Thermo-mechanical Analysis of Jute, E-glass and Carbon Fabrics

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Abstract

Textile materials are one of the most favored reinforcement materials in the composite industry. In this study, thermo-mechanical properties of six various fabrics which are woven with three different yarns (jute, E-glass and carbon) are investigated by dynamic mechanical analysis (DMA), differential scanning calorimetry (DSC) and thermogravimetric analysis (TGA) methods. According to DMA results, moduli of E-glass and carbon samples decrease with increasing temperature while it increases at jute samples. DSC graphs showed that there is not any phase change between 25°C - 200°C at any of the samples. Considering the TGA results, it is realized that while jute fabrics have two sharp weight losses at about 255°C and 340°C, carbon fabrics have a weight loss at about 530°C.

Jüt, E-cam ve Karbon Kumaşların Termo-mekanik Analizi

Öz

Tekstil malzemeleri, kompozit sektöründe en çok tercih edilen takviye malzemelerinden biridir. Bu çalışmada, üç farklı lifle dokunmuş (jüt, karbon ve E-cam) altı farklı kumaşın termo-mekanik özellikleri dinamik mekanik analiz (DMA), diferansiyel taramalı kalorimetre (DSC) ve termogravimetrik analiz (TGA) metodlarıyla incelenmiştir. DMA sonuçlarına göre E-cam ve karbon kumaşların modülleri artan sıcaklıkla birlikte azalırken, jüt kumaşların modüllerinde artış görülmüştür. DSC grafikleri ise 25°C - 200°C arasında numunelerde bir faz değişimi olmadığını göstermiştir. TGA sonuçları göz önünde bulundurulduğunda ise, jüt kumaşlarda 255°C ve 340°C civarlarında ani ağırlık kayıpları olduğu görülürken, karbon kumaşlarda 530°C civarında ağırlık kaybı olduğu tespit edilmiştir.

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1. INTRODUCTION

Composite materials are ideal materials for engineering applications, in view of their good strengths and ease of manufacturing. The first composite material which was developed by ancient Egyptians 3000 years ago, was a fibre reinforced composite (clay reinforced by straw) [1, 2]. During the last two decades, fibre reinforced composites gained more importance owing to their excellent weight-saving and load-bearing capacites [3].

In fiber reinforced composites, natural fibers and man-made fibers are used as the reinforcement material. Usage of both type of fibers have pros and cons in composite industry. Although environmental concerns put a question mark in the minds, man-made fibers (E-glass, carbon, etc.) are greatly preferred as a reinforcement material, thanks to their properties, such as excellent thermal and mechanical properties (high specific modulus, high stiffness to weight ratio and high strength to weight ratio) and durability [4]. Polymer composites that are reinforced with these man-made fibres are four times stronger and stiffer than pure polymer matrices [1]. However, these materials are extremely expensive and the fact remains that this restricts the usage areas of man-made fiber reinforced composites in some certain areas [5]. On the other hand, the properties such as, biodegrability, cheapness, accesibility, low density and high specific properties make natural fibers (banana, cotton, jute, sisal, etc.) advantageous over man-made fibers [4, 6]. Natural fiber reinforced composites have good thermal and acoustic insulating properties and they are resistant to fracture [5].

Among the natural fibers, jute fibers have received much attention because of their biodegradability and low cost. Besides, jute rei nforced composites have moderate mechanical properties compared to other natural fibers. However, the properties of jute fibers are mostly unsteady and depending on the fiber processing technique, geographic origin and fibers' hydrophilic nature, the adhesion between jute fiber and hydrophobic polymer matrix can be also very poor [2, 5, 7, 8].

Lightweight, high strength, good resistance to corrosion, low cost, excellent insulation properties and high chemical resistance are some of the properties of E-glass fibers [1, 6, 9, 10]. E-glass fiber reinforced composites have better damping characteristics than metals and also their weight properties and bulk strengths are better than metals [1, 10]. E-glass fibers can be both used with thermoplastic and thermoset matrices [6]. When compared with carbon reinforced composites, E-glass reinforced composites have lower strength but their strain-to-failure is higher owing to their low modulus [10, 11].

Carbon fiber is a favoured reinforcement material due to its properties, including high specific strength and stiffness, corrosion resistance, high modulus and thermal stability [12-15]. Lightness is one of the most important properties of carbon fibers. It is estimated that the use of carbon fiber reinforced composites as structural components of a vehicle could yield a weight reduction of 40-60% [16].

Table 1 shows the densities and mechanical properties of fabric samples.

Table 1. Densities and mechanical properties of jute, E-glass and carbon fibers [17]

Fiber	Density (g/cm^3)	Elastic Modulus (GPa)	Tensile Strengh (MPa)	Elongation at break (%)
Jute	1.45	10-32	450-550	1.1-1.5
E-glass	2.6	73	1800-2700	2.5
Carbon	1.8	260	3500-5000	1.4-1.8

It is indicated in the literature that, using woven structures instead of fibers could provide better mechanical and tribological properties in composite materials due to their orderly aligned structure and better integrity. Moreover, it will not pass over that, varying densities of fabrics will affect the mechanical properties of fabrics [1, 15].

When the applicaton areas of textile reinforced composites are investigated, it is seen that while

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jute reinforced composites have application areas such as, suitcases, helmets, shower and bath units, roof tiles, post boxes and panels for partition and false ceilings, E-glass and carbon fiber reinforced composites have application areas where higher mechanical properties are needed, such as automotive and aircraft industries, the manufacturing of spaceships, sea vehicles, space launchers and satellites [1, 2, 12, 18].

Dynamic mechanical analysis (DMA) is a test method that is used to investigate the viscoelastic property and structure of a material. Measurement is done by applying sinusoidal force and then determining the materials reaction to that force [19, 20]. It measures the modulus and damping properties of materials [20, 21]. Modulus is divided into two parts, these are; storage modulus (E´) and loss modulus (E´´). While storage modulus shows the elastic behavior of material and it is proportional to the energy stored in one cycle, loss modulus shows the viscous behavior of material and is proportional to energy dissipated in one cycle. The ratio of loss modulus to storage modulus is known as tan delta which shows the damping property of material by measuring the balance of elastic and viscous phases of material. Besides, glass transition temperature (Tg) of a material can be determined by using tan delta curve (peak point of curve is the Tg of material) [19, 21, 22].

Differential scanning calorimetry (DSC), is a thermal analysis method that measures heat flow rate as a function of time and temperature. DSC records the amount of heat needed to make the temperature difference zero between reference material and sample. This recorded heat flow gives information about materials physical and chemical transformations [23, 24].

Thermogravimetric analysis (TGA) shows the weight loss of materials with increasing temperature [25]. It can quantitatively resolve mixtures by means of each components characteristic thermal decomposition temperature [26].

When the literature is examined, it is seen that although there are many studies about investigating thermo-mechanical properties of textile reinforced composite structures, there is not any study about thermo-mechanical properties of these reinforcement materials. Besides, measuring the strength of carbon and E-glass fabrics by tensile strength testing machine is nearly unfeasible due to the slippage of these fabrics from jaws during testing. The purpose of this study is to investigate both the mechanical properties that could not obtained from tensile testing measurement and the effect of increasing temperature on the properties of jute, E-glass and carbon fabrics that are potential reinforcement materials of textile reinforced composites.

2. EXPERIMENTAL STUDY

2.1. Materials

In this study, plain weave jute (supplied by Ege İzmir Çuval, Izmir, Turkey), E-glass (supplied by Omnis Kompozit, Istanbul, Turkey) and carbon fabrics (supplied by Spinteks, Denizli, Turkey) were used. These fabrics' basis weight, thickness, warp and weft densities and yarn counts are given in Table 2.

Table 2. Fabric parameters

Fabric	Basis Weight (g/m²)	Thickness (mm)	Warp X Weft Densities (e.p.c X p.p.c.)	Warp Yarn Count (Tex)	Weft Yarn Count (Tex)
Jute_200	200	0.99 (±0.10)	4X4	375	234
Jute_300	300	0.93 (±0.05)	6X6	269	295
E-glass_200	200	0.41 (±0.01)	4X3	288	409
E_glass_300	300	0.57 (±0.02)	3X2	600	857
Carbon_200	200	0.29 (±0.005)	5X5	206	203
Carbon_300	300	0.43 (±0.008)	6X5	219	390

e.p.c : ends per cm and p.p.c:picks per cm

2.2. Methods

2.2.1. Dynamic Mechanical Analysis

Dynamic mechanical analysis was carried out by means of stress–strain oscillation measurements using a RMI DX04T dynamic mechanical analyzer. Samples that have dimension of 10mmx50mm were cut from warp and weft directions of fabric samples. For each fabric type three samples from warp direction and three samples from weft direction were cut. Tests were performed at a frequency of 1 Hz and the temperature was run from 30 to 150°C under a controlled sinusoidal strain, at a heating rate of 3 °C /min.

2.2.2. Differential Scanning Calorimetry

Differential scanning calorimetry analysis was performed by using a DSC-6 Perkin–Elmer differential scanning calorimeter. Samples of about 8 mg were taken from three different parts of the fabrics. They heated from 25°C to 200°C at a heating rate of 10°C /min and then, the samples were cooled to 25°C at a rate of 10°C /min. Samples wait 1 minute at 25°C and then heated to 200°C at a heating rate of 10°C /min and the samples were cooled to 25°C.

2.2.3. Thermogravimetric Analysis

Mettler Toledo TGA/SDTA851e Analyzer was used to conduct the thermogravimetric analysis. Samples that have weight between 6-7 mg were prepared and put into aluminium oxide crucibles. Three samples for each fabric type were taken from different parts of the fabrics. After that, closed crucibles put into heating tunnel and experiment was started. Samples were heated from 25°C to 600°C with a heating rate of 5°C/min in nitrogen atmosphere.

3. RESULTS AND DISCUSSION

Thermo-mechanical analysis results of the fabric samples are given in three sections. Analysis were repeated three times for each fabric and the median
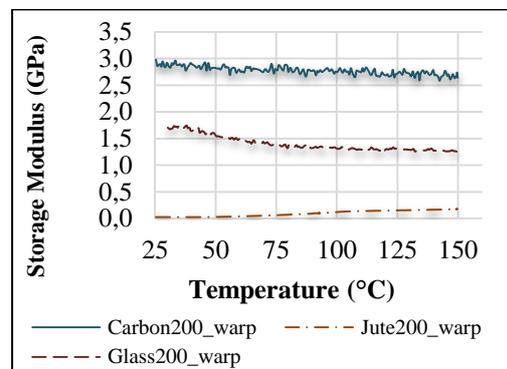
result of each analysis was chosen within three results to make comparison with other fabric types.
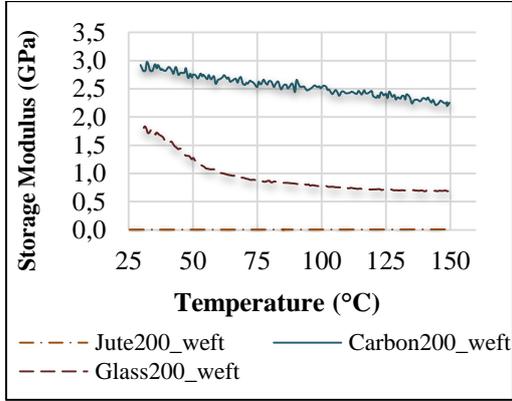
3.1. Dynamic Mechanical Analysis

3.1.1. Storage Modulus

Figure 1 shows the storage modulus comparisons of jute, carbon and E-glass fabrics. It is obviously seen from the figure that carbon fabrics have the highest storage modulus while jute fabrics have the lowest. It is seen that except Carbon_300_warp sample, storage modulus of carbon fabric and glass fabric samples are about 3 GPa and 1.7 GPa, respectively. When storage modulus of Carbon300_warp sample is considered, it is as low as 1.5 GPa. This can be due to the fact that, the unbalanced yarn count among two orthogonal yarns - warp yarn count of Carbon300 sample (219 tex) is approximately half of weft yarn count (390 tex) - can cause some yarn slippage at the jaws on the warp direction which lowers the storage modulus in this direction.
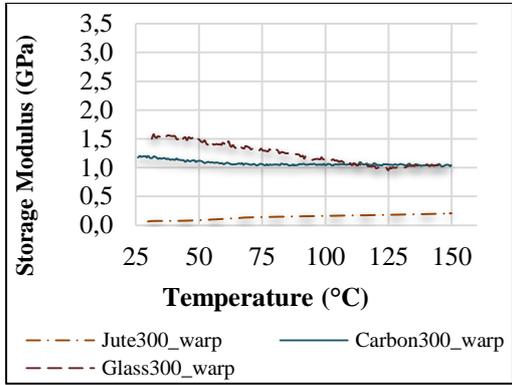
Besides, it is observed that while the storage modulus of E-glass and carbon fabrics decrease with increasing temperature, the storage modulus of jute fabric increases. This is an inherent characteristic of some natural cellulosic fibers and modulus of natural fibers decreases with water absorption [27]. To this respect, it is thought that with increasing temperature moisture content of jute fiber decreases and due to this its modulus increases.
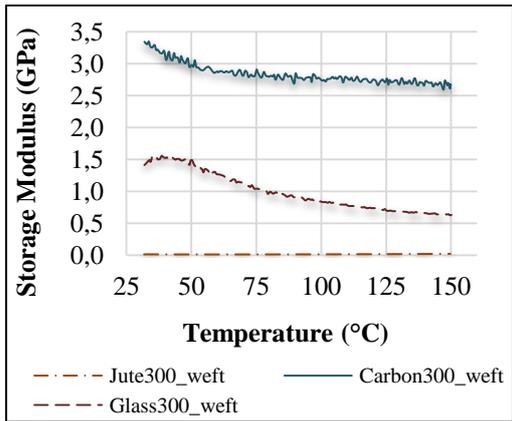

(a)

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(b)

(c)

(d)

Figure 1. Storage modulus comparisons of (a) 200 g/m^2–warp, (b) 200 g/m^2–weft, (c) 300 g/m^2–warp, (d) 300 g/m^2–weft fabric samples

Results showed that, there is a strong bond between storage modulus and fabric type. This situation also affects the storage modulus of the composite structures that are reinforced with fabric and can be proven by studies in the literature. In one of the studies, Owuor et al. (2014) measured the storage modulus of E-glass and carbon reinforced epoxy composites and they found out that storage modulus of carbon reinforced composites (20 GPa) were two times higher than storage modulus of E-glass reinforced composites (10 GPa) [28]. In another study, Ghosh et al. (1997) found out that E-glass reinforced epoxy composites (7 GPa) had higher storage modulus values than jute reinforced composites (4 GPa) [29]. Niedermann et al. (2015) determined the dynamic mechanical properties of jute and carbon reinforced epoxy composites. From the results, it was indicated that carbon reinforced samples had four times higher storage modulus value than the jute reinforced samples.

3.1.2. Loss Modulus

Figure 2 shows the loss modulus comparisons of jute, carbon and E-glass fabrics. When E-glass fabrics are examined, it is seen that at both 200 and 300 g/m^2 samples, loss modulus of warp and weft directions are similar to each other. However, when carbon fabrics are taken into consideration it is observed that, while loss modulus of Carbon200_warp and Carbon200_weft samples are so close to each other, loss modulus of Carbon300_warp sample is lower than Carbon300_weft samples'. This result can be in connection with the yarn counts of warp (219 tex) and weft yarns (390 tex). When warp samples are examined, it is seen that E-glass and carbon fabrics have similar loss modulus values. However, carbon fabrics have higher loss modulus values at weft direction. Similar to storage modulus results, the loss modulus of jute fabric samples increase with ascending temperature. It is thought that, this fact is also related to the descending moisture content of jute.
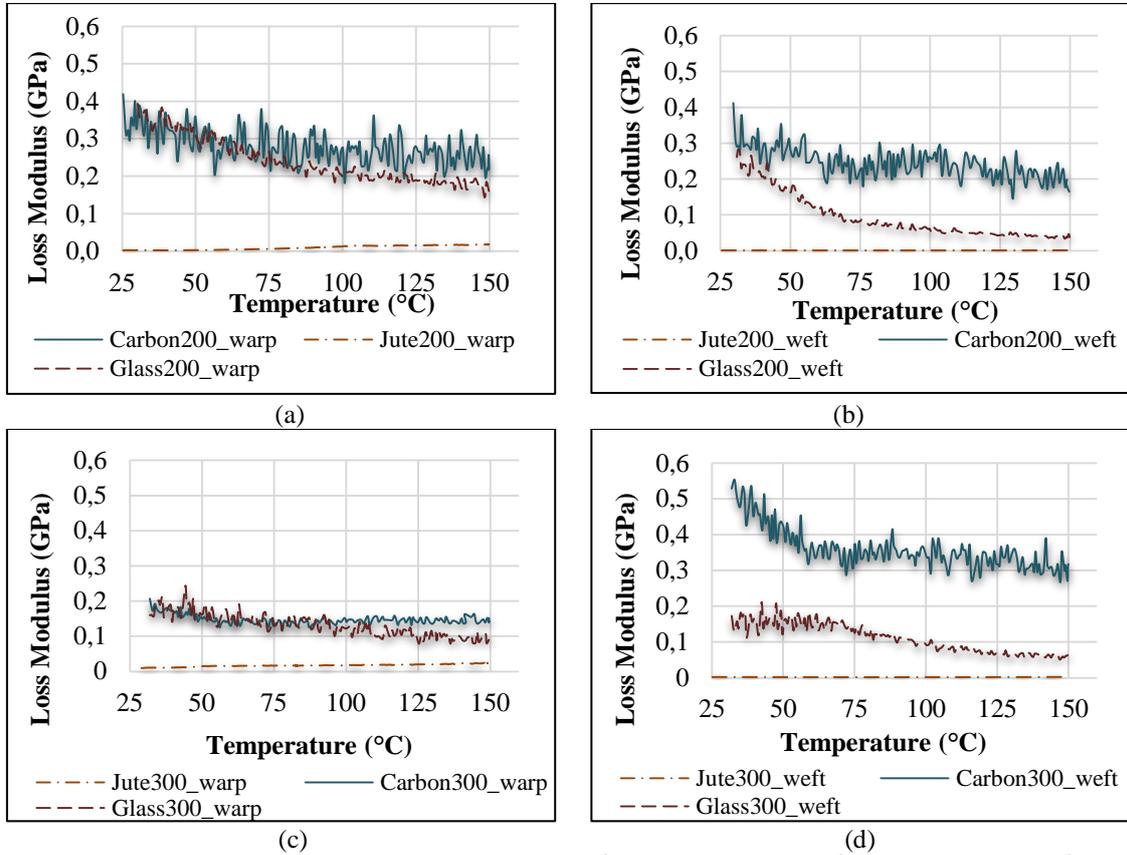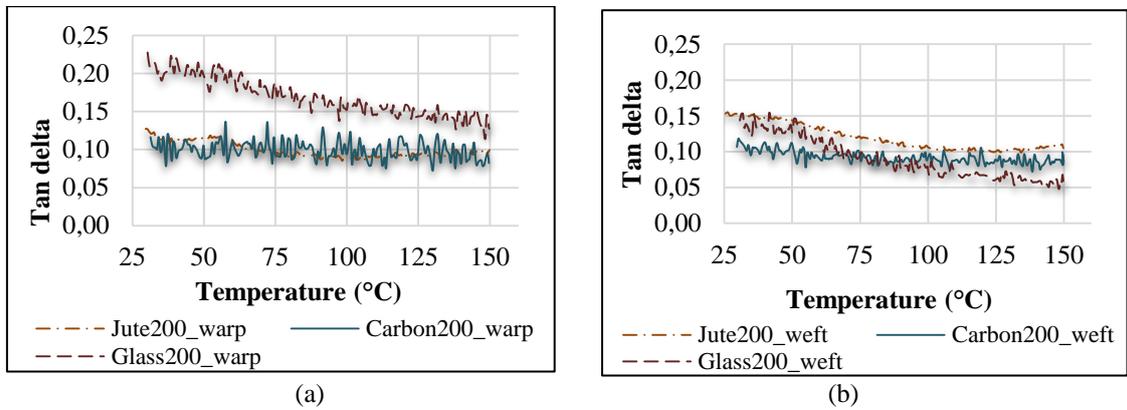
Figure 2. Loss modulus comparison of (a) 200 g/m²–warp, (b) 200 g/m²–weft, (c) 300 g/m²–warp, (d) 300 g/m²–weft fabric samples

It is revealed from the results that, jute fabrics have so lower loss modulus values than other fabric types. Like storage modulus, loss modulus of composites are also affected from the properties of the reinforcement material. Ghosh et al.'s (1997) results showed that loss modulus of jute reinforced epoxy composites were one fourth of the loss modulus of E-glass reinforced composites [29].
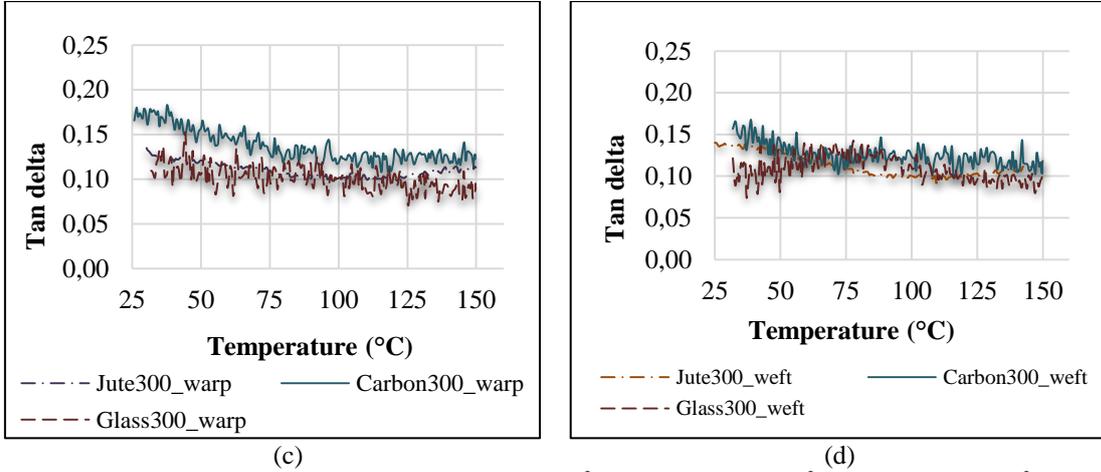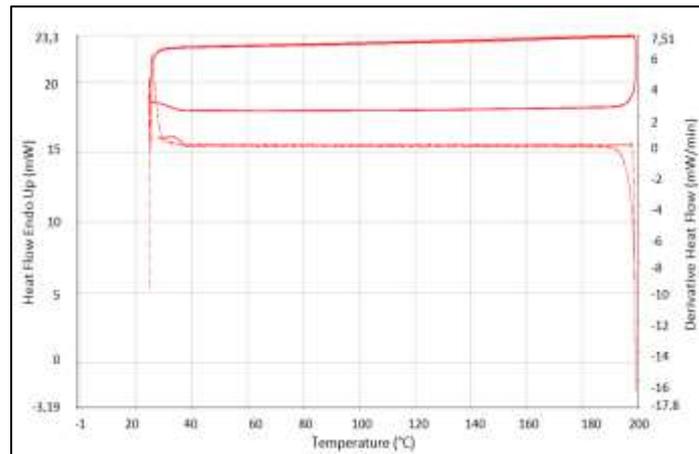
(c)   (d)

Figure 3. Tangent delta comparisons of (a) 200 g/m^2–warp, (b) 200 g/m^2–weft, (c) 300 g/m^2–warp, (d) 300 g/m^2–weft fabric samples
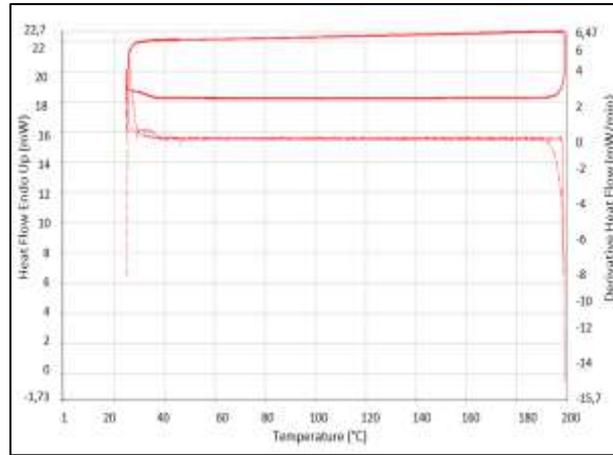
3.1.3. Tangent Delta

Tangent delta comparisons of fabrics samples are given in Figure 3. Tangent delta is the ratio of loss modulus to storage modulus. Fabrics show different characteristics at each graph. When 200 g/m^2 samples are investigated, it is observed that while glass fabric has the highest tan delta value at warp direction, jute fabric has the lowest at weft direction. As for 300 g/m^2 samples, carbon fabrics have higher tan delta value than other samples.

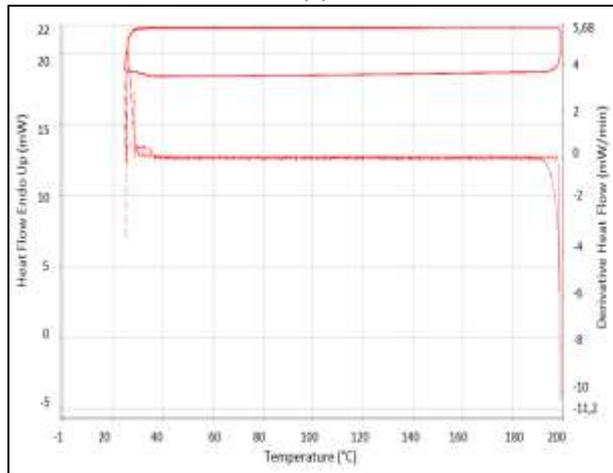### 3.2. Differential Scanning Calorimetry

Figure 4 shows the DSC graphs of fabric samples. As it is seen from the figure, E-glass and carbon fabrics do not show any endothermic or exothermic reaction during both two heating and cooling cycles. Jute fabrics show endothermic reactions at the first cycle of heating at about 80°C, but when the second cycle examined, it is observed that jute fabrics do not demonstrate any endothermic or exothermic reaction. This endothermic reaction can be due to the impurities that are located within the jute fiber.
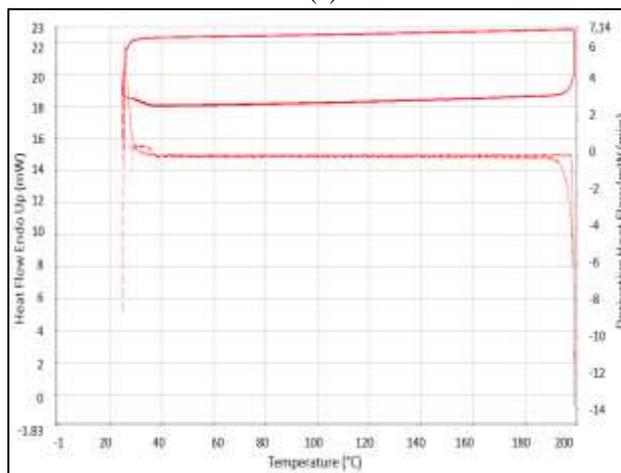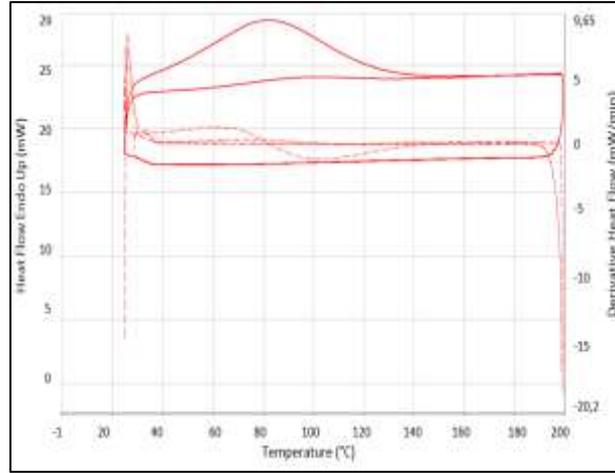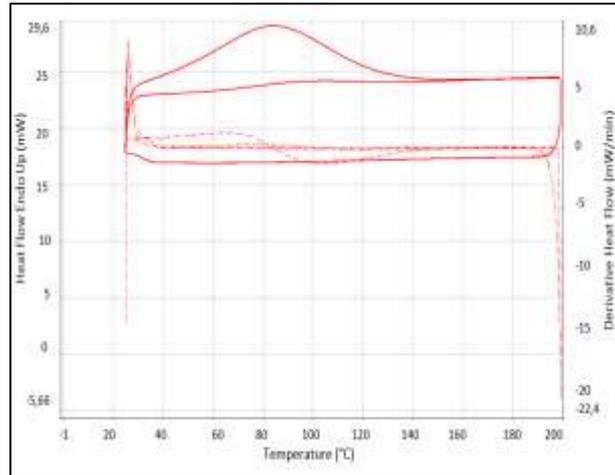

(a)

(b)

(c)

(d)

(e)

(f)

Figure 4. DSC graphs of (a) Carbon_200, (b) Carbon_300, (c) E-Glass_200, (d) E-Glass_300, (e) Jute_200, (f) Jute_300 fabric samples

3.3. Thermogravimetric Analysis

Figure 5 shows the TGA graph of one of the fabric samples (Carbon-200g/m^2) that is drawn by Mettler Toledo Software Program. Graph shows the weight change of sample with increasing temperature. Onset temperature that is marked in the figure, is the temperature that sharp decrease of sample weight is started.

Initial and final temperatures, weight loss and onset temperatures of fabric samples are given in Table 3. It is observed that carbon fabrics have

weight loss of about 5-11% and their onset temperature are about 530°C while weight difference of E-glass fabric is about 1%. Due to the fact that E-glass fabrics has nearly no weight loss, they don't have onset temperature. On the other hand, jute fabric samples have weight loss of about 96% and they have two onset temperatures 255°C and 340°C. This can be due to the fact that jute fiber contains 15.86 % lignin, 23.2 % hemi-cellulose and 62.6 % cellulose and they are started to degrade at a temperature of 200°C, 180°C and 315°C, respectively [31-34].
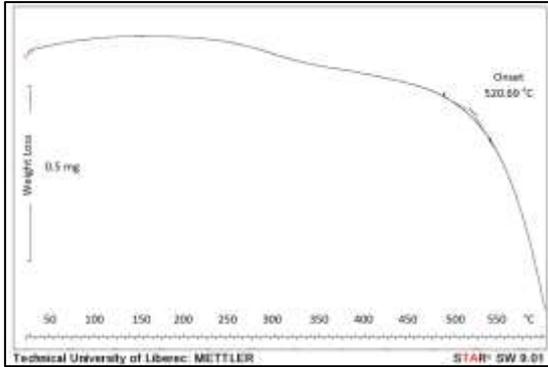
Figure 5. TGA graph of carbon (200g/m^2) fabric sample

Table 3. Weight loss and onset temperature of fabric samples

Sample	Initial Weight (g)	Final Weight (g)	Weight loss (%)	Onset Temperature (°C)
Carbon_200	6.56	5.84	11	520.69
Carbon_300	6.18	5.88	5	549.86
E-Glass_200	6.28	6.24	0.6	-
E-Glass_300	6.80	6.72	1.2	-
Jute_200	6.35	0.20	97	255.40 / 344.56
Jute_300	6.80	0.30	96	255.67 / 341.05

4. CONCLUSION

Fabrics, which are the one of the main components of fabric reinforced composites, have a very significant influence on the properties of composite structures. In this study, thermo-mechanical properties of jute, E-glass and carbon plain woven fabrics are examined by DMA, DSC and TGA methods. From DMA graphs it is achieved that, distinct from other materials, both storage and loss moduli of jute fabrics which are related to the stiffness of material decrease with increasing temperature due to the descending moisture content of jute fiber. Besides, it is observed from tan delta graphs that, among 300 g/m^2 samples carbon fabrics have higher tan delta value which shows the damping property of the material. It is also obtained that the material type of the fabric is the most important factor which affects the moduli of the fabric and accordingly the moduli of the composite structures.

DSC results show that samples do not show any endothermic or exothermic reaction between 25°C - 200°C. When TGA results are analyzed, it is observed that jute fabrics have a huge weight loss at about 255°C and 340°C due to the degradation of lignin, hemi-cellulose and cellulose that jute fiber contains. Moreover, it is come out that among these three fibers, glass fiber is most resistant to heat.

It is realized that fabric parameters highly affect the thermo-mechanical properties of fabrics. Especially in the composite industry, fabric reinforcement properties is not known very well in the sector, on the other hand the structure of the reinforcement should be very well identified in order to reach to the preferred composite structure in practice. As a consequence, the thermo-mechanical properties of these fabrics, which are mostly preferred reinforcement materials, will be instructive for the following studies related to textile reinforced composite materials.

5. ACKNOWLEDGMENTS

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