POTENTIAL APPLICATIONS OF FLAX FIBERS

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POTENTIAL APPLICATIONS OF FLAX FIBERS

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The Supervisory Committee certifies that this ***disquisition*** complies with North Dakota State University's regulations and meets the accepted standards for the degree of

MASTER OF SCIENCE

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ABSTRACT

There has been a substantial increase in the usage of natural-fibers and biodegradable polymers due to the needs of the environmental sustainability. The use of natural fibers is inclusive of wide range of applications in load bearing structures, nursing and commercial commodities. In this study, tensile behavior of flax fiber tows removed from woven fabrics were investigated at different moisture levels and compared because one of the major challenges faced in the use of natural fibers is their hydrophilicity. As the moisture content increased from 5% to 80% the tensile strength increased by 75%. The diffusion process through the flax fiber mat with different areal densities was investigated using the desorption curves obtained using an oven drying method. Diffusion coefficients were not found to significantly change with varying areal densities of 200 gsm to 400 gsm, but were significantly different when dried at 55 °C versus 80 °C.

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I would like to thank my first family and my friends for moral support.

DEDICATION

I would like to dedicate this work to my parents and sister who have been there through all my ups and downs.

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1. INTRODUCTION

1.1. Background

Natural fibers are obtained from plants, animals and some by geological processes (alteration and metamorphism of basic igneous rocks rich in magnesium silicates [1]. They can be made into sheets and textures. Common filaments from vegetable strands are obtained from different pieces of the plants. These strands are arranged into three classifications relying upon the piece of the plant from which they are removed. Those three classes are bast or stem filaments (jute, mesta, banana and so on.), leaf strands (sisal, pineapple, screw pine and so on.) and seed strands (cotton, coir, old palm and so on.). The classification of the natural fibers is shown in Figure 1 [2].

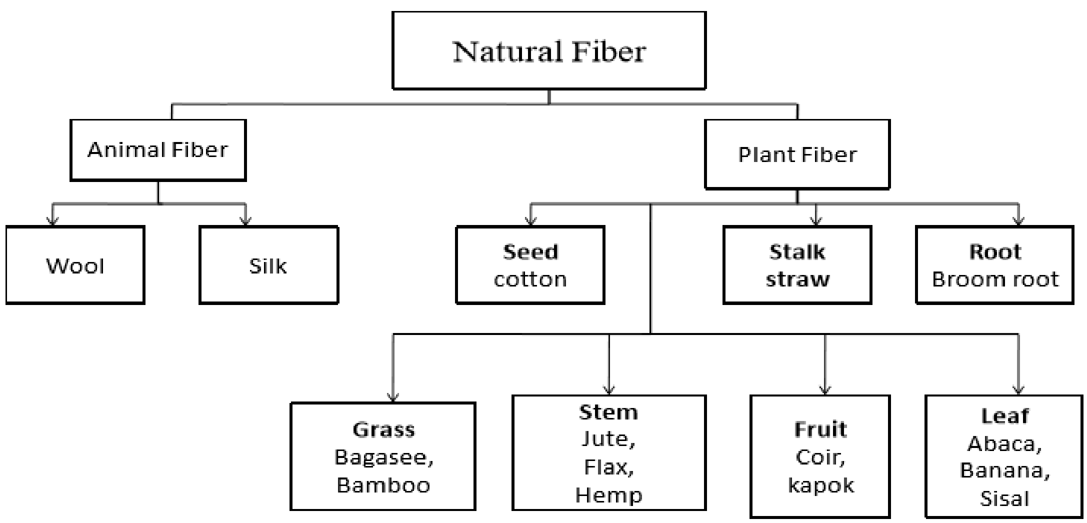

Figure 1: The classification of natural fibers on the basis of their origin of source [2].

A significant number of the plant filaments, for example, coir, sisal, jute, banana, pineapple, and hemp discover applications as an asset for modern materials [3]. Properties of characteristic filaments depend basically on the idea of the plant, territory in which it is developed, the age of the plant, and the extraction strategy utilized [4]. A characteristic fiber additionally might be additionally characterized as an agglomeration of cells in which the width is immaterial in examination with the length. In certain applications, regular filaments are supplanting glass strands in fortified polymers, where the rigidity of the fiber isn't as imperative as the solidness [5].

Focal points of regular strands are that they can be created with low venture requiring little to no effort, which makes the material an intriguing item for low income nations as warm reusing is conceivable. This is on the grounds that in circumstances where glass causes issues in combustion furnaces, low specific weight of regular filaments results in a higher explicit quality and firmness than glass [6]. This is an advantage particularly in parts intended for bowing solidness. Further it is a sustainable asset where the creation requires little vitality and CO_2 is utilized while oxygen is offered back to the earth [7].

Burdens of regular filaments incorporate variance of cost by collect outcomes or agrarian arrangements and lower sturdiness. Fiber medications can improve this impressively, dampness retention, which causes swelling of the filaments and lower quality properties, especially its impact strength [8].

As of late, vehicle manufacturers have been keen on joining common fiber composites into both inside and outside parts of their vehicles. This serves a two-overlay objective of the organizations; to bring down the general load of the vehicle along these lines expanding eco-friendliness and to build the supportability of their assembling procedure [9]. Numerous companies, for example, Mercedes Benz, Toyota and Daimler Chrysler have officially achieved this and are hoping to extend the employments of common fiber composites.

Natural fibers are picking up notoriety over engineered materials because of biodegradability, sustainability and lower costs [10]. Natural fibers are moisture reliant as their mechanical properties are progressively influenced by smaller changes in water content which goes about as a plasticizer. The hydrophilic nature of the fiber and the quality of the normal fiber composites are the key issues which must be handled for their utilization over glass fiber [11]. Natural fibers likewise are biomaterials as there are confirmations which demonstrate that the human body responds decidedly to the protein embeds and acknowledges them as perfect common tissue fixing materials.

Bast strands are plant filaments gotten from external cell layers of the stem. The instances of these are flax, jute, kenaf, hemp, ramie, ratten and vine strands. Since these are yearly harvests, there is a huge supply of materials, and they are increasing expanding enthusiasm for an assortment of non-wood composite assembling forms. Bast filaments are gathered from the fibrovascular pack area of plant stems, known as bast (or phloem), situated between the epidermis or bark surface, and an inward woody center of dicotyledonous plants. Such filaments are normally portrayed by fineness and adaptability and are likewise alluded as delicate strands [12]. Each plant is composed of about 30% bast and 60% hurds; the bark, cortex and cambium remain to the staying 10%.

Bast filaments run over the whole length of the stem and are consequently long. All bast strands are extricated from plants by a retting procedure pursued by scutching to isolate the filaments [12]. Retting is a microbial procedure that breaks the substance securities, crumbles the normal plant gum and permits simple partition of the bast strands from the woody center by mechanical procedures. Retting is finished by the joined activity of water, amphibian and plant surface living beings. The two customary strategies for retting are dew retting and water retting. Choice of the sort of retting relies upon the accessibility of water and the expense of the retting procedure. With dew or field retting, plant stems are cut or pulled up and left in the field for four to five weeks to enable dew and precipitation to influence the procedure under appropriate climate conditions including air, humidity and encompassing temperature [13]. The procedure is checked to stay away from under-retting or over-retting to guarantee that the bast filaments separate from the internal center weakening in quality. The dew retting process is climate ward and tedious, so it is typically supplanted by different techniques.

Water retting is a quicker technique and creates progressively uniform and astounding fiber. In water retting, the piles of cut plants are drenched in water (streams, lakes or tanks) and are checked every now and again. The water is kept at around 35 °C and flows through the mass of material. This procedure is viable however work and capital-escalated and the procedure utilizes vast volumes of clean water that must be treated before being released.

When the process retting is finished, the stalks are left to dry in the field, which is named 'gassing' [14]. Now, the retted gather is dried to under 10% dampness and baled to convey to a focal area for preparing. The fiber partition process is done either physically or in modern machines. The fiber detachment procedures of bast fiber comprise of breaking, scutching and bothering activities. With mechanical partition, in a procedure called breaking, the woody center is pulverized and breaks into short pieces (called hurds) and some of it is isolated from the bast fiber [14]. Breaking might be done physically with a wooden mallet or by passing the stalks between fluted rollers. The remaining hurds and strands are isolated in a procedure called scutching. Scutching should be possible by hand or by a machine known as a scutcher [15].

Hand scutching of bast strands is finished with a wooden scutching blade and an iron scrubber [15]. In the heckling procedure, filaments are part and isolated by unraveling them; parallelization is done beyond what many would consider possible on machines with spike bars in stages with progressively better teeth. Strands are typically liberated from the stalk by retting, yet some development advances have been created to quicken the system of fiber extraction: for instance, synthetic retting utilizing glyphosate and diquat.

Fiber and hurds likewise can be isolated by decortication, which is a mechanical stripping task to isolate bast from the hurds without an extra scutching process [15]. The procedure of decortication for flax utilizing a scutcher is appeared in the Figure 2. Amid detachment, the filaments are commonly kept at full length so that toward the end they can be sliced to the required length for further preparing (i.e., the length required for turning or weaving, or for nonwovens utilized in geotextiles and composites). The strands in the wake of slicing to the required length are baled by a programmed water powered baling press and are prepared for the following assembling process. The finished results of fiber partition process are long filaments, short coarser strands and waste woody issue. Long strands of the essential class are the most grounded and most profitable ultra-cleaned material. Their cut length can be from 12 to 154 mm and can be reasonably changed over into woven or nonwovens materials and composites. The auxiliary and exceptionally short fiber classes are broadly useful levels with 50– 65% cleaned fiber. These filaments are utilized for applications, for example, geo-tangling, as bond fillers, and in protection [14].

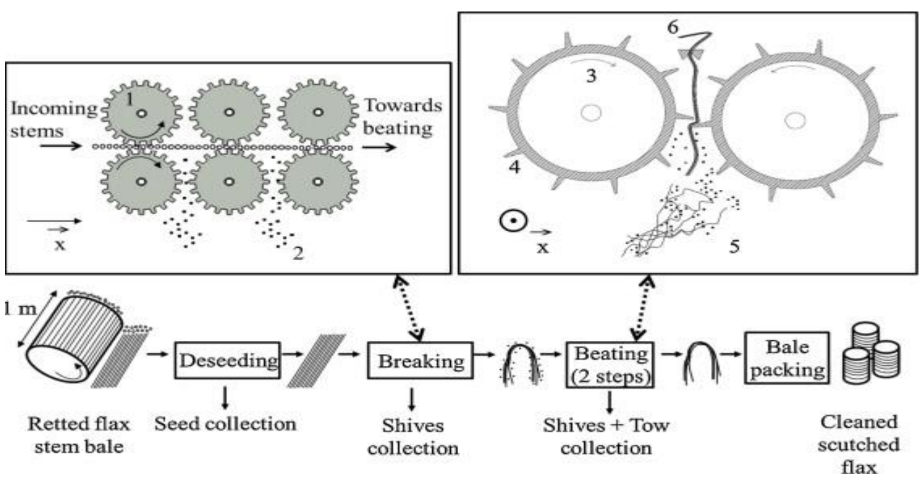

Figure 2: Diagram of the scutching line used for the flax decortication. 1 – fluted roller, 2 – shives, 3 – beating turbine, 4 – blade, 5 – shives + tows, 6 – scutched flax [16].

Flax fiber is obtained after the extraction from the bast or skin of the stem of the flax plant. It is typically fragile, lustrous and versatile; and the fibers have blonde hair appearance. The adaptability of flax fiber is less however it is an engaging fiber. It relies upon considerable proportion of dietary fiber and there is broad measure of unsaturated fats [17]. Flax is plant which benefits us because of its accessibility as strands just as seeds. Research on natural fiber composites has existed since the mid 1900's yet has not gotten much consideration until late in the 1980's. In view of this method of reasoning this investigation has proposed uses of flax dependent on logical data required for its business use. The flax strands have been used as sources of clothing and as a fortification in composites [17].

Numerous North American farmers are developing flax for applications in nourishment as seeds and for composites. The flax is a plant which does not require exceptionally extraordinary conditions for the development of the plant. It needs lesser assets to develop and keep up than numerous other mechanical yields. The advancement in flax hereditary qualities has improved because of the promising properties like better rigidity, lower extension, firmness and biocompatibility. At the point when dried adequately, a consolidate gatherer at that point reaps the seeds like wheat or oat. The quantity of weeds in the straw influences its attractiveness, and this combined with market costs decides if the farmer collected the flax straw [18]. On the off chance that the flax isn't gathered, it is commonly scorched, since the straw stalk is very extreme and deteriorates gradually (i.e., not in a solitary season), and yet being to some degree in a windrow from the collecting procedure, the straw would frequently stop up culturing and planting gear. Usually, in the flax developing areas of western Minnesota, to see the gathered flax straw (square) bundle stacks begin seeming each July, the measure of certain stacks being evaluated at 10-15 yards wide by at least 50 yards in length. The developed plant is pulled up with the roots (not cut), to boost the fiber length [18].

After this, the flax is dried, the seeds are evacuated, and is then retted. Subordinate upon the climate conditions, qualities of the sown flax and fields, the flax stays on the ground between about fourteen days and two months for retting. As a result of rotating precipitation and the sun, an enzymatic activity debases the gelatin which tie filaments to the straw. The farmer turn over the straw amid retting to uniformly ret the stalks. At the point when the straw is retted and adequately dry, it is moved up. It will at that point be put away by ranchers before beginning to separate filaments [19]. Flax is accessible in nations like India, Bangladesh, United States of America, Canada, China, Ethiopia, Russia, Ukraine, France and Argentina. Current uses of common filaments are composites which are utilized as auxiliary applications also. Lower thickness, better thermal insulation and diminished skin irritation have improved them choice for use even in day by day lives [20].

1.2. History

Linen otherwise called 'Flax' with the binomial name Linum usitatissimum. The most punctual proof of people utilizing wild flax as a material originates from the present-day Republic of Georgia, where spun, colored, and knotted wild flax filaments were found in Dzudzuana Cave and dated to the Upper Paleolithic, 30,000 years prior [21]. Flax was first trained in the prolific Crescent area. In Mesopotamia, flax was tamed, and material was first created. It was utilized for the most part by the wealthier class of the general public, including ministers. The Sumerian ballad of the romance of Inanna and Dumuzi (Tammuz), deciphered by Samuel Noah Kramer and Diane Wolkstein and distributed in 1983, specifies flax and cloth. It opens with quickly posting the means of getting ready material from flax, as inquiries and replies among Inanna and her sibling Utu. In antiquated Egypt, material was utilized for preservation and for internment covers. It was likewise worn as apparel regularly; white material was worn due to the outrageous warmth [22].

Material texture has been utilized for table covers, bed covers and garments for a considerable length of time. The noteworthy expense of cloth gets not just from the trouble of working with the string, yet in addition on the grounds that the flax filaments requires a lot of consideration. The utilization of material for clerical vestments was not limited to the Israelites; Plutarch composed that the ministers of Isis likewise wore cloth on account of its virtue. Eastern Slavs regarded flax with amazement, and credited mending properties to it [21]. They trusted that material apparel keeps clean and ensures the body of a man who wears it. Material garments have dependably been considered a rich.

Flax has been known in Russia since 2000 B.C. The principal standard endorsed by Peter the Great, was the standard for flax. Old original copies of the ninth tenth century B.C. contain proof of material made by Slavs. Oriental journalists of the time portrayed Slavs attired in material garments. Preceding the development of Kievan Rus, every single Slavic clan that occupied the eastern European fields raised flax. Flax was utilized to make sailcloth, angling nets, ropes and linseed oil. In the tenth eleventh century A.D. flax was widely developed for fiber and seed. It was respected to be an essential yield both for specialties and trade. Laborers utilized it to pay primitive levy and make installments to the autocrat's treasury. Russian sovereigns gathered tribute in material. Due to the astounding flexibility of the plant – maybe just to be contrasted and the job that bamboo plays in the Asian culture – individuals have constantly held it in high regard [23].

1.3. Properties of flax fibers

1.3.1. Physical and chemical properties

The primary components of plant strands are cellulose, hemicellulose, lignin and gelatin. The flax strands are of around 1 meter long and made of basic filaments with lengths shifting between 2 to 5 cm and distances across fluctuating 10 and 25 μm. They are stuck together by a gelatin interface which is a polyhedron helping in better packing [24]. For the better clarification of the flax fiber breakdown from the breaking stage to the microfibril organize is appeared in Figure 3.

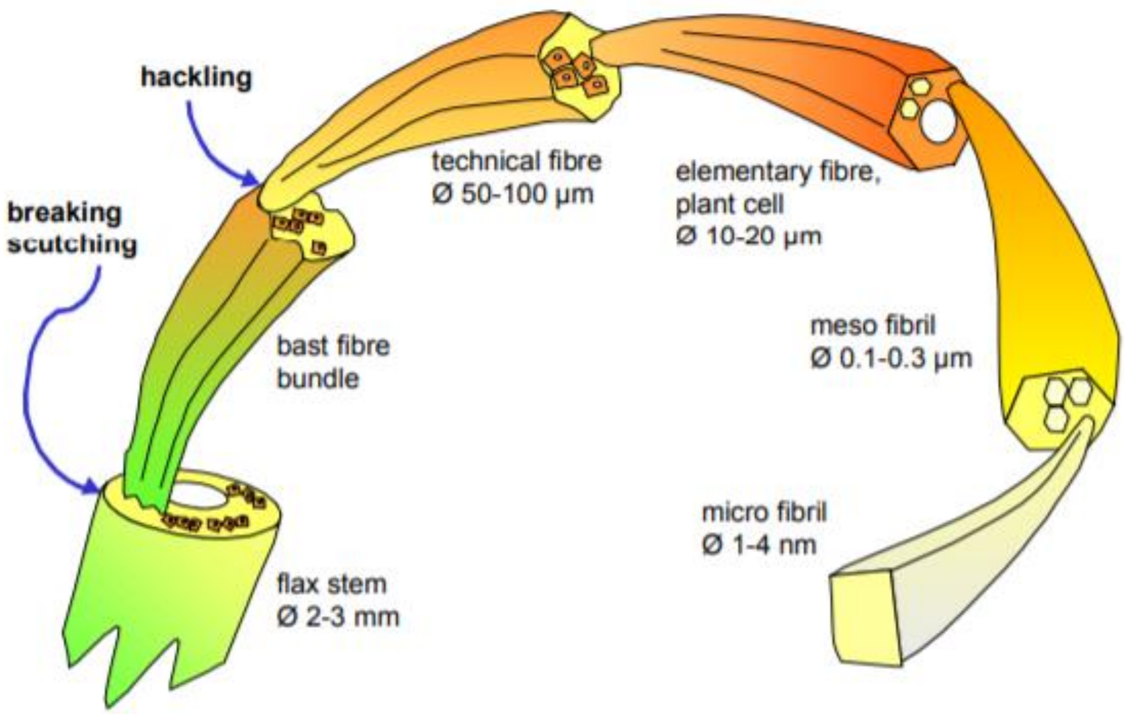

Figure 3: Composition and structure of the flax stem in the order of breaking, scutching and hackling [24].

The elementary fibers are single arrangement of plant cells. The cell walls of the plants have cellulose as their essential material. All the flax strands comprise of situated, profoundly crystalline cellulose fibrils and amorphous hemicellulose. The crystalline cellulose fibrils in the cell walls are located at an axis of around 10 ° with the fiber hub which are in charge of the quality of the fiber. About 70% of flax fiber weight is the cellulose. Hemicellulose comprises about 15% is weight, lignin is 2-5%, gelatin is 1-15%, phenolic acid is 0.1% and waxes and inorganic mixes are 2-5% [25]. Cellulose is an unbranched biopolymer acquired in two structures crystalline and formless. The more the amorphous cellulose the lesser is water take-up. It has some free - OH gatherings and consequently is hydrophilic in nature. The hemicellulose oversees hydrogen holding. The acetyl assemble in hemicellulose makes it somewhat solvent in water [17]. Lignin is covalently bonded with hemicellulose. Numerous other plant metabolites which are amazingly helpful are additionally present in the plant. The distinctive factor about flax filaments are that they are organically dynamic due to phenylpropanoid mixes. The substance structures of cellulose, hemicellulose, gelatin and lignin is shown in Figure 4.

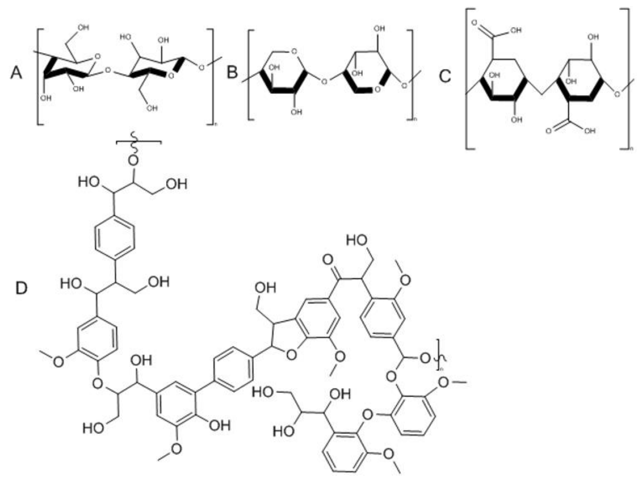

Figure 4: Structural representations of cellulose (A), hemicellulose (B), pectin (C) and lignin (D) [26].

Cellulose is the most plenteous sustainable and an abundant polymer on earth. Cellulose is made of polymer chains comprising of unbranched β (1→4) connected to D-glucopyranosyl units (anhydroglucose unit). The length of these β (1→4) glucan chains relies upon the origin of cellulose. Three hydroxyl bunches put at C2 and C3 (auxiliary hydroxyl gatherings) and C6 (essential hydroxyl gatherings) position can shape intra-and intermolecular hydrogen bonds. These hydrogen bonds license the making of profoundly requested, three-dimensional crystal structures. Degree of polymerization (DP) of cellulose is up to 10,000. Nonetheless, the chain length may contain as low as 2,500 monomers. The chain length of each cellobiose atom is 10.3 Å, and one particle is isolated from the other by 8.3 Å. The crystal lattice structure of cellulose is appeared in the figure. The dimension of cell structure is as per the following: a=8.3 Å, b= 10.3 Å, c=7.9 Å and β=84° [17]. The crystal cross section structure is appeared in the Figure 5.

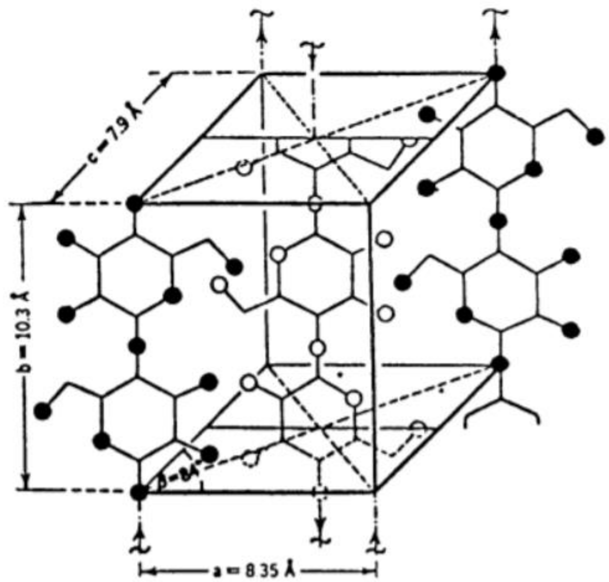

Figure 5: Crystal lattice structure of cellulose with the dimensions of elementary cell structure [27].

Biodegradation converts materials into water, carbon dioxide and biomass cellulosic biopolymers are susceptible to microbial growth which might lead to aesthetic, functional and infection problems. Steps in biodegradation are biodeterioration, bio fragmentation and assimilation [28]. The reaction in the aerobic bio degradation are as follows-

$$C_{polymer} + O_2 \rightarrow CO_2 + H_2O + C_{residue} + C_{biomass} + Salts \quad (3)$$

$$C_{polymer} \rightarrow CO_2 + CH_4 + H_2O + C_{residue} + C_{biomass} + Salts \quad (4)$$

Factors affecting the rate of biodegradation are, the presence of microorganisms, availability of oxygen, water, temperature and chemical environment affect the rate of biodegradation. microorganisms attack on materials in following steps. In the first place, they adhere to the outside of the material by attachment or conglomeration. At that point the expansion of connected microbial cells prompts the catalyst creation. The biodegradation is the consequence of this generation after which there is a decrease of level of polymerization of material polymers.

The yield is the creation of degradable items. The degradation of flax shows the following macroscopic result [28]. A soil burial experiment in which the biodegradation of the flax mat was observed in direct contact with soil and after indirect contact as well. Samples of linen fabric were severely attacked by microorganisms and only after two weeks it was difficult to separate the fabric samples from the soil [7]. The quick degradation effects from the soil burial test are because of the structure of the linen fabric, as the fibers are not tightly twisted in the yarns [7]. The experimental results found in the SEM images are shown in the Figure 6.

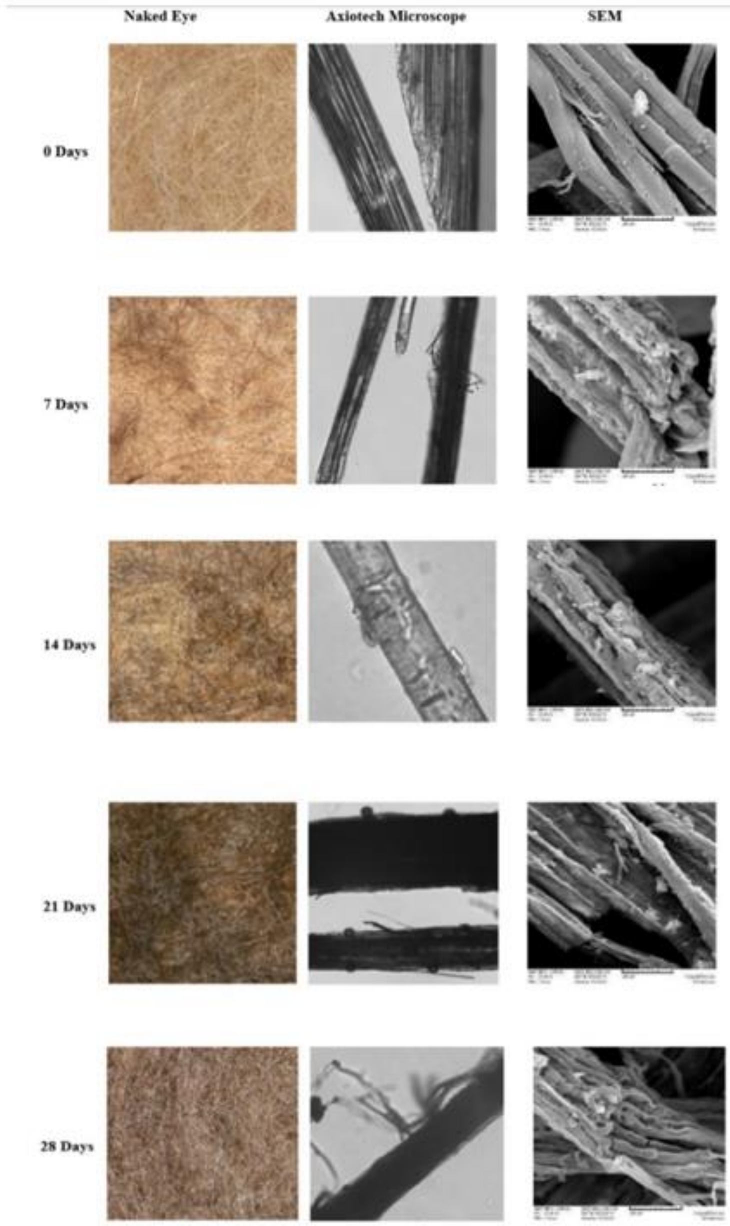

Figure 6: Microscopic visuals of flax biodegradation of fibers [28].

1.3.2. Mechanical properties of flax fibers

Variability in mechanical properties of natural fibers is obvious due to the difference in origin environment [24]. Comparison of different fiber properties in shown in Table 1.

Table 1: Comparison of properties of flax, hemp and jute [24]

Fibers	Modulus (GPa)	Strength (MPa)	Density (g/cm^3)	Specific Modulus	Specific Strength
Flax	50-70	500-900	1.4-1.5	~41	~480
Hemp	30-60	300-800	1.48	~30	~370
Jute	20-55	200-500	1.3-1.5	~27	~250

The following properties of flax fibers distinguishes them from the synthetic fibers. The variation in chemical composition, crystallinity, surface properties, diameter, cross sectional shape, length, strength and stiffness is evident even from fiber to fiber. It is therefore difficult for any characterization of a specific property. The tensile strengths of flax fibers in MPa as reported by various authors are shown in the Table 2.

Table 2: Comparison of tensile strengths of flax, hemp, jute, kenaf and sisal fibers by various authors [94]

Fibers	Kessler et al.	Nova et al.	Morton et al.	Satyanarayana et al.
Flax	400 - 1500	800 - 930	756	
Hemp		600-1100	658	
Jute		540	434	533
Kenaf		930		
Sisal		855		641

The mechanical properties of flax fibers are mentioned in the Table 3.

Table 3: Mechanical properties of flax fibers [29]

Property	Flax
Diameter [µm]	10-80
Density [g/cm^3]	1.4
E-modulus [GPa]	50-70
Tensile strength [GPa]	0.5-1.5
Elongation to fracture [%]	2-3
Specific E-modulus [GPa per g/cm^3]	36-50
Specific tensile strength [GPa per g/cm^3]	0.4-1.1

There have been endeavors for single fiber tensile test trials of flax strands which have had the capacity to fit the Weibull appropriation for their quality. The Young's modulus increments with strain because of rearrangement of cellulose filaments toward stacking. Compressive strength of the filaments then again is 80% of the tensile strength. The tractable properties of flax fiber shifts along the length of the stem of flax plants and the highest strength execution happens in the center bit of the stem. Also, the fiber diameter diminishes from the base to the highest point of the stem. It was indicated that the decrease in diameter correlates with the increase in tensile strength; however, the actual cause of the mechanical performance was attributed to the biochemical differences, rather than morphological ones. The middle fiber cell walls exhibit the highest contents of both cellulose and non-cellulosic polymers which favors the load transfer from one microfibril to another [24]. When fibers with similar diameters from different sections of the stem were compared, the mechanical differences were still present. The distinction in biochemical constituents was proposed to be because of the distinctions in developing conditions. The base and best strands are typically created in a less alluring developing conditions. Since smaller stems may need to depend more intensely on fiber support to oppose outer stacking conditions. A similar guideline may clarify inside stem fiber contrasts; strands at the originate from bottoms, middles and tops are presented to various stacking conditions and distinctive stem geometry, which results in a distinction in fiber morphology. On that premise, contrasts in biochemical constituents may likewise be available among vast and little stem strands, which may result in contrasts in mechanical execution of the equivalent.

For advanced mechanical execution and in the perspective on a more extensive application, fiber introduction related to part geometry is fundamental. Amid the assembling procedures of composite materials, for example, fiber winding, plaiting or sheet framing, the fortification experiences disfigurement and its union is expected to ensure great quality preforms. Flax yarns have effectively been utilized as material contribution to pultrusion and fiber winding. Be that as it may, although the utilization of flax spun yarns is an advancement towards the utilization of sustainable based asset, this may not be successful regarding vitality utilization related to their assembling procedure. Besides, it has been demonstrated that the utilization of spun yarns tends to diminish the potential mechanical properties of the composite when contrasted with the tows. Flax tows are accessible available for composite application as spools or in a woven architecture [90]. It has been appeared complex shapes could be accomplished with flax tow based woven texture by sheet framing process. There has been no standard by ASTM for the tensile test of bast fiber tows. The most relevant standard is ASTM D3822/D3822M (Standard Test Method for Single Textile fibers). The scope of this standard is applicable to continuous (filament) and discontinuous (staple) fibers or filaments taken from yarns or tow. Hence a test method to test the fiber tows must be developed independently to characterize the mechanical properties of bast fiber tows.

The flax fiber mats are also a source of reinforcement in composites. Due to its hydrophilic nature there is a reduction of about 25% in the tensile strength when immersed in water [91]. There is a need of finding a drying method of the fiber mat which is being used prior to the reinforcement to reduce the moisture content in the mat. The desorption of water through the flax fiber mat can be studied to remove the moisture from the mat at a maximum level to ensure better tensile performance. This can be achieved using diffusion testing method. The hygroscopicity of flax fiber mat can be assessed which indicates the affinity of the material with the environment. The evolution of drying speeds according to applied temperatures may be observed. A drying method for optimum temperature may be developed for the flax fiber mat before reinforcing it in the composites.

1.4. Current applications of flax fibers

Flax is an industrial fiber and is processed to form long-line and short strands [30]. Long line fiber is utilized in assembling high value linen items, while short staple fiber has truly been the loss from long line fiber and utilized for lower esteem items like covers, mats, sleeping pads and covers. Flax fiber strings are enough for planning of sewing strings, catch strings and shoe strings. Cloth is likewise utilized in making the most astounding quality hankies, bedding, window ornaments, drapery, pad covers, divider covers, towels, other enlivening materials and materials for suits and conventional dresses in Asia. It can likewise be utilized for assembling composites, for example, particleboard [31].

Flax strands are additionally becoming an integral part of new composite materials used in automobile industry. The natural fibers are utilized in the business due to different promising properties like low density which may prompt a weight decrease of 10 to 30 %, adequate mechanical properties, great acoustic properties and beneficial processing properties.

Other great properties are high dependability, less fragmenting, better eco balance for part creation as well as amid vehicle activity because of weight investment funds. The difficulties observed in utilizing flax strands are absence of consistency because of fiber quality variety, dampness affectability, both amid handling and amid application, constrained flame retardancy, varieties in quality and consistency of delivered parts and conceivable embellishment and decaying. Many companies utilize natural fiber composites in different pieces of their vehicles and some of them are recorded in Table 4. There are a few favorable circumstances of utilizing flax strands for mechanical applications. It is a biodegradable, inexhaustible crude material as well as nonabrasive. In any case, for specialized utilizations, the mechanical properties like tensile strength and elastic modulus it may not be reasonable [33]. The connection between the expense of generation and the advantages of the fiber may confine the utilization of flax in vast scale applications.

Table 4: Use of natural fiber composites in the various models of automotive companies [32]

Manufacturer	Model
Audi	A3, A4, A4 Avant, A6, A8, Roadster, Coupe Seat back, side and back door panel, boot lining, hat rack, spare tire lining
BMW	3, 5 and 7 Series and others Door panels, headliner panel, boot lining, seat back
Daimler/Chrysler	A-Series, C-Series, E-Series, S-Series Door panels, windshields/dashboard, business table
Fiat	Punto, Brava, Marea, Alfa Romeo 146, 156
Ford	Mondeo CD 162, Focus Door panels, B-pillar
Opel	Astra, Vectra, Zafira Headliner panel, door panels, pillar cover panel, instrument panel
Peugeot	New model 406
Renault	Clio
Rover	Rover 2000 and others Insulation, rear storage shelf/panel
Saab	Door panels
SEAT	Door panels, seat back
Volkswagen	Golf A4, Passat Variant, Bora Door panel, seat back, boot lid finish panel, boot liner
Volvo	C70, V70

Healthcare is a very important aspect for daily living and wellbeing. Various developments regarding the materials used for wound management and dressings have taken place. Manufacturers and providers have found wound care as an important and rapidly growing sector in the healthcare market.

The idea of moist wound care started to get genuine consideration in the late 1980s. Preceding this time, drying of the injury was carried out by the following methods: the utilization of povidone iodine as a drying specialist, heat lights, wet-to-dry dressings, and leaving the wound open to air. A wound dressing is an adjunct utilized by an individual to advance the way toward mending the wound.

Different composite materials which are textile based are reasonable for appropriate wound management because of their porosity, moisture permeability and surface area. Composites join two unique kinds of dressings with a few capacities in a single dressing that can address diverse requirements. They can be utilized as an essential as well as optional dressing and highlight an absorptive layer, an adhesive layer and a strike-through boundary. These dressings are adaptable and helpful offering alternatives for both fractional and full thickness wounds. Their water-verification nature settles on them a prevalent decision for regions inclined to dampness ambush from incontinence [39].

Conventional wound dressing items including cloth, build up, mortars, swathes (regular or manufactured) and cotton fleece are dry and utilized as essential or auxiliary dressings for shielding the injury from defilements. Cloth dressings produced using woven and non-woven filaments of cotton, rayon, polyesters manage the cost of a type of insurance against bacterial contamination. Some sterile cloth cushions are utilized for retaining exudates and liquid in an open injury with the assistance of filaments in these dressings. The cotton dressings were utilized before because of the moisture holding capacity however has a few weaknesses. One of the inconveniences was the microbial intrusion was not being smothered by the cotton dressing. The patients experience trauma while expulsion of the dressing takes place. By and large customary dressings are demonstrated for the perfect and dry injuries with mellow exudate levels or utilized as optional dressings. Since customary dressings neglect to give enough moist condition to the injury, they have been supplanted by current dressings with further advancements [89].

Exudates were not completely expelled from the outside of the wound when a cotton dressing was utilized, and the microbial assault was trailed by it around then. The chronic wounds can't be productively recuperated utilizing the cotton wound dressings. They give a comparatively drier condition for the wound to recuperate. Even though the cotton dressings have burdens, they are yet utilized in the market on a vast scale. The moisture retention of the cotton is lesser than that of flax which is not ideal for the wound dressing. Hence the flax fiber random mat with a lesser grammage and higher porosity can be an ideal for the application of wound dressing if coupled with proper wound healing promoting gels. The ideal wound dressings must have 85% water content and inherent permeability. The cotton dressings have provided a drier environment for the wound dressing because of its moisture uptake percentage which ranges from 10%-14% [89]. As flax is hydrophilic in nature it has better moisture absorption and retention and can be proposed as a suitable material for wound dressing. Along with the medicinal advantages, the mechanical behavior of moisture through non-woven flax fiber mats as compared to traditional dressings can be helpful using the diffusion testing method.

Domestic animal safety has been paid attention to since several decades. The wellbeing of the pets is a critical viewpoint and anything that may act as a hindrance to their wellbeing must be supplanted or expelled from their utilization. The pets interact with various environments when inside a house as well as outside. An animal toy interaction must be considered as they are orally using them. The toys which the pets bite and press are made with less expensive plastics which may conceivably contain BPA (Bisphenol An) and phthalates which are incredibly unsafe as they influence numerous frameworks in the body. A few synthetic compounds that mirrored estrogen have been found by an examination which was made by creating a pseudo dog salivation. As the connection of pet wellbeing and natural synthetics is understudied, they can be corelated with the investigation on people, rodents or rodents.

The most unsafe synthetic for any living being is the BPA. There have been confirmations of the fatal impacts of BPA and phthalates on laboratory species. The impacts of which can firmly associated with the human or other creature species. The rodents have undergone F1 generation BPA exposure and have significantly shown a decreased rate in fertility and also modification of the morphology of the reproductive organs [42]. Alternate impacts are on the human species are obesity and an obstruction in metabolism. The capacity of the BPA to create estrogens has been accounted for to be the serious issue of the advancement of tumors among canines and the reason for mammary malignancy. The phthalates are another very dangerous concoction which causes the phthalate disorder which fundamentally is an aggregate word for every one of the variations from its norm related with reproductive system abnormalities. This end was made when dogs in Italy were examined. The adipogenesis rate increments, expanding the corpulence drastically and has appeared 37% expansion in canine obesity and about 32% expansion in the incessant metabolic ailments in the course of recent years in the US [43]. The impacts of biting plastic pet items must be cautiously concentrated to comprehend the general impact of the components causing issues in the creatures and their behaviorism. On the off chance that the proprietors of the pet have an exact learning of the synthetic compounds presented to their canines, at that point they will better comprehend the significance of utilizing safe pet items.

Hence toys which are 100% natural must be used to make dog toys. Synthetic toys which are popular in the market are harmful to the animals, especially the rope toys which ret with time and are eventually consumed by the pets. The natural and earthy scent of these organic toys is appealing to the dogs and even if the dogs chew these toys made with ecofriendly naturally grown fibers, they are completely digestible. In addition, these fibers are anti-bacterial and anti-microbial and resistant to mold and mildew. The natural fibers are strong and hence long lasting. The dog toys can be multilayered with layers of the woven fabric so that even if the animal chews them they will have other layers to play with. The natural fiber toys are BPA free, which is generally added to the common plastic toys to increase elasticity and has effects on the developing fetuses and can have lifelong effect on the offspring. Some of the companies have already made toys with hemp hence the toys can be made with flax as its properties are like those of hemp. Flax fibers are strong and completely digestible and hence can be a viable alternative for synthetic dog toys.

2. OBJECTIVES

The overall goal of the thesis is to identify properties of flax fibers which promote them for engineering and industrial applications. As there has been an increase in human population and the demand of resources we need green composites and identifying properties of natural fibers as a reinforcement in the composites need a larger scale of study as they have a lot of benefits as seen above in Chapter 1. There has been a lack of usage of natural fibers as it can minimally compare with synthetic fibers which have better structural properties which contributes to most of the engineering and industrial application. This study tries to cover the identification properties of flax fibers which have made them applicable in engineering and industries.

- Comparison study of mechanical properties of flax fiber tows in wet and dry conditions to provide an appropriate data set to support an independent ASTM tensile testing standard for natural fiber tows.

  The mechanical properties of natural fibers must be studied as there is a lot of variability of the fiber properties when it comes to tensile properties due to various factors and the growth conditions and the origin of extraction of the fibers. In this regard the flax fibers are studied to characterize the tensile strength which form the basis of reinforcement of the natural fibers in composites. The tensile tests of flax fiber tows which are woven in a mat used to be reinforced in a composite are studied and proposed to be a standard method to test other natural fiber tows as well.

- Study and measure the rate of moisture diffusion in flax fiber mats by desorption method for different areal densities making the flax fiber mats ideal as hydrophilic wound dressings.

The hydrophilic nature of the flax fibers is the most observed hindrance in the usage of these fibers in structural applications. The diffusion behavior of water is studied using the desorption method for flax fiber mats and using the moisture retention as an advantage, an application has been proposed which has found way in biomedical engineering.

- Postulate other potential applications for flax fibers based on characterization results of the tensile strength of the fibers and diffusion of moisture through the flax fiber mat like toys for pet animals and commercial body sponges.

  Fibers (The phenolic contents of flax fiber are being studied for their metabolism activity and prove useful to make products out of flax plants for biomedical applications like wound dressing. The chronic non-healing wounds has poor cell proliferation in the presence of oxygen in the wound environment. But the flax plant content prevents apoptotic cell death. This study will be carried out by reviewing and studying existing literature and evaluate whether the to the diffusion process of water has any effect on the healing of the wound). The animals need toys which are safe for them even when digested. Today's toys are made of plastic materials containing BPA and have proven to be harmful to living beings. As the flax fibers have better tensile strength they can be made into ropes for the animals to play or stuffed into their toys for chewing. A study of available literature on how the flax fiber is for the animals has been carried out trying to make the toys. As the United States do not have laws for toys for dogs, the commercial toys made with natural fibers have already been in use by the conscious citizen and this study tries to prove it.

3. EXPERIMENTAL METHODS

3.1. Diffusion co-efficient of water through flax fiber mats of different areal densities

For the moisture diffusion in and out of the polymer composite fiber mats depends on Fick's second law. Untreated non-woven flax fiber mats of different areal densities. (228 gsm, 300 gsm and 400 gsm) were used to study the process of desorption for the maximum removal of moisture. The standard used to perform this experiment was SR ISO 6741-1/1998. The samples were immersed in distilled water to permit the continuation of sorption until saturation limit was reached after two hours for making sure that the flax fiber mat was not damaged or decomposed. Figure 7 shows the non-woven flax fiber mat cut in the size of 0.0508 m x 0.0254 m x 0.00635 m.

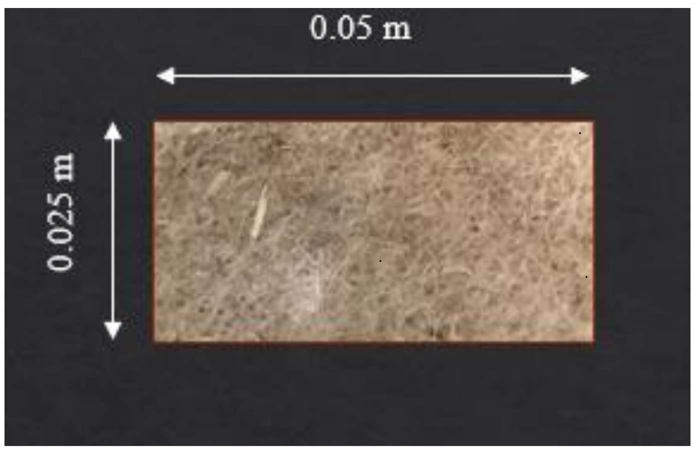

Figure 7: Non-woven flax fiber mat before the immersion into the distilled water.

The initial moisture content was measured using a moisture analyzer. The moisture desorption was observed for different areal densities of 228 gsm, 300 gsm and 400 gsm for 55 °C or 80 °C for each of the mat. The moisture analyzer used for this purpose was Computrac® MAX® 4000XL as shown in the Figure 8. The moisture analyzer is used to know the initial moisture content of the mat before conditioning.

Figure 8: Moisture analyzer to measure the initial moisture content of the non-woven flax fiber mat.

The specimens used for moisture desorption test were dried at 55°C and 80°C for the moisture to be removed at the maximum level. At intervals of 10 minutes, the specimens were recorded and again kept in the oven for further recording of the mass reduction in an oven set at these temperatures. The oven used for drying is shown in Figure 9.

Figure 9: Oven for drying samples.

This experiment was conducted three times for reproducibility of results. The amount of the water content (Mt) at instantaneous time was determined using the following equation [38].

$$M(t) = \frac{M_t}{M_0} \quad (3)$$

The desorption diffusion co-efficient was calculated using the following equation,

$$\text{Slope} = \frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}} = \frac{4M_m\sqrt{D}}{h\sqrt{\pi}} \quad (4)$$

M_m is the minimum moisture content of the Mat at an instant.

D is the diffusion co-efficient of desorption or the rate at which the moisture diffuses through the fiber mat.

3.2. Tensile testing

To study the different properties of tensile strength and stiffness for structural analysis, the specimens to be tested were pulled out from a woven flax fiber mat as shown in Figure 11. The woven flax fiber mat has same number of threads both in weft and warp direction. The fibers from the warp direction were tested. These mats are used as reinforcements in structural applications.

They are dependent on the strength of the fiber bundles and hence this study involves specimens taken from these mats. The plain-woven mat is shown in the Figure 10 from which the samples were pulled out for testing. Figure 11 shows the pulled-out fiber which was tested at room temperature and 65% relative humidity.

Figure 10: Woven mat of the flax fibers (Plain weave).

Figure 11: Flax fiber tow.

The tensile test was performed according to the ASTM D3822. An Instron 5567 shown Figure 12 is equipped with a 2 kN capacity load cell with a crosshead speed of 0.01 mm/min was set to different gauge lengths of 153 mm, 175 mm, 200 mm, 220 mm and 242 mm respectively. One of the previous studies shows an important decrease between 4- and 125-mm gauge lengths for both the tensile strength and modulus, and a rather low decrease between 125- and 500-mm gauge lengths for the tensile strength curve and a stabilization occurring between 125- and 250-mm gauge length for the modulus [90]. To confirm the similar behavior of the flax fiber tows used in this study various gauge lengths were used to study the mechanical behavior of the tows. The samples were fiber tows made of four strands whose ends were casted with epoxy resin for better clamping in the grips.

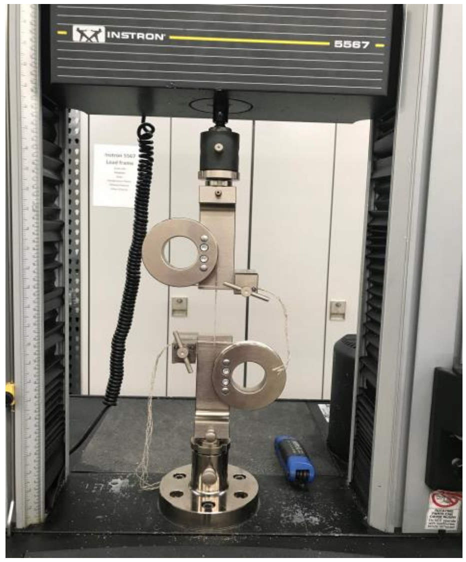

Figure 12: Tensile testing on Instron 5567.

The tensile behavior at gauge lengths 153 mm, 175 mm, 200 mm, 220 mm and 242 mm was investigated in dry condition and wet condition. The fibers were also tested for wet condition at the same gauge lengths by the process of immersing them in water until saturation was reached and the moisture content was measured. The samples were also tested for 5%, 25%, 60% and 80% moisture levels by immersing them in the water prior to testing. The tenacity and stiffness were studied. Test matrix for tensile testing is shown in the Table 5. The comparison of this data gives a better understanding of the tows in a specific condition.

Table 5: Test matrix for tensile testing of flax fiber tows

Gauge Length (mm)	Moisture (%)
153	5 (dry), 25, 60 and 80 (wet)
175	5 (dry), 25, 60 and 80 (wet)
200	5 (dry), 25, 60 and 80 (wet)
220	5 (dry), 25, 60 and 80 (wet)
242	5 (dry), 25, 60 and 80 (wet)

4. RESULTS AND DISCUSSIONS

4.1. Moisture behavior in flax fiber non-woven random mats

When the moisture diffuses into any composite it affects the mechanical properties due to degradation of the interfacial bond between the fiber and the matrix. The reduction in glass transition temperature of the thermoplastic polymers is a result of moisture diffusion in the matrix. Hence it is important to remove the moisture from the natural fibers before impregnating them with the matrix of the polymer. Natural fibers have hydroxyl group present in their surface which absorbs moisture from the environment. Hence a drying method was implemented in this study to characterize the rate of evaporation of moisture through these mats. The two separate set temperatures of 55 °C and 80 °C were considered in this study based on current practices in the industry. In all results, the rate of evaporation is plotted against the square root of time. The desorption curve for 55 °C (228 gsm) is shown in the Figure 13, the desorption curve for 55 °C (300 gsm) is shown in the Figure 14 and the desorption curve for 55 °C (400 gsm) is shown in the Figure 15. The desorption curve for 80 °C (228 gsm) is shown in the Figure 16, the desorption curve for 80 °C (300 gsm) is shown in the Figure 17 and the desorption curve for 80 °C (400 gsm) is shown in the Figure 18. Each graph has three curves as this experiment was performed three times for testing the reproducibility of the results.

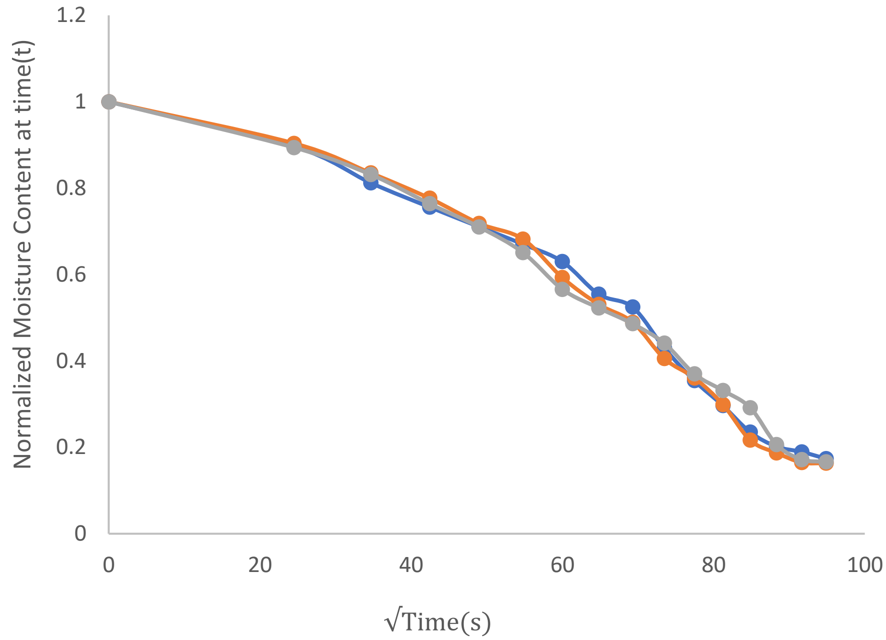

Figure 13: Desorption curve for 55 °C (228 gsm).

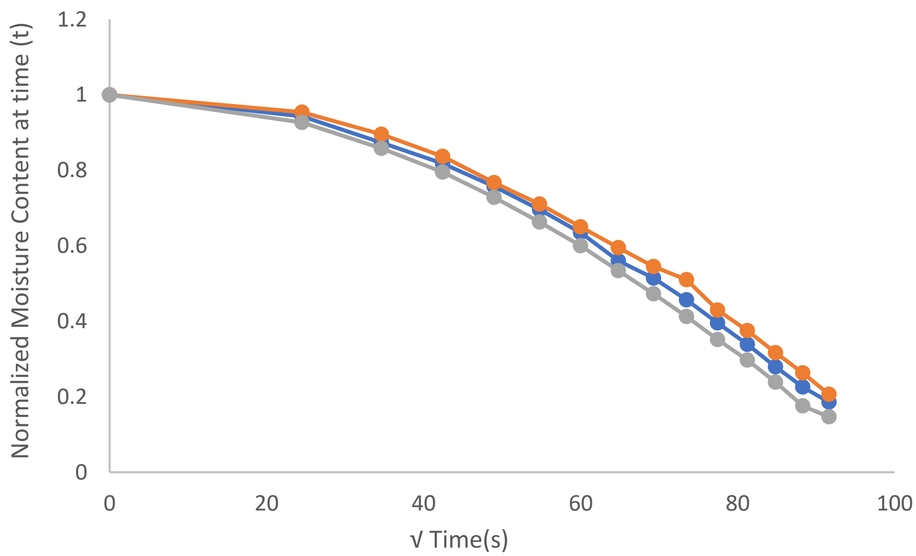

Figure 14: Desorption curve for 55 °C (300 gsm).

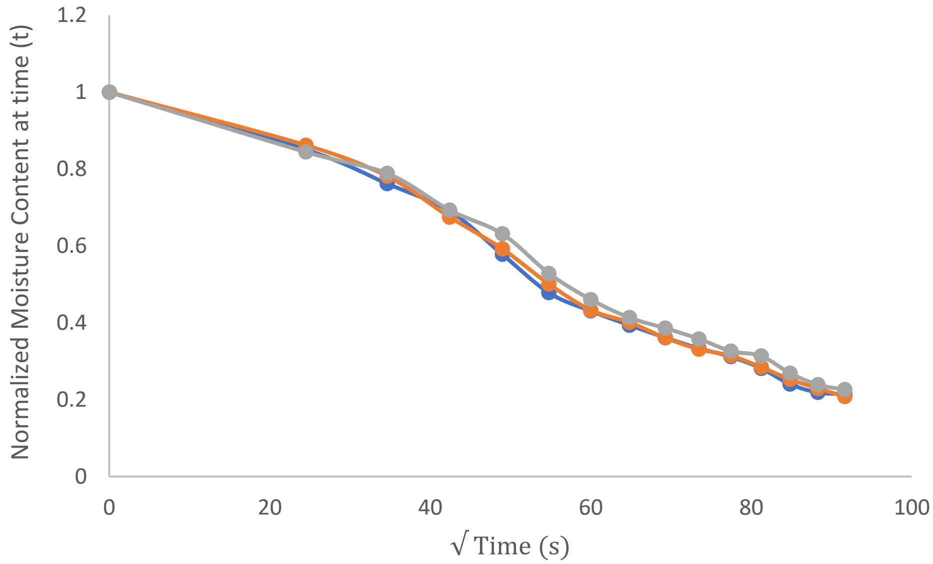

Figure 15: Desorption curve for 55 °C (400 gsm).

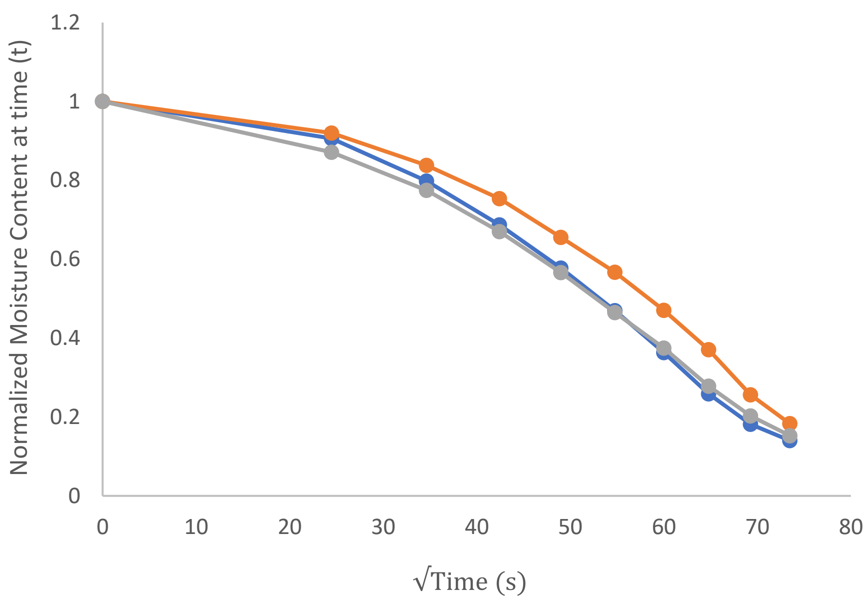

Figure 16: Desorption curve for 80 °C (228 gsm).

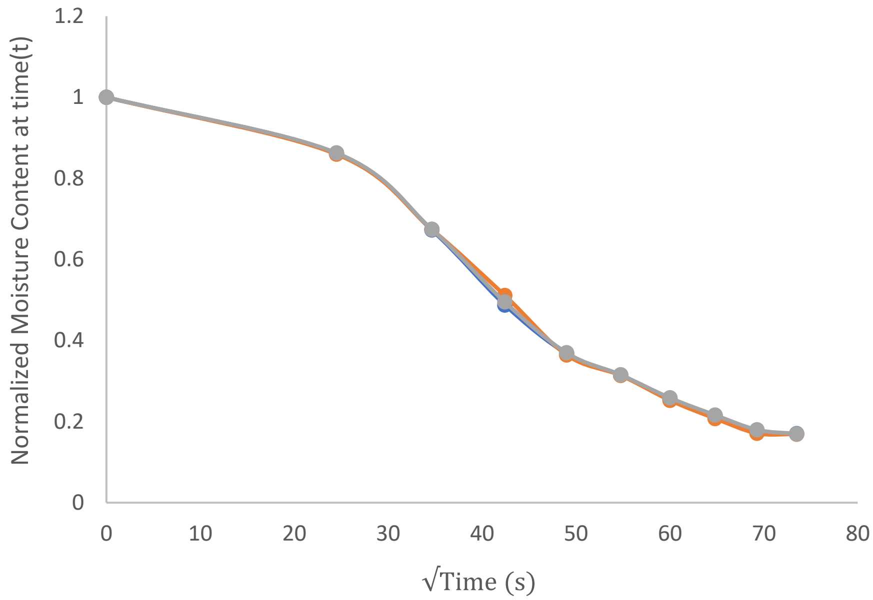

Figure 17: Desorption curve for 80 °C (300gsm).

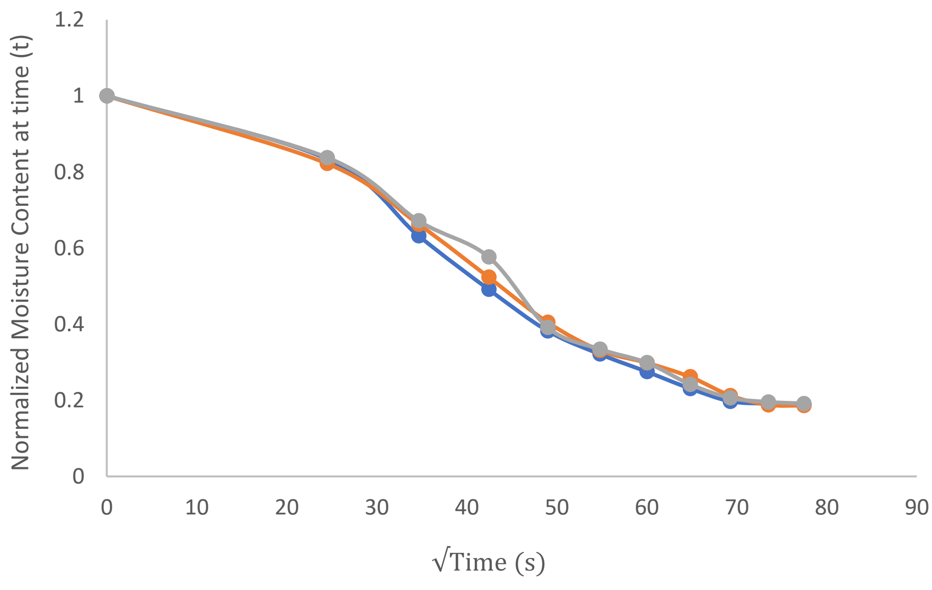

Figure 18: Desorption curve for 80 °C (400 gsm).

The diffusion process follows the Fickian behavior in the linear region of the plot which allows the calculation of the diffusion co-efficient. The initial moisture content at 55 °C was 5.23% and the final moisture content was 1.46% and for 80 °C the initial moisture content was 6.12% and the final moisture content was 1.12%. The initial moisture content varies between 4% to 6% and the final moisture content varies between 1% to 2.5%. This shows that there is some moisture left in the mat and it cannot be removed as the water molecules have strong bonds with the fiber. The drier mats can be reinforced in the composites so that they will be less hydrophilic improving the mechanical properties of the composite in which they are reinforced by 25% [91]. The curves of the data are approximately linear which agree with Fickian behavior. The moisture retention for the flax mat ranges from about 14% to 19% whereas it is only 7%-9% [32] for cotton dressings. The moisture content ranges from 82% to 91%. This proves that flax fiber non-woven mats are ideal wound dressings as ideal is 85% water content [38]. Also, the diffusion co-efficient of moisture through the cotton fabric was found to be in the range of $10^{-7}cm^2/sec$ [92] and diffusion through non-woven flax mat is $10^{-10}cm^2/sec$ indicating better retention of moisture needed for the wound environment. Hence flax is a better alternative for cotton wound dressings.

4.1.1. Statistical analysis of the diffusion testing

The statistical analysis was performed using ANOVA with a 95% confidence interval. To determine whether any of the differences between the means are statistically significant, the p-value was compared to the significance level to assess the null hypothesis. The null hypothesis states that the population means are all equal. Usually, a significance level (denoted as α or alpha) of 0.05 is used to conduct the analysis. A centrality dimension of 0.05 shows a 5% danger of inferring that a distinction exists when there is no genuine contrast. If the p-value is less than or equal to the significance level, the null hypothesis is rejected and can be concluded that not all of population means are equal. If the p-value is greater than the significance level, there is not enough evidence to reject the null hypothesis that the population means are all equal.

Temperature had significant effect on moisture and concentration does not have significant effect on moisture. The t test analysis is shown Table 6. Least significant mean for 55 °C is significantly different from least significant mean for 80 °C which is shown in Table 7. There is no significant difference between any two concentrations of flax fiber mats and is evident from the Table 8. The variation of the means for 55 °C is in the range 1.98 E-8 ± 4.75 E-9 m^2/s. This variation is very similar in the range of diffusion of water through flax fiber mats. The variation of the means for 80 °C is in the range 4.05 E-8 ± 8.67 E-9 m^2/s. The variation of the means for the areal densities is not significantly different implying that that the ability of the concentration was not affecting the diffusivity in an extraordinary way. The interaction plot indicates diffusion value and its independence with the concentration of the mat. The behavior of diffusion w.r.t temperature and concentration can be observed to be significantly different for different temperature and the behavior of diffusion w.r.t temperature and concentration can be observed to be significantly not different respectively.

Table 6: t Test analysis of diffusion co-efficient of water through non-woven random flax fiber mats

Parameter	Estimate	Standard Error	t Value	Pr> |t|
Intercept	3.29E-8	2.55E-9	12.90	0.006
Temp 55	-2.07E-8	2.55E-9	-8.10	0.01
Temp 80	0	-	-	-
228 gsm	1.24E-8	3.12E-9	3.98	0.05
300gsm	1.02E-8	3.12E-9	3.26	0.08
400gsm	0	-	-	-

The ANOVA method is used to show the significance of the results. Further Tukey test is performed to show whether the means of the population being compared are significantly different.

The interaction plot between the diffusion co-efficient and the areal densities indicated that there was an increase in the diffusion co-efficient value as the temperature increased.

Table 7: The results of ANOVA for Type I SS for diffusion of water through non-woven random flax fiber mats

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Temperature	1	6.42E-16	6.42E-16	65.69	< 0.0149
Grammage	2	1.76E-16	8.80E-17	9.00	0.1

Table 8: The results of ANOVA for Type III SS for diffusion of water through non-woven random flax fiber mats

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Temperature	1	6.42E-16	6.42E-16	65.69	< 0.0149
Grammage	2	1.76E-16	8.80E-17	9.00	0.1

The blue line in Tukey analysis graph shows a significant difference in the means of the populations tested for different temperatures and hence indicated that the test performed were statistically valid. The interaction plot between diffusion co-efficient and areal densities indicated that as the areal density increases the value of diffusion co-efficient reduces. The red lines shown in the Tukey analysis graph indicate that there is no significant difference in the values of the means of the populations of the diffusion co-efficient with respect to the areal densities of the flax fiber mat. This indicated that the test that was conducted was not able to produce data that is statistically valid.

4.2. Tensile testing of flax fiber tows

The specific tensile strength of flax fibers is found to be approximately 5 cN/tex-14 cN/tex. The strength values lie within the tensile strength values of hemp fibers (10.9 cN/tex – 52.4 cN/tex) [93] which are used to make commercial dog toys. Hence flax fibers have a potential to be used in animal toys. The tensile properties are observed to be independent of the gauge length and it was clear from the force displacement curves of the gauge lengths investigated. A typical load displacement curve for the flax fiber tow of the same gauge length is shown in the Figure 19. The first nonlinear stage in the force displacement diagram indicated that the fibers were arranging themselves with the loading axis during the loading stage. The first non-linear region (at low cross-head displacement) corresponds to the stage where the fibers or fiber bundles within the tow arrange themselves with the loading axis during the tensile loading. The maximum tensile force is taken as the peak point of the curve according to ASTM: D2256 standard. After this peak point, the load falls until complete failure of the tow. The strain at break is identified as the corresponding strain to the maximum tensile force [31].

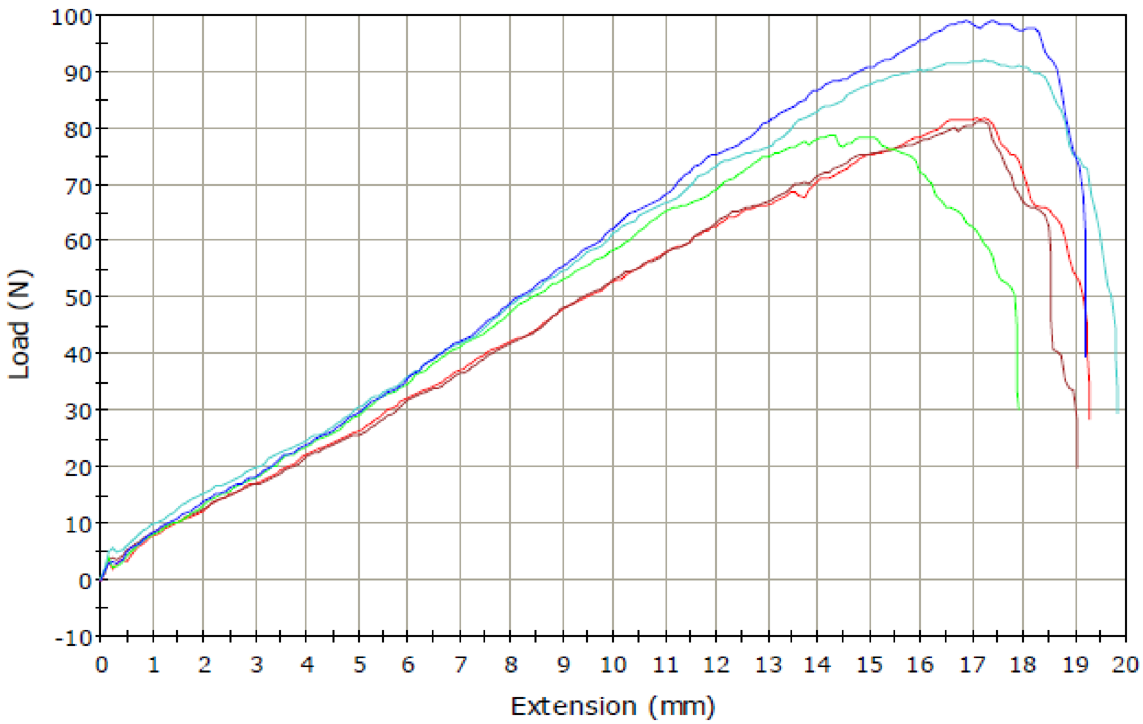

Figure 19: Typical load-displacement curve for flax fiber tow.

4.2.1 Statistical analysis of mechanical properties of flax fibers

The statistical analysis was performed using one-way ANOVA method. The data used for the analysis for tensile testing is presented in the Table 9 given below. The behavior of tows w.r.t to gauge lengths and moisture was investigated and the results were compared, and the dependence of the flax fiber properties was investigated.

Table 9: Data for the statistical analysis of the tensile testing of flax fiber tows

Serial No	Moisture (%)	Gauge_Length (mm)	Max Strength (cN/tex)	Stiffness (N/m)	Total Elongation (%)
1	5	153	5.700	4635.00	11.06
2	5	175	6.800	4740.00	12.47
3	5	200	7.660	4873.00	12.93
4	5	220	8.080	3860.00	13.69
5	5	242	8.325	3656.00	13.72
6	25	153	10.980	3615.38	29.38
7	25	175	10.510	3220.51	23.88
8	25	200	10.400	3214.28	21.12
9	25	220	10.810	3566.04	20.09
10	25	242	10.930	3095.23	19.22
11	60	153	12.690	3122.00	27.31
12	60	175	12.760	3025.00	22.79
13	60	200	12.160	3051.00	19.29
14	60	220	12.160	3214.00	18.90
15	60	242	14.590	3295.00	19.19
16	80	153	14.670	2777.77	28.77
17	80	175	14.000	2918.60	28.10
18	80	200	13.880	2545.65	27.80
19	80	220	14.110	2679.06	28.15
20	80	242	14.680	2583.33	28.53

Overall model appears to explain statistically significant amount of variation since the p-value is less than .05 (the usual protection level used by default). The tow factor appears to be statistically significant using the 5% protection level. The follow up tests i.e. Least Significant Difference Tests (LSD) are shown below. Gauge length does not seem to be significant at the 5% level (since the p-value is greater than .05). This implies that the gauge length does not affect the tensile strength, but the moisture level significantly affects the tensile performance of the tows. The increase in moisture increased the increase in tensile strength of the flax fiber tows. The distribution of maximum strength w.r.t moisture level is shown in the Figure 20 and the distribution of maximum strength w.r.t gauge length is shown in the Figure 21.

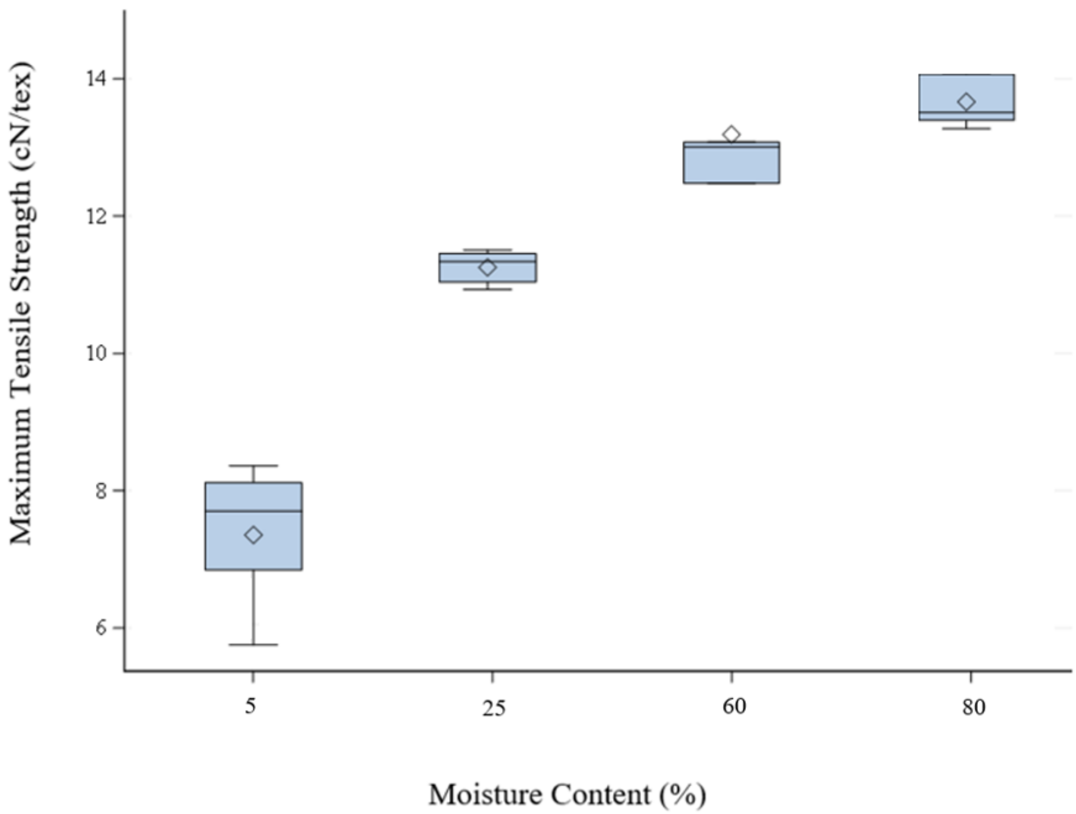

Figure 20: Distribution of maximum strength for various tow moisture levels.

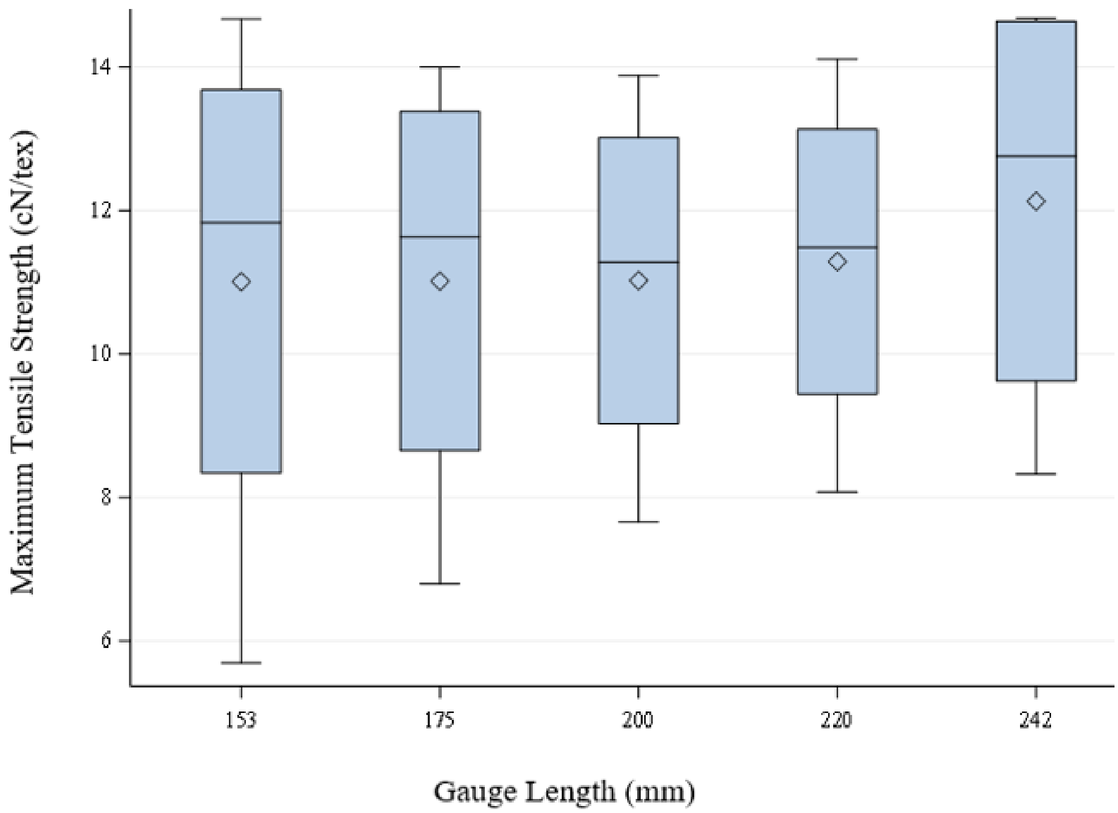

Figure 21: Distribution of maximum strength for various gauge lengths.

Box plots for the gauge length- The effect was not significant, so this suggests the means are similar which is what appears to be shown here. Since the main effect of gauge length was not significant, usually the LSD tests would be ignored.

There are two of extreme data points which yield standardized residuals greater than two in absolute value. Otherwise the diagnostics seem normal. Box plots for the stiffness means dry was high with the remainder of the treatments less different than for the previous dependent variable. This implies that the variation of stiffness was inverse to that of the tensile strength and the stiffness of the flax fiber tows reduces as the moisture increases. Both these are relations are evident in Figure 22 and Figure 23.

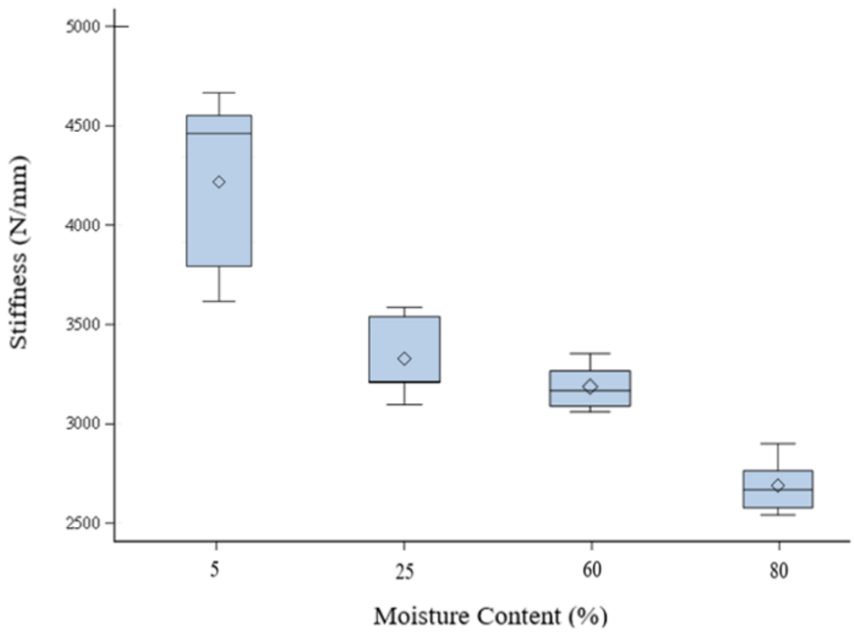

Figure 22: Distribution of stiffness for various moisture levels.

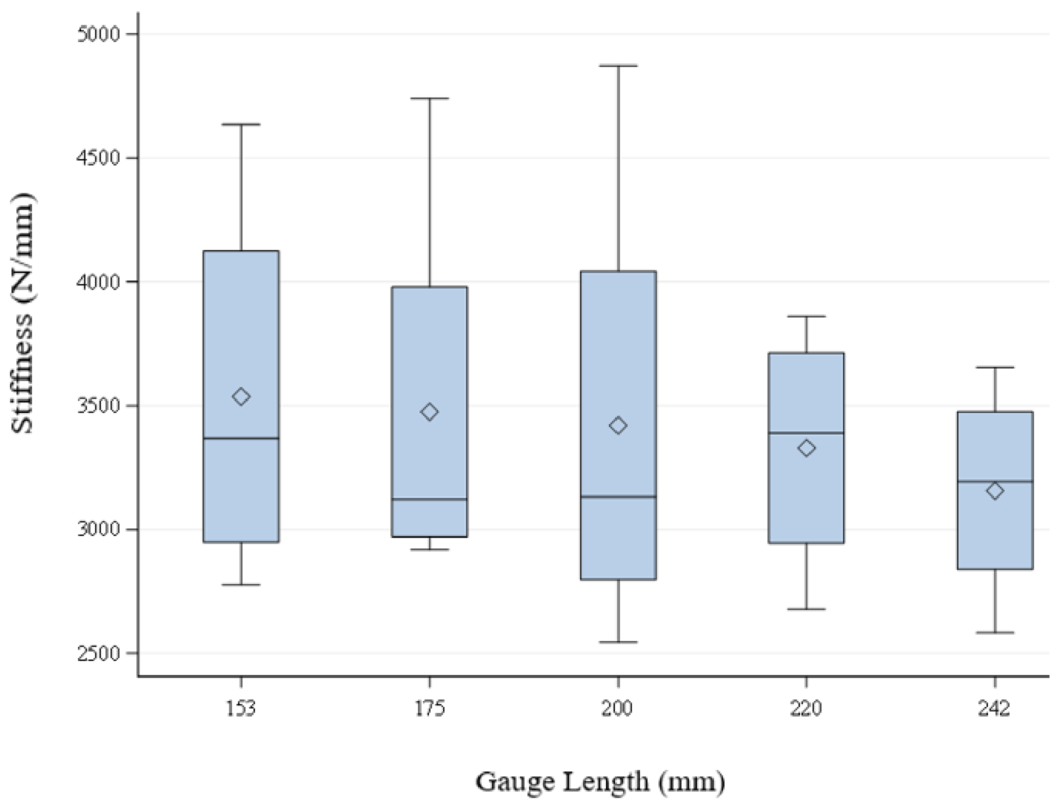

Figure 23: Distribution of stiffness for various gauge lengths.

Moisture was significant, but gauge length is not. As earlier, there are some large standardized residuals. Again, gauge length the means were not that different. This implies that the increase or decrease in gauge length does not affect the tensile strength in a significant way but as the moisture increases the total elongation increases and is inversely proportional to the stiffness values. The relationship between moisture levels and total elongation is shown in the Figure 24 and Figure 25.

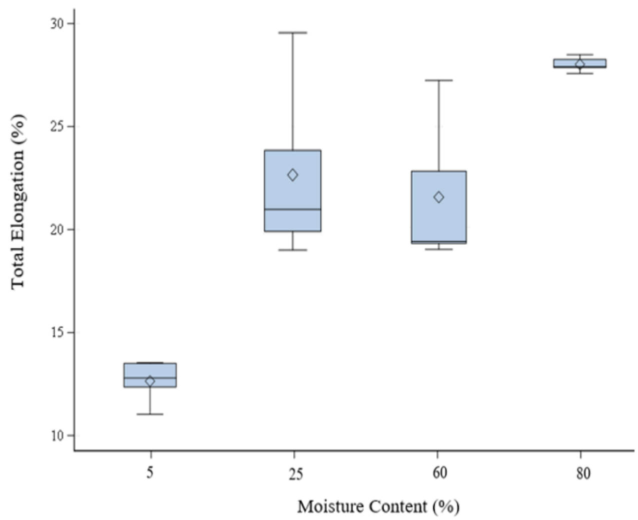

Figure 24: Distribution of total elongation for moisture levels.

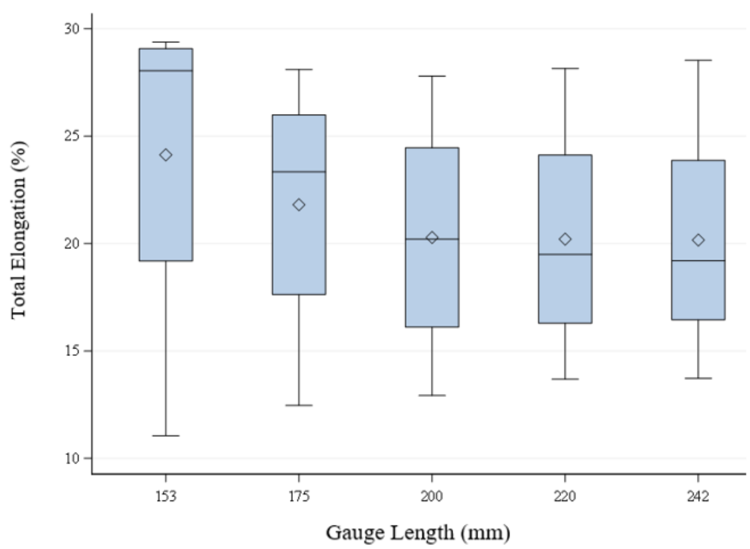

Figure 25: Distribution of total elongation for various gauge lengths.

5. CONCLUSIONS

This study has produced physical and mechanical results explaining how flax fiber tows behave when they undergo tensile loading and how the flax fiber mats allow moisture to diffuse through them. The results obtained in this study are relative to the specific areal densities for flax fiber mat and specific moisture levels and gauge lengths for tensile testing only. Varying results might be obtained for other areal densities besides those considered for this study for the diffusion experiment as well as for different gauge lengths for tensile experiment results will be different.

The tensile testing of flax fiber has given normal values which are stable for its usage in structural applications of high performance at lower cost. The maximum tensile strength of the flax fiber tows increases with moisture content and is maximum in the wet condition. There might be variations in the strength values due to different genotypes. Ultimate deformation of the samples does not depend on the cross-section but the linear density. Hence all the calculations are based on textile units. Even though the gauge lengths studied did not affect the tensile properties there has been a 75% increase in tensile strength of the wet fibers than the dry fiber tows. There has been a limited study done on the testing of the bast fiber tows and does not have specific standards to test the mechanical behavior of the fiber tows. This data can be used to set an ASTM standard for the mechanical testing of natural fiber tows. The flax fibers are stronger enough as we saw its tensile behavior and hence its application in animal toys has proven to be ideal one compared to the hemp toys which have started being used commercially. The stiffness value is the least for the wet condition which might be an important factor for the wet fibers to be used. The applications of flax fibers include reinforcements, automotive, rubber, shoe and even aircraft industry. The desorption of moisture reduces the moisture content in the flax mat substantially and can be implemented as a drying method before reinforcement in composites to avoid the loss of mechanical properties.

The theoretical study of flax fibers for wound dressing indicates that the flax fiber hydrophobic extract maybe valuable for use as it promotes skin cell migration, promotes extracellular matrix remodeling, inhibits chronic inflammation and stimulates the limiting stages in the long-lasting non-healing wounds. The diffusion of water through a non-woven flax fiber mat was successfully investigated to indicate the potential for it being a suitable wound dressing material. This is also applicable for the body sponges which can be made from such flax fiber mats and indicating them as safe to be used for commercial purposes as well.

6. FUTURE RECOMMENDATIONS

The tensile testing of fiber flax fiber tows helps set a better standard for testing all other bast fibers and plant fibers as well. This method can be used by ASTM for natural fiber testing. The characterization of the range of the fiber strength and stiffness can be used to find more applications where natural fibers can be replaced with the synthetic ones. For applications in load bearing structures the natural fibers need to be reinforced with an appropriate matrix.

Further study of the flax fiber mat as a wound dressing is necessary concerning the adhesion of the dressing with wound. This could be achieved using a gel which helps heal the wound in harmonization with the flax fiber extract. The effect of the flax fiber wound dressings can be tested for trauma in more and more experiments as the intensity of pain cannot be monitored. The bacterial growth on the flax fiber mat can be further studied by keeping it in a specific environment like the wound environment. This might help better understand the wound and the dressing behavior for a long-term use.

The strength of the fibers is not enough but also the study of the reaction of these flax fibers can be combined with animal compatible and edible natural organic substances which act as binders for animal stuffing. This can be achieved by testing the product behavior along with the saliva of the pet. The actual experimentation of the reaction of these toys with digestive system of the animals if ingested by the pets can be a future scope. If there is a success in this aspect the flax fiber toys will be a much-preferred commercial product by the pet owners.

Finding potential applications is an extremely important aspect of the study of natural fibers as this is going to help run the world. Not only flax but all other natural fibers must be studied more in depth to optimize their use for applications that can replace the synthetic fiber applications.

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APPENDIX A

Table A1: The GLM procedure for statistical analysis of the diffusion of water through non-woven random flax fiber mats

Class Level Information		
Class	Levels	Values
Temperature	2	55, 80
Grammage	3	228 gsm, 300 gsm, 400 gsm

Table A2: Error wise comparison analysis of diffusion of water through non-woven random flax fiber mats

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	3	8.18E-16	2.72E-16	27.89	0.03
Error	2	1.95E-17	9.78E-18		
Corrected Total	5	8.38E-16			

Table A3: Statistical mean values of diffusion of water through non-woven random flax fiber mats

R-Square	Co-eff Var	Root MSE	Max_Strength Mean
0.97	10.37	3.12E-9	3.01E-8

Table A4: Tukey test for the study of diffusion co-efficient of water through non-woven random flax fiber mats

Temperature	D_Value LS Mean	H0:LS Mean 1=LS Mean 2 Pr> |t|
55	1.98E-8	0.0149
80	4.05E-8	

Table A5: Analysis using least square means to study the diffusion co-efficient of water through non-woven random flax fiber mats

Least Squares Means for effect cone Pr> |t| for H0: LS Mean 1= LS Mean 2			
i/j	1	2	3
1		0.77	0.10
2	0.77		0.14
3	0.10	0.14	

APPENDIX B

Table B1: The classes with levels for statistical analysis of tensile strength of the flax fiber tows

	Class	
Tow	4	5, 25, 60, 80
Gauge Length	5	153, 175, 200, 220, 242
Class	Levels	Values

Table B2: The results of ANOVA for Type I ss for maximum tensile strength

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	141.25	20.17	42.25	< 0.0001
Error	12	5.73	0.477		
Corrected Total	19	146.98			

Table B3: The statistical values of tensile strength of the flax fiber tows

R-Square	Co-eff Var	Root MSE	Max_Strength Mean
0.961004	6.118959	0.691121	11.29475

Table B4: The results of ANOVA for Type III ss for maximum tensile strength of flax fiber tows

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Tow	3	137.52	45.84	95.98	< 0.0001
Gauge Length	4	3.72	0.93	1.95	0.16

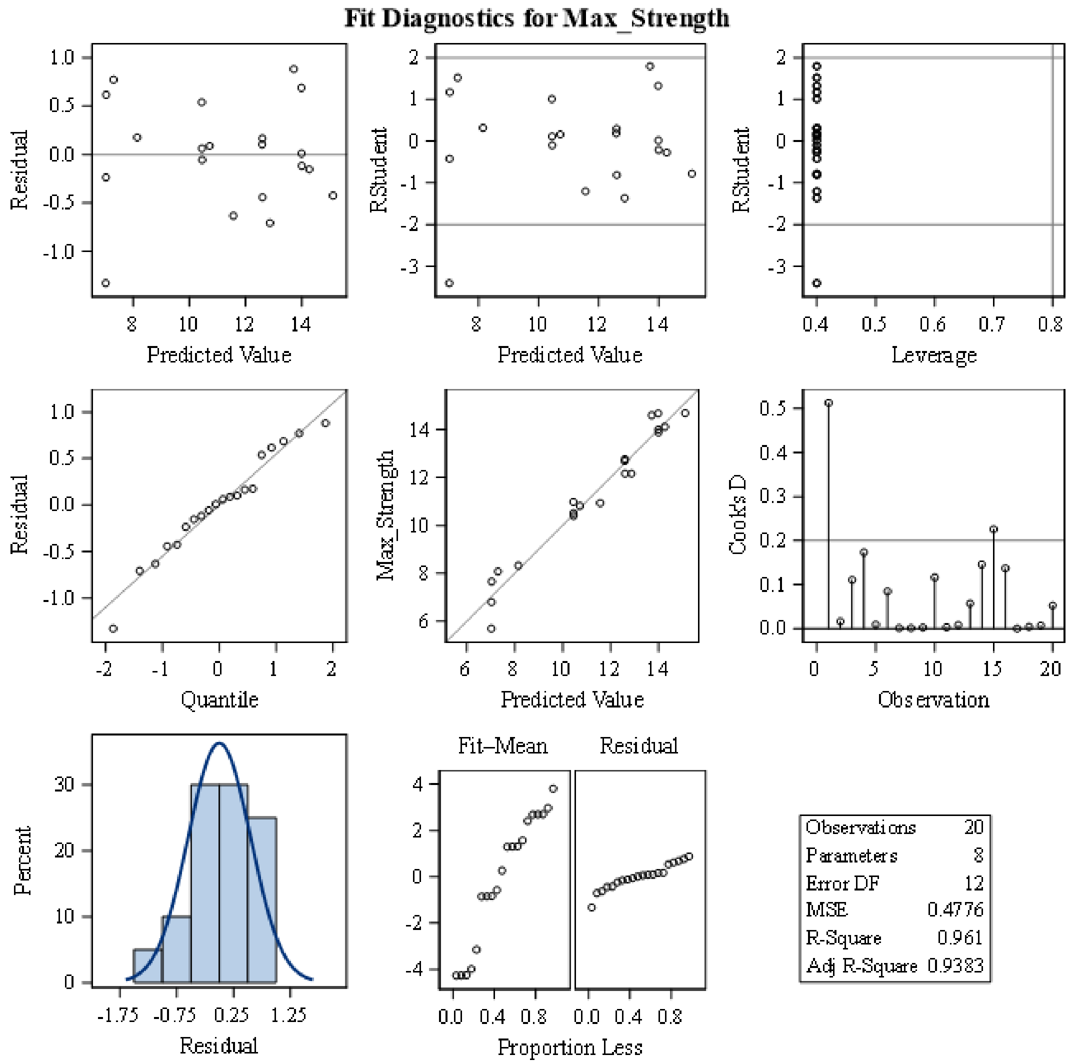

Figure B1: Fit diagnosis for maximum strength of flax tows**.**

Table B5: Type I comparison wise error rate for tensile strength the flax fiber tows

Alpha	0.05
Error Degrees of Freedom	12
Error Mean Square	0.477
Critical Value of t	2.17
Least Significant Difference	0.95

Table B6: LSD (t test) for tensile strength of flax fiber tows

Means with the same letter are not significantly different			
T grouping	Mean	N	Tow
A	14.26	5	Wet
B	12.87	5	60
C	10.72	5	25
D	7.31	5	Dry

Table B7: The results of ANOVA for Type I ss for stiffness of the flax fiber tows

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	7679898.66	1097128.38	10.64	0.0003
Error	12	1237304.77	103108.731		
Corrected Total	19	8917203.43			

Table B8: The statistical values of stiffness of the flax fiber tows

R-Square	Co-eff Var	Root MSE	Stiffness Mean
0.86	9.48	321.10	3384.34

Table B9: The results of ANOVA for Type III ss for stiffness of flax fiber tows

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Tow	3	7329089.11	2443029.70	23.69	< 0.0001
Gauge Length	4	350809.54	87702.38	0.85	0.5201

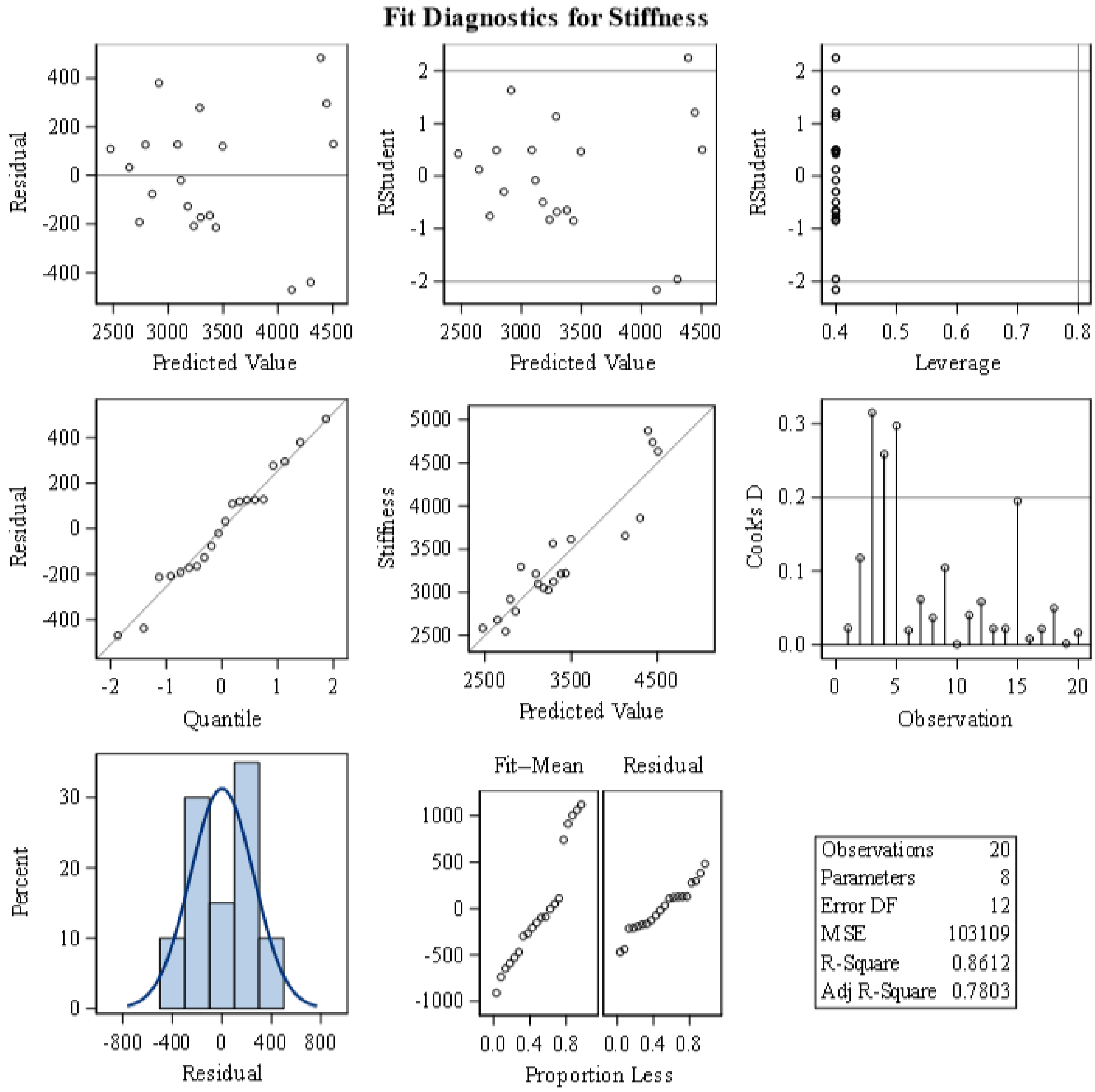

Figure B2: Fit diagnosis for maximum stiffness of flax tows**.**

Table B10: The results of ANOVA for Type I ss for total elongation of the flax fiber tows

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	64.006	94.85	14.58	< 0.0001
Error	12	78.08	6.5		
Corrected Total	19	742.088			

Table B11: The statistical values of total elongation of the flax fiber tows

R-Square	Co-eff Var	Root MSE	Stiffness Mean
0.89	11.96	2.55	21.31

Table B12: The results of ANOVA for Type III ss for total elongation of flax fiber tows

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Tow	3	616.89	205.63	31.60	< 0.0001
Gauge Length	4	47.11	11.77	1.81	0.19

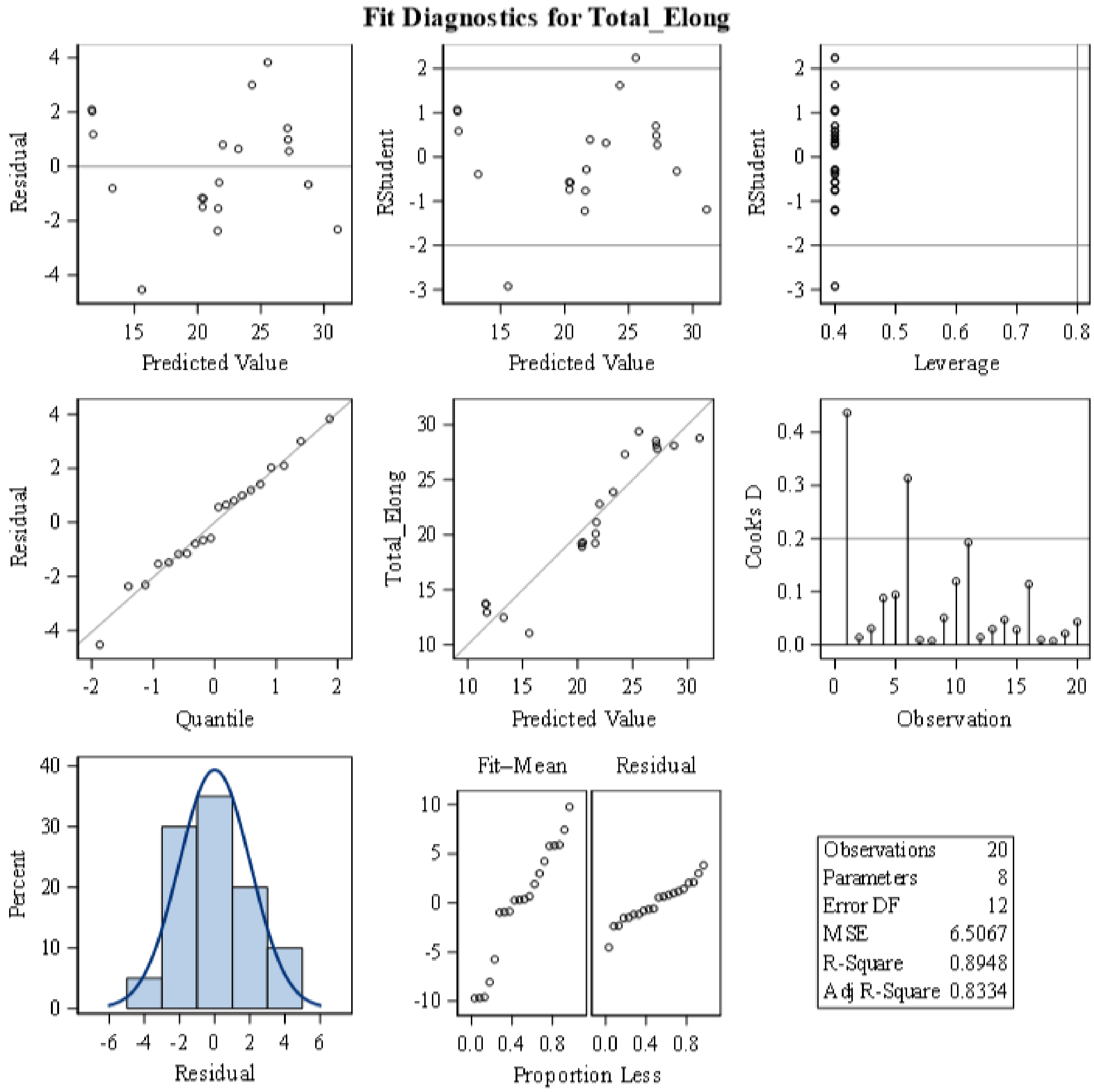

Figure B3: Fit diagnosis for total elongation of flax tows**.**