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Mechanical behavior and long-term life prediction of carbon/epoxy and glass/epoxy composite laminates under artificial seawater environment

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Abstract: This paper presents an investigation on the long-term performance of carbon/epoxy and glass/epoxy laminates in an artificial seawater environment with 3.5% salinity. Accelerated aging tests were conducted at 60 ºC for 45 days to characterize the long-term effect of seawater on the mechanical response of fiber-reinforced composite laminates. Several mechanical tests including tensile and 3-point bending tests have been carried out on the reference/dry and aged standard samples at room temperature and 60 ºC to evaluate tensile strength, young's modulus, flexural strength, secant and chord modulus of elasticity in the composite samples. The long-term behavior of carbon/epoxy and glass/epoxy samples under the service construction condition in the coast of Ireland was also predicted using Arrhenius degradation theory.

Key words: Aging Process, Composite, Seawater Immersion, Water Uptake**.**

1. Introduction

The coupling of aging and water ingress in polymer-composites is a very slow process. Heat is a means by which the rate of aging can be magnified and this combination of heat induced aging with water ingress, termed hygrothermal aging, is a known method to evaluate the long-term life [1], stiffness, yield stress and hardness [2], strain rate and the tensile ductility [3] and mechanical strength [4] of composite laminates in service condition. In this study, the mechanical properties of carbon/epoxy (CE) and glass/epoxy (GE) composite laminates have been investigated under aging process in artificial seawater at room temperature and elevated aging temperature (60ºC). The long-term behavior of composite samples under the service construction condition in the coast of Ireland was predicted using Arrhenius degradation theory.

1. Materials

High strength carbon fibre sheet was provided from Easycomposites™ [5] made of 100% carbon fibre reinforcement and epoxy resin matrix. To create a more uniform distribution of strength, the sheets were manufactured using both layers of 0°/90° and 45°/-45° oriented reinforcement (Table 1) in what is known as quasi-isotropic fibre orientation.

Table 1: Fiber orientation and surface density of the composite layers with 2mm thickness [5].

Surface Density	Type
200 g/m^2	2/2 twill 3k carbon
300 g/m^2	-45 Biaxial Carbon
650 g/m^2	2/2 twill Carbon
300 g/m^2	-45 Biaxial Carbon
200 g/m^2	2/2 twill 3k carbon

Six layers of Biaxial glass reinforcement with ± 45° fibre orientation and surface density 320 gr/m^2 was used as reinforcing in EL2 epoxy AT30 FAST resin to manufacture glass/epoxy samples made by hand lay-up method.

2. Aging process

To make seawater at laboratory, 35 grams of salt was added to a beaker, and then added tap water until the total mass was 1000 grams, stirring until the salt was completely dissolved in the water. For aging process on composite laminates, a water-heating WiseBath with circulating pump was used for continuous testing condition.

3. Tensile test

The characterization of elastic properties was performed using tensile tests on composite laminates by an Instron 4467 machine with 30 kN load cell at a crosshead displacement rate of 2 mm/min, according to ASTM D3039, with dimensions 200mm long, 23mm wide and 1.92mm thick for CE samples (and 2.9mm for GE specimens) before and after sea water ageing in room temperature and 60ºC. Tensile strength and elastic modulus were determined, obtaining a mean value of 532.64 MPa and 26.76GPa, respectively, for un-aged (dry) CE specimens. In the same way, tensile strength and elastic modulus for GE were measured 106.33 MPa and 6.19GPa, respectively. Mean tensile strength and elastic modulus at ambient temperature after 45 days immersion in salt water were 527.06MPa and 26.65GPa (Fig. 1). Tensile strength and elastic modulus were 475.77MPa and 26.05GPa, respectively, for aged CE specimens at 60ºC. The effect of seawater on tensile properties of CE at elevated temperature and room temperature was significant while Young's Modulus has not changed remarkably over aging process. A slight reduction on tensile elastic modulus due to seawater ageing, 0.52% at ambient temperature and 2.76% at the elevated temperature were observed. However, artificial seawater produces a loss on tensile strength in CE samples with 1.04% at room temperature and 10.67% at 60ºC (Fig. 1).

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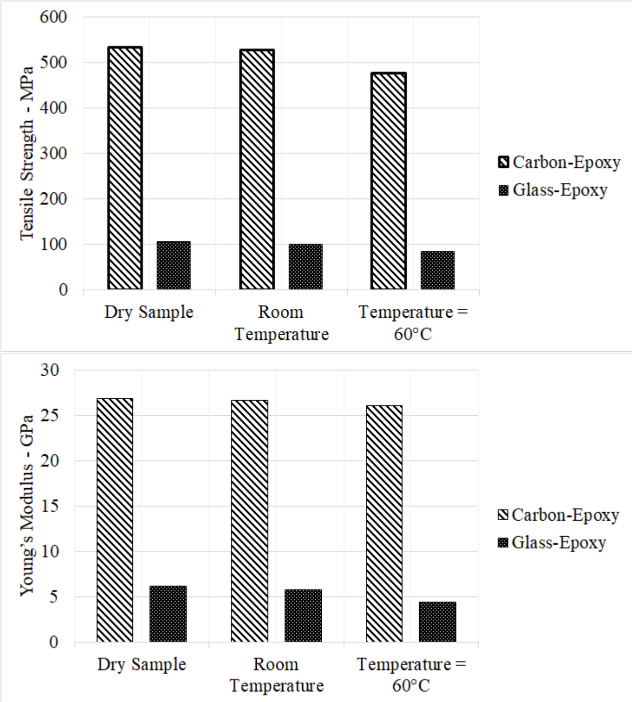

Fig. 1. Tensile strength and Young's Modulus of un-aged/dry and aged samples.

Mean tensile strength and elastic modulus for GE at ambient temperature in the same period immersion were 100.03MPa and 5.8GPa, respectively, while these values at 60ºC were 83.66MPa and 4.41GPa, respectively. The experimental data presented a reduction on tensile elastic modulus due to seawater ageing, 6.3% at ambient temperature and 28.7% at the elevated temperature for GE specimens. The aging process in this work produced a loss on tensile strength with 5.92% at room temperature and 21.3% at 60ºC. Plasticization and swelling are the main physical degradation on polymer resins, which may cause the polymer to become more ductile reducing its glass transition temperature. Water absorption can also cause hydrolysis of polymer matrix inducing that the fiber/matrix interface is degraded.

4. Three-point bending test

Flexural strength, flexural chord modulus of elasticity (E_{chord}) and flexural secant modulus of elasticity (E_{Secant}) for CE dry specimens were determined according to ASTM D7254 at 1 mm/min crosshead speed, obtaining a mean value of 631.17 MPa (116.81 MPa for GE specimens), 36072 MPa (6966 MPa for GE specimens) and 34311 MPa (8660 MPa for GE specimens), respectively. The effect of seawater at room temperature on flexural strength of CE was about 7.7% loss on this value after 45 days, whereas a reduction of 6.82% (33610 MPa) and 6.17% (32193 MPa) in E_{chord} and E_{Secant}, respectively were revealed from the experimental work (Fig. 2). With regards to the flexural properties for the specimens at 60 ºC, mean flexural strength and flexural elastic modulus were affected significantly by elevated temperature so that flexural strength fell down to 455 MPa (27.9%). Concerning E_{chord} and E_{Secant} of aged CE samples at 60 ºC, 32943 MPa and 32105 MPa were measured, respectively (Fig. 2).

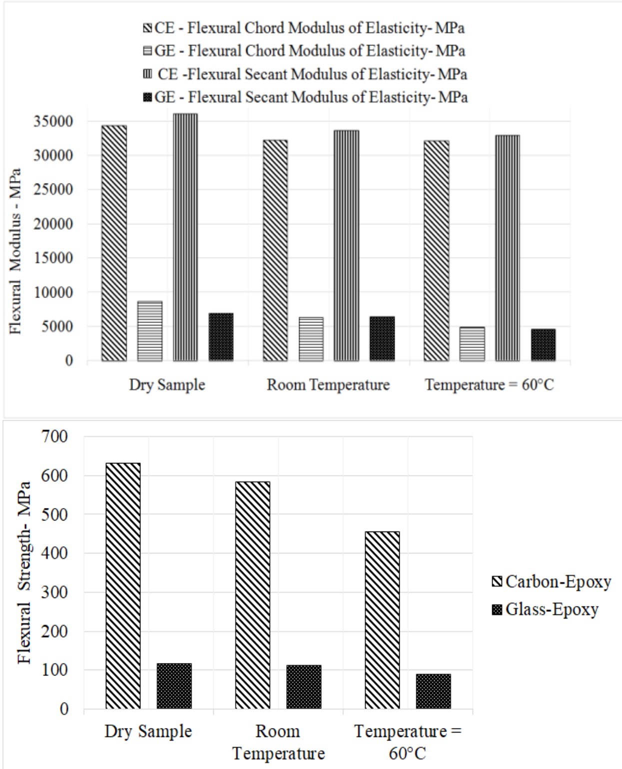

Fig. 2. Flexural strength and modulus of carbon/epoxy specimens.

The effect of seawater at room temperature on flexural strength of GE laminates was about 3.1% loss on this value after 45 days, whereas a reduction of 8.62% (6365 MPa) and 29.5% (6499.26 MPa) in E_{chord} and E_{Secant}, respectively were measured from the experimental work. About the flexural properties for the GE specimens at 60 ºC, the mean flexural strength and flexural elastic modulus were affected significantly by elevated temperature so that flexural strength dropped to 89.77 MPa. On the other hand, E_{chord} and E_{Secant} of aged GE samples at 60 ºC, 4905 MPa and 4618.17 MPa were calculated using equation 4 and 5, respectively (Fig. 2).

5. Prediction of long-term life of composite samples

To evaluate the long-term life of composite samples in environment, the popular Arrhenius relation was adopted by researchers based on the short-term data from accelerated aging tests [1]. The model presented in equation (1) was used by some researchers [6], which suggested a service life prediction procedure for composite materials that the accelerated aging data could be calculated and plotted with the property (tensile strength) retention versus time. Where Y represents the tensile strength retention (%); t represents the exposure time; τ represents the fitted parameter.

$$Y = 100\exp(\frac{-t}{\tau}) \quad (1)$$

In this model, the degradation rate can be expressed in the Arrhenius relationship and the time-shift factor (TSF) for the tensile strength to reach the same value at temperatures T_1 and T_0 can be obtained from the the Arrhenius curves [1].

$$TSF = \exp[\frac{E_a}{R}(\frac{1}{T_0} - \frac{1}{T_1})] \quad (2)$$

Where E_a represents the activation energy; R represents the universal gas constant; and T represents the Kelvin temperature.

Fig. 3 indicates the variation of time shift factor or acceleration factor for CE and GE composite samples for a range of reference temperatures and an aging temperature of 60 °C. This information is useful in linking the accelerated aging test results in this work to the actual aging experienced by real applications such as turbine blade materials over the expected operational life of a tidal energy device immersed in water temperatures between 4 °C and 24 °C. Based on a reference temperature of 12 °C, estimated as the operating temperature of a tidal turbine device off the coast of Ireland [7], an acceleration factor of 8.2 is estimated for glass/epoxy tested. In this work, accelerated aging and tensile strength retention for GE specimens (78.67%) took place over 45 days at 60 °C, corresponding to an aging period of 370 days at 12 °C. In the same way, tensile strength retention for CE specimens (89.32%) took place over 45 days at 60 °C, corresponding to an aging period of 1552 days (TSF=34.5) at 12 °C.

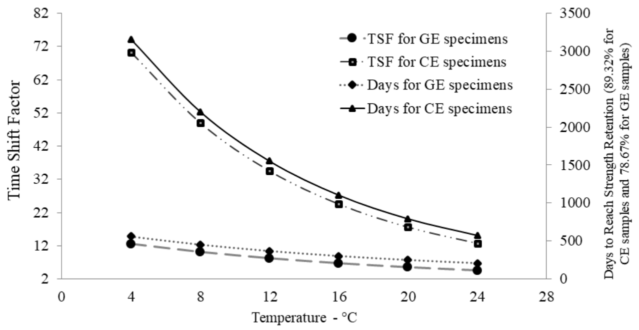

Fig. 3. Plot of acceleration factor against reference temperature for an aging temperature of 60 °C.

6. Conclusion

In summary, the CE and GE composite laminates at elevated temperature, 60°C, and ambient temperature experienced loss in the mechanical properties including tensile and flexural strength. A model has been used to predict the long-term life of CE specimens (1552 days) and GE samples (370 days) in saltwater environment with 3.5% salinity to reach 89.32% and 78.97% of the initial tensile strength in service condition, 12 °C, respectively.

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