Effect of Strain Rate on Fracture Toughness of Hemp Fiber Composites

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***Abstract*—Many fiber reinforced polymer composites are finding increasing use as primary load-bearing structures and also in a wide range of high technology engineering applications. For upgrading the structural applications in engineering, natural fiber composites can be chosen for functional efficiency, increasing or improving various properties of structures, not pollute the environment and endanger bio-reservoir should be such that they are self-sustaining and promote self-reliance, should help in recycling of polluting wastes into usable materials are best choice. Present work contains a detailed experimentation of strain rate and thickness dependency on fracture toughness (K_{IC}) of hemp natural fiber composite. With 40% of hemp fiber content and 60% of Matrix (Epoxy) content is used for the preparation of laminates of different thickness. Thickness of varying size 3.1mm, 5.3mm and 7.5mm and Varying strain rates as 0.0165/s, 0.025/s and 0.034/s are used for experimentation. Experiments are carried out by Universal Testing Machine. SENT (Single Edge Notched Tensile) specimens of varying crack lengths are used. In fracture test, by using stress intensity factor approach, fracture toughness is of 1.68MPa√m. Results shown that, strain rate influencing the fracture properties of hemp natural composites and thickness also varies the fracture properties of material.**

Keywords — Composites; hemp; fracture toghness; SENT; strain rate

I. INTRODUCTION

Mankind has been aware composites materials since several hundred years before Christ and applied innovation to improve the quality of life. Although it is not clear has to how man understand the fact that mud bricks made sturdier houses if lined with straw, he used them to make building that lasted. A composite is a heterogeneous material system consisting of two or more phases on macroscopic level whose mechanical performance are designed to be superior to that of the constituent material acting independently [1]. A composite may be the only effective vehicle for exploiting the unique properties of certain special materials, e.g. high strength of graphite, boron or aramid fibers [2]. Although natural composites- wood, bones and teeth have been existence for many million years, fiber reinforced resin matrix materials were not developed until the early 1940's. Since the 1940's the variety of reinforcements, matrices and end uses, have increased dramatically. Composite materials of many types are now widely employed in the transport, constructions; chemical, electrical, marine, medical, aerospace and automobile industries are a well-established class of materials. Composites are used in aircraft, helicopters, space craft, satellites, ships, submarines, automobiles, chemical processing equipment's, sporting goods and civil infrastructure, and there is the potential for common use in medical prosthesis and microelectronic devices. Composites have emerged as important materials because of their light-weight, high specific strength and stiffness, excellent fatigue resistance and outstanding corrosion resistance compared to most metallic alloys such as steel and aluminum. Other advantage of composite includes the ability to fabricate, directional mechanical properties, low thermal expansion co-efficient and high dimensional stability.

The study interest in using natural fibers such as different plant and wood fibers as reinforcement in plastic has increased dramatically since from last few years. With regard to the surrounding aspects it would be very interesting if natural fiber could be used instead of glass fibers as reinforcement in many structural applications. Natural fibers have many advantages compared to glass fibers for example, they have low density, and they are recyclable and bio-degradable. Additionally they are renewable raw materials and have relatively high strength and stiffness. Unlike synthetic fibers natural fibers are more environment friendly in terms of production and disposal. Their low density values allow to producing composites that combine good mechanical properties with a low specific mass. In tropical countries fibrous are available in abundance. Globally, the natural fiber production will provides employment to millions of people by providing work and food, especially small scale farmers and processors. Natural fibers such as sisal, banana, hemp and pineapple have huge potential.

Discontinuous like sharp corners, grooves, voids, surface nicks and material imperfections (flaws, cracks) are present in almost all engineering structures even though the structure may have been inspected during design and fabrication. However, increasing demands for better and optimum design resulting conservation of material to require that structures to be designed with smaller safety margins. The role of fracture mechanics helps to meet the needs of accurately estimating the strength of pre-cracked structures. In general, fracture mechanics deals with the conditions under which a load bearing body can fail due to enlargement of a dominant crack contained in body. By finding out of fracture toughness of specimen, it can conclude fracture strength of the material or structure. It has always been a cause for concern that the mechanical properties of composite materials may be poor at high strain rates. Hence the study of how the mechanical properties of these composites especially natural composites would change with strain rate is warranted to be able to design structures that would not fail prematurely and unexpected at high loading rates.

II. LITERATURE SURVEY

A vast amount of research in polymer matrix has been done either trying to combine new elements or improving existing PMC with chemical treatment, matrix percentage variation or stabling better fabrication methods. Since the cost of elements such as metals are expensive and non-renewable. Some of the focus of PMC turned to the application of natural fibers. Composites which are mainly used in aerospace and automobile industries where these components will subjected to various loads and varying loads, hence the effect of load rate on mechanical properties of natural fiber composites are important to known.

Fracture toughness testing was carried out at loading rates varying from 0.5 to 20 mm/min using single edge notched bending specimens with 0 to 30% weight fiber. The details of hemp natural composites such as alkali treatment, testing of composites, Results were conducted for short hemp fiber polylactide bio-composite was found to decrease with increased loading rate until plane strain condition is met at 10 mm/min and above. K_{IC} was found to decrease with increased fiber content. Kim L Pickering.et.al., [3]. Haider Al-Zubaidy.et.al., [4] investigated work on Mechanical characterization of the dynamic tensile properties of CFRP sheet and adhesive at medium strain rates. The material which is used is UD CFRP and adhesive such as Araldite 420 and Mbracesaturent. This paper focuses on the experimental determination of the tensile mechanical properties of such materials at quasi-static and intermediate strain rates. Mizi Fan.et.al., [5] this review article describes the detail mechanical properties of hemp fiber composites and factor influencing the tensile strength. Outcomes of the results are an extensive investigation on the structure and geometry of single hemp fiber. The instruments which are used in this work are emission scanning and optical microscopy. The results showed that tensile strength increased with decrease of diameter of individual test pieces of single fiber, shear failure between single fibers in a test pieces played a significant role in test results. FE simulation of tensile testing and Dynamic Mechanical Analyzer are carried out in this work and gave information about an effect of strain rate and temperature on observed properties A.Shakoor.et.al. [5]. effect of interfacial damage on mechanical performance of a starch composites reinforced using hemp fibers. Local damages on the composites were created and tested by using digital image acquisition. Experiments are conducted and these damages are affecting the mechanical performance of hemp composites seriously. FE results also carried out and showing the same results M.Hbib.et.al. [6]. P S Shiva Kumar Gouda.et.al., [7] Fracture Toughness of Glass-Carbon (0/90) S Fiber Reinforced Polymer Composite, Mode-I fracture behavior of glass-carbon fiber reinforced hybrid polymer composite was investigated based on experimental and finite element analysis. Compact Tension specimens were used for the experiment work. For numerical studies, ANSYS software was used. Results indicated that the cracked specimens are tougher along the fiber orientations as compared with across the fiber orientations. M.S. Sham Prasad.et.al. [8] Experimental Methods of Determining Fracture Toughness of Fiber Reinforced Polymer Composites under Various Loading Conditions. The new aspects in the experimental studies of inter-laminar and intra-laminar fracture toughness of polymer matrix composites were emphasized.

III. METHODOLOGY

A. Selection of fiber

To prepare any composite material, a fiber is the primary material. The loads are mainly carried by the fiber in the composite. Hemp fiber is cultivated from the plants belonging to the Cannabis genus. Cannabis sativa, L has two varieties named Industrial hemp and marijuana. Marijuana typically contains 3-15% of the psychoactive ingredient called delta-9-tetrahydrocannabinol (THC) on a dry-weight basis, while industrial hemp generally have less than 1% of THC. Hemp is an annual plant and can grow on a wide spectrum of soils. There is an increasing awareness of hemp fiber and a wide spectrum of hemp products are now available in the market, made of different parts of the plant. France, Germany, China are among the major producers. Production of hemp is restricted in some countries, where it is confused with marijuana.

Hemp is a natural fiber which contains many organic and inorganic substances such as cellulose, lignin, pectin etc. The properties like density, moist absorption, stiffness, tensile strength etc. of hemp fiber plays an important role in the strength of composites. Hence the chemical composition and properties of hemp natural fiber are as given in the Table 1.

TABLE 1. Properties of Hemp natural fiber

Chemical composition	**Hemp Fiber**	**Properties**	**Hemp fiber**
Cellulose (%)	57-77	Moist Absorption (%)	8
Lignin (%)	3-13	Density (kg/m^3)	1500
Hemi cellulose (%)	14-22	Tensile Strength (Mpa)	550-900
Pectin (%)	0.9	Stiffness (Gpa)	70
Ash (%)	0.8		

B. Selection of Matrix Material

Epoxy resins are the most commonly used resins. They are low molecular weight organic liquids containing epoxide groups. Epoxide has three membersin its ring: one oxygen and two carbon atoms. The reaction of epichloro-hydrinwith phenols or aromatic amines makes most epoxies. Hardeners plasticizers and fillers are also added to produce epoxies with a wide range of properties of viscosity, impact, degradation, etc. Epoxy is such a matrix material of having very good properties like shear modulus, density, tensile strength etc.The Table 2. shows the details of the properties of Epoxy.

TABLE 2. Typical properties of Epoxy Resin

Shear Modulus	**Elongation**	**Density**	**Elastic Modulus**	**Tensile Strength**	**Specific Strength**
1.6 GPa	2%	1.2 g/cc	3.45 GPa	1.3 GPa	36 MPa

Although epoxy is costlier than other polymer matrices, it is the most popular PMC matrix. More than two-thirds of the polymer matrices used in aerospace applications is epoxy based.

C. Hardner and other material

In the present work Hardener (K-6) is used. This has a viscosity of 10-20 poise at 25 ^{0}C. For making composite using hemp natural fiber and Lapox resin, there are so many other materials are used, those are peel ply, release film, Vaseline, knife, scissor etc. Peel ply are used for the purpose of getting good surface finish and it absorbs the excess resin coming out from the mold. Release film and Vaseline are used for the easy removal of laminate from the mold.

D. Fabrication of Laminates

Laminates are fabricating by using hemp natural fiber and epoxy resin. Hemp is a plant based naturally available fiber but it is in the form of plant stem. So it needs to extract the fiber from the Hemp plant and afterwards processes can be carried out for making composites material. A laminates of different thickness are fabricating of required dimensions and then cut into specimens according to ASTM standards. Fabrication of laminates involves Extraction of fiber, layer preparations, chemical treatment (NaOH treatment), mould preparation etc.

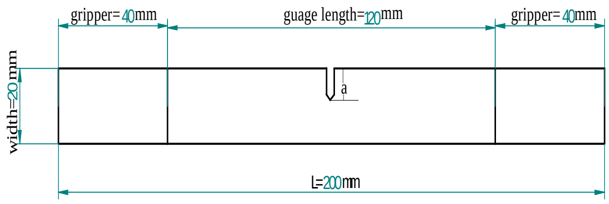
The unidirectional laminates are fabricating on the basis of weight fraction i.e.40% of fiber content and 60% of matrix material (epoxy hardener mixture).Each hemp mat of thickness 0.7mm is weighing an average weight of 21 grams which is measured in weighing machine. Epoxy and hardener mixture are in the ratio of 10:1 are used for the fabricating laminates.

Fig 1. Fabricated laminates

After curing, the laminates are taken out from the mould and shown in Fig 2.. The proper cured laminates are very stiff, strong and well bonded. Each laminates thickness are measured by micrometer in the laboratory, compared to required thickness, calculated thickness are not much varying with measured values.

IV. SPECIMEN PREPARATION

The laminates which are prepared initially were marked for required dimensions and then are cut to the markings using a wire saw. The cut edges of specimens were then rubbed against emery paper in order to bring them to the exact size. The specimens were prepared according to ASTM standards. The Fracture Toughness test is conducted on specimens according to ASTM D3039 standard. Fig 2. shows the dimensional view of Single Edged Notched Tensile specimen (SENT). The varied cracks are created by using wire saw. The Table 3 shows the standard dimensions of the SENT specimen for testing fracture toughness of hemp fiber composites. Fig 3 shows specimen used for testing.



(SENT)

TABLE 3. The standard dimensions of the SENT specimen

Thickness	**3.1mm, 5.3mm, 7.5mm**
Width	20mm
Gauge length	1200mm
Total length of specimen	Gripper + Gauge length (40+40)+120=200mm
Crack length variations 9mm,9.5mm,10mm,10.5mm,11mm	0.45 a/w 0.55mm 9.00

Fig 3. SENT specimen of Hemp fiber composite

V. EXPERIMENTATION

Fracture Toughness is a property which describes the ability of a material containing a crack to resist fracture and is one of the most important properties of any material for many design applications. The Fracture Toughness test is conducted on specimens according to ASTM D3039 standard. These test method properties of polymer matrix composite materials reinforced by high test five specimens of varying crack lengths are tested for 3 combination thickness. The validity requirements are tested for each specimen and if the test is valid, then that value is Provisional Fracture Toughness. The Universal Testing Machine were to get load-displacement readings from cracked specimen by varying strain rate and different thickness specimens.

A. Stress intensity factor approach

When a pre-cracked test specimen is loaded to failure, load and displacement are monitored. Three types of load-displacement curves are shown in Fig 4. The critical load P_Q is determined in one of the several ways, depending on the type of the curve. One must construct a 5% secant line (i.e., a line from the origin with a slope equal to 95% of the initial elastic loading slope) to determine P5. In the case of type I behavior, the load-displacement curve is smooth and it deviates slightly from linearity before reaching a maximum load P_{max}. This nonlinearity can be caused by plasticity, subcritical crack growth or both. For a type I curve, $P_Q=P_S$. With a type II curve, a small amount of unstable crack growth (i.e., pop-in) occurs before the curve deviates from linearity by 5%. In this case P_Q is defined at the pop-in. A specimen that exhibits type III behavior fails completely before achieving 5% non-linearity, in such cases $P_Q=P_{Max}$.

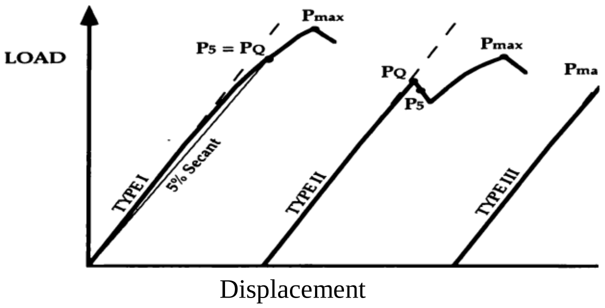


Fig 4. Load-Displacement behaviors in K_{IC}

Once P_Q and crack growth length are determined, provisional fracture toughness K_Q is computed from the following relationship.

$$K_Q=P_Q/(B\sqrt{W})f(a/w) \quad (1)$$

Where f(a/w) is a dimensionless function of (a/w) which can be obtained by following equation for SENT specimen as,

$$(\sqrt{2\tan\frac{\pi a}{2w}})/(\cos\frac{\pi a}{2w})\left[0.752+2.02\left(\frac{a}{w}\right)+0.37\left(1-\sin\frac{\pi a}{2w}\right)3\right]$$

The K_Q value is computed from the above equation is valid K_{IC} only if all validity requirements in the standard are met, they includes following conditions.

$$0.45\leq(a/w)\leq0.55 \quad (2)$$

$$B\geq 2.5(K_Q/\sigma_{ys})^2 \quad (3)$$

$$a\geq2.5\ (K_Q/\sigma_{ys})^2 \quad (4)$$

$$P_{max}\leq 1.10P_Q \quad (5)$$

After testing of specimens, the readings are taken and calculate the required fracture toughness by above method. Fig 5 shows the specimens after fracture testing.


Fig 5. Tested Single Edge Notched Tensile (SENT) specimens

VI. RESULTS AND DISCUSSION

A. *Load-displacement behaviour of SENT specimen*

A SENT (Single Edge Notched Tensile Specimen) was subjected to tensile test at a strain rate of $0.0165s^{-1}$ with different crack lengths varying 9.00mm, 9.50mm, 10.00mm, 10.50mm and 11.00mm according to equation (2) of three different thickness of specimens i.e. 3.1mm, 5.3mm and 7.5mm. Table 4 shows the load and displacement values for all specimens of all five crack lengths.

TABLE 4. Readings obtained from Fracture test

Thickness (mm)	Crack Length, a (mm)	Time taken to break (sec)	Maximum Load(KN)	Maximum Displacement(mm)
3.1	9.00	135	2.10	2.15
	9.50	125	1.80	2.10
	10.0	110	1.50	2.20
	10.5	90	1.25	1.70
	11.0	85	0.9	1.50
5.3	9.00	165	3.40	2.62
	9.50	140	2.98	2.50
	10.0	125	2.38	2.20
	10.5	110	1.98	1.85
	11.0	105	1.72	1.50
7.5	9.00	175	4.80	2.90
	9.50	155	4.50	2.95
	10.0	145	4.10	2.89
	10.5	120	3.30	2.25
	11.0	110	2.90	2.30

B. *Analysis of compliance*

The compliance of SENT specimen of hemp fiber composites were determined by recording curves of load-displacement as the specimens loaded in axial tension. It is observed from the Fig 6 shows that, as crack length increases the stiffness of the material decreases. For SENT specimen of thickness 3.1mm, the maximum stiffness is 1555.56N/mm at crack length of 9.00mm which goes on decreases to 800N/mm at crack length of 11.00mm. Compliance for the same specimen increases as crack length increases this is because compliance is inversely proportional to stiffness of the material. Hence Compliance for crack length 9.00mm for 3.1mm SENT specimen is increases from 0.000642 mm/N to 0.00125 mm/N at crack ends to 11.00mm. Similarly SENT specimen of thickness 5.3mm, Stiffness at crack length 9.00mm is 2000N/mm as crack length increases stiffness becomes 1090.90N/mm at 11.00mm. Compliance increases as 0.0005mm/N to 0.000916 mm/N as crack length increases. Similarly for thickness of 7.5mm specimens, stiffness decreased from the value 2222.23N/mm to 1428.57N/mm as crack length increases. From Fig 6 where curve changes its path that corresponding crack length should consider for the calculation of fracture toughness of material.

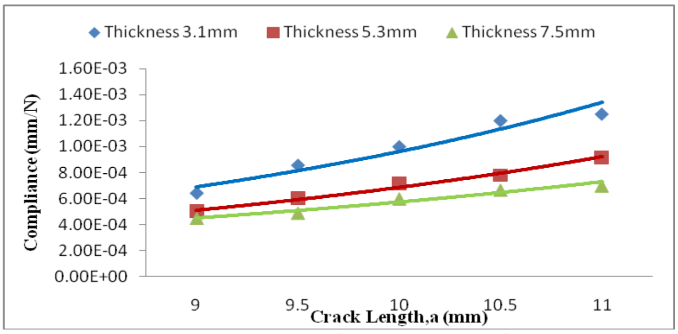


Fig 6. Compliance v/s Crack Length of varied thickness of SENT specimens

C. Fracture Toughness of Hemp fiber

Table 6 shows the data required for the calculations of fracture toughness by using stress intensity approach. Equations of (1) to (6) are satisfied hence provisional toughness taken as fracture toughness of material. It is decreasing with increasing thickness as shown in Fig 7.

TABLE 6. Fracture toughness values of hemp fiber composites

Thickness(mm)	Fracture load P_Q(N)	Yield Stress (N/mm^2)	Provisional toughness K_Q(MPa $\sqrt{m}$)	Fracture Toughness K_{IC} (MPa $\sqrt{m}$)
3.1	1900	82	1.51	1.51
5.3	3400	100	1.65	1.65
7.5	4300	83	1.67	1.67

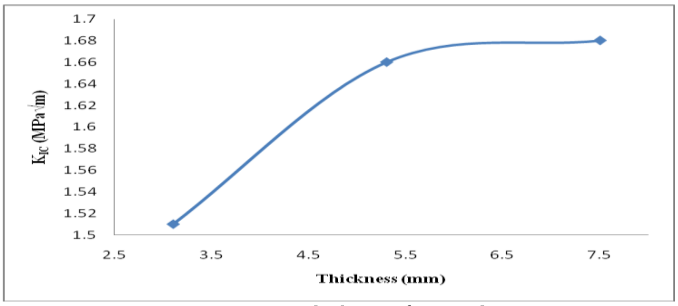


Fig 7. K_{IC} v/s Thickness of material

VII. CONCLUSIONS

In this present work Hemp fiber composites are used for experimental investigation by varying strain rate as well varying thickness of specimens. The experiments are conducted to evaluate toughness of material of hemp fibers were evaluated to assess their suitability for use as reinforcement in composite of the material with different thickness. The strain rates are varied from 0.0165/s to 0.034/s. The following observations can be made and conclusions drawn based on the limited test results.

It is observed that, strain rate has a significant influence on both load-displacement and stress-strain relationship of the unidirectional hemp fiber composites. It is also observed that, thickness of specimen shows significant effects on mechanical properties of unidirectional hemp natural fiber composites.

It is observed that, in fracture test, load decreases as crack length increases, since load decreases stiffness of the material also decreases. The maximum load for specimen of thickness 3.1mm is 2.10KN, for 5.3mm is 3.4KN and 7.5mm is 4.80KN.Stiffness for 3.1mm specimen is 1555.56N/mm, for 5.3mm is 2000N/mm and for 7.5mm is 2222.23N/mm. Compliance is the inverse property of stiffness. Compliance increases with increase in crack length and also compliance increases with increase in thickness.

The Fracture toughness by stress intensity factor study shows that, it increases as thickness of material increases. Hemp fiber composite of thickness 7.5mm has 1.68MPa√m. The medium thickness of hemp natural fiber with all three type of strain rate has very good tensile properties and fracture toughness.

VIII. SCOPE FOR FUTURE WORK

Hemp fiber composites subjected to fracture test, shown better results under varying crack length and in tensile test shown very good mechanical properties with varying strain rates. Hence hemp composites can be recommended many secondary structures in aerospace as well as automobile industries to fabricate components.

The tests are also can examine by using FEA and further improvement in design can adopted.

Since Hemp is a natural fiber, by providing the global marketing will improve the growth in agriculture field. In India agriculture is the main source of national income. Improving and using the hemp fiber in industries will improve the life of our formers.

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