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Compressive Mechanical Properties and Water Absorption of Glass fiber-reinforced Plastics Pipes Aged in Caspian SeaWater

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ABSTRACT

Glass fiber-reinforced plastics (GFRPs) have been widely used in marine structures, recently. In this paper, the water absorption and compressive behaviour of pultruded fiber-reinforced plastic pipes (GFRPs) after immersion in Caspian sea water and distilled water for 1, 7, 14, 21, 28, 35, and 40 days is experimentally investigated. In this respect, the specimens are submerged in Caspian seawater and distilled water and then their water absorption rate, length, and their compressive strength were measured every day. The compressive mechanical properties of the specimens in the as-received and water-aged states are obtained using quasi-static compression tests. The amount of water absorption and length change due to immersion in these two cases have also been investigated. After 40 days, the average relative humidity absorption of the samples in Caspian Sea water and distilled water were 2.88% and 2.89%, respectively. It was observed that after immersion in both Caspian Sea water and distilled water, the final compressive strength and absorbed energy of the pultruded pipes increased.

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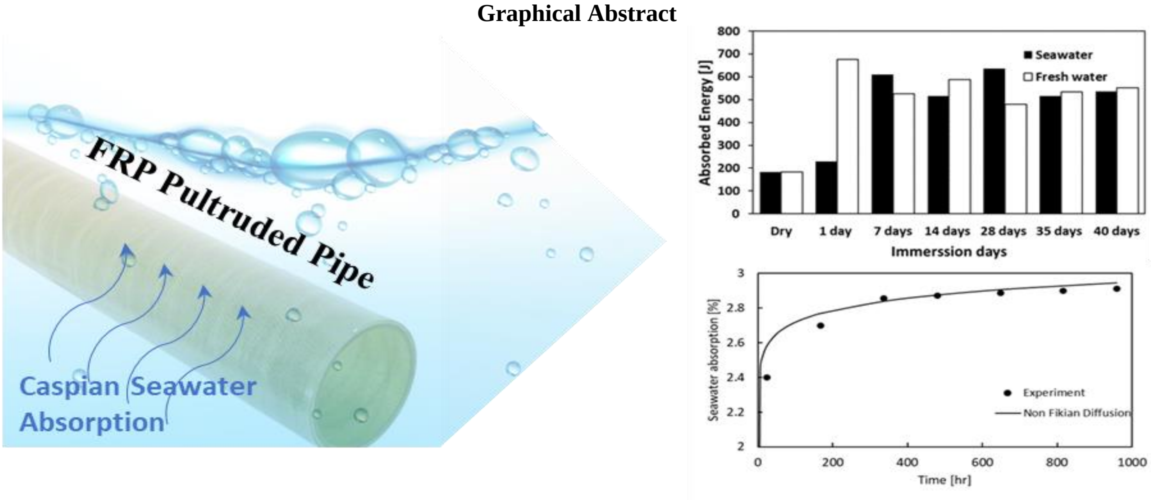
Graphical Abstract



NOMENCLATURE

m_t	mass of specimens after immersion	m_0	mass of specimens before immersion
M_i	percentage of moisture absorbed	W_i	weight of the sample in the ith stage
W_b	initial weight of the sample	C	moisture concentration
z	thickness	D_z	diffusion coefficient

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1. INTRODUCTION

Fiber-reinforced plastics (FRPs) have been used in marine structures since the 1940s (1). In a marine environment, the polymer-based matrix will absorb water and its strength might significantly decrease; moreover, the interface strength between the fibers and matrix might adversely decline with respect to time due to aging in water or seawater. Given that the FRP marine structures are designed to withstand various severe load cases, it is of great importance to understand the aging process of marine FRP in different environments. It is also observed that the composite geometrical dimensions changes when they absorb water. This study investigated the changes in weights, compressive mechanical behaviors and geometrical properties of pultruded GFRP pipes after immersion in seawater.

Therefore, many researchers have conducted studies on how water absorption may affect the strength of fiber-reinforced plastics. The first serious discussions and analyses of the problem emerged during the 1970s when Ishai (2) studied the effect of cyclic water exposure on the weight gain, length change, and tensile strength deterioration of unidirectional Glass-Fiber-reinforced Plastics (GFRP). A literature review demonstrates that, after Ishai (2), many researchers have experimentally studied the effect of distilled water absorption on the mechanical properties of the various ranges of fibrous composites, including Carbon fiber reinforced polymer (CFRP), GFRP, and basalt fiber-reinforced polyme (BFRP). In some experiments, after exposure to distilled water, there was no change in the strength of the specimens. For instance, Selzer and Friedrich (3) observed that the strength of the FRP composite did not change in the direction parallel to the fibers. Similarly, Zulueta et al. (4) concluded that water absorption did not change the strength of the carbon fiber-reinforced epoxy panels. On the contrary, many researchers observed that the mechanical properties of the water-aged composites were decreased due to the matrix and matrix-fiber interface degradation (5, 6).

Having studied the effect of distilled water on FRPs, it is also of great importance to know the seawater effect on composite marine structures. In recent years, there has been an increasing amount of literature on the effect of seawater on the mechanical properties of marine composite structures. Wood and Bradley (7) considered two different seawater exposure conditions, one saturated specimen and a specimen immersed in water 80 days after saturation. They observed that the cracks are more difficult to initiate in the aged specimen rather than in the intact specimen. Jeshti and Nayak (8) proposed a new hybrid CFRP and GFRP laminated composite to increase the durability of the composite's structures exposed to seawater. They succeeded in decreasing the hybrid composite seawater diffusivity by 44%. Li et al. (9) immersed the CFRP specimens in artificial seawater with different salt concentrations for 7 months. They found that the tensile strength was sensitive to aging duration, while the salinity of the water did not change the tensile strength of the CFRP. Abdallah et al. (10) investigated the shear behaviour of beams reinforced with GFRP bars in seawater. They studied the effect of fiber reinforcement fraction. Gani et al. (11) also studied the water absorption in membrane of chitosan-resveratrol.

In addition to the studies above, there has been an increasing amount of literature on the mechanical properties of composite pipes, profiles, and piles in water and seawater. Shao and Kouadio (12) observed that composite piles immersed in 20°C and 70°C water would gain and lose weight respectively. The weight loss in 70°C water was due to leashing out some of the material. Ellyin and Maser (13) studied the multi-axial strains in FRP pressurized vessels which were immersed in water. Like Shao and Kouadio (12), they saw that the structure's strength loss is proportioned to the water temperature. They also noted that the swollen wet matrix can cause stress in the structures. Yao and Ziegmann (14) and d'Almeida et al. (15) conducted a series of tests to evaluate the strength of FRP pipes immersed in distilled water. They identified that the mechanical properties of the FRP pipes degrade by immersion in the distilled water. Liao et al. (16) conducted the flexural strength test on pultruded GFRP samples immersed in 70°C water, two different salt solutions. They observed that the salt concentration did not have much effect on flexural strength. Akil et al. (17) used distilled water, seawater, and acidic solutions at room temperature for a period of up to 3 weeks. They compared the strength of jute fiber-reinforced unsaturated polyester composite exposed to a different aqueous environment. Hawa et al. (18) studied water-aging at high temperatures and its effect on the impact and bursting strength of E-glass fiber/epoxy composite pipes. They proposed that the hyperbolic tangential method is a better method to model water absorption in pipes. Eslami et al. (19) modeled the transient moisture diffusion of E-glass fiber-reinforced Vinyl Ester composite pipes fabricated by a filament winding machine and investigated the buckling strength of aged specimens. Silva et al. (20) studied the flexural and radial compression of composite pipes aged in various fluids and observed that the compressive strength of the pipes was reduced, while the flexural strength of the pipes increased after 60 days. Mei et al. (21) studied the moisture absorption and compressive strength in the hygrothermal environment for a composite lattice core sandwich panel. They concluded that the failure modes did not change by aging time, while the strength of the sandwich panel decreased with aging time and temperature.

From the literature review, it is clear that various studies have assessed the tensile and flexural strength reduction due to immersion in aqueous solutions. While there remain several aspects of water immersion effects on compressive strength which relatively little is known about it. Recently, Li et al. (22) and Liu et al. (23) presented a review of the research on the aging and environmental effects on the mechanical performance of composites. They concluded that water and seawater may cause matrix plasticization and –matrix-fiber debonding and decrease the strength of the composites immersed in water. They argued that –matrix-fiber debonding can affect the compressive strength of the composite structures more than the tensile strength. Thus, it is important to study this failure mode, while the study on this subject is rare. However, researchers have not studied compressive strength change due to immersion in water and seawater in much detail. On the other hand, the Caspian Sea is one of the important inland water bodies, and its water's ionic composition is different from that of open seawaters (24), and the standard solutions are not appropriate to model its effect on the structures. Thus, the objective of this study is to investigate the ultimate compressive strength of pultruded FRP pipes in an in-situ condition, in which, the specimens are immersed in Caspian seawater and distilled water for 1, 7, 14, 21, 28, 35, and 40 days and after that, their water absorption, length change, and ultimate compressive strength are measured. In this article, cylindrical samples of GFRP (pultruded) were immersed in distilled Caspian sea water, the edges of the sample were sealed. The purpose of this article is to study the water absorption behavior of composite materials and compare the compressive strength and absorbed energy before and after It was immersion

2. MATERIALS AND METHODS

In this study, the compressive mechanical behaviors of pultruded GFRP pipes, from the Asia Composite Company in Iran, in as-received conditions as well as after immersion in Caspian seawater and distilled water for 1, 7, 14, 21, 28, 35, and 40 days were investigated by conducting quasi-static compression tests. The pipes' diameter and thickness are 50 mm and 5 mm, respectively. The test procedure is conducted in the following steps (Figure 1), and then the results of the experiment were extracted and analyzed:

1. The test specimens are cut from commercial pultruded FRP pipes to 50 mm specimens in length.
2. The specimens are immersed in the Caspian seawater and distilled water at ambient temperature for 1, 7, 14, 21, 28, 35, and 40 days.
3. Before and after the immersion test, the specimens are weighed and their dimensions are measured using a Vernier scale.
4. The quasi-static crushing tests are conducted for as-received, water-aged, and Caspian seawater-aged

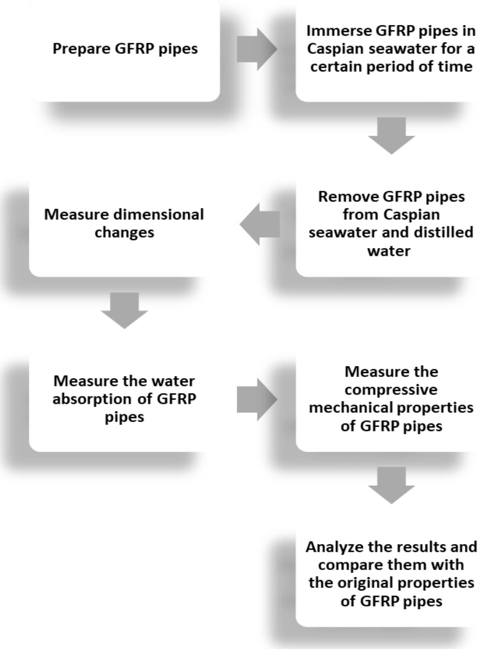

Figure 1. The test procesure

specimens using the SANTAM compression test instrument.

The water absorption for the test specimens at each day is calculated as follows:

$$M_i = \frac{m_t - m_0}{m_0} \times 100 \quad (1)$$

m_0 and m_t are the mass of specimens before and after immersion in (sea)water for t hours.

Moisture penetration inside most composites follows Fick's law Equation 2:

$$\frac{\partial c}{\partial t} = D_z \frac{\partial^2 c}{\partial c^2} \quad (2)$$

where c is the moisture concentration of the sample (g/mm), (t) time (s), (z) the thickness of the sample (mm) and D_z is the diffusion coefficient along the thickness (mm^2/s). By solving Fick's second law with the help of boundary conditions, two practical relationships 3 and 4 are obtained to find the weight gain percentage:

$$M(T,t) = M_b + G(T,t)(M_b - M_b) \quad (3)$$

$$G(T,t) = 1 - exp\left[-7.3\left(\frac{D_z(T)t}{h^2}\right)^{0.75}\right] \quad (4)$$

With the help of Equation 3, the moisture content of the material is obtained at different temperatures and times, and Equation 4 is the moisture absorption function, where M_b is the initial moisture absorption rate and M_m is the moisture absorption rate in the saturated state. If only one side of the sample is in contact with the environment, instead of using parameter h as thickness, 2h is used in equation G. To predict the amount of penetrant at time t, it is necessary to have the values of D_z and M_m. By calculating the slope, the linear part of the graph of weight gain in terms of the root of immersion time can be used to obtain the value of D with the help of Equation 5, and the horizontal asymptote of the graph also determines the value of M_m (25).

$$D_z = \pi\left(\frac{h}{4M_m}\right)^2\left(\frac{M_2-M_1}{\sqrt{t_2}-\sqrt{t_1}}\right)^2 \tag{5}$$

In relation 6, h is the thickness of the sample (mm), Mm is the percentage of equilibrium moisture, M_1 is the percentage of moisture at time t_1, M_2 is the percentage of moisture at time t_2, and D_z is the permeability coefficient of the composite. According to Figure 1, an increase in weight percentage is A maximum limit is reached and over time, the rate of moisture absorption increases and decreases, which is the reason for the filling of voids, cracks, and holes in the composite.

The diffusion mechanisms were divided into three: (1) typical behaviour according to Fick's law; when n = 0.5; and (2) when n = 1. the composites rapidly achieved water balance and maintained it as the immersion duration increased. the n was between 0.5 and 1 for anomalous diffusions. the water absorption diffusion mecha-nism was determined using the kinetic parameters of the slope (n) and intersection (k), which were obtained from the initial linear portion of the water absorption curve (log(Mt/Max) vs. log (t))

$$\log(\frac{M_t}{M}) = \log(k) + n\log(t) \tag{6}$$

Our samples did not match the Fickian sample, so we used the non-fickian method according to Equation 6.

3. RESULTS AND DISCUSSION

Figures 2 and 3, which show the relative content of water after immersion in distilled water and Caspian sea water, show the relative amount of water after immersion in distilled water and Caspian sea water at equal time intervals. Each data point represents the relative content. water in a certain period of time. Analyzing the general trend of the curve can provide insight into the water absorption behavior of the material. If it is increasing, it indicates that the material absorbs more water over time. The steepness of the curve, it shows water absorption. A steeper curve indicates rapid water absorption, while a gentler curve indicates slower absorption, until the material has reached its maximum water absorption capacity. It indicates that the materials have reached equilibrium with water. This means that further immersion does not significantly affect the relative water content. It can be concluded that the amount of saturated water is the same for both cases (aged in Caspian Sea water and distilled water), while the water absorption process is faster for samples in Caspian Sea water before saturation. After saturation, the average relative humidity of the samples in Caspian sea water and distilled water is 2.88% and 2.89%, respectively.

The change in length due to water absorption may cause additional stresses or create geometric defects in the structures. Therefore, the length change after immersion is also studied. Figure 4 shows the relative length change after immersion in Caspian Sea water and distilled water.

It shows the relative length change of the samples that were exposed to immersion in Caspian Sea water and distilled water. Each data point represents the relative length change after immersion in Caspian Sea water and distilled water. By comparing the length change The ratio of each substance in Caspian sea water and distilled water, the effect of these two liquids on the dimensional stability of the materials can be evaluated. A higher data point for Caspian Sea water indicates that the material has experienced a greater length change in seawater than in distilled water, and vice versa. The relative length change can be positive or negative, depending on whether the material expands after immersion. or contracted. Positive values indicate an increase in length and negative values indicate a decrease in length. Samples in Caspian Sea

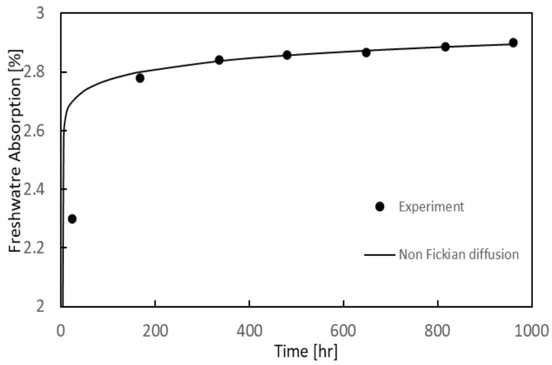

Figure 2. Relative water content after immersion in distilled water

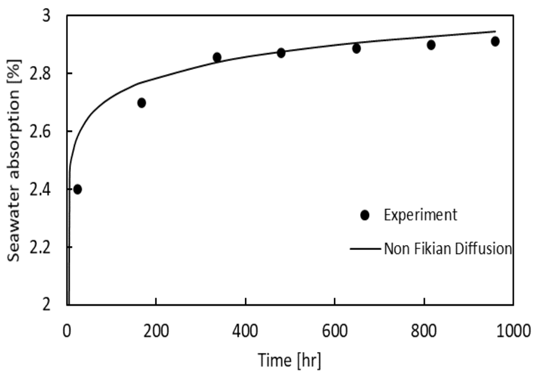

Figure 3. relative water content after immersion in Caspian seawater

water increased to 1% of their length in 14 days, and then their length remained almost unchanged. On the other hand, the length of samples aged in distilled water increases in the first 14 days, and then their length decreases until the final length is 1% shorter than the initial length. The reduction in the length of the pipes is due to the washing of material at both ends of the cut. The color change at both ends of the cut and the significant reduction of their local stiffness at both ends of the cut confirm this assumption.

In this study, a quasi-static compression test is performed using the SANTAM compression test instrument, which applies displacement at a constant rate of 5 mm/min to one end of the specimen and measures the applied load. The displacement load diagram obtained for aged samples in distilled water and Caspian sea water are shown in Figures 5 and 6, respectively. It can be the physical displacement or deformation of a substance or object. It shows the amount of force applied to the object. Each data point represents a specific measurement of force and displacement. The line shows the trend or relationship between force and displacement. By examining the trends of data points or lines, the relationship between force and displacement can be determined. The curved line represents a non-linear relationship.

The diagram can provide insight into the behavior of materials under external forces. Initially, the line or data points may show a linear relationship indicating elastic deformation. When a certain point is reached, the line may begin to curve or the data points may deviate, indicating plastic deformation where the material undergoes permanent deformation. The graph can identify the maximum force and displacement. Help the material before it breaks or becomes permanently deformed. This can be determined by the point at which the line level turns off or the data points do not increase.

The damage modes under the compressive loads for all the specimens aged in seawater and distilled water were the same. At first, at the bottom and top of the specimen small cracks started to grow and with a

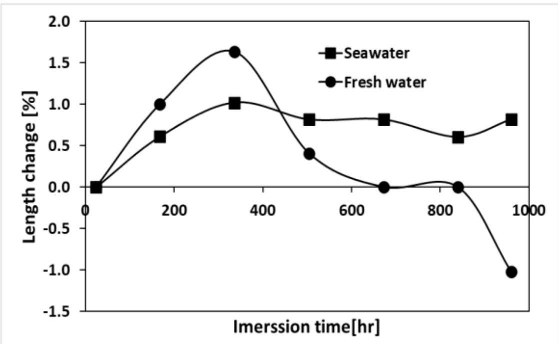

Figure 4. Effects of Distilled Water and Caspian Seawater on the Relative Length of Immersed Materials

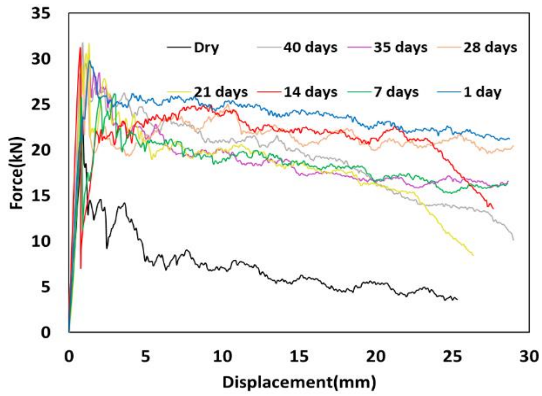

Figure 5. Force-displacement diagrams for specimens after n days in Caspian seawater

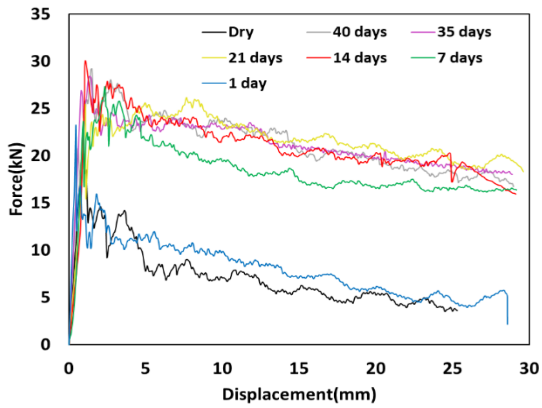

Figure 6. Force-displacement diagrams for specimens after n days in distilled water

cracking sound, the load gets to the ultimate load. Then the load decreased drastically and cracks grew larger and the fiber-matrix debonding occurred. The damage modes for a typical specimen are shown in Figure 7.

The mechanical properties of the aged specimens in seawater and distilled water under compression are obtained by quasi-static axial compression tests.

The ultimate compressive strength (σ_{ult}), and absorbed energy (EA) are calculated from the force-displacement diagrams for each specimen. From the force-displacement diagram, the nominal ultimate compressive strength of the specimens can be calculated and is equal to:

$$\sigma_{ult} = \frac{P_{max}}{A} \tag{7}$$

in which, Pmax and A are the first maximum force in the force-displacement diagram and the cross-section area of the specimen, respectively. The nominal ultimate compressive strength for aged specimens in Caspian seawater and distilled water is shown in Figure 8. The nominal ultimate compressive strength of the aged specimens is increased in both cases after some days in

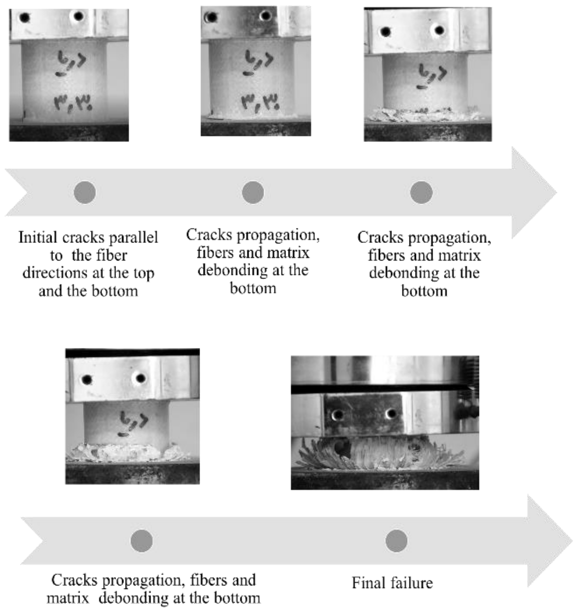

Figure 7. The failure modes and damage propagation in a specimen after one day of submersion in Caspian seawater

the water and after that, it remains almost constant, but it is notable that in distilled water the ultimate compressive strength increases faster. Figure 8, which shows the ultimate compressive strength. It is usually measured in units of pressure such as megapascals(MPa). It represents the maximum compressive stress that a material can withstand before failure. Each data point represents the ultimate compressive strength for a particular sample. By comparing the values of the data points, the relative strength of different materials can be evaluated in terms of compressive strength. The material with the highest ultimate compressive strength has the highest data point.

The other important parameter that can be derived from the force-displacement diagram is absorbed energy and can be calculated as follows:

$$EA = \int P . du \tag{8}$$

in which, P and u are the force and the displacement in the force-displacement diagram. The absorbed energy is increased for aged specimens in both cases in comparison to the as-received specimen. However, the ultimate compressive strength of the aged specimens in distilled water is increased after one day of immersion. The amount of energy absorbed during the crushing test vs the immersion time in distilled water and Caspian seawater is plotted in Figure 9; the amount of absorbed energy is increased in both groups. However, from the force-displacement diagram (Figures 5 and 6), it can be deduced that the elastic modulus of the specimens, remains almost the same. An increase in the absorbed energy is due to the increase in average crushing force for all specimens.

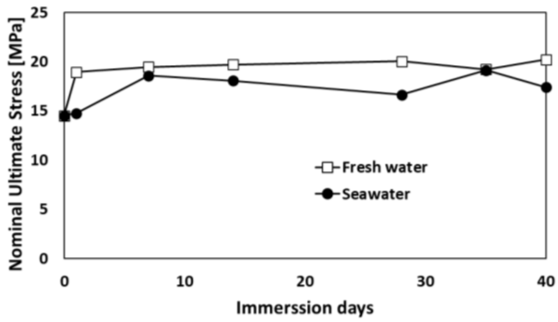

Figure 8. Ultimate compressive strength of pultruded pipes after immersion in Caspian seawater and distilled water

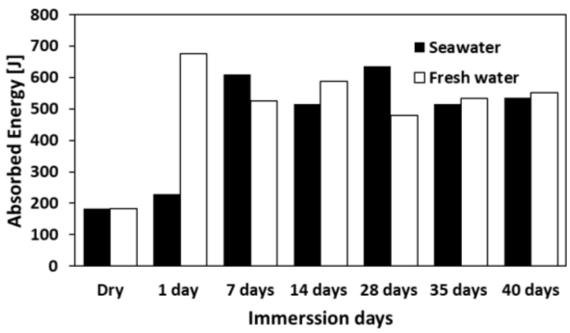

Figure 9. Absorbed energy during compression of pultruded pipes after immersion in Caspian seawater and distilled water

Increasing the nominal ultimate compressive strength and absorbed energy can be explained by Zhou and Lucas' theory [26]. The absorbed water in the polymeric matrix of the GFRP material can create two types of hydrogen bonds within the epoxy structure. These bonds seem to improve the compressive mechanical behavior of the Pultruded FRP pipes. Das et al. [27] in thier work, E GFRP samples have used to monitor the moisture absorption behavior. The amount of water absorption is almost the same, but the slope is different It was observed that after immersion in both Caspian sea water and distilled water, the final compressive strength and absorbed energy of the filled tubes increases.

4. CONCLUSIONS

This paper presents the ultimate compressive strength and energy absorption of pultruded fiber reinforced plastic pipes (GFRPs) after immersion in Caspian sea water and distilled water for 1, 7, 14, 21, 28, 35 and 40 days. It was investigated experimentally by performing quasi-static compression tests with the SANTAM tool. After saturation, the average absorption of relative humidity of the samples in Caspian sea water and distilled water were 2.88% and 2.89%, respectively. The amount of water absorption, length change and final compressive strength were measured. The samples are immersed in Caspian sea water and distilled water for a certain period of time. By comparing the length change of the ratio of each material in Caspian sea water and distilled water, the effect of these two liquids on the dimensional stability of the materials can be evaluated.The samples in the Caspian sea water increased to 1% of their length in 14 days and then their length remained almost unchanged. On the other hand, the length of samples aged in distilled water increases in the first 14 days and then their length decreases until the final length is 1% shorter than the initial length. The damage modes under compressive loads were the same for all aged specimens in seawater and distilled water. It is noteworthy that the ultimate compressive strength increases faster in distilled water. The ultimate compressive strength of aged samples in distilled water increases after one day of immersion. The amount of absorbed energy increases in both groups.The ultimate compressive strength of all pultruded pipes immersed in Caspian seawater and distilled water is increased after saturation. And after 7 days it stays almost unchanged. The absorbed energy is also increased for both distilled water and Caspian seawater and after saturation, it stays almost constant as well.

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Persian Abstract

چکیده

اخیراً پلاستیک های تقویت شده با الیاف شیشه (GFRPs) به طور گسترده در سازه های دریایی مورد استفاده قرار گرفته است. این مقاله، مقاومت فشاری نهایی لوله های پلاستیکی تقویت شده با الیاف pultruded (GFRPs) پس از غوطه وری در آب دریای خزر و آب مقطر به مدت ۱، ۷، ١٤، ۲۱ ارائه شده است. ، ۲۸، ۳۵ و ٤٠ روز با انجام تست های فشرده سازی شبه استاتیکی با ابزار SANTAM به صورت تجربی بررسی می شود. خواص مکانیکی فشاری نمونه ها در حالت های دریافتی و پیری آب با حل قانون دوم فیک با کمک شرایط مرزی به دست می آید. میزان جذب آب و تغییر طول ناشی از غوطه وری در این دو مورد نیز بررسی شده است. پس از اشباع، میانگین جذب رطوبت نسبی نمونه ها در آب دریای خزر و آب مقطر به ترتیب ۸۸ / ۲ درصد و ۸۹ / ۲ درصد است. پس از آن، خواص فشاری نمونه های غوطه ور در دو مایع اندازه گیری و مقایسه می شود. یک آزمایش فشاری شبه استاتیک انجام شده و مقاومت فشاری نهایی و جذب انرژی مورد ارزیابی قرار می گیرد. مشاهده شد که پس از غوطه ور شدن در هر دو آب دریای خزر و آب مقطر، مقاومت فشاری نهایی و انرژی جذب شده لوله های پرشده افزایش می یابد.