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# Investigation of the Properties of Natural Fibre Woven Fabrics as a Reinforcement Materials for Green Composites

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**Abstract**
*The mechanical properties of flax and jute woven fabrics were investigated and compared with each other. Mechanical properties of the yarns and fabrics were characterised and compared for each scale. The fabric structure, yarn physical properties, fibre cross-section, and fibre molecular structure parameters of the fabric were investigated. FTIR and TGA thermogram analyses were applied to the fabrics to characterise them. The fabric tensile strength was attributed to the composite tensile strength, but there was not a direct relation. The tensile strength of natural fibre fabrics was determined as significantly reduced depending on the temperature increase. This condition should be considered as an important limitation for composite applications.*

**Key words:** *natural fibre, fabric reinforcement, natural fiber composites, mechanical properties, physical properties.*

## Introduction

In the recent decades, natural fibres used as an alternative reinforcement material in polymer composites have attracted the attention of many researchers and scientists due to their advantages over conventional glass and carbon fibres, thereby increasing environmental concern and creating a high demand for environmentally friendly materials [1, 2]. Europeans used about 315,000 tonnes of natural fibres in 2010, which was 13% of the total reinforcement materials for composites. It is forecasted that the amount will increase to 830,000 tonnes in 2020, with a share of 28% for the total amount of reinforcement materials [3]. These natural fibres include flax, hemp, jute, sisal, kenaf, coir, kapok, henequen and many others. Jute and flax fibre are the kind of high-performance natural fibres which have a high specific strength and specific modulus, hence they are attractive as natural fibre reinforced composites. They are composed of cellulose, lignin and hemicelluloses. There is a big variation in the cross-sectional area of bast fibres like jute and flax. Unlike cotton fibres, which can be separated into single fibres or very few fibre bundles, industrial bast fibres are not separated into single fibres but into fibre bundles, which may contain hundreds of fibre bundles or thousands of single fibre cells. The strength, length, fineness, chemistry and homogeneity are important properties of bast fibre for use in composite production as reinforcement. The proportions of molecules like cellulose, hemicelluloses, lignin, and structural proteins in the secondary walls should control variability in the mechanical properties of the fibre [4, 5]. The structural parameters, which are the degree of polymerisation, cellulose crystallinity, micro-fibril angle, and the amount and structure of noncellulosic polysaccharides, have an important influence on the tensile properties of the fibre [6]. Jute and flax fibres are used in composites as reinforcement materials in the form of long, short and woven fabrics. The fibre length and orientation have different effects in different forms of reinforcement with respect to mechanical properties. The fibre length and fibre orientation have a maximum influence in the case of unidirectional reinforcement in the long fibre form. The fibre length has a maximum influence, and the fibre orientation has a medium effect in the case of the woven fabric reinforcement form. The fibre length and fibre orientation have a minimum influence in the case of the short fibre reinforcement form. The limiting fibre volume fractions are around 75% for unidirectional reinforcement, 65% for woven reinforcement and 30% for short fibre reinforcement [7, 8]. The various advantages of natural fibres over man-made glass and carbon fibres are low cost, low density, comparable specific tensile properties, nonabrasiveness for equipment, non-irritation for the skin, reduced energy consumption, lower health risk, renewability, recyclability and biodegradability [9].

Many factors can influence the performance of natural fibre reinforced composites. Apart from the hydrophilic nature of fibre, the properties of natural fibre reinforced composites can also be influenced by the fibre volume fraction. In general, high fibre content is required to achieve the high performance of composites. Therefore the effect of fibre content on the properties of natural fibre reinforced composites is of particular significance [10]. The fibre-matrix interface is another factor that affects composite mechanical properties with respect to load transfer. The interface of the fibre-matrix is composed of physical and chemical bonds between the reinforcement and resin. Enhancement of the interface bond is made by surface modification of the fibre via physical and chemical methods such as the application of coupling



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*Table 1. Properties of woven fabrics used in this study.*

| Reinforcement definition | Flax fabric | Jute fabric |
|---|---|---|
| Reinforcement code | K1 | K2 |
| Weave type | Plain woven | Plain woven |
| Number of threads, threads/cm<br>Weft yarn<br>Warp yarn | <br>12<br>12 | <br>7<br>7 |
| Yarn linear density, tex<br>Weft yarn<br>Warp yarn | <br>46<br>46 | <br>230<br>230 |
| Yarn type<br>Weft yarn<br>Warp yarn | <br>Ring<br>Ring | <br>Ring<br>Ring |
| Yarn definition and composition<br>Weft yarn<br>Warp yarn | <br>100% Flax<br>100% Flax | <br>100% Jute<br>100% Jute |
| Yarn crimp in the fabric, %<br>Weft yarn<br>Warp yarn | <br>5.8<br>6.0 | <br>7.7<br>6.3 |
| Mass per square meter, g/m$^2$ | 120 | 300 |

agents to the fibre surface and/or the use of compatibilisers in the matrix [11].

The mechanical properties of natural fibres show serious variability due to the age of the plant, the geographical and climatic growth conditions, the harvesting method, the retting and combing technique etc. [12], contrary to synthetic fibres. The variability of these mechanical properties, the compatibility between the matrix and natural fibre, and the moisture absorption [13] are the principal disadvantages which may prevent the use of natural fibre as a reinforcement material for composites from large-scale production [14]. There are many review articles on the fibre scale properties of the most widely considered natural fibres such as flax, hemp, jute, sisal, kenaf etc. [15, 16].

The swelling of cellulosic fibre, especially jute and flax is also a problem when using reinforcement materials in composites. The cross-section area and volume of the fibre increase with increased swelling, because of which the interface of the fibre-matrix may be affected and form a crack in the matrix.

The microstructure of natural fibres is complicated. The fibre diameter is about 10 –20 µm and consists of a microfibrillar cellulose phase and matrix phase, which is mainly composed of hemicelluloses and lignin. Cellulosic fibrils have a diameter of around 10 nm and are made up of 30–100 cellulose molecules in extended chain conformations, which provide mechanical strength to the fibre [13]. The fibrils consist of monocrystalline cellulose domains with the fibril axis parallel to the cellulose chains. Each fibril can be considered as a string of polymer whiskers, linked along the fibril by amorphous domains, and having a modulus close to that of perfect crystal native cellulose [17].

It is clear that despite the significant advantages of natural fibres due to their limited mechanical properties, the hydrophilic nature lowers the compatibility with the hydrophobic polymer matrix, presenting poor dimensional stability due to swelling with water and a limited processing temperature under 200 °C, and they are not favoured for use alone in composite materials to obtain adequate reinforcement. Therefore hybridising with conventional carbon and glass fibres may form good results. Unlike synthetic fibres, the mechanical properties of natural fibres show a wide range of variation, therefore it is more critical to determinate the properties of these materials (fibre or yarn) in a fabric and composite. The properties of a composite plate can also show variations depending on the properties of yarn and fabric in it.

In this study, the mechanical properties of flax and jute woven fabrics were investigated and compared with each other. Mechanical properties of the yarns and fabrics were investigated separately and compared for each scale. FTIR and TGA thermogram analyses were applied to the fabrics to characterise them. In addition, yarn and fabric structures were characterised. It is well known that the fabric structure, yarn physical properties and fibre cross-section parameters of the reinforcement have a serious effect on the composite's mechanical properties [18]. Because of that these parameters were also examined and identified. The aim of this study was the characterisation of flax and jute fabrics used as a composite reinforcement and determining of some of their limitations for use in a composite reinforcement.

*Table 2. Properties of the fibres used in this study [1].*

| Parameters | Flax | Jute |
|---|---|---|
| Fibre diameter, µm | 15 - 50 | 40 - 350 |
| Fibre Young modulus, GPa | 27 - 32 | 26.5 - 34 |
| Fibre strength, MPa | 500 - 1500 | 393 - 773 |
| Fibre ultimate elongation, % | 2.7 - 3.2 | 1.5 - 1.8 |
| Fibre density, g/cm$^3$ | 1.50 - 1.55 | 1.3 - 1.34 |

## Materials and experiments

### Materials

The properties and production parameters of jute and flax woven fabrics and fibres (Colan Products Pty Limited, Australia) used in this study are presented in ***Table 1*** and ***2***. Surface images of the fabrics are presented in ***Figure 1***. Surface and cross-sectional images of the flax and jute yarns are presented in ***Figures 2*** and ***3*** (see page 100), respectively. Surface images of the fabrics and yarns presented in ***Figure 1*** were taken with a high resolution camera, while those of yarns presented in ***Figure 2*** were obtained at a magnification of 1,6× under a Leica M 125 microscope (Leica Microsystems, Turkey). Cross-sectional images of yarns presented in ***Figure 3*** were taken using a Leica DM 2500 research microscope.

The properties of jute and flax yarns and fabrics were experimentally determined. All woven fabrics were produced under

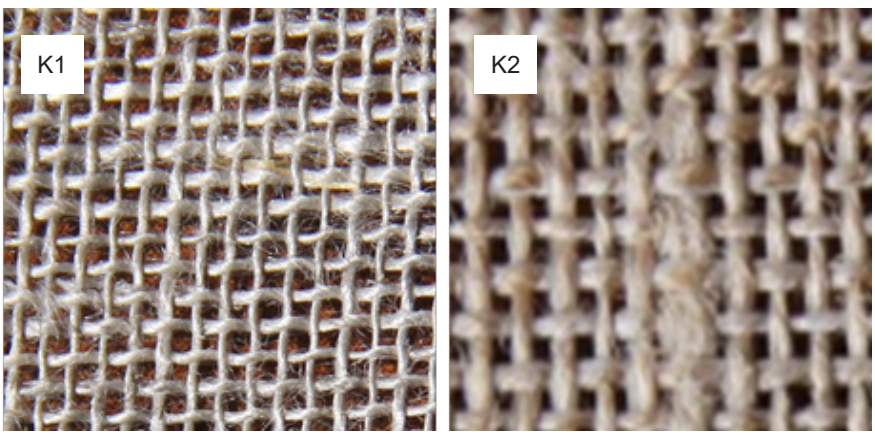


***Figure 1.*** *Surface images of reinforcement materials: flax (K1) and jute (K2) used in this study.*


***Figure 2.*** *Surface images of flax (a) and jute (b) yarns used in the fabrics.*

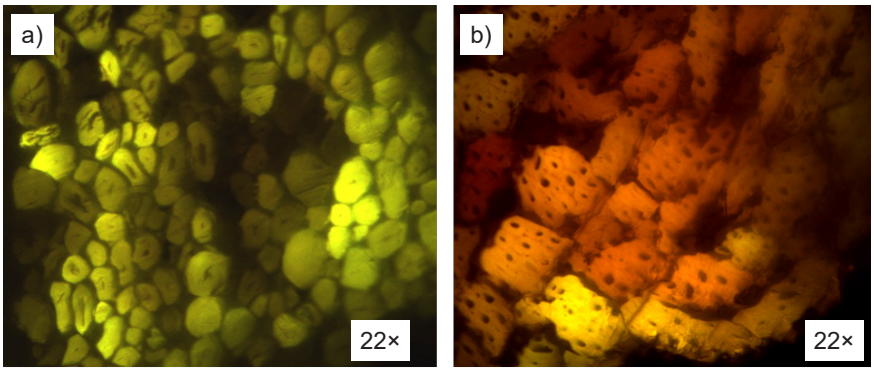


***Figure 3.*** *Cross-sectional images of flax (a) and jute (b) yarns.*

the same production conditions and with the same weaving machine (Dornier, Germany).

**Experimental method**

A Perkin Elmer, STA 600 model thermogravimetric analyser (TGA) was used for TGA analysis. The initial temperature of TGA was 50 °C, the final temperature 900 °C, the heating rate 30 °C/min, and the purge gas was nitrogen until 600 °C, afterwards changing to oxygen.

The tensile strength and strain of the fabrics were tested according to EN ISO 13934-1 using a universal tensile tester - Shimadzu Autograph AGS-X with 5000 N load cells. Four specimens were tested for each sample both at room temperature, as in the standard, and also at 75 and 150 °C. The gauge length was 100 mm and the crosshead speed 100 mm/min. The maximum load was used for tensile strength calculation. Tensile strain was measured at the maximum load.

Tensile strength and strain of the yarn were tested according to ISO 2062 using a universal tensile tester Shimadzu Autograph AGS-X with 5000 N load cells. The test specimen preparation was made as yarns were pulled out from reinforcement fabric. Five specimens were tested for each sample. The gauge length was 100 mm. The crosshead speed was 100 mm/min. The maximum load was used for tensile strength calculation. The tensile strain was measured at maximum load.

FT-IR spectra were obtained by using a Thermo scientific-Nicolet i550 FTIR model device with Smart Orbit-Diamond model ATR auxiliaries in the transmission mode. The spectra were taken at wave numbers of between 4000 – 550 $cm^{-1}$ with a resolution of 4 $cm^{-1}$. The absorption bands in the FTIR spectra were analysed by Omnic 9 software. An average of 16 scans were accumulated for each spectrum.

Study of the cross-sections of yarns was made using a Leica DM 2500 research microscope. Surfaces of the yarns were investigated under a Leica M 125 stereo microscope. Physical properties of the reinforcement fabrics were calculated according to EN 12127 (mass per unit area of fabric), ISO 7211-2 (number of threads per unit length), and ISO 7211-5 (yarn linear density).

## Results and discussion

**Fibre characterization by FT-IR analysis**

According to the FTIR spectra of K1, the weft and warp yarns of K1 fabric composed of cellulosic fibre can be determined (***Figure 4***). The cross-section and surface images of fibre imply that this fibre is pure flax fibre (***Figure 2.a, 3.a***). The broad peak at 3347 $cm^{-1}$ and the broad but less intensive peak at 1646 $cm^{-1}$ are related to OH chemical units of the cellulosic molecule structure and water molecules. The series of peaks between 2820 $cm^{-1}$ and 2850 $cm^{-1}$ belongs to the $CH_2$ groups in the cellulose molecule structure. The peak series between 1665 $cm^{-1}$ and 984 $cm^{-1}$ are related to the cellulosic group. The spectrum of weft yarn involves a peak at 1737 $cm^{-1}$, contrary to warp yarn. This peak is related to C=O, which results from damage to the cellulose molecular structure in the form of a ring opening. This type of damage does not affect the tensile strength of the fibre.

The FTIR spectra of weft and warp yarns of K2 are similar in view of the peak position and spectra shape (***Figure 5***). Both spectra include a deformed cellulose molecular structure peak group between 1100 and 1012 $cm^{-1}$, an OH group at 3344 $cm^{-1}$, $CH_2$ and $CH_3$ peak groups between 2959 $cm^{-1}$ and 2850 $cm^{-1}$, and a C=O peak at 1722 $cm^{-1}$; thus there are peaks at 1505 $cm^{-1}$ and 728 $cm^{-1}$ as well. It can be easily observed from ***Figure 2.b*** and supported with ***Figure 3.b*** that the peak at 3343 $cm^{-1}$ as well as the peak series between 1100 and 1012 $cm^{-1}$ and that between 2859 and 2850 $cm^{-1}$ come from the cellulose moleculur structure. The C-O bond gives a series of peaks between 1100 and 1012 $cm^{-1}$ which deformed the cellulose peak shape.

There are some serious differences when compared to ***Figure 4***. The peak area started at 1719 for the weft and 1722 for the warp, not visible in the case of flax (***Figure 4***). It is thought that these differ-

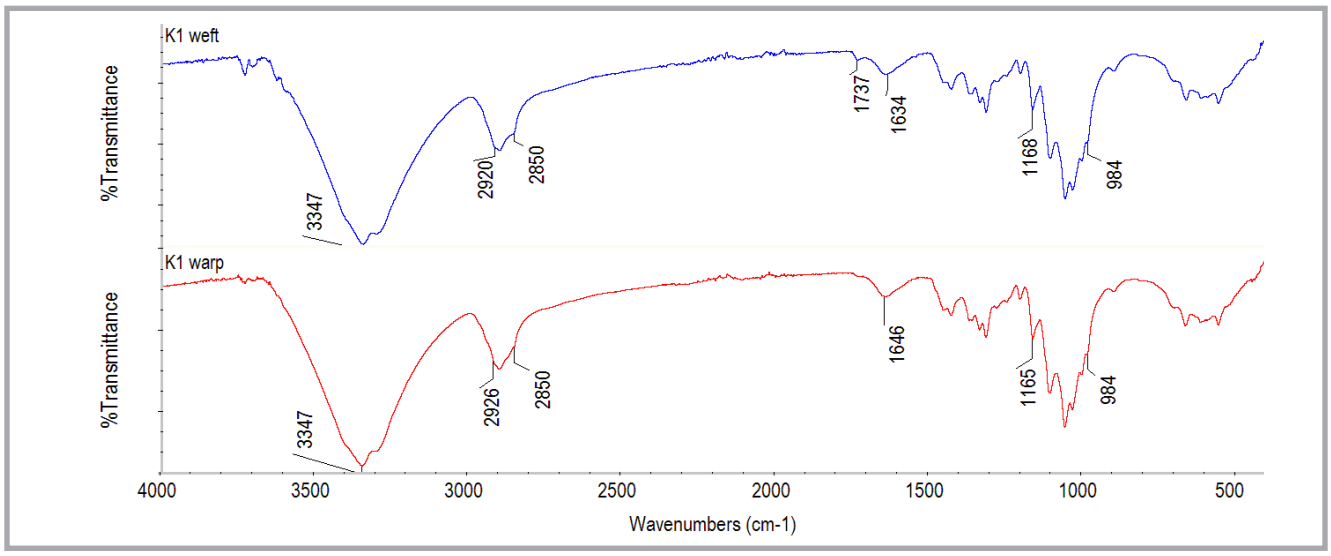


***Figure 4.*** *FTIR spectra of weft and warp of flax fabric (K1).*

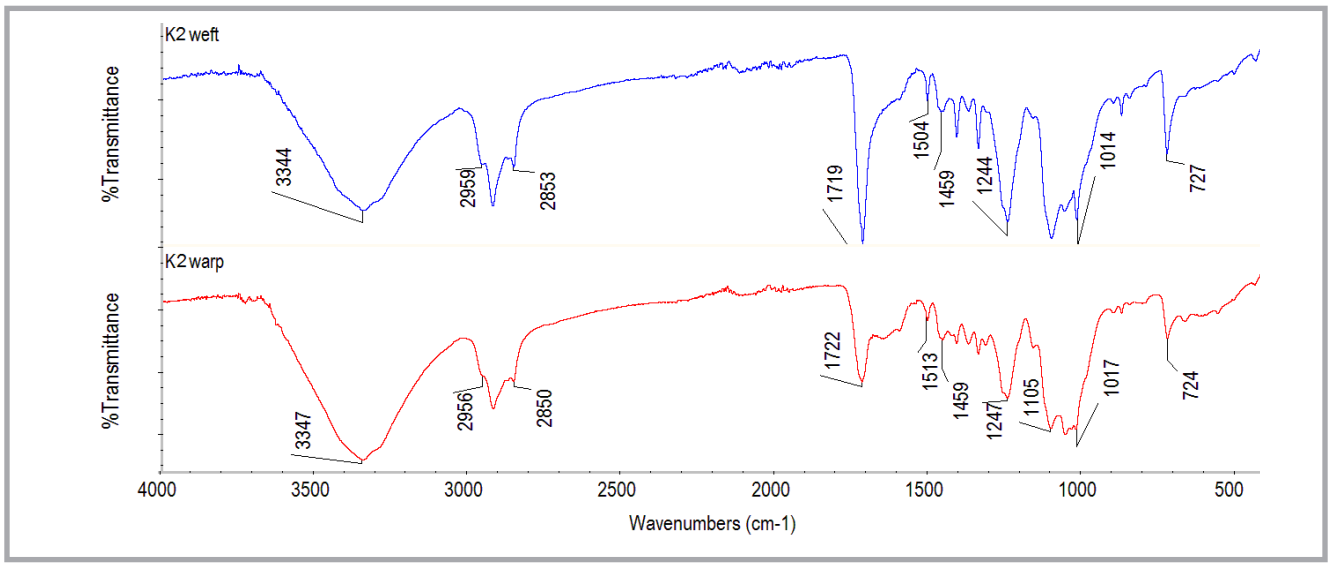


***Figure 5.*** *FTIR spectra of weft and warp of jute fabric (K2).*

ences are as a result of the higher lignin proportion of jute.

**Characterisation of fibre thermal behavior by TGA analysis**

The TGA thermogram of K1 fabric includes three thermal weight loss points (***Figure 6***, see page 102), with the first one occurring between 54 and 213 °C. This thermal event was related to the loss of the water molecule in the fibre structure. Thermal decomposition took place between 217 and 437 °C, forming a second weight loss point. The third one was related to the decomposition of carbon black under oxygen atmosphere conditions, which occurred between 567 and 727 °C. The decomposition of organic matter caused carbon black formation. The amount of loss of water was 3.6%, the amount of lost matter which formed during decomposition 74.8%, and 15.7% of matter was lost during carbon black decomposition. The residue ratio was 6%.

K2 fabric gave four weight loss points on the TGA thermogram (***Figure 7***, see page 102). The first one was related to the loss of the water molecule, which was in the jute fibre structure, occurring between 55 °C and 158 °C. The second weight loss point was related to thermal decomposition of the jute fibre. The last one was related to the decomposition of carbon black, which was caused by jute fibres under oxygen atmosphere condition, occurring between 528 °C and 709 °C. The amount of loss of water was 2.3%, the amount of lost matter which formed during decompositions - 59.7% and 16.3%, and 18.5% of matter was lost during carbon black decomposition.

The natural fibre content of composite materials could be determined using TGA analysis via the water loss parameter, which is related to the loss of the water molecule in fibre macromolecules, called the moisture regain of fibre. All natural fibres have a specific moisture regain value. The specific moisture regain of flax and Jute is 12% and 10% [19]. The matrix does not include moisture regain, and because of which all water loss in the TGA thermogram belongs to natural fibre. The result of the natural fibre content determined by this method is an approximate result for the imaging fibre content of the composite.

**Tensile properties**

An increase in temperature during composite production and curing is unavoida-

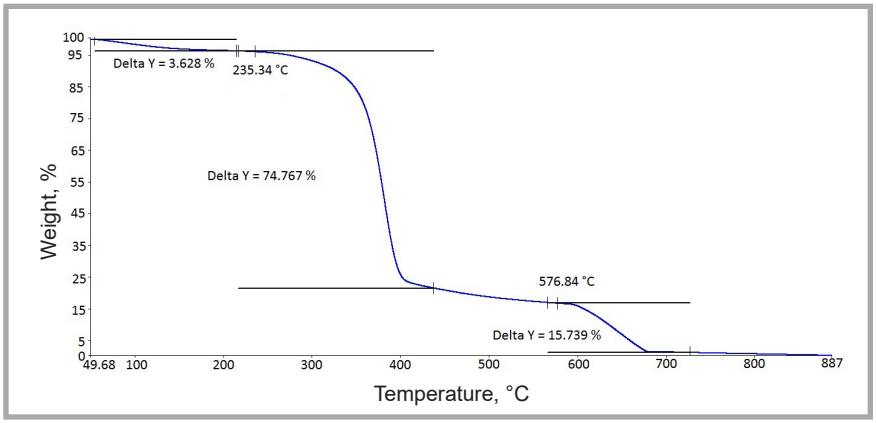


***Figure 6.*** *TGA thermogram of flax fabric (K1).*

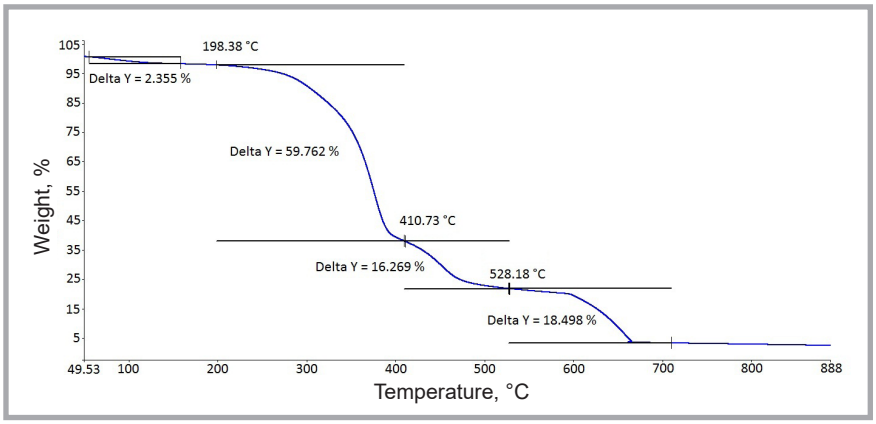


***Figure 7.*** *TGA thermogram of jute fabric (K2).*

ble. The mechanical properties of natural fibres can show serious variability due to production parameters such as temperature. Therefore tensile properties were investigated over a temperature range used in composite material production.

The tensile strength and strain of reinforcement fabrics K1 and K2 are presented in ***Table 3***. The tensile curves of fabrics in both directions are presented in the form of stress versus strain curves in ***Figure 8***. The stress-elongation curves are highly similar and clearly show how the fabric strength varies with temperature.

Whereas the tensile strength of K1 for the weft direction decreased by 13.9% and 40.7%, the tensile strength along the warp direction decreased by 21.3% and 75.3% when the temperature was increased from room temperature to 75 °C and 150 °C, respectively. Similarly whereas the tensile strength of K2 in the weft direction decreased by 14.52% and 33.57%, along the warp direction the tensile strength decreased by 29.1% and 46.28% when the temperature was increased from room temperature to 75 °C and 150 °C, respectively. These results demonstrate that both types of natural fiber were affected by the change in temperature; but flax fibers were more sensitive than jute fibers (***Figure 9***). It is assumed that the decrease in tensile strength with the increase in temperature resulted from morphological changes in the fibers. It is well known that the tensile strength of cellulosic fibers is affected by changes in temperature and moisture [20]. Changes in temperature can lead to permanent alterations in the physical and chemical properties of lignocelluloses fibers [19].

***Table 3.*** *Tensile properties of flax and jute fabrics.*

| Sample | Flax fabric | Jute fabric |
|---|---|---|
| **Sample Code** | **K1** | **K2** |
| Fabric tensile behavior at room conditions | | |
| Strength, MPa | | |
| Weft direction | 11.80 ± 0.97 | 11.02 ± 0.63 |
| Warp direction | 11.64 ± 0.70 | 15.60 ± 0.53 |
| Elongation at break, % | | |
| Weft direction | 4.50 ± 0.08 | 7.0 ± 0.36 |
| Warp direction | 8.60 ± 0,35 | 9.5 ± 0.23 |
| Fabric tensile behavior at 75 ℃ temperature | | |
| Strength, MPa | | |
| Weft direction | 10.16 ± 0.82 | 9.42 ± 0.56 |
| Warp direction | 9.16 ± 0.75 | 11.06 ± 1.47 |
| Elongation at break, % | | |
| Weft direction | 4.0 ± 0.22 | 6.70 ± 0.32 |
| Warp direction | 7.7 ± 0.29 | 9.40 ± 0.52 |
| Fabric tensile behavior at 150 ℃ temperature | | |
| Strength (MPa) | | |
| Weft direction | 7.00 ± 1.34 | 7.32 ± 0.06 |
| Warp direction | 6.64 ± 1.30 | 8.38 ± 0.74 |
| Elongation at break, % | | |
| Weft direction | 4.10 ± 0.32 | 6.8 ± 0.35 |
| Warp direction | 8.30 ± 0.87 | 8.9 ± 0.79 |

***Table 1*** shows the yarn crimp values obtained for two different fabrics. The yarn crimp values of flax and jute fabrics along the warp and weft direction were much higher compared to those obtained for carbon fabric, [18] due to the yarn construction and cross-sectional area. It is generally observed that yarn crimp in the warp direction is much higher than that in the weft. The difference in yarn crimp percentage in the warp and weft directions may have been due to high tension in one direction, causing crimp interchange in the other direction [21]. Theoretically, less crimp will result in greater fabric strength because the free inter yarn and fibres contribute to the overall force [22]. If a load is applied on a woven fabric and the yarns are straight and show no crimp, a full load will be sustained in tension at full strength. However, if the yarns are crimped or bent, then the initial load will be dissipated in straightening bent tows, leading to the formation of a low-strength material. The results obtained for the tensile strength of the fabrics presented in ***Table 3*** confirm this behaviour. Along the direction of lower crimp percentage, the tensile strength of the dry fabrics was somewhat because more of the fibres' strength was utilised.

The fibres used in this study can be sorted with respect to the tensile strength decline for flax, and jute (***Table 2***). The tensile strength of K1 weft and warp yarns are also similar to each other, and these yarns were called flax yarn. K2 weft yarn was called jute yarn.

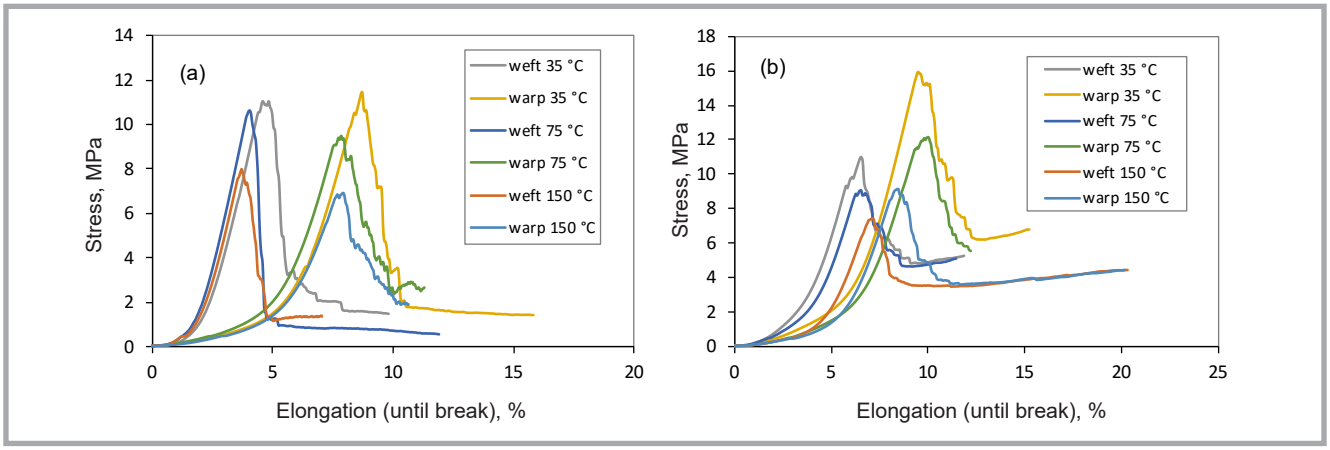


***Figure 8.*** *Stress-elongation (until break) variations at different temperatures for flax (a) and jute (b) fabrics.*

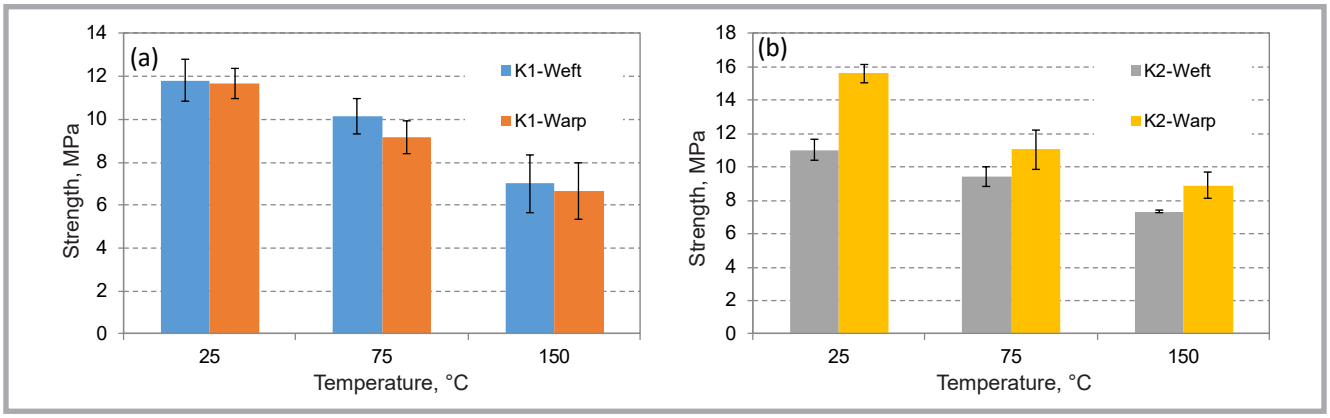


***Figure 9.*** *Variation in tensile strength as a function of the change in temperature for flax (a) and jute (b) fabrics.*

Taking into consideration this condition, this difference came from calculation of the tensile test strength according to the standard test method. Although the fibre tensile strength of flax fibre is more than jute fibre's, the tensile strength of flax yarn was less than jute yarn's. This contraction may be result from twist on the yarn. According to the many studies, the tensile strength of yarn increases with increasing twist on the yarn [20, 23]. The other reason for that contraction may arise from treatment of the fibre for good wetting with a polymer matrix via alkali treatment. It is known that alkali treatment decreases the fibre strength while increasing fibre-matrix interface bonding [2]. Damage to the cellulose macromolecule with respect to breakage of macromolecular chains, and decrease in the degree of polymerisation and of crystallinity cause a decrease in fibre strength during alkali treatment [24].

When the results at room temperature in this study are compared with previous ones [18], there was a direct relation between the reinforcement and its composite tensile strength. Tensile strength results of reinforcement fabrics and composites were obtained as quite proportional.

## Conclusions

In this study, the properties of natural fibre woven fabrics were investigated experimentally. FTIR and TGA thermogram analyses were applied to the fabrics to characterise them. The results are as follows:

The tensile strength of the natural fibre fabrics was affected by temperature changes. While flax fibre fabric lost about 75% of its tensile strength, jute fibre fabric lost about 35% of its at 150 °C temperature. This proves that the thermal stability of natural fibre is very poor, which should be definitely considered in the composite production process and during service life.

The reinforcement fabric could be characterised using FT-IR and TGA analyses both before and after being embedded in the matrix.

The tensile test result shows us that there was a direct relation between the reinforcement and its composite tensile strength.

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