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Influence of Temperature and Moisture on the Compressive Strength of Carbon Fiber Reinforced Polymers

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ABSTRACT

The effect of moisture absorption and high temperature on the compressive strength of unidirectional IM7/977-2 carbon/epoxy resins have been investigated experimentally. The specimens were divided into 4 groups, and tested under 4 different conditions by varying the testing temperature and moisture parameters. The fiber orientation selected were 0º, ±45º and 90º. The reported results showed that the compressive strength, fracture load and compressive modulus of the specimens were degraded under the influence of moisture absorption and high temperature. The largest compressive strength degradation was observed in the unidirectional specimens. Furthermore, the most severe case was noted for the specimens that were immersed in water and tested at 80°C. The observed reduction in the strength varies depending on the fiber orientation, immersion time and test temperature. The results indicate the importance of considering environmental parameters in designing the composite structures for compression loadings.

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1. INTRODUCTION

The use of fiber reinforced polymeric (FRP) materials is gaining much attention in many applications including aerospace, marine, medical, automobiles, civil and mechanical infrastructure. This is mainly because these composites possess high strength to weight ratio and corrosion resistance.

FRP materials have drawn a lot of attention in research community. Many studies have been carried out to characterize these materials under different loading conditions [1-7].

The prime applications of these materials in the Gulf Cooperation Council (GCC) countries include pipelines for water desalination plants, water storage vessels, repair and strengthening of reinforced concrete structures and manufacture of leisure boats. FRP materials become very attractive in these applications mainly due to their high corrosion resistance. Studies have confirmed that properties of some FRP composite systems are compromised in adverse environmental conditions. Many researchers [8-12] have characterized a range of water absorption and degradation of mechanical properties for water immersed FRPs.

Structural components are subject to severe environmental attacks such as humidity and variation in temperature. It is well known that matrix properties as well as fiber/matrix stress distribution are severally got affected under humidity and temperature variation condition. Many studies e.g. [13-17] reported the effect of moisture uptake on different mechanical properties of composites to estimate the strength and stiffness reduction due to moisture uptake.

Research studies [18-21] have been conducted to investigate the effect of moisture absorption on the mechanical properties of Carbon Fiber Reinforced Polymers (CFRPs). Reductions in matrix/interface dominated properties is seen as a general trend in almost all the studies conducted so far. For example, 22-29% loss of interlaminar strength is reported in literature with reductions in short beam shear strength, depending on sizing and in $[0]_n$ carbon fibre-epoxy laminates.

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Significant losses of around 19-33% in compression properties are also reported [20-21].

Despite the above-mentioned efforts, yet the exact nature of environmental attacks in the form of humidity and temperature on the durability of any specific material is generally not understood completely. The influence of moisture absorption on the mechanical properties of CFRP materials with unidirectional fiber architectures have been investigated. Higher temperatures influence more in accelerating the moisture absorption and degradation as well as significant changes in structural performance and failure mechanisms of CFRP [22, 23].

This paper, therefore aims to do a comprehensive experimental study to consider the effect of different significant parameters including moisture content, temperature and fiber orientation in the compression performance of IM7/977-2 carbon/epoxy laminates.

Following the introduction section, the structure of the manuscript is designed as follows: Materials and Sample Preparation is described in Section 2 while in Section 3, water uptake by the samples is mentioned. Section 4 of the manuscript highlights the Testing Methodology followed by Results and Discussions in Section 5. Finally, concluding remarks are presented in Section 6 of this manuscript.

2. MATERIAL AND SAMPLES PREPARATION

A Composite system IM7 12k/977-2, a thermoset epoxy resin matrix toughened with thermoplastic material, was used for the current study. 977-2 has a 350 ˚F (177 ˚C) curing with a 260-280˚F (126 - 138 ˚C) dry and 220 ˚F (104 ˚C) wet service capability manufactured by Cycom® [24]. It has shelf life of 12 months at 0 ˚F (-18 ˚C) , 42 days at 72 ˚F (22 ˚C). It is available in a broad range of fibers and forms such as tape, fabric and roving. The material has its applications in aircraft primary and secondary structures, ballistics, space structures, cryogenic tanks and any application where light weight and impact resistance are required.

Large sheets of IM7/977-2 with 0.20 mm nominal cured ply thickness were cut into the required ply shapes. Plies with three lay-up angles namely 0^o, $\pm45^o$ and 90^o are used in this study. These orientations of angles refer to the direction of longitudinal fibers. For 0^o ply orientation, the laminates comprised of 10 plies producing a nominal cured laminate thickness of 2 mm, while for $\pm45^o$ and 90^o plies orientations, each laminate comprised of 16 plies producing a nominal cured laminate thickness of 3.2 mm. All the laminates were produced by hand lay-up in clean room conditions. Vacuum consolidations were applied frequently to the lay-up stack at least after every 3 plies. These were then cured in autoclave. The completed ply stack for each orientation was vacuum bagged. To obtain the smooth surface of cured samples, upper and lower tooling of aluminium was used during autoclave curing. The manufacturers specified cure schedule for this material, and it was followed for curing the samples.

Diamond saw was used to subsequently trim the cured laminates. General dimensions of a typical specimen used for 0^o Unidirectional layup for compression testing is shown in Figure 1.

In order to achieve the optimum end-tab bond strength, all surfaces prior to bonding were degreased and grit blasted. Improper surface preparation cause damage to the reinforcing fibers and can penetrate the matrix material resulting in improper failure. Therefore, full attention was paid that during grit blasting; reinforcing fibers must not be damaged or exposed. Test specimens were 90 mm long by 9.75 mm wide with 10 mm gauge section, as shown in Figure 1. Prior to testing, width and thickness of each specimen was measured and recorded. The laminates were end-tabbed with cross-ply glass fiber-reinforced polymer (GFRP) 9.75 mm and 40 mm long strips on both ends. End-tab material used has good impact resistance and damage tolerance. Letoxit LH 149 is used for end-tabbing. It is a high-strength, two-component paste epoxy-based adhesive. 100 weight parts of A component with 40 weight parts of B component were mixed thoroughly. After mixing the two-components until an even color is achieved, the paste was applied to surfaces to be bonded. It was noted that, on average, the joint thickness was from 0.1-0.2 mm. The bonded parts were clamped and cured for 4 hours at 50 °C in oven.

3. WATER UPTAKE

A soft cloth was used to remove any excess tab materials after taking specimens out from the oven. After this, each specimen was labeled and then weighed and recorded. After weighing the specimens, half of the specimens from batch of each orientation (i.e. 0^o, $\pm45^o$ and 90^o) were

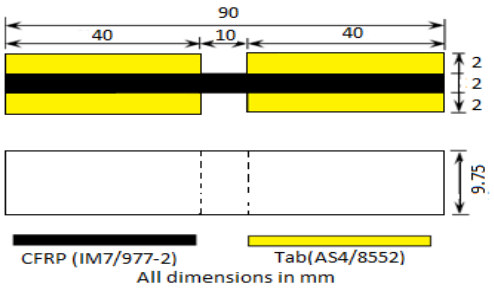

Figure 1. Typical specimen used for 0^o UD layup

put in the water bath to measure the effect of water uptake on the specimens. Initially, the water bath temperature was kept at room temperature (RT) for 60 days. After initial 60 days, the temperature of the water was raised to80° C for next 30 days in order to accelerate the water absorption in the samples. This rise in temperature was done to fully saturate the samples in less time as temperature rise increases the absorption rate. Lightweight, economic PP anti-evaporation spheres were used. These spheres form a blanket on the water surface hence reduce the evaporation rate. It is reported that these spheres reduce heat loss and evaporation by approximately 77% and 87%, respectively. Further to this, water bath was fully covered with a metallic lid. This was done to avoid accidental falling of any substance in the bath and damaging to the specimens. A total of 28 specimens were put in the water bath. Out of the 28 samples, 12 were of ±45º configuration and 8 for each of 0º and 90º layup configuration.

Weights of the specimens before placing in the water bath and at the time of just before testing were recorded to know moisture contents gained. Effect of the immersion tine on the specimens is reported in Table 1.

4. TESTING METHODOLOGY

The specimens were divided into 4 groups as detailed below:

Group 1: In this group, those specimens are kept which were not immersed in water (i. e dry specimens) and were tested at ambient laboratory temperature conditions.

TABLE 1. Effect of Immersion time on the water uptake

Fiber Orientation	Immersion time (days)	Mean Moisture contents (%)
0º		0.00
±45º	0	0.00
90º		0.00
0º		0.67
±45º	30	0.59
90º		0.62
0º		0.97
±45º	60	1.01
90º		0.93
0º		1.31
±45º	90	1.25
90º		1.28

Group 2: This group comprises of those specimens which were immersed in water and water moisture intakes was noted in them (i. e wet specimens), but tested at ambient laboratory conditions.

Group 3: In this group, those specimens are reported which were not immersed in water (i. e dry specimens), but were tested at high temperature (80°C) conditions.

Group 4: In this final Group, those specimens are categorized which were immersed in water and water uptakes was noted in the specimens (i. e. wet specimens) and were tested at high temperature (80°C) conditions.

Testing procedure for groups 1 and 2 is reported (i.e. dry and wet specimens, tested at ambient laboratory temperature conditions) in sub section 4.1, while for groups 3 and 4 (i.e dry and wet specimens tested at high temperature (80°C) testing is reported in subsection 4.2.

4. 1. Mechanical Testing for Group 1 and 2 Samples Any standard testing machine capable of accommodating the samples with specified dimensions, as reported in Figure 1, can be used for testing these specimens. Machine with hydraulically operated type grips should be used. All the tests were performed on a Zwick 1478 of 100 kN load capacity, fitted with compression jig, as shown in Figure 2. More information for the compression testing configuration can be found in [24].

The specimen is installed in the grips of the test machine, making sure that it is accurately aligned. During fitting the specimens in the jig, extra care was taken to make sure that there was no induced bending in the

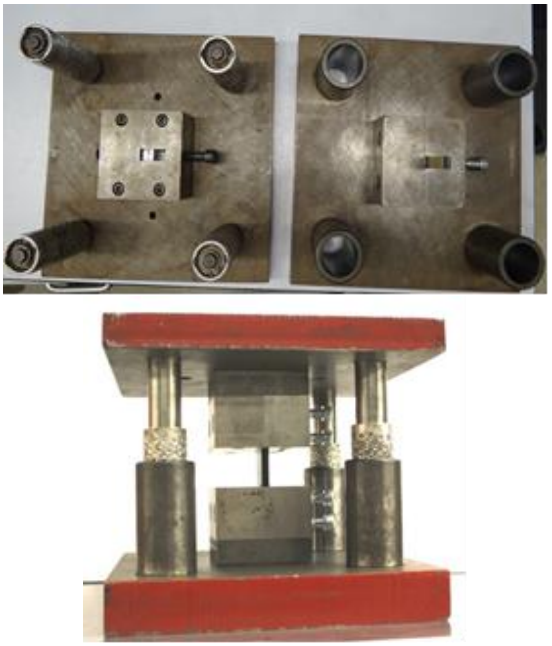

Figure 2. Compressive test fixture with specimen installed

specimen A high-speed video camera was used and the camera was positioned normal to the specimen. The use of the video camera in the testing was very helpful as it really helped to capture the formation and propagation of the damage through the specimens. Two high power light sources were continuously used along with the camera to illuminate the specimen. The camera was initially positioned and focused, and was used continuously throughout the testing.

The test machine actuator was driven under displacement control at a rate of 1 mm/min until catastrophic failure was observed. The failure was manifested by significant load drop in load displacement graph. The computerized control system of the mechanical testing machine was used to record the load and displacement data continuously throughout the test. The initial mechanical testing set-up used is shown in Figure 3.

In all the tests reported, the specimen failure occurred in or around its gage section. The testing data was converted to excel sheets and analyzed carefully after completing the mechanical testing.

Stress-strain graphs for each specimen in each configuration were plotted and were carefully analyzed. It was noted that the scatter in the data lied in the range of 3 - 5% for all the specimens tested in room temperature conditions.

Figure 3. Mechanical testing at room temperature for Group 1 and Group 2 test specimens

4. 2. Mechanical Testing for Group 3 and 4 Samples Specimens were mounted in the grips of compression jig as shown in Figure 2. The high temperature environmental chamber was used as shown in Figure 4 for high temperature testing on Zwick 1478 machine. The specimens were mounted in the compression jig. The load cell was protected keeping them outside the environmental chamber. The chamber used for present testing maintained the gage section of the test specimens at the required test temperature during the mechanical testing. All the specimens (Dry and Wet) reported for high temperature (80 °C) were performed on Zwick 1478. Apart from temperature, all other specifications were kept same as reported in the subsection 4.1.

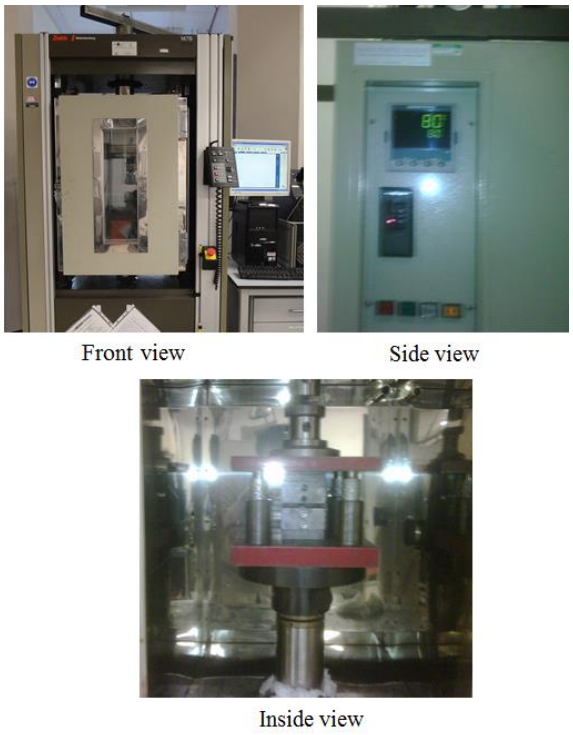

Figure 4. Fixture used for mechanical testing at high temperature for Group 3 and 4 test specimen

5. TEST RESULTS AND DISCUSSIONS

A typical stress strain graph for the 0^o fiber orientation test specimens is shown in Figure 5, where a dry specimen tested at room temperature (22 C) is compared with a graph for the 0^o fiber orientation wet specimen tested at a high temperature (80° C). The curve clearly shows that the failure strength, and Young modulus of the wet specimen have clearly reduced when tested at a high temperature (80° C). The test results show that the exposure of the specimens to the environmental conditions such as high temperature and humidity (water uptake) affects both stiffness and strength of the materials depending on the conditions to which the materials is exposed. It was seen during the testing that wet specimens tested at elevated temperature (i.e. 80° C) produce the worst effect on the material properties as shown in Figure 5.

For strain calculations, the cross-head displacement of the testing machine was used because of the high

temperature testing involved in environmental chamber. The gauge length of the specimen was very small (i.e 10 mm). Summary of the test results for all the four groups in all the three fiber orientations selected have been presented in Table 2.

The specimens immersed in hot water and tested at high temperature (80° C) for fiber orientations of 0º, ±45º and 90º undergone significant compressive strength showed a decrease of 27%, 20 % and 22%, respectively. Decrease in stiffness for 0º, ±45º and 90º fiber oriented specimens were noted to be 6%, 8 % and 8 % for the wet specimens under high temperature testing conditions. Summary of compressive strength reduction for all the test specimens tested under different fiber orientations and environmental conditions is presented in Figure 6.

TABLE 2. Summary of Group 1- Group 4 Test Data

	Fiber Orientation	Mean Fracture Load *kN*	Strength Mean *MPa*	Modulus Mean *GPa*
Group 1	0º	29	1494	16.6
	±45º	7.1	236	1.62
	90º	6.77	197	2.4
Group 2	0º	23	1186	15.89
	±45º	5.2	206	1.54
	90º	4.8	166	2.26
Group 3	0º	25.3	1311	15.97
	±45º	5.9	229	1.57
	90º	5.67	175	2.31
Group 4	0º	21.84	1090	15.51
	±45º	3.5	189	1.49
	90º	3.88	153	2.19

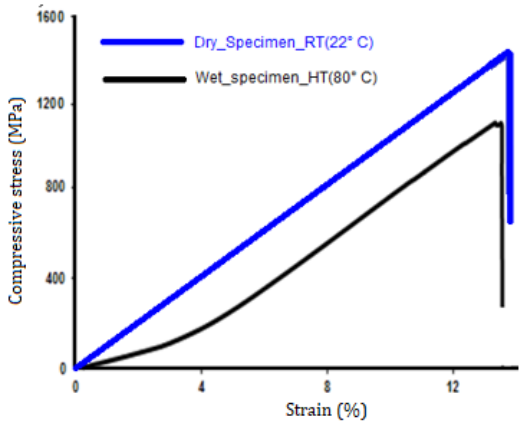

Figure 5. Comparison of 0º fiber orientation test specimens when tested dry and wet at 22° C and 80° C respectively

All the investigated samples failed from their gauge section, showing the validity and reliability of the results for the compression tests. As an example, failure mode in the 90º fiber orientation wet specimens tested at room temperature (22° C) is shown in Figure 7.

Since environmental conditions have played a major role in reducing the strength and stiffness of composite materials. Therefore, it is necessary that studies must be conducted to investigate environmental conditions under realistic conditions. Otherwise, if the environmental conditions are ignored for structural design applications, then there might be a catastrophic failure due to reduction in strength and stiffness.

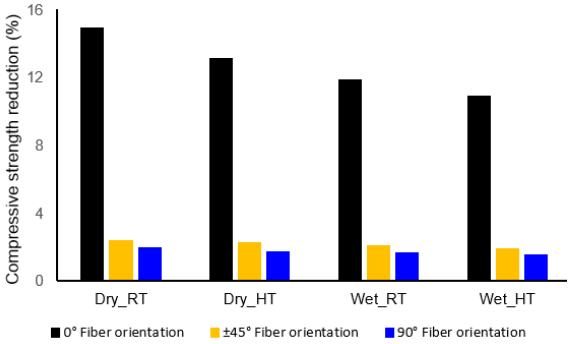

Figure 6. Summary of compressive strength reduction for all the test specimens tested under different fiber orientations and environmental conditions

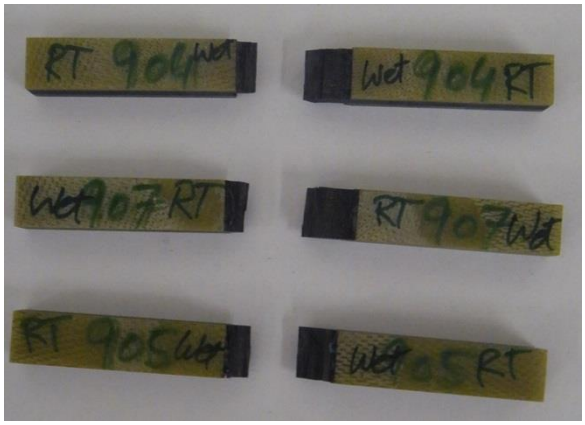

Figure 7. Failure mode in 90º fiber orientation wet specimens tested at room temperature (22° C)

6. CONCLUDING REMARKS

In this work, IM7 /977-2 carbon fiber/epoxy composite samples with different stacking sequences, were manufactured and exposed to different levels of moisture and temperatures to understand the environmental variables effect on their compression behavior. Compressive strength and stiffness of the coupons, with

0°, ±45° and 90° fiber orientations, were determined at room/high temperatures and dry/wet environmental conditions.

The results showed that water uptake in the specimens increased gradually with increase in immersion time. Absorption of water was more significant when its temperature was raised to 80° C. Specimens that were not immersed in water (i.e. dry samples) but were tested under high temperature conditions also experienced degradation in compressive strength. Significant impact on the compressive strength and stiffness was noted on those specimens that were immersed in water and tested at a high temperature (80° C). It was observed that the orientation of the fibers had an effect on the level of mechanical degradation. The largest compressive strength degradation was observed in the unidirectional specimens.

Based on the results, it can be concluded that studies must be conducted under realistic environmental conditions as these can play a significant role in material's behavior. The information from the results can provide necessary input to assess in-field material integrity and develop analytical model as a function of service parameters to predict material behavior.

7. REFERENCES

1. Abdulhameed, A.A., Hanoon, A.N., Abdulhameed, H.A. and Mohaisen, S.K., "Energy absorption evaluation of cfrp-strengthened two-spans reinforced concrete beams under pure torsion", ***Civil Engineering Journal***, Vol. 5, No. 9, (2019).
2. Barzegar, M.H. and Fallahiyekta, M., "Increasing the thermal efficiency of double tube heat exchangers by using nano hybrid", ***Emerging Science Journal***, Vol. 2, No. 1, (2018), 11-19.
3. Ehsan, M.A., Yaqub, M., Khan, M.U., rehman Amir, M.U.A. and Hussain, I., "Effectiveness of prolonged air-recuring on strength of fire damaged rc columns", ***Civil Engineering Journal***, Vol. 5, No. 10, (2019), 2207-2220.
4. Khorramshahi, M.R. and Mokhtari, A., "Automatic construction by contour crafting technology", ***Emerging Science Journal***, Vol. 1, No. 1, (2017), 28-33.
5. Akbarpour, H. and Akbarpour, M., "Finite element modeling of axially loaded cfrp-confined rectangular reinforced concrete columns", ***Civil Engineering Journal***, Vol. 2, No. 8, (2016), 414-425.
6. Mekonnen, B. and Mamo, Y., "Tensile and flexural analysis of a hybrid bamboo/jute fiber-reinforced composite with polyester matrix as a sustainable green material for wind turbine blades", ***International Journal of Engineering***, ***Transactions B: Applications***, Vol. 33, No. 2, (2020), 314-319.
7. Yousefsani, S.A., Tahani, M. and Selahi, E., "Analytical solution of stress field in adhesively bonded composite single-lap joints under mechanical loadings", ***International Journal of Engineering***, ***Transactions C: Aspects,*** Vol. 27, No. 3, (2014), 475-486.
8. Toufigh, V. and Rahmannejad, M., "Influence of curing time and water content on unconfined compressive strength of sand stabilized using epoxy resin", ***International Journal of Engineering***, Vol. 31, No. 8, (2018), 1187-1195.
9. Gellert, E. and Turley, D., "Seawater immersion ageing of glass-fibre reinforced polymer laminates for marine applications", ***Composites Part A: Applied Science and Manufacturing***, Vol. 30, No. 11, (1999), 1259-1265.
10. Chin, J.W., Nguyen, T. and Aouadi, K., "Effects of environmental exposure on fiber-reinforced plastic (frp) materials used in construction", ***Journal of Composites, Technology and Research***, Vol. 19, No. 4, (1997), 205-213.
11. Thwe, M.M. and Liao, K., "Effects of environmental aging on the mechanical properties of bamboo–glass fiber reinforced polymer matrix hybrid composites", ***Composites Part A: Applied Science and Manufacturing***, Vol. 33, No. 1, (2002), 43-52.
12. Li, S., Hu, J. and Ren, H., "The combined effects of environmental conditioning and sustained load on mechanical properties of wet lay-up fiber reinforced polymer", ***Polymers***, Vol. 9, No. 7, (2017), 244.
13. Sathishkumar, T., Satheeshkumar, S. and Naveen, J., "Glass fiber-reinforced polymer composites–a review", ***Journal of Reinforced Plastics and Composites***, Vol. 33, No. 13, (2014), 1258-1275.
14. Afshar, A., Mihut, D. and Chen, P., "Effects of environmental exposures on carbon fiber epoxy composites protected by metallic thin films", ***Journal of Composite Materials***, Vol. 54, No. 2, (2020), 167-177.
15. Brunner, A., Blackman, B. and Davies, P., "A status report on delamination resistance testing of polymer–matrix composites", ***Engineering Fracture Mechanics***, Vol. 75, No. 9, (2008), 2779-2794.
16. Wei, B., Cao, H. and Song, S., "Degradation of basalt fibre and glass fibre/epoxy resin composites in seawater", ***Corrosion Science***, Vol. 53, No. 1, (2011), 426-431.
17. Mouzakis, D.E., Zoga, H. and Galiotis, C., "Accelerated environmental ageing study of polyester/glass fiber reinforced composites (gfrpcs)", ***Composites part B: Engineering***, Vol. 39, No. 3, (2008), 467-475.
18. Kafodya, I., Xian, G. and Li, H., "Durability study of pultruded cfrp plates immersed in water and seawater under sustained bending: Water uptake and effects on the mechanical properties", ***Composites part B: Engineering***, Vol. 70, (2015), 138-148.
19. Pérez-Pacheco, E., Cauich-Cupul, J., Valadez-González, A. and Herrera-Franco, P., "Effect of moisture absorption on the mechanical behavior of carbon fiber/epoxy matrix composites", ***Journal of Materials Science***, Vol. 48, No. 5, (2013), 1873-1882.
20. Almeida, J.H.S., Souza, S.D., Botelho, E.C. and Amico, S.C., "Carbon fiber-reinforced epoxy filament-wound composite laminates exposed to hygrothermal conditioning", ***Journal of Materials Science***, Vol. 51, No. 9, (2016), 4697-4708.
21. Selzer, R. and Friedrich, K., "Mechanical properties and failure behaviour of carbon fibre-reinforced polymer composites under the influence of moisture", ***Composites Part A: Applied Science and Manufacturing***, Vol. 28, No. 6, (1997), 595-604.
22. Barbosa, A.P.C., Fulco, A.P.P., Guerra, E.S., Arakaki, F.K., Tosatto, M., Costa, M.C.B. and Melo, J.D.D., "Accelerated aging effects on carbon fiber/epoxy composites", ***Composites part B: Engineering***, Vol. 110, (2017), 298-306.
23. Korkees, F., Arnold, C. and Alston, S., "Water absorption and low-energy impact and their role in the failure of±45° carbon fibre composites", ***Polymer Composites***, Vol. 39, No. 8, (2018), 2771-2782.
24. Mukhopadhyay, S., Jones, M.I. and Hallett, S.R., "Compressive failure of laminates containing an embedded wrinkle; experimental and numerical study", ***Composites Part A: Applied Science and Manufacturing***, Vol. 73, No., (2015), 132-142.

Persian Abstract

چکیده

تأثیر جذب رطوبت و دمای بالا بر استحکام فشاری رزین‌های کربن/ اپوکسی کربن/ اپوکسی یک طرفه IM7 / 977-2 به صورت تجربی بررسی شده است. آزمونه‌ها به ٤ گروه تقسیم شدند و با تغییر متغیرهای دما و رطوبت، تحت ٤ حالت مختلف آزمایش شدند. جهات انتخاب شده برای استقرار الیاف ۰، ٤٥و ۹۰ درجه بودند. نتایج نشان می‌دهد که مقاومت فشاری، نیروی شکست و مدول فشاری آزمونه‌ها در اثر جذب رطوبت و دمای بالا تخریب می‌شود. بزرگترین تخریب فشاری در آزمونه‌های یک‌طرفه مشاهده شد. علاوه بر این، شدیدترین مورد برای آزمونه‌هایی که در آب غوطه‌ور بودند و در دمای ۸۰ درجه‌ی سانتی‌گراد آزمایش شدند، مشاهده شد. کاهش مشاهده شده در قدرت بسته به زاویه‌ی استقرار الیاف، زمان غوطه‌وری و دمای آزمایش متفاوت است. نتایج حاکی از اهمیت توجه به متغیرهای محیطی در طراحی سازه‌های کامپوزیتی زیر بارهای فشاری است