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Effects of Environmental Conditions on the Mechanical Properties of Composite Materials

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ABSTRACT

Environmental conditions have significant effects on the mechanical characteristics of composite materials. Irreversible changes occur in the original characteristics of composite materials when exposed to environmental conditions such as temperature and humidity for a long time. This process of change in composite material characteristics over time is called "ageing". In order to determine the strength and service life of composite materials in the usage areas, the change in the mechanical characteristics of the materials under environmental conditions such as temperature, humidity, pure water, seawater, and ultraviolet light should be well known. Thanks to the knowledge of the effect of environmental conditions on the mechanical characteristics of composite materials, designs made with these materials will be more reliable in the application areas. The aim of this study is to examine the effect of various environmental conditions on the mechanical characteristics of composite materials and to provide a collective information source for future scientific studies.

1. INTRODUCTION

Nowadays, the use of economical, high-strength, and lightweight materials is increasing day by day. The use of composite materials, one of the material types that can meet these requirements, is much higher than other materials in many sectors such as aviation, aerospace, and automotive. The use of composite materials has increased due to their characteristics such as lightness, high corrosion resistance, good energy absorption behavior, and fatigue performance, high rigidity, and strength (Ulus, 2014).

Composite materials are materials that have new properties that are formed as a result of the physical combination of two or more materials in order to produce a suitable material that can provide the desired properties in design. Composite materials are a structure that is combined to obtain better mechanical, thermal and electrical properties. Composite materials consist of two phases: the matrix component, which is the main material of the composite, and the reinforcement component that determines the strength and bearing strength of the composite (Kara, 2006). There are many production methods of composite materials such as hand lay-up, resin transfer, spraying, molding, and filament winding (Üstün, 2015).

Environmental conditions are one of the most important parameters affecting the mechanical characteristics of composite materials. Irreversible changes occur in the original characteristics of composite materials when exposed to environmental conditions such as temperature and humidity for a long time. This process of change in composite material characteristics over time is called aging. In order to determine the strength and service life of composite materials in the places of use, the change in the mechanical and thermal characteristics of the materials under environmental conditions such as temperature, humidity, pure water,

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salt water, and ultraviolet rays should be well known. The sensitivity of composite structures to environmental conditions is different in itself. For example, temperature and humidity are important environmental factors to consider in wind turbine design. Composite materials used in the petrochemical industry are exposed to corrosive chemicals (Doğan, 2014).

2. ENVIRONMENTAL CONDITIONS

Under conditions such as humidity, temperature, ultraviolet light (UV), saltwater, external loads, and their combination, which are the main environmental aging factors, composite materials may deteriorate and a change in their mechanical characteristics may occur. As a consequent of this change, a decrease in the working life of the material may occur. Therefore, there are many studies in the literature on the aging tendencies of composite materials.

2.1. Hydrothermal

The hydrothermal aging process, in which the effects of temperature and humidity are seen together, is one of the examples of environmental conditions that materials can be exposed to. During the hydrothermal aging process, expansion occurs in composite materials depending on the temperature. In composite materials, stresses occur at the matrix/fiber interface due to the difference in thermal expansion coefficients of matrix and fiber, which are two different components. These stresses create separations at the fiber/matrix interface. As the glass transition temperature (Tg) of the samples subjected to hydrothermal aging decreases, the service temperature of the material changes. This change causes plasticization in the matrix due to water/polymer interaction (Meurs et al. 1996). Below the glass transition temperature, polymers are generally hard and brittle. But above this temperature, the polymers are viscoelastic and is elastic. For polymers subjected to stress, the temperature at which the material is used should be below glass transition temperature to prevent creep under sustained loads (Davies and Rajapakse, 2014).

Vieille et al. (2012) examined the change in the mechanical characteristics of some composite materials exposed to hydrothermal aging. They found that in composite materials subjected to hydrothermal aging at 120 °C, hydrothermal aging significantly affects the lifetime of this material.

Starkova et al. (2013) studied the effects of hydrothermal aging on the thermomechanical characteristics of multi-walled carbon nanotube (MWCNT) doped epoxy matrix nanocomposites. As a consequent of the study, it was observed that the water absorption capacity of the MWCNT-added samples decreased significantly compared to the pure samples, thus increasing their resistance to hydrothermal aging. They observed that the water content of MWCNT additive epoxy decreased approximately 3 times compared to pure epoxy.

Zhong and Joshi (2015) examined the effect of water difusion on the mechanical characteristics carbon fiber reinforced epoxy matrix composite materials. As a result of their work, they stated that moisture absorption softens the matrix and causes a decrease in the Tg.

Rocha et al. (2017) investigated the effect of hydrothermal aging on the fatigue life and shear strength of glass fiber reinforced epoxy composite material. As a consequent of the study, they observed that the shear strength of aged glass fiber reinforced epoxy matrix composite samples was approximately 35% lower than the non-aged composites. In addition, it was determined that the fatigue life of aged samples was three times shorter than the non-aged samples.

Fitriah et al. (2017) examined the effect of hydrothermal aging on the compression behavior of glass fiber reinforced epoxy matrix composite pipes. Pressure tests were carried out on samples kept in tap water at 80 °C for 500, 1000, 1500 hours at 25, 45 and 65 °C. At the end of the tests, it was seen that the strength of the composite pipe samples decreased with temperature and waiting time.

In his study, Akın (2018) subjected glass fiber reinforced epoxy matrix composite pipes to the hydrothermal aging process by soaking them in 80 °C pure water for 1, 2, 3, and 4 weeks. Tensile test was performed to the composite samples after aging. As a result of the experiments, it was determined that the tangential stress and maximum strength values of the samples decreased depending on the aging time.

Arribas et al. (2019) added carbon nanotube (CNT) into epoxy resin, subjected the samples to hydrothermal aging conditions for two years, and performed dynamic mechanical thermal analysis on the samples. As a result of the study, the glass transition temperature (Tg) and storage modulus (E') of CNT-added composite samples were observed to be increased compared to pure samples.

2.2. Ultraviolet Light (UV)

Another source of the degradation of fiber reinforced polymers (FRP) is UV light, which is attributed to the cause of chemical alterations in the resin due to the complex sequence of processes characterizing oxygen (Bazli et al. 2017; Ching et al. 2019). Ultraviolet light can generate enough energy to break the molecular bonds in the polymer and cause the material properties of the polymer to change through chain cutting or crosslinking (Han and Kim, 2006; Doğan, 2019).

Ultraviolet (UV) light can disrupt the polymeric surface of the composite, thus exposing the fibers while further increasing water absorption. A composite material that is exposed to both moisture and ultraviolet radiation may experience significant changes in its mechanical characteristics, especially its modulus of elasticity and interlayer shear strength (Doğan, 2019). The simultaneous exposure of fiber reinforced polymers (FRP) to UV radiation and water vapor condensation accelerates the degradation mechanisms in different ways (Bazli et al. 2019). Some research has been done in the literature on the mechanical characteristics of FRP composites exposed to UV radiation and hydrothermal aging (Sousa et al. 2016; Ching et al. 2019; Bazli et al. 2020).

Shin et al. (2003) investigated the effect of environmental conditions on the physical and mechanical characteristics of fiber reinforced composite materials. They exposed the composite samples to natural environmental conditions for five years. At the same time, they were subjected to accelerated aging for 2000 hours in environmental conditions including ultraviolet radiation, temperature, and humidity. As a result of the study, they observed that the bending properties are very sensitive to environmental effects. Matrix cracks and loss of matrix were observed on the surface of aged specimens during the investigations performed by scanning electron microscopy.

Mouzakis et al. (2008) investigated the effect of temperature, humidity, and ultraviolet radiation on polymer composites. In this study, the environmental aging cycle has been established and tested. At the end of this cycle, tensile, three-point bending and dynamic mechanical analysis (DMA) were performed. It has been observed that tensile strength and elongation at break decrease when the duration of environmental aging increases.

Martins et al. (2011) examined the behavior of polymer composite materials after exposure to ultraviolet radiation and water vapor. Tensile and creep tests were carried out in this study. Significant changes have occurred in the mechanical characteristics of the composite material after aging for a long time.

Yan et al. (2015) investigated the effect of ultraviolet (UV) light and hydrothermal aging on the mechanical characteristics of linen-reinforced epoxy resin composite materials. The composite materials were subjected to an accelerated aging condition of ultraviolet light and hydrothermal environment for 1500 hours. As a result of the experiments, they stated that the tensile strength of aged composites decreased approximately 30%. They observed that the bending strength decreased by 10%.

Bazli et al. (2020) exposed glass fiber reinforced epoxy matrix polymer profiles to aging with ultraviolet radiation and water vapor cycles in four different periods of 1000, 1500, 2000, and 3000 hours. After aging, they applied bend, tensile, and compression tests to the samples. As a result of the study, they observed that the strength of the specimen decreased by 34%, 28%, and 23% in the bending, tensile, and compression tests, respectively.

2.3. Seawater

Salinity rates in the seas vary between 3.1-3.8%. The average salinity value is considered to be approximately 3.5%. Inland research activities have increased considerably in recent years due to the fact that our country is surrounded by seas on three sides and the importance of its geopolitical position. This has increased the importance of the use of various composite materials in salty seawater in areas such as drilling activities at sea, below sea level drinking water transmission lines, and oil exploration activities. In the lower parts of the sea level, in addition to the various liquids or gases transported through the pipes used in transmission lines, the outer surfaces are only in contact with seawater. It is known that polymer composite materials are widely used in the storage and transportation of water (Tsotsis et al. 2001).

In their study, Deniz and Karakuzu (2012) exposed glass/epoxy composite pipe samples to aging in seawater for 3, 6, 9, and 12 months. They performed a low-velocity impact test on aged samples. As a result of the experiments, they concluded that aging in seawater has an important effect on the impact characteristics and failure of composite materials.

Deniz et al. (2013) studied the effect of environmental conditions and impact damage on fatigue life of internally pressurized glass fiber reinforced epoxy matrix composite pipes. They exposed the pipes to seawater at certain periods of time. They examined the fatigue life of the pipes according to different impact energies and holding times in seawater. As a consequent of the study, they observed that the fatigue life of the samples decreased due to the effect of seawater.

Kim et al. (2014) investigated the effect of seawater aging on the fracture behavior of basalt fiber reinforced composites. The fracture behavior of composites was significantly affected by seawater. The average fracture toughness of samples aged in seawater was determined to be approximately 20% lower than dry samples.

Karakuzu et al. (2017) examined the effect of seawater on the impact behavior of glass fiber reinforced composite pipes. Impact tests were applied at different energy levels at 20 °C ambient temperature to the pipes kept in seawater with 3.5% salt content in the laboratory environment. They used the contact force curve and absorbed energy data in impact tests to examine the aging effect. They emphasized that parameters such as absorbed moisture, salt content, pipe size, maximum impact force, impact energy affect the damage on the material.

Wang et al. (2017) investigated the interlaminar shear behavior of basalt, glass, and carbon fiber reinforced polymer rods aged in seawater solution. They found that the higher the exposure time and temperature to seawater in all composite rods, the higher the degradation rates of their shear strength.

Davies and Verbouwe (2018) examined the interlayer shear strength and static and dynamic bending behavior of basalt fiber reinforced and glass fiber (E-glass) reinforced epoxy composite samples aged in seawater at different temperatures. The results showed that both materials displayed similar mechanical performance before and after seawater exposure. The very similar results for both materials before aging were associated with the similar interfacial quality of the samples. Flexural stiffness values for both materials decreased after exposure to seawater. After the seawater absorption reaches the saturation limit, a decrease in the shear properties between the layers was determined around 20% for both composites.

Gunoz et al. (2020) subjected glass fiber reinforced composite pipes to the aging process for 1, 2, and 3 months in the seawater to understand the effects of seawater absorption behavior on tensile strength. As a consequent of this study, the average tensile strength of composite pipes exposed to seawater has significantly decreased. In addition, as the residence time of the composite pipes in seawater increased, the average tensile strength values decreased.

2.4. Cryogenic

Fiber reinforced polymer matrix composites, which are increasingly used in many industries, have application areas that require operating at cryogenic temperatures, where the material response can vary significantly, both inside and beyond the atmosphere. Liquid fuel tanks; satellite and spacecraft; Devices operating at cryogenic temperatures, supporting elements and electrical insulation for superconducting magnets are some of the application areas of composites operating in cryogenic conditions (Sápi and Butler, 2020).

Song et al. (2004) performed mechanical experiments on E-glass/urethane composite plates at different temperatures (−196, −100, −50, 0, and 25 °C). As a result of the study, they observed an increase in the compressive strength and elasticity modulus of the samples as the ambient temperature decreased.

Shen et al. (2012) conducted impact and tensile tests on epoxy composite plates reinforced with graphene nanosheets at room temperature and −196 °C. As a result of the study, they concluded that the cryogenic environment conditions improved the tensile and impact strength of the samples and made the samples more rigid.

Kara et al. (2018) investigated the low-velocity impact behavior of carbon nanotube reinforced carbon fiber/epoxy composite pipes under cryogenic conditions. They applied low-velocity impact to composite pipe samples at temperatures of 23 °C, 0 °C, −50 °C, 100 °C, and −196 °C. As a consequent of the study, they reported that the amount of energy absorbed by the sample and the damage to the sample increased with the decrease in the temperature value. They also observed that as the stiffness increased due to the decrease in temperature, the contact force generated during the impact also increased.

Li et al. (2020) performed a bending test at room temperature and −196 °C on the carbon fiber reinforced epoxy composite plates they produced in their study. As a result of the study, they concluded that the flexural strength of the samples tested in the cryogenic environment increased significantly compared to room conditions.

Qu et al. (2020) carried out bending and interlaminar shear tests on carbon fiber reinforced epoxy composite plates at room temperature and −196 °C. As a result of the experiments, they concluded that the bending and interlayer shear strengths of the test samples in the cryogenic environment were significantly higher than the samples at room temperature.

3. CONCLUSION

Composite materials are exposed to environmental conditions that may have an aggressive effect on the material structure such as temperature, humidity, ultraviolet light, saltwater, cryogenic environment for a long time under operating conditions. This causes irreversible changes in the mechanical characteristics of composite materials. In this study, studies investigating the change in the mechanical characteristics of composite materials exposed to hydrothermal, ultraviolet, saltwater, and cryogenic environments were compiled. In the studies examined, it was determined that different environmental conditions significantly affect the strength and service life of the composite materials at the places of use.

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