Structural\ Mechanism)}$$

$$V_{p(Processing)} = 0.06 * W_f$$

$$V_{p(Structural\ Mechanism)} = 0.32 * W_f - 0.20,$$

if w_f >0.625 else zero.

Gohil and Shaikh [28] have proposed the models which describes as the concept of soft and hard interphase.

$$E_c = (E_{fl} v_{f1}) + (E_i\_soft * v_i^a) + (E_m v_m) \ldots\ldots .(4)$$

$$E_c = (E_{fl} v_{f1}) + (E_i\_hard * v_i^a) + (E_m v_m) \ldots\ldots (5)$$

All the above models were assessed and compared with the present experimental results and minimum bias average errors are determined. The results obtained are discussed in next section.

VII. RESULTS AND DISCUSSION

The salient features of results obtained from the experimental investigations and micro mechanical assessment carried out for the prepared cotton fiber reinforced polyester composites material specimens are presented and discussed here.

The experimental results on effect of reinforcement fraction on longitudinally placed fiber on composite strength and composite elastic modulus with polyester matrix combination are discussed here. All the specimens were subjected to longitudinal tensile testing.

Fig. 11 shows the variation in composite strength as a function of v_f for longitudinally placed cotton fiber with polyester resin. The composite strength with polyester resin is observed in the range of 27.94 MPa to 71.16 MPa for longitudinally placed cotton fiber adjacent to the v_f range of 10.41% to 35.27% .

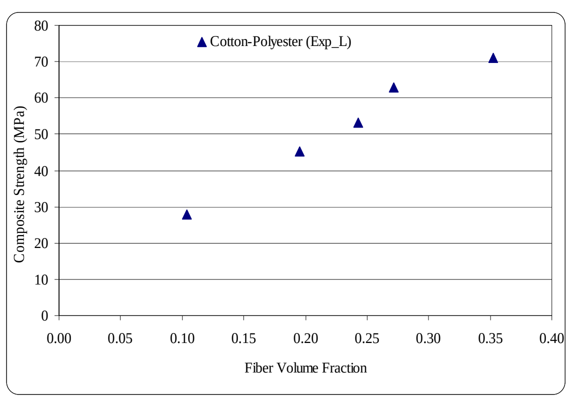

Fig. 11. Effect of volume fraction of cotton fiber with polyester resin on longitudinal composite strength

Fig. 12. shows the variation in composite elastic modulus as a function of v_f for longitudinally placed cotton fiber with polyester resin. The composite elastic modulus with polyester resin is observed in the range of 2.70 GPa to 4.04 GPa for longitudinally placed cotton fiber adjacent to the v_f range of 10.41% to 35.27%.

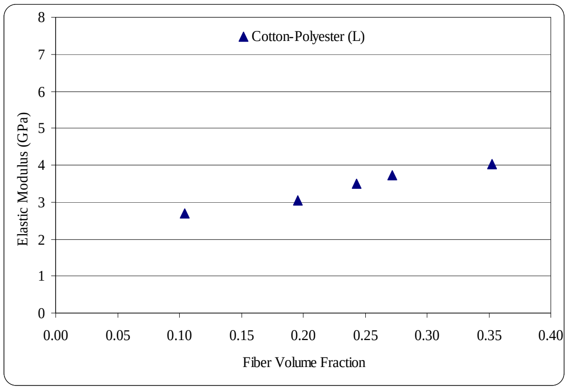

Fig. 12. Effect of volume fraction of cotton fiber with polyester resin on longitudinal composite elastic modulus

The experimental investigation indicates that, as the fiber volume fraction increases the strength as well as longitudinal elastic modulus increases linearly. This is inline with the rule of mixture which predicts the linear increase in composite strength with increase in volume fraction of fibres holds true for longitudinally placed fiber composite for all the fiber-matrix combination

Various models [26, 27] to predict the composite elastic constant are available in literature. An attempt is made for comparative assessment of these models for longitudinal elastic modulus with present experimental results, which is shown in Fig. 13.

The deviations in terms of minimum average bias error obtained by available model are depicted in Table VI.

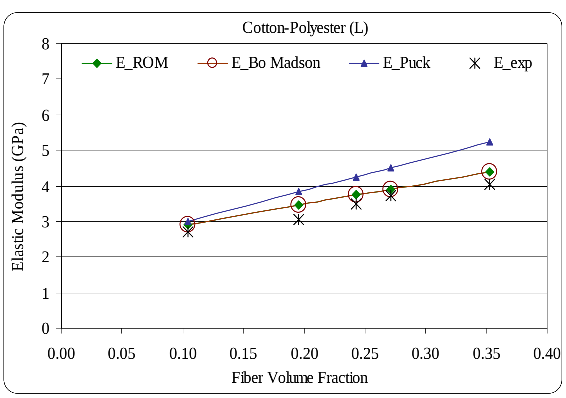

Fig. 13. Comparison of micro mechanics model for longitudinally placed cotton fiber-polyester composite experimental results

TABLE V I

COMPARATIVE ASSESSMENT OF AVAILABLE MODELS IN LITERATURE

Fiber Volume Fraction	Micro Mechanics Model Available in Literature		
	ROM	Madson	Puck
v_f	(% Error)	(% Error)	(% Error)
0.1041	8.3620	8.3560	11.1619
0.1955	13.6143	13.5931	25.5879
0.2431	7.2597	7.2293	22.0338
0.2717	5.0675	5.0308	21.3447
0.3527	8.6967	8.6347	30.0574
Average Bias Error (%)	8.6000	8.5688	22.0371

Gohil and Shaikh [28] proposed models of soft and hard interphase are compared with present experimental result which is shown in Fig. 14. The deviations in terms of minimum average bias error obtained by proposed developed model for longitudinal elastic modulus are depicted in Table VII.

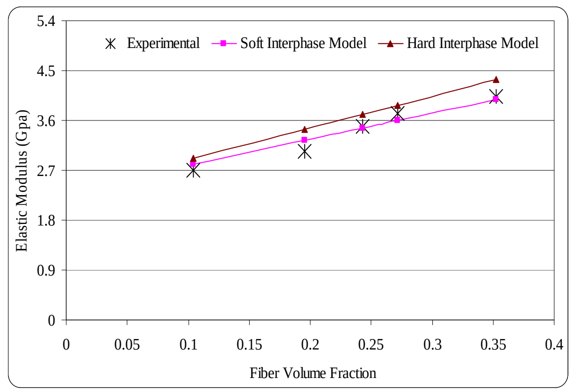

Fig. 14. Comparative assessment of proposed models by author for longitudinally placed cotton fiber-polyester composite experimental results

TABLE VII

COMPARATIVE ASSESSMENT OF AUTHOR'S PUBLISHED MODEL

Fiber Volume Fraction v_f	Author's Published Model	
	Soft Interphase (% Error)	Hard Interphase (% Error)
0.1041	3.9025	7.8262
0.1955	6.2066	12.7311
0.2431	-0.7803	6.3052
0.2717	-3.3469	4.0768
0.3527	-1.3772	7.5083
Average Bias Error (%)	0.9209	7.6895

The author's proposed models of soft interphase and hard interphase are giving good agreement with that of experimental results of cotton-polyester composites compared to models available in literatures. Thus, proposed model is very useful for the prediction of longitudinal elastic modulus and it can be applied to high strength fiber, natural fiber and even the textile fiber composite also.

VIII. CONCLUSION

Based on experimental investigations and micro mechanics assessment for the properties of cotton fiber reinforced polyester composite following conclusions are drawn.

- The fiber volume fraction increases longitudinal elastic modulus also increases this shows that cotton-polyester composite can be used. Thus, the use of cotton-polyester composites can be employed to various applications based on the property needed for a product.
- Fiber-matrix interface/interphase plays an important role in the natural fiber composite properties. The author's proposed models for soft and hard interphase is giving better agreement compared to models available in literature as these models are derived without much emphasis on interface/interphase characteristics.
- Currently, about 40,000 composite products are in use for an array of applications in diverse sectors of the industry all over the world. While China and India started making use of composites almost simultaneously about 30 years ago, the progress made by china is rather astounding with an annual consumption level of about 2,00,000 MT, as compared to about 30,000 MT in India, which needs awareness for composite product and their merits. Multiple commercial applications for composites and potential for export have not been tapped even in a limited way in the country.

ACKNOWLEDGMENT

I am very much thankful to Dr. Y.P. Kosta, (Dean, Faculty of Technology and Engineering, Charotar University of Science and Technology) and management of CHARUSAT for constant motivation and encouragement.

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NOMENCLATURE

Parameter	**Description**
E_c	Composite elastic modulus
E_f	Fiber elastic modulus
E_{fl}	Fiber elastic modulus in longitudinal direction
E_m	Matrix elastic modulus
E_i	Interphase elastic modulus
v_f	Original fiber volume fraction
v_{f1}	Modified fiber volume fraction
v_m	Matrix volume fraction
v_i	Interphase volume fraction