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Research Article

Water absorption parameters of glass/epoxy composites based on dimension effect

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ABSTRACT

In this study, the water uptake parameters of S glass/epoxy samples have been assessed experimentally. The glass/epoxy specimens were manufactured by the vacuum assisted resin transfer method (VARIM) have been kept in distilled water and sea water at 25°C and 70°C temperatures for 1000 hours in a hydrothermal aging cabin. The water gain behavior of samples with different length/width (L/w) ratios has been investigated based on criteria such as different water types and different temperatures. Furthermore, the water uptake trend of samples has been assessed analytically based on the Fick's law in addition to the experimental method. The results have shown that the L/w ratio, water type, and temperature have an important influence on the water gain character of glass/epoxy composites. The experimental weight measurements showed that temperature increase was caused to more water absorption in both water types. Furthermore, it was noted the increase in L/w ratio was caused to more water sorption. Moreover, experimental and analytical results have shown that water intake trends consistent in both methods.

1. Introduction

Compared to traditional materials, superior features, for example, high specific strength, high specific stiffness, well corrosion resistance, excellent resistance to chemical attack have increased the interest in composite materials [7,22,23]. However, the high water absorption disadvantage of composite materials compared to traditional materials has led researchers to work on the hydrothermal, hygrothermal aging issues. Many studies have been looked into the water intake character of composite materials, as the water molecules absorbed by the polymer composites play a plasticizer role and disrupt the fiber/resin structure and cause deterioration of the fiber/matrix interface.

The effect of hydrothermal/hygrothermal aging on the mechanical characteristics of composites has been studied extensively in the literature. However, researches on the water gain character based on dimension effect is limited. In this section, the information will be given about similar studies that can be associated with this study.

Boukhoulda et al. [1] studied the moisture gain behavior of glass/polyester samples experimentally and theoretically. Composite samples were kept in hygrothermal conditions with 50°C temperature and 95% relative humidity for 289 days. The moisture gain trend of glass/polyester composites was evaluated according to the Carter-Kibler's model and Fick's law, in addition to experimental study. It was found that Carter-Kibler's model showed excellent accordance with experimental results for this study. Also, the maximum moisture gain ratio of glass/polyester composites was found above 0.7%. Abdel-Magid et al. [2] investigated the aging performance of the E-glass/epoxy samples in hydrothermal conditions. Composites were immersed in distilled water 25°C and 65°C for 500, 1000, and 3000 hours. It was found that an increment in temperature and aging period was caused to an increase in the water intake ratio of composite samples. The maximum weight gain ratio was found as 0.9% and

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1.73% for 500 hours and 1000 hours aging period, respectively at room temperature. Furthermore, the maximum weight gain ratio of samples immersed at 65°C for 3000 hours was found as 7.8%.

Soykok et al. [3] analyzed the aging period and temperature effects on the water sorption character of glass fiber/epoxy composite experimentally. Samples were immersed in water at 50°C, 70°C, and 90°C temperatures for 168 and 336 hours. Moisture uptake ratios did not change with increasing time for 50°C and 70°C temperatures, although the moisture uptake ratio of composites aged at 90°C increased with an increasing aging period. The maximum moisture gain ratios of specimens immersed at 50°C and 70°C were reported as 0.31% and 0.71%, respectively. Also, the maximum moisture ratios of specimens immersed at 90°C were found as 0.76% and 0.97% for 168 and 336 hours aging periods, respectively.

Jiang et al. [4] investigated the hydrothermal/ hygrothermal character of the different parts of the bridge deck was manufactured by glass-fiber-reinforced polymer composite. Composite parts immersed in two different hygrothermal aging condition with 50% and 96% relative humidity at 20°C and 40°C. Further, specimens were kept in water at 20°C and 40°C. The aging period was limited to 24 days for this study. Researchers observed that the maximum moisture uptake ratios and aging behavior of different parts of the glass-fiber-reinforced bridge deck were changed with varied aging conditions and temperature. It was noticed that increased humidity and temperature led to more water absorption. Besides, samples aged in a hydrothermal environment absorbed more moisture than samples aged in a hygrothermal environment.

Jiang et al. [5] assessed the shape factor on the water sorption parameters of the sandwich FRP composite deck. Samples with square and rectangular shapes were exposed to hydrothermal and hygrothermal environments with different temperatures and relative humidity degree. At the end of 250 days immersing time, researchers observed that the maximum water gain ratio of square samples kept in water (20°C) and 50% relative humidity (20°C) was bigger than rectangular samples. However, it was found that the maximum water gain ratio of square samples kept in water (40°C) and 96% relative humidity (40°C) was smaller than rectangular samples.

Chakraverty et al. [6] investigated the water sorption character of the glass fiber reinforced epoxy (GRE) samples by using hydrothermal and hygrothermal aging conditions. The E-glass/epoxy composites were aged in distilled water at 65°C for 120 days and exposed to hygrothermal condition with 95% relative humidity at 60°C for 90 days. Similar water sorption tendencies were noticed for both hydrothermal and hygrothermal aging conditions. The maximum water intake ratios were found as 1.642% and 1.682% for hydrothermal and hygrothermal aging conditions, respectively.

The effect of aging in sea water and distilled water on the water uptake character of glass/vinyl ester samples was investigated by Larbi et al. [21]. Composite samples aged at 40°C in both water types. It was revealed the sea water absorption rate of composites kept in sea water was higher than composites kept in distilled water. Maximum water gain ratios of samples were nearly 1.3% and 0.8% for sea water and distilled water aging, respectively.

Mourad et al. [8] assessed the hydrothermal aging influence of the glass composites by using different resin systems. Glass/epoxy and glass/polyurethane composite samples aged in sea water at 25°C and 65°C for 12 months. The weight gain rate of both composite groups was recorded to increase as the aging period increased. The maximum water gain ratios were found as 2.5% and 5% for glass/epoxy samples aged at 25°C and 65°C, respectively. Further, the maximum water gain ratios were found as 3.2% and 4.7% for glass/ polyurethane composites aged at 25°C and 65°C, respectively.

Bulut et al. [20] investigated the influence of nano-particle inclusion on the mechanical, thermal, and water intake behavior of intraply carbon/aramid samples. It was reported from the study the inclusion of nano-silica and nano-clay was caused to more water absorption.

In summary, since the water/moisture absorbed by composite materials disrupts the structure of the fiber/resin system, many studies have been conducted by researchers on how much water/moisture composites absorb in different environments. In these studies, many ideas have been developed on criteria such as water types, temperature, and aging time. However, these criteria have not been studied based on the dimension effect in the literature. Furthermore, it is essential to examine water absorption behavior in order to guess not only the outcomes of the water absorbed, but also how to minimize water sorption. Hence, the hydrothermal aging effect on the glass/epoxy composites based on dimension effect has been evaluated in this study. Two composite groups with different L/w (length/with) ratios were exposed to distilled water and sea water for 1000 hours. The water absorption behavior results of glass/epoxy composites were evaluated with criteria such as temperature and water type based on L/w ratio.

2. Materials and Procedures

2.1 Materials

In this study, plain woven S-glass fabric, with an areal density of 202 g/m^2, was used as a reinforcement phase in the composite. Also, an epoxy MGS L 285 resin with MGS H 285 hardener was used as a matrix system. The properties of reinforcements and resin systems are illustrated in Table 1 and Table 2, respectively. The reinforcement materials were provided from Dost Kimya, Istanbul, Turkey.

2.2 Manufacturing Process

The vacuum assisted resin infusion method (VARIM) was used to create the composite specimens in this study. The composite samples were fabricated at laboratory conditions by twelve ply laminates of plain-woven glass fabrics. The resin/curing agent ratio was used at a ratio of 100/40 according to the manufacturer's recommendation. The epoxy and curing agent was mixed for 5-10 minutes with a special apparatus attached to the mixer at 1000 rpm. The designation of VARIM method and manufacturing process are showed in Figure 1 a) and b), respectively.

Table 1. Mechanical and physical properties of reinforcements

Material	Specifications	Dimensions
Glass Fabric	Areal Density	202 g/m^2
	Fabric thickness	0.15 mm
	Tensile Strength	3000-5000 (MPa)
	Elastic Modulus	72-82 (GPa)

Table 2. Physical properties of resins systems

Material	Specifications	Dimensions
MGS L 285	Density	1.18-1.23 g/cm^3
	Viscosity	600-900 mPa.s
MGS H 285	Density	0.94-0.97 g/cm^3
	Viscosity	50-100 mPa.s

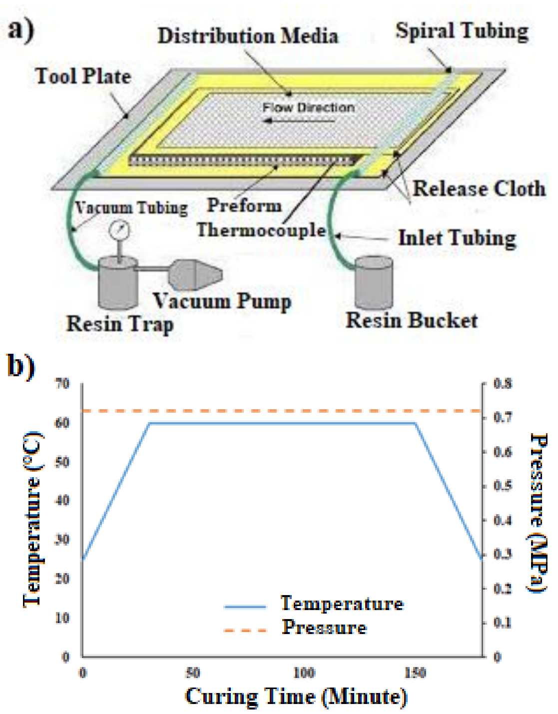

Figure 1. a) Designation of VARIM method [9] b) Production process

The composite plates were produced as 350×500 (mm2) plates. Samples of each test class were simultaneously produced to avoid different plate thicknesses. The test specimens were cut with the help of the CNC router based on the two different L/w ratios. By keeping the length measurement constant, composite samples with 2 different widths were cut as L/w ratios were 10 and 15. The thickness of glass/epoxy samples was recorded as 2.24±0.02 mm.

2.3 Hydrothermal Aging

The glass/epoxy samples were kept in sea water (SW) and distilled water (DW) at 25°C and 70°C temperatures for 1000 hours. Because of the geographical position, there is not able to obtain seawater continuously from the sea, artificial sea water was created using natural sea salt with a density of 3.5 percent, based on the average global ocean salt concentration. Since this rate deteriorates due to heating, periodical rate control has been performed with a suitable densitometer, and water and salt have been added as needed. The aging cabin is illustrated in Figure 2.

To prevent restriction of water absorption during the test, the samples that would be immersed in water before the test was not sandpapered due to the sandpapering process could prevent water absorption. Furthermore, to maximize the water absorption, a suitable separator was used to prevent the contact of the samples in order to achieve water sorption from all surfaces.

Depending on ASTM D5229/D5229M-14 [10], hydrothermal aging was performed in which the water absorption amount M_t can be determined as below

$$M_t = \frac{m_t - m_0}{m_0} x100 \quad (1)$$

where m_t and m_0 are the weight at time t and the first weight of the specimen, respectively.

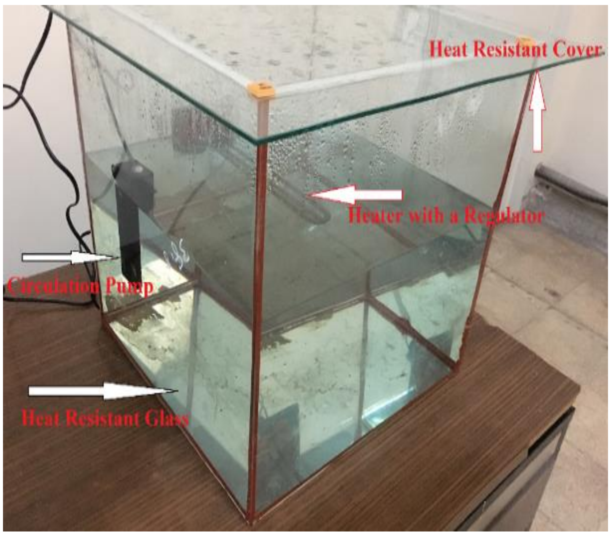

Figure 2. Hydrothermal aging cabin

Furthermore, using Fick's law as a theoretical basis, the water sorption potential of samples was determined. With thickness h, Fick's law yields the following equation [11].

$$\frac{M_t}{M_m} = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left[\frac{-(2n+1)^2\pi^2 Dt}{h^2}\right] \quad (2)$$

where M_t and M_m are the water gain at time t and the overall water gain at equilibrium plateau, respectively and D is the diffusion coefficient.

Shen and Springer [12] simplified the equation 2 based on Dt/h^2 ratio as:

$$\frac{M_t}{M_m} = \left\{\frac{4}{h}\sqrt{\frac{Dt}{\pi}} \qquad for\ \frac{Dt}{h^2} < 0.05 \quad (3)\right.$$

$$\frac{M_t}{M_m} = \left\{1 - \frac{8}{\pi^2} exp\left[-\frac{\pi^2 Dt}{h^2}\right] \qquad for\ \frac{Dt}{h^2} > 0.05 \quad (4)\right.$$

The diffusion coefficient (D) of samples can be determined using the following formula:

$$D = \pi\left(\frac{h}{4M_m}\right)^2 k^2 \quad (5)$$

where k is the initial slope of the plot M_t versus square root of time, $\sqrt{t}$.

Due to the water intake experiments involve water intake from all surfaces, the estimated value of D from equation (5) causes to mistake [13,14]. For the correct diffusion coefficient, a correction factor can be calculated for the edge effect, so the corrected diffusion coefficient D_c can be counted as;

$$D_c = D\left(1 + \frac{h}{L} + \frac{h}{w}\right)^{-2} \quad (6)$$

where w and L are the width and length of the sample, respectively [14].

A nomenclature is given to the samples showing the parameters studied. For instance, 15-DW25 is a specimen that was manufactured with an L/w ratio of 15 and aged in distilled water at 25°C temperature, whereas 10-SW70 is a specimen that was manufactured with an L/w ratio as 10 and aged in sea water at 70°C temperature.

3. Results and Discussions

The theoretical mass change line (Mt) and experimental mass change line (Me) of glass/epoxy composites immersed in hydrothermal conditions at 25°C and 70°C are illustrated in Figure 3 and Figure 4, respectively. The water uptake lines of samples were plotted against the square root of an aging period in figures.

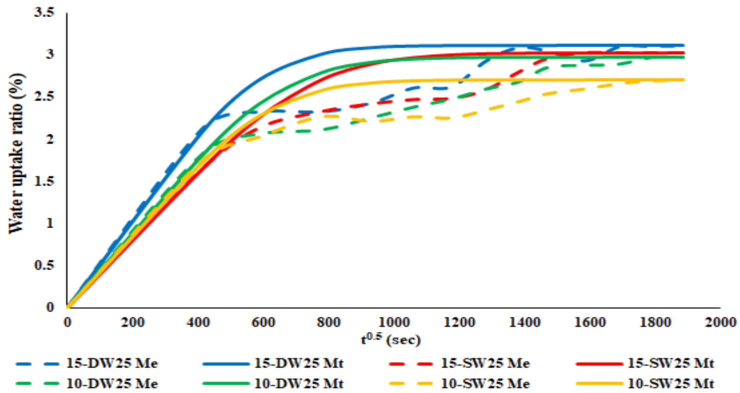

Figure 3. Water uptake ratio of composites aged at 25°C

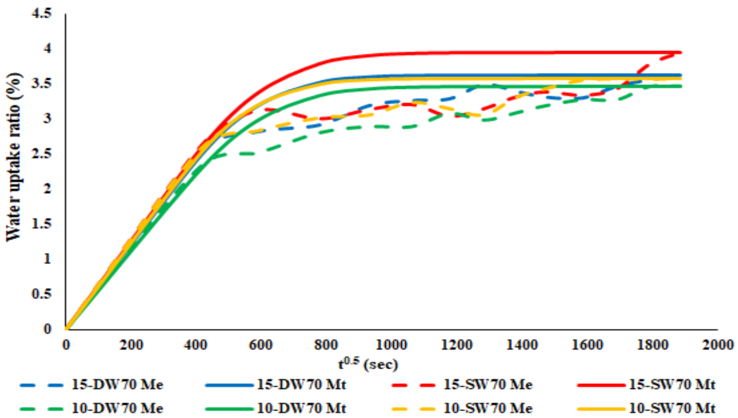

Figure 4. Water uptake ratio of composites aged at 70°C

It is clear from Figures 3 and 4 that water uptake rates of composites are time-dependent. The findings revealed the water sorption of glass/epoxy samples increased rapidly in the early period of the aging period. As the aging time prolonged, the rate of water absorption started to decrease and gradually approached the near saturation point. The main reasons for this situation can be explained as void/pore presence on the composite surface and the difference in humidity between the composite material and the aging environment [15].

Furthermore, it is clear from Figure 3 and Figure 4 that experimental and analytical weight gain ratio showed compatible results each other. For both temperature and water types based on L/w ratio, glass/epoxy composites showed a Fickian like absorption tendency. The small discrepancies between experimental and analytical mass changes of samples can be associated with integrative effects of the matrix, micro-pores, and interface between fiber/matrix are present [16].

When the two groups with different L/w ratios were evaluated separately, it was seen that the temperature increase directly affected the increment of the maximum water gain rate of glass/epoxy composites for both water types, as seen in Figure 5. The high temperature was caused to deteriorate the resin/matrix system. Deterioration of fiber/matrix interface was caused by to increase of voids/pores at high temperature [2]. One of the most significant considerations that disrupts the matrix and fiber/matrix structure is high temperature. Cracks and voids tend to increase in structures that deteriorate at high temperatures. Excessive water absorption occurs as voids and cracks fill with water [17].

Moreover, the comparison of distilled water aging and sea water aging results revealed that samples aged at 25°C absorbed more distilled water, while samples aged at 70°C absorbed more sea water, with negligible weight gain ratio differences. It can be said the overall water intake rates of glass/epoxy samples are not exact results. Because the immersing period of samples was limited as 1000 hours for this study. Hence, further immersing period can change the small differences between distilled water and sea water results. The more sea water sorption can be associated with the pH level that causes micro-cracks in the matrix [21]. The amount of water that fills the micro-cracks causes the sea water to be absorbed more. In addition, since salt particles restrict the free movement of sea water molecules [13,18], it has been observed in some studies in the literature that sea water absorption is less than distilled water.

The periodical weight measurements showed that the L/w ratio of composite samples has directly affected the water absorption of the samples. Glass/epoxy samples with different L/w ratio aged under the same conditions showed that increase of L/w ratio was caused to more water absorption in both water types and temperatures, as seen in Figure 5. The maximum water gain ratios for distilled water aging were found as 3.106% and 2.965% for 15-DW25 and 10-DW25, respectively. The similar water uptake trend was noticed for sea water aging at 25°C. The maximum water gain ratios were found as 3.025% and 2.701% for 15-SW25 and 10-SW25, respectively. Furthermore, the experimental measurements revealed that the difference between the maximum water absorption amounts of composite samples with different L/w ratio was greater at 70°C compared to 25°C. The maximum water gain ratios for distilled water aging were found as 3.621% and 3.464% for 15-DW70 and 10-DW70, respectively. A similar water gain trend with distilled water aging was observed in sea water aging at 70°C. The maximum water gain ratios for distilled water aging were found as 3.955% and 3.580% for 15-SW70 and 10-SW70, respectively.

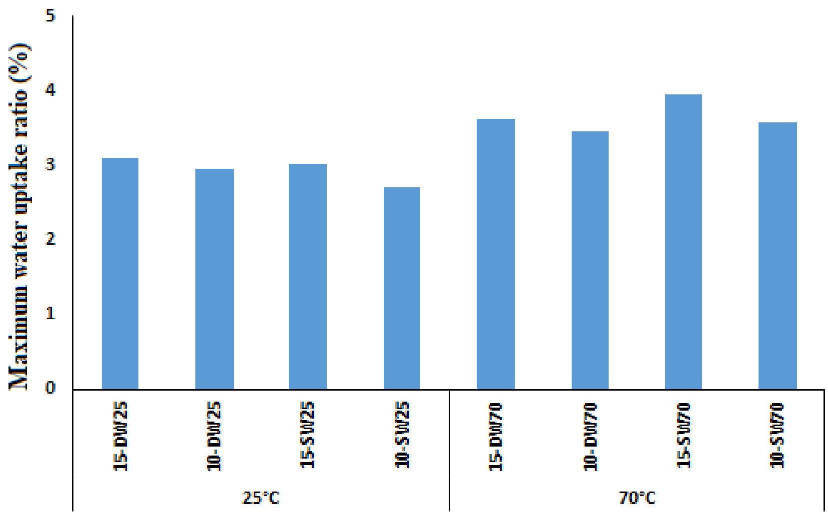

Figure 5. Maximum water uptake ratio of glass/epoxy composites

The diffusion coefficient (D) that displays how much water molecules can penetrate the composite samples is one of the most major factors of Fick's model [19]. Although the diffusion coefficient results did not give regular results as well as the results of the maximum water absorption rate, they showed consistent results in itself. Increasing L/w ratio of glass/epoxy composites aged at both temperatures in distilled water was caused an increase in diffusion coefficient values. The findings showed results consistent with the literature [4,5]. However, sea water results showed the opposite trend from distilled water aging results. The diffusion coefficients of glass/epoxy composites are displayed in Figure 6.

The diffusion coefficients of composites aged at 25°C temperature were found as 2.706 *10-6, 2.187 *10-6, 1.733 *10-6 and 2.848 *10-6 for 15-DW25, 10-DW25, 15-SW25 and 10-SW25, respectively. In addition, the diffusion coefficients aged at high temperature showed a similar tendency with 25°C. The diffusion coefficients of composites aged at 70°C temperature were found as 2.962 *10-6, 2.424 *10-6, 2.541 *10-6 and 3.152 *10-6, for 15-DW70, 10-DW70, 15-SW70 and 10-SW70, respectively.

The corrected diffusion coefficients (Dc) of composite samples were found as smaller than diffusion coefficients as expected because of edge factor, as seen in Figure 6. Further, the Dc of composites showed a similar trend with D results. Increase of L/w ratio was caused to increase of Dc values for distilled water aging whereas, an opposite tendency was observed in sea water aging results. The corrected diffusion coefficients of glass/epoxy samples immersed in distilled water were found as 1.916 *10-6, 1.732 *10-6, 2.086 *10-6 and 2.234 *10-6 for 15-DW25, 10-DW25, 15-DW70 and 10-DW70, respectively. In addition, the corrected diffusion coefficients of composite samples immersed in sea water were found as 1.227 *10-6, 1.919 *10-6, 1.799 *10-6 and 2.483 *10-6 for 15-SW25, 10-SW25, 15-SW70 and 10-SW70, respectively.

4. Conclusion

In this study, the water sorption parameters of glass/epoxy samples based on dimension effect were investigated. The results revealed that water type, temperature and L/w ratio of samples affected the water sorption behavior of glass/epoxy samples. It was observed that maximum water absorption rates of glass/epoxy specimens immersed in distilled water were higher than specimens immersed in sea water in all conditions. Further, the experimental results showed that temperature increase was caused to more water absorption in both water aging conditions. Besides, the experimental and analytical weight measurements showed consistent results. Also, the increase of L/w ratio was caused to more water absorption in both water types and temperature. The overall water intake ratios of samples aged at 25°C were found as 3.106%, 2.965%, 3.025%, and 2.701% for 15-DW25, 10-DW25, 15-SW25, and 10-SW25, respectively. In addition, the maximum water intake ratios of samples at 70°C were found as 3.621%, 3.464%, 3.955%, and 3.580% for 15-DW70, 10-DW70, 15-SW70, and 10-SW70, respectively. Moreover, the increase of L/w ratio was caused to increase of diffusion coefficient of specimens immersed in distilled water. However, the decrease of L/W ratio was caused to increase of diffusion coefficient of specimens immersed in distilled water. As a result, the effect of sample sizes on water absorption, which is an important parameter for design, has been observed in this study.

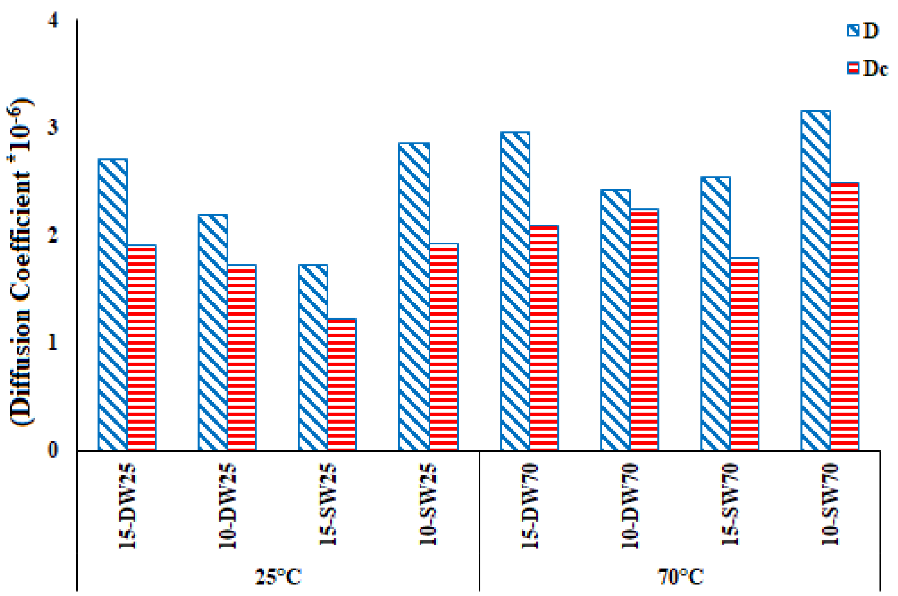

Figure 6. Diffusion coefficients of glass/epoxy composites

Declaration

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article. The author(s) also declared that this article is original, was prepared in accordance with international publication and research ethics, and ethical committee permission or any special permission is not required.

Author Contributions

Z.A. Oğuz: Investigation, methodology, writing original draft preparation. A. Erkliğ: Investigation, supervision, writing, reviewing and editing.

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