Mühendis ve Makina
cilt 62, sayı 705, s. 845-859, 2021
Araştırma Makalesi

Engineer and Machinery
vol. 62, no. 705, p. 845-859, 2021
Research Article

DOI: 10.46399/muhendismakina.1034138

Effect of Humidity and Temperature on Composite Plates With Different Fiber Orientations

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ABSTRACT

In this study, the effect of humidity and temperature on glass fiber reinforced epoxy composite plates with different fiber reinforcement angles and different widths were experimentally investigated. For this purpose, composite plates with fiber reinforcement angles of $[0°]_8$ and $[45°/-45°/0°/90°]_s$ were prepared in 25 mm and 30 mm dimensions and kept in hot water at 40 °C, 60 °C and 80 °C for 15, 30 and 45 days. At the end of the duration, the moisture absorption rates and strengths of the specimens were obtained. The obtained data were compared among themselves and with that of dry specimens. In addition, the morphologies of the specimens were visualized with the help of Scanning Electron Microscope (SEM) and the effects of humidity and temperature on failure behavior were examined. It was determined that the strength of the $[45°/-45°/0°/90°]_s$ fiber orientations specimens was lower than the strength values obtained from the $[0°]_8$ fiber orientations specimens. It has been determined that when the waiting time and temperature increase, the matrix/fiber structure of the specimens deteriorates and the strength values decrease accordingly.

Keywords: Moisture effect, temperature effect, failure load, composite plate, SEM

Farklı Fiber Dizilimlerine Sahip Kompozit Levhalar Üzerinde Nem ve Sıcaklık Etkisi

ÖZ

Bu çalışmada, farklı fiber takviye açılarına ve farklı genişliklere sahip cam fiber takviyeli epoksi kompozit levhalar üzerinde nem ve sıcaklık etkisi deneysel olarak araştırılmıştır. Bu amaçla, fiber takviye açıları $[0°]_8$ ve $[45°/-45°/0°/90°]_s$ olan kompozit levhalar, 25 mm ve 30 mm ölçülerinde hazırlanarak 40 °C, 60 °C ve 80 °C sıcak suyun içerisine, 15 gün, 30 gün ve 45 gün süre ile bekletilmiştir. Süre bitiminde numunelerin nem emilim oranları ve dayanımları elde edilmiştir. Elde edilen verilerin kendi aralarında ve kuru numuneler ile karşılaştırılması yapılmıştır. Ayrıca Taramalı Elektronik Mikroskop (SEM) yardımıyla numunelerin morfolojileri görüntülenerek, nem ve sıcaklığın hasar davranışları üzerindeki etkileri incelenmiştir. $[45°/-45°/0°/90°]_s$ fiber dizilimli numunelerin dayanımının, $[0°]_8$ fiber dizilimli numunelerden elde edilen dayanım değerlerinden daha düşük olduğu tespit edilmiştir. Bekleme süresi ve sıcaklık derecesi arttığı zaman numunelerin matris/fiber yapısında bozulmaların meydana geldiği, buna bağlı olarak da dayanım değerlerinin düştüğü tespit edilmiştir.

Anahtar Kelimeler: Nem etkisi, sıcaklık etkisi, hasar yükü, kompozit levha, SEM

[*] Iletişim Yazarı
Geliş/Received : 07.07.2021
Kabul/Accepted : 08.09.2021

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1. INTRODUCTION

Factors such as composite materials' suitable design flexibility, geometries, load carrying capacity, low cost, lightness, etc. place them in an advantageous position, hence, many application areas for composite materials are available in various sectors such as automotive, aviation, maritime and industry. On the other hand, environmental effects have a significant impact on composite materials. However, the results of these effects are not always clear and in order to clarify the results, researches are carried out continuously in the abovementioned area. For this reason, it is significant for engineering purposes to analyze the effects of humidity and temperature well and to make appropriate designs accordingly.

Many studies have been conducted in the literature [1-26, 28, 29] on the effect of humidity and temperature on composites. Mouzakis et al. [1] investigated the damage behavior of glass fiber/polyester composite materials exposed to different environmental conditions. They stated that the tensile strength of the specimens decreased as the parameters such as temperature, humidity, thermal aging, and waiting time increased. Leveque et al. [2] investigated the effects of thermal aging on polymer matrix composites. In the study, it was stated by the researchers that when carbon epoxy composites with different reinforcement angles were exposed to thermal aging under the effect of 120 °C constant temperature for the durations in between 720 and 4400 hours, mechanical properties of the composites changed. Tsotsis et al. [3] investigated the mechanical behavior of carbon/epoxy composite plates at 121 °C at different pressures (0.101, 0.345, 1.03, and 1.72 MPa) for 5000 hours. They determined that these processes affect mechanical behavior. Alcock et al. [4] investigated the change of mechanical performance of polypropylene tapes exposed to temperatures between -50 and 120 °C. They determined that increasing temperatures have a negative effect on the tensile strength. Dlouhy et al. [5] investigated the effects of thermal aging on fracture toughness and mechanical properties of glass matrix composite sheets reinforced with short carbon fibers. They determined that the thermal aging process reduces the tensile strength. Hu and Sun [6] investigated the creep behavior of carbon/epoxy composite plates thermally aged for certain durations of time. Belaid et al. [7] investigated the effects of thermal aging on the mechanical behavior of glass fiber/polyester composite plates. The specimens, which were kept at a constant temperature of 80 °C for 30, 60, 90, and 120 days, were subjected to the tensile test. They determined that an increase in the duration decreased the tensile strength. Sauder et al. [8] investigated the mechanical properties of various carbon fibers up to 2400 °C. In the study, they stated that Young's modulus decreased and the tensile strength increased as the temperature increases. Nikolaev et al. [9] investigated the effect of temperature in cycles ranging from 120 °C to 196 °C on specimens produced from CFRP. In particular, they obtained results on strength, linear expansion coefficient, and hardness on specimens produced with different winding angles. Eric et al. [10]; investigated the changes in the mechanical properties of the porous-Matrix Ceramic composites kept at 1000 °C, 1100 °C, 1200 °C for 1000 hours. In their study, they stated that the elasticity modulus of the [0°/90°] orientation composite slightly increased after a heat treatment at 1200 °C is being applied. Plecnik [11] investigated the strength of epoxy resin by performing compression, tensile, and shear tests at elevated temperatures. In the tests, he stated that the strength decreases at temperatures close to the glass transition temperature, and reaches a constant value when the glass transition temperature is exceeded. Parker [12]; investigated the strength of CFRP-CFRP joints bonded with epoxy adhesives and the effect of hot and humid environments on failure types. He stated that the strength of the joints decreased with increasing both the moisture absorption and the test temperature. Park et al. [13] investigated the effect of environmental conditions on the strength of single-acting lap joint carbon epoxy composites. They stated that high temperature and humidity increase the strength of the layer, yet decrease the adhesive shear strength. Soykok [14] investigated the behavior of single-lap glass fiber reinforced epoxy composites, obtained with the help of adhesive, in water at certain temperature ranges. He stated that water absorption reduces strength. Assarar et al. [15] studied the effect of water on the mechanical properties of flax and glass fiber reinforced composites. They stated that the tensile modulus of flax fiber composites was affected slightly as the immersion time increased, while the tensile strength of glass fiber reinforced composites decreased. Mariam et al. [16] investigated the effects of glass fiber reinforced epoxy composites, obtained as a single-lap through bonding, by keeping them in 50 °C hot water for 20, 40, 60, 80, 100, and 120 days. They stated that as the waiting time in hot water increases, their strength decreases. Budhe et al. [17] presented a study discussing the influence of many parameters in composite bonds. They stated the failure effect on the connections, especially when humidity and temperature applied together. Li et al. [18] demonstrated that the fiber structure of the unidirectional linen woven epoxy composite is disrupted by water absorption. Sang et al. [19] experimentally and analytically investigated the effects of hydrothermal aging on the mechanical strength of short carbon fiber reinforced polyamide 6 composites at 20 °C, 40 °C, and 60 °C. They stated that the tensile stress and elastic modulus decrease linearly as the temperature increases. Abdesselam et al. [20] investigated the effect of hydrothermal aging on glass fiber reinforced polyester composite morphology. SEM analyzes were conducted and observations were made in the microstructure. Zhang et al. [21] investigated the effect of hydrothermal conditions on composite structures using experimental and progressive failure analysis. They stated that hydrothermal environments did not affect the tensile properties of the composite plates at all, but significantly reduced their compression behavior. Dhakal et al. [22] experimentally investigated the effects of water absorption on mechanical properties of hemp fiber reinforced unsaturated polyester composites. They stated that the tensile and bending properties of the specimens decreased with the increase of moisture uptake percentage. Scida et al. [23] investigated the hydrothermal effect of semi-unidirectional flax fiber reinforced epoxy (FFRE) composite on the mechanical properties and failure behavior. They stated that there were decreases in Young's modulus and tensile strength and were affected by the hydrothermal environment. Beura et al. [24] kept glass fiber reinforced epoxy composite specimens in distilled water and seawater. They stated that hydrothermal aging causes degradation in the material and a longer aging process causes further deterioration of the composite structure. Wang et al. [25] investigated the effects of hydrothermal conditions on the bending behavior of 3D-printed composites reinforced with continuous glass fibers. They stated that glass and matrix fractures occur in composite specimens with high glass density due to the hydrothermal effect. Mansouri et al. [26] investigated the effect of hydrothermal aging on the mechanical behavior of short fiber/woven composite laminates. In addition to the effect of temperature, water absorption was also reported to be effective in the degradation of composites.

The combined effect of humidity and temperature in composite plates and consequences of the combined effect create an important area of research. For this purpose, the combined effect of humidity and temperature on composite plates with two different reinforcement angles and two different widths was investigated. This effect has been investigated especially under close consecutive times and temperatures. Pursuing this further, failure loads and moisture absorption rates were obtained from the specimens kept at 40 °C, 60 °C, 80 °C for 15, 30 and 45 days. The data obtained at the end of the waiting period were compared among themselves and with that of the dry specimen results. In addition, the combined effect on the specimens was examined and compared thanks to the SEM images. These results are important in terms of creating a database for designs to be made in these intervals.

2. EXPERIMENTAL STUDY

2.1 Specimen Preparation and Experimental Stages

In this study, glass fiber epoxy composite plates with fiber orientations of $[0°]_8$ and $[45°/-45°/0°/90°]_S$ were produced by İzoreel Composite Insulation Materials Industry

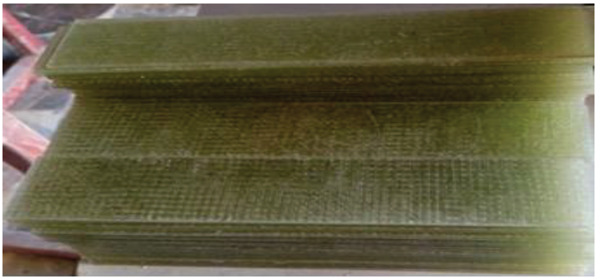


Figure 1. Specimen Preparation

and Trade Ltd. Co. Composite plates are produced with a thickness of 2 mm (t). The length (L) of the composite plates with both fiber orientations was taken as 175 mm and their widths were prepared as (w) 30 mm and (w) 25 mm (Figure 1). Three specimens were prepared from each geometry.

In addition, specimens were formed by gluing additional pieces of the same material using adhesive to prevent the formation of stress concentrations in the compression regions during in the tensile test. Composite specimens with both geometric dimensions and fiber orientations were placed in closed boilers filled with hot water in which thermostats adjusted to 40 °C, 60 °C, and 80 °C. Additional hangers were made for the placement of the specimens in the boilers (Figure 2). They were kept at each temperature for 15, 30, and 45 days.

Figure 2. Placing Specimens in a Thermostated Hot Water Boiler

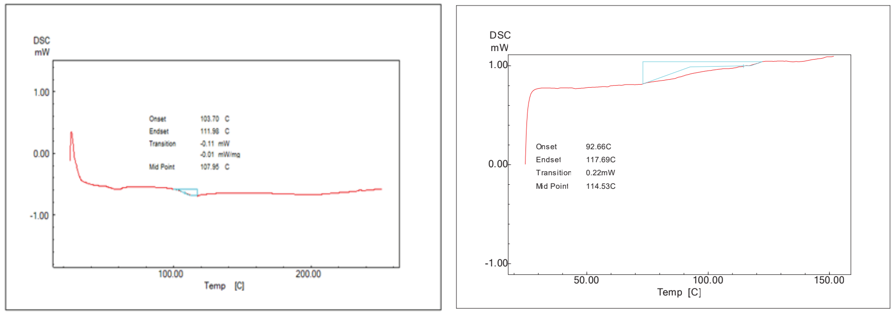
At the end of the test period, the excess water on the specimens removed from the water was wiped and their weights were measured with a precision balance with a capacity of 0.01 g. Moisture absorption rates of each specimen were calculated by comparing the measured weights with their weights before being placed in hot water. For the moisture absorption rate (M_t) of each specimen, the formulation we used is given below, and the initial weights of the specimens (w_o) are the measured weights after removal from the water (w_s) [27].

$$M_t = [(w_s - w_o) / w_o] \times 100 \tag{27}$$

The weighted specimens were then subjected to the tensile test. Tensile test was carried out thanks to Instron brand's 10 kN test device, and 1 mm/min tensile speed was realized.

2.2 Detection of Glass Transition Temperature

The composites used in the study are epoxy-containing materials. The mechanical



(a) (b)

Figure 3. T_g plots of a) $[0°]_8$ Orientations [28, 29], b) $[45°/-45°/0°/90°]_s$ Orientations Glass Fiber Epoxy Composite Materials

properties of these materials may vary at different temperatures, -especially below or above the glass transition temperature. Therefore, the glass transition temperatures (T_g) of the plates in both fiber orientations were determined by Differential Scanning Calorimetry (DSC) analysis in order to better understand the effects of humidity and temperature. This analysis was carried out with Schimadzu DSC-60 type device by increasing the temperature by 10 °C per minute. As a result of DSC analysis, T_g of glass fiber reinforced epoxy composite materials with $[0°]_8$ and $[45°/-45°/0°/90°]_s$ fiber reinforcements were 107.95 °C, 114.53 °C respectively (Figure 3).

3. RESULTS AND DISCUSSION

3.1 Water Absorption

Since, three pieces of each specimen were produced, the average value was taken and the moisture absorption rates of the specimens were transferred to Table 1.

The greater the infiltration of water into the resin matrix, the greater the susceptibility to moisture absorption at higher temperatures [17]. In this study, the highest moisture absorption occurred in the specimens with the $[45º/-45º/0º/90º]_s$ orientation at 80 ºC (Table 1). The moisture absorption rate of the specimens with a 30 mm width $[45º/-45º/0º/90º]_s$ orientation kept at 80 ºC for 45 days; it was determined that the rate obtained from the specimen with the $[0º]_8$ orientation was 158.5% higher than the that of specimen which has the same width and was kept at the same waiting time and the same temperature.

When the specimen with 25 mm width and $[45º/-45º/0º/90º]_s$ orientation is kept at 80 ºC for 45 days, the moisture content obtained was calculated to be 73.89% higher than the that of $[0º]_8$ orientation specimen stored under the same conditions.

Table 1. Moisture Absorption Rates (%) of Specimens According to Fiber Orientations

Waiting time		w:30 mm		w:25 mm	
		$[0^o]_8$	$[45^o/-45^o/0^o/90^o]_s$	$[0^o]_8$	$[45^o/-45^o/0^o/90^o]_s$
40 °C	15 days	0.36	1.42	0.73	1.58
	30 days	0.72	1.78	1.01	1.97
	45 days	0.91	2.08	1.11	2.10
60 °C	15 days	0.40	1.03	0.78	1.09
	30 days	0.63	1.36	1.23	1.84
	45 days	0.79	1.41	1.28	2.07
80 °C	15 days	1.23	3.15	1.92	3.07
	30 days	1.25	3.69	2.01	3.26
	45 days	1.47	3.80	2.03	3.53

It was determined that the moisture absorption rates increased when the previous temperature and waiting time were taken into account (Table 1).

3.2 Effect of Failure Loads

The values obtained as a result of the tensile test of glass fiber reinforced composite specimens and the standard deviation rates of these values are given in Table 2. Load-displacement plots obtained according to fiber orientations and specimen width are given in Figure 4 over the maximum waiting time (45 days). At the same time, the waiting times of composite specimens in hot water - with regard to their fiber orientations - and the load values obtained at the end of these periods are given in Figure 5 and Figure 6 comparatively.

The failure load value obtained from the specimens (30 mm) with $[0^o]_8$ and [45°/-

Table 2. Failure Load Values Obtained Depending on Temperature and Waiting Times

	Environmental conditions	Dry	40 °C			60 °C			80 °C		
	Waiting time	0	15 days	30 days	45 days	15 days	30 days	45 days	15 days	30 days	45 days
w=30 mm	$[0^o]_8$ (N)	29816.25	27337	26276	26214.5	26068.8	25850.1	25120.5	24541	23477.5	22506.5
	Std.Dev. (%)	3.17	5.11	5.36	3.04	4.07	6.09	4.51	5.66	4.88	4.56
	$[45^o/-45^o/0^o/90^o]_s$ (N)	12201	11437	10145.2	9891.45	10901.7	10084.8	9366.08	6759.82	6187.06	6044.7
	Std.Dev. (%)	5.45	4.03	3.02	5.15	4.16	5.72	5.8	5.64	4.19	5.26
w=25 mm	$[0^o]_8$ (N)	20041	19354	16282.9	15980.1	16444.1	14307.2	13881.3	11471.3	11019.2	10697.1
	Std.Dev. (%)	2.52	4.2	4.6	4.23	5.26	5.96	4.35	5.45	5.21	5.03
	$[45^o/-45^o/0^o/90^o]_s$ (N)	10244.2	9388	9019.46	8739.3	9187.38	8983	8647	6075.93	5468.7	5355.25
	Std.Dev. (%)	4.63	5.12	3.72	4.65	5.2	3.81	5.64	4.27	3.65	4.81

45º/0º/90º]$_s$ orientations are kept at 80 ºC for 45 days is found to be lower respectively by 14.14% and 38.38% compared to the failure loads values obtained from the specimens kept at 40 ºC for 45 days (Table 2, Figure 5). Similarly, for the specimens with [0º]$_8$ and [45º/-45º/0º/90º]$_s$ orientations (30 mm); It was determined that the failure load values obtained when kept at 60 ºC for 45 days decreased by 15.74% and 17.37%, respectively, compared to the failure load values obtained from the dry specimens (Table 2, Figure 5).

The failure load values obtained when the 25 mm wide specimens with the [0º]$_8$ and [45º/-45º/0º/90º]$_s$ fiber orientations are kept at 80 ºC for 45 days is found to be decreased respectively by 33.06% and 38.72% compared to that of specimens that were kept at 40 ºC for 45 days. (Table 2, Figure 6). For the specimens with [0º]$_8$ and [45º/-45º/0º/90º]$_s$ orientations and 25 mm width; It was determined that the failure load values obtained when kept at 60 ºC for 45 days decreased by 30.73% and 15.59%, respectively, compared to the failure load values obtained from the dry specimens. (Table 2, Figure 6).

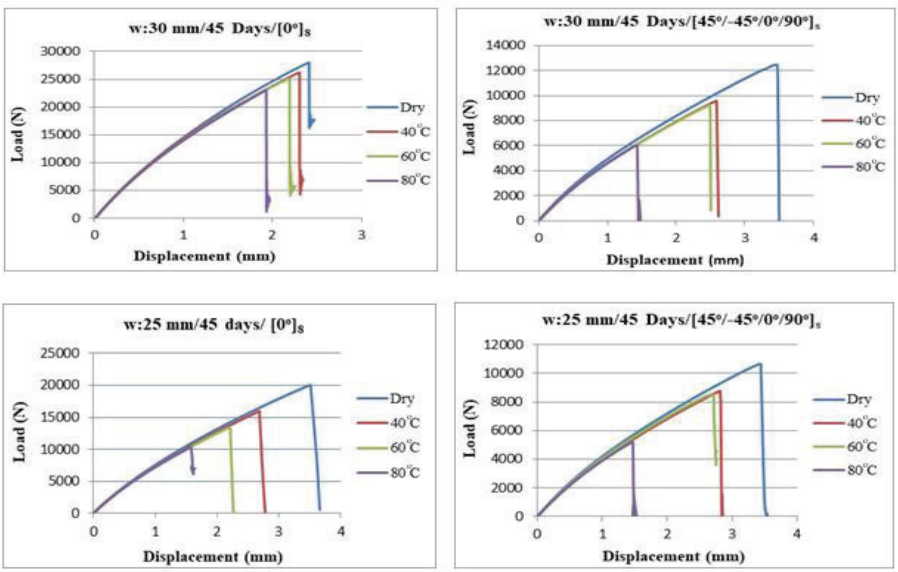


Figure 4. Load/displacement Plots of Specimens According to Fiber Orientations

The amount of free water absorbed increases due to immersion parameters (temperature, time). Indeed, temperature contributes significantly to the excitation of water molecules, hence, allows them to acquire an increasingly significant kinetic energy. This also allows the water to disperse into the specimen more easily and quickly [20]. Considering the water absorption, it is seen that with the increase of water uptake,

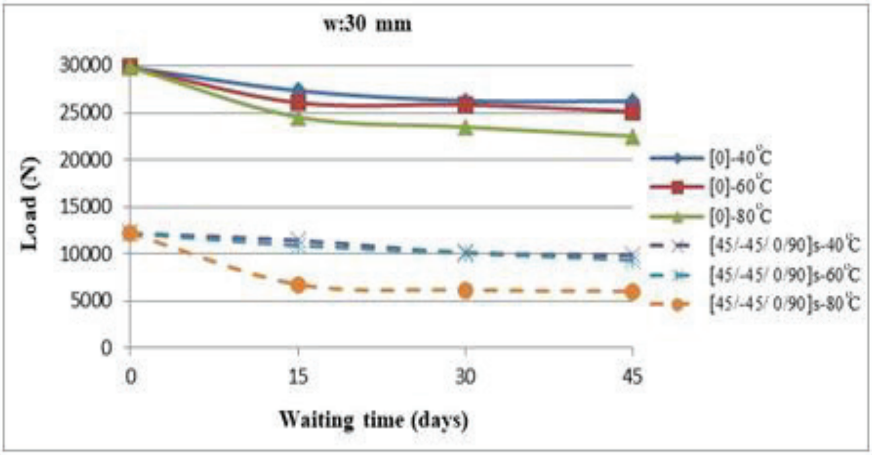


Figure 5. Waiting Time and Load Relationship Graph

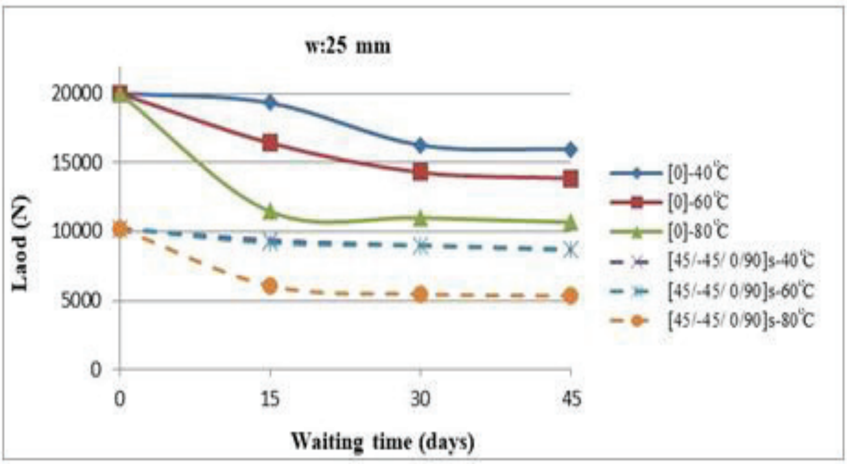


Figure 6. Waiting Time and Load Relationship Graph

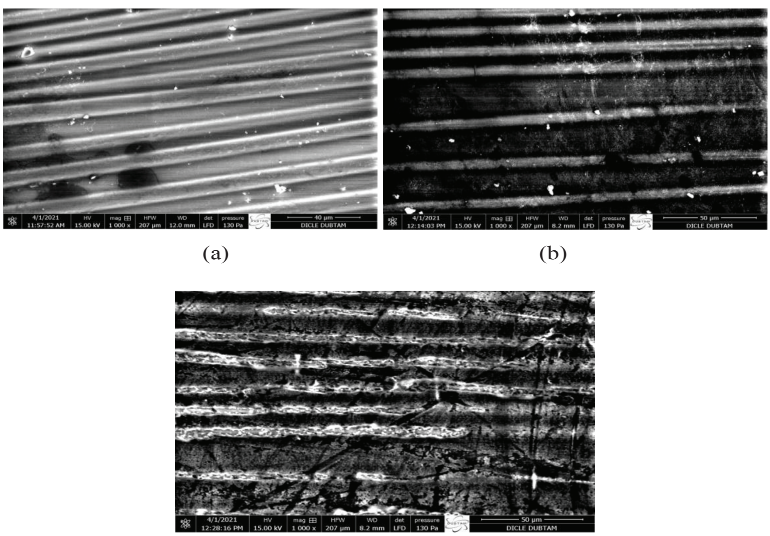
the material strength tends to decrease significantly due to the plasticization of the epoxy [18]. In our study, the strength values of the composites with $[0º]_8$ and $[45º/-45º/0º/90º]_s$ orientations decreased depending on the waiting time in hot water and the amount of moisture absorbed during these periods. Specimens with both orientations and widths presented a significant decrease at 80 ºC (Table 2, Figure 5 and Figure 6).

3.3 SEM Images

Increasing the time and temperature parameters also affect the morphological aspect of the material [20]. In particular, these cause an active attack of water molecules on the interface and, as a result the separation of the bonds for the fiber and the matrix occurs [22]. Therefore, the images of the specimens were observed with the help of SEM for the evaluation of the hydrothermal failures. These images were captured using the Quanta FEG 250 type SEM device. SEM images were for captured for the specimens that were kept for a maximum of 45 days and have a width of 30 mm to observe the effects of temperature and humidity, and the abovementioned images are given in Figure 7, Figure 8, and Figure 9.

Figure 7 (b) shows SEM images of $[0^o]_8$ orientation specimens with 0.91% moisture absorption and 26214.5 N failure load when kept at 40 ºC for 45 days. In Figure 7 (c), SEM images of $[0^o]_8$ orientation specimens with 0.79% moisture absorption and 25120.5 N failure load when kept at 60 ºC are shown. In Figure 8 (b), SEM images of specimens with 9891.45 N failure load and $[45^o/-45^o/0^o/90^o]_s$ orientation that presents 2.08% moisture absorption when kept at 40 ºC for 45 days are presented. In Figure 8 (c), SEM images of specimen - with the same orientation - that displayed 9366.08 N failure load due to the 1.41% moisture absorption rate when kept at 60 ºC are presented.

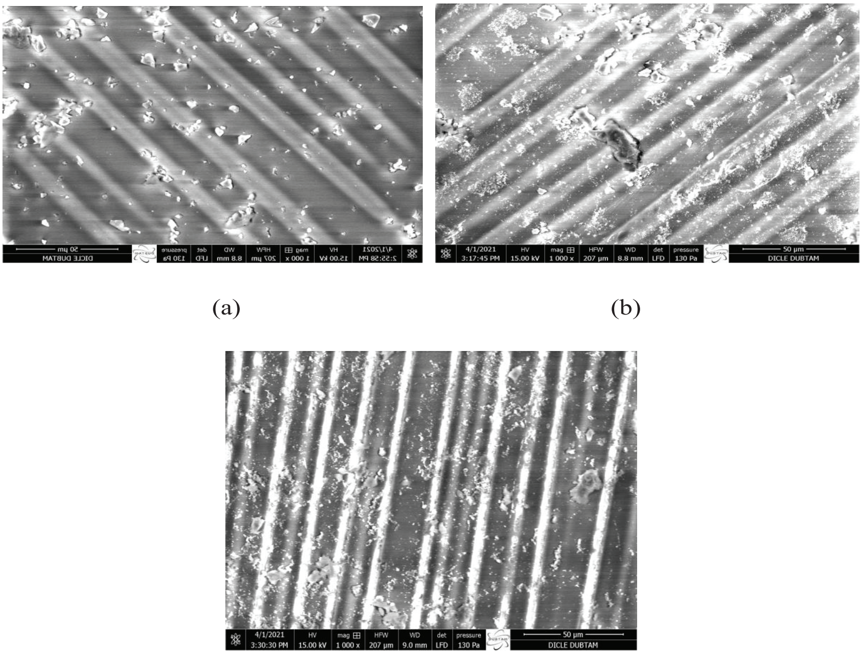
In Figure 7 (b, c) and Figure 8 (b, c), deterioration stages that occur in the matrix or at the interface, depending on the temperature and humidity changes, are presented. This deterioration is more evident, especially for specimens with higher moisture ab-



(a) (b)

(c)

Figure 7. SEM Images of [0°]8 Orientation Specimens a) Dry b) 40 °C -45 Days c)60 °C-45 Days



(a) (b)

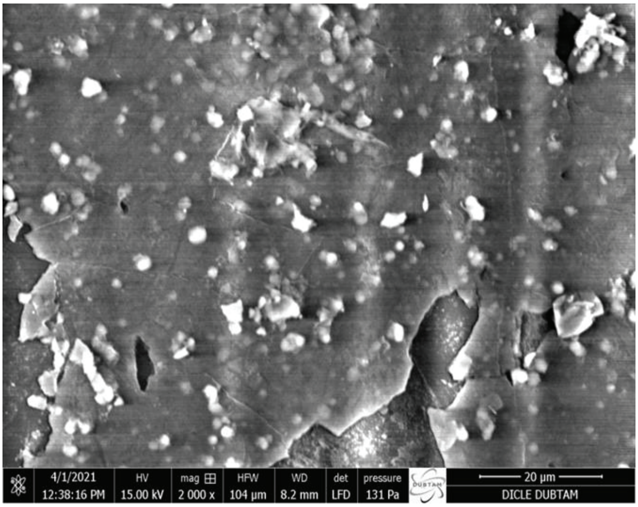
(c)

Figure 8. SEM İmages of $[45^o/-45^o/0^o/90^o]_s$ Orientation Specimens a) Dry b) 40^{o}C -45 Days c) 60 ^{o}C-45 Days

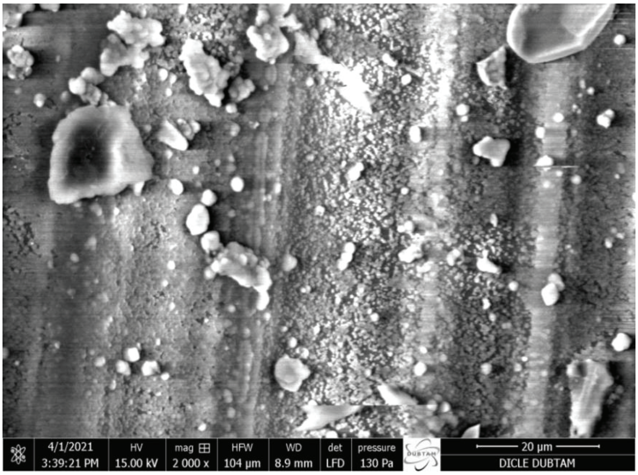
sorption rates and $[45^o/-45^o/0^o/90^o]_s$ orientation, in the SEM images and the images are presented in Figure 8 (b, c).

This clearly reveals that the low strengths are the result of humidity, and temperature, hence, humidity and temperature effects are more evident for the specimens that are kept at 80 ^{o}C for 45 days. In particular, it was observed that the deterioration in these specimens was clearer (Figure 9). Therefore, SEM images- with 2000x magnitude - of specimens in the given range and with two different fiber orientations are displayed in Figure 9 (a,b).

In Figure 9 (a), SEM images of the $[0^o]_8$ orientation specimen with a failure load of 22506.5 N and a moisture absorption rate of 1.47% at 80 ºC are presented. In Figure 9 (b), SEM images of the $[45^o/-45^o/0^o/90^o]_s$ orientation specimen with 3.8% moisture absorption rate and 6044.7 N failure load at 80 ºC is presented. In Figure 9 (a)' and Figure 9 (b), it is seen that particles in the form of fractures/cracks are formed in the matrix material along with the interfacial deterioration as a result of moisture rates. It is observed that the effects of humidity are especially greater on the resin, a new interface is formed and the resin incurred losses due to fractures (Figure 9a). It was



(a)



(b)

Figure 9. a) 80 °C -45 Days for $[0^o]_8$ Specimens b) 80 °C -45 Days For $[45^o/-45^o/0^o/90^o]_s$ Specimens

determined that the interface formed in Figure 9 (b) deteriorated more due to moisture absorption. These interface defects caused by moisture absorption weakened the stress transfer from the matrix to the fibers,hence, resulted a reduction in tensile strength [19].

Among the literature researches, especially in the studies conducted by the authors [14], [15], [22], [23], it was stated that the increase in the moisture absorption time caused a decrease in the failure loads of the specimens. In this study, we obtained results that are compatible with the abovementioned situation. In this sense, it has been determined that the experimental results are compatible with the SEM images.

4.CONCLUSION

In this study, the combined effect of humidity and temperature on glass fiber reinforced epoxy composite specimens with fiber orientations $[0^o]_8$, $[45^o/\text{-}45^o/0^o/90^o]_s$ and, widths of 30 mm, 25 mm was investigated with regard to different temperatures and waiting times. For this purpose, the specimens were kept in water at 40 ^{o}C, 60 ^{o}C and 80 ^{o}C for 15 days, 30 days and 45 days. The following results were obtained from the study.

- Depending on the fiber orientations, the moisture absorption rates were increased correspondingly with the temperature and waiting time, yet their strength decreased.
- The lowest strength with the highest absorption rate was obtained from the specimens kept in 80 ^{o}C water for 45 days.
- It was determined that the strength of the 25 mm wide dry specimen with the $[0^o]_8$ orientation was 95.63% higher than the strength of the specimen with the same width and $[45^o/\text{-}45^o/0^o/90^o]_s$ orientation.
- It was determined that the strength of the 30 mm wide dry specimen with the $[45^o/\text{-}45^o/0^o/90^o]_s$ orientation was 144.38% lower than the strength of the specimen in the same geometry and with the $[0^o]_8$ orientation.
- The $[45^o/\text{-}45^o/0^o/90^o]_s$ orientation specimens were affected most by humidity and temperature, hence, the resulting deterioration was more severe.
- It has also been determined by the SEM images that the combined effect of humidity and temperature has a significant effect on the deterioration of composites.
- Considering the parameters used in this study, the results of the experiments created a database that can be used as a reference for the composites investigated in the study.

ACKNOWLEDGEMENT

This study was carried out with the support of DUBAP, ENGINEERING.17.018.

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