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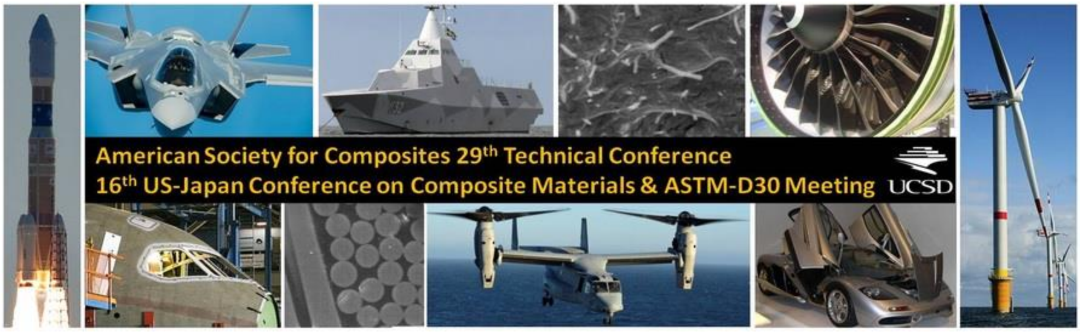

Title: **Durability of E-glass/Vinyl Ester Composite Structures and Their Modeling in ABAQUS**

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ABSTRACT

The use of fiber-reinforced polymer composite materials (FRP) in various applications such as aerospace, automotive, sports equipment, and oil and gas industries has been growing in recent years. Nonetheless, the potential use of FRP pipes in harsh environmental conditions of oil and gas industry-related applications could become significantly greater if there was minimal degradation to the mechanical and physical properties of the materials used to form the pipes. The feasibility study of this potential, however, requires several systematic investigations for assessing the long-term durability of glass fiber-reinforced polymer composite pipes.

This paper presents results from our preliminary investigation on the response of E-glass/Vinyl ester composite pipes aged in water and seawater at various temperatures. Scanning electron microscopy is used to assess the material's response, and ABAQUS simulations are used to assess the capacity of the modeling software to predict the moisture absorption process in E-glass/Vinyl ester composites using a diffusion module. As the results obtained in the experiments and ABAQUS simulations have good agreement, ABAQUS can be used to simulate the long-term durability of E-glass/Vinyl ester composite pipes exposed to humid environments.

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INTRODUCTION

Due to their desirable properties and performance, polymer matrix composites (PMCs) have been used as construction materials for corrosive and submarine environments over the past few decades. Likewise, glass fiber-reinforced polymer composites (GFRPs) have been widely used in the oil and gas industry due to their superior corrosion-resistant characteristics. In comparison with other conventional materials, GFRPs offer better mechanical properties, including high strength and stiffness-to-weight ratio [1, 2]. To better understand the effects of environmental conditions such as moisture and temperature on the properties of GFRPs as well as their long-term life, the response of these composites should be assessed in their actual applications.

The moisture absorption behavior of GFRPs has been extensively studied due to its considerable influence on the weakening of the fiber-matrix interface strength and consequent mechanical degradation of the composites [3, 4]. The properties of a composite are defined by the strength of the fiber-matrix interfacial bond [5-7]. Moisture diffusion has several effects on the matrix element of a composite such as plasticization and softening, which can lead to the deterioration of its mechanical properties [8-11]. It is reported that there are major differences between the mechanical properties of initial specimens and others that were exposed to similar environmental conditions [12]. Several investigations have proved that water uptake in glass fiber-reinforced polymer composites consists of three stages: penetration of the water molecules into the resin and fibers; diffusion of the water molecules along the fiber-resin interface; and the movement of water through voids (and other damage).

It has been documented that the mass absorption rate of GFRP plates aged in distilled water is higher than that in salt water. Consequently, the weight gain percentage of specimens exposed to distilled water is greater than that in specimens immersed in seawater. These findings were attributed to the existence of ions and their atomic weight in salt water [13].

Vinyl Ester resin is highly suited to marine-environment construction owing to its superior properties such as chemical stability and corrosion resistance. Thus, we chose it as a matrix material for our tubular composite specimens.

The main objective of this investigation is to examine the influence of aqueous environments on the properties of Vinyl Ester-GFRP pipes. In order to conduct the experimental study, glass fiber-reinforced Vinyl Ester composite tubes were placed in three different aqueous conditions. Subsequently, scanning electron microscopy (SEM) was used to compare the physical changes that occur among fibers, matrices, and fiber-matrix interfaces.

In this research, the moisture diffusion into glass fiber-reinforced vinyl ester composite pipe is simulated and comparisons of the experimental data and ABAQUS results are reported. Our study assessed whether or not FEA software could accurately predict the saturation times of specimens immersed in aqueous conditions.

THEORETICAL BACKGROUND

Fick’s equation can be used to compute the moisture absorption characterization of fiber-reinforced polymers (FRPs). The following equation develops Fick’s law to determine the mass of absorbed moisture in substances [14, 15]:

$$\frac{M_{\%}}{M_{\infty}} = 1 - \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp[-D(2n+1)^2\pi^2 t/h^2] \qquad \text{(1-a)}$$

The following relation demonstrates the simple form of the previous solution:

$$\approx 1 - \exp\left[-7.3(\frac{Dt}{h^2})^{0.75}\right] \qquad \text{(1-b)}$$

where M% and M∞ are the moisture weight gain at the aging time t and saturated condition, respectively, h and D are the thickness of the specimen and diffusion coefficient, respectively.

The absorbed moisture percentage versus the square root of time curve can be used to measure the diffusion coefficient of the diffusion phase. The following equation calculates the amount of D [1]:

$$D = \pi\left(\frac{h}{4M_{\infty}}\right)^2\left(\frac{M_2 - M_1}{\sqrt{t_2} - \sqrt{t_1}}\right)^2 \qquad \text{(2)}$$

where t_1 and t_2 are the times that could be selected from every point of the first linear part of the curve, M_1 and M_2 are the mass of the moisture uptake, corresponding to t_1 and t_2, respectively.

TEST PROCEDURE

In this study, three groups of glass fiber-reinforced vinyl ester composite tubular specimens were immersed in a humid environment. Each group included nine specimens with a height, radius and thickness of 10 cm, 5 cm and 1.5 mm, respectively. Three different environmental conditions were used for the immersion, including water at room temperature, water at 2°C, and seawater at room temperature. ASTM D5229 standard [16] was employed to calculate the percentage of mass absorption during the aging time in order to examine moisture uptake behavior.

In addition, SEM pictures were captured from saturated and unsaturated specimens to assess the physical changes that occurred during the aging of the fracture surfaces.

EXPERIMENTAL RESULTS AND DISCUSSION

Absorption Behavior

The following equation can be used to measure the mass of absorbed moisture of specimens exposed to humidity:

$$M_t = \frac{m - m_0}{m_0} 100\% \tag{3}$$

Where M_t is the moisture uptake percentage at time t, m_0 is the mass of the initial dry specimen, and m is the mass of the aged specimen at time t.

Table 1 indicates the saturation time for each environment, showing that decreases in aging temperature lead to increases in saturation time. Furthermore, comparisons between water and seawater environment data reveal that the saturation times of the composite tubes in seawater are shorter than those in a water environment.

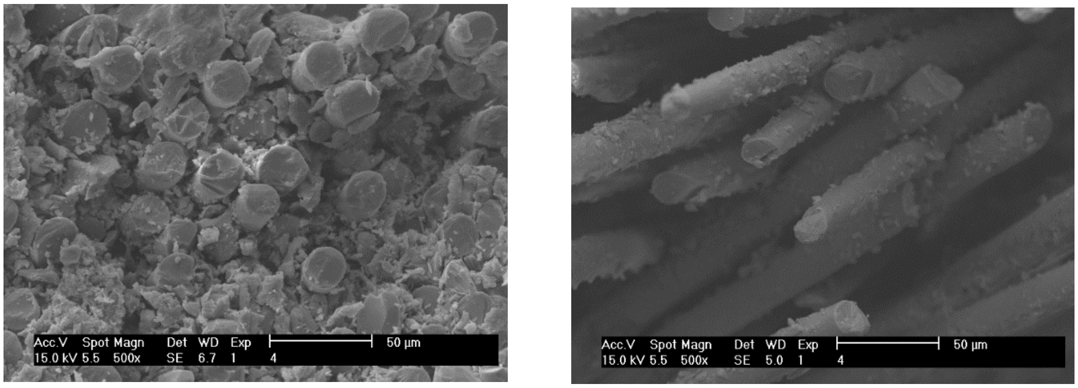
Table 1: The experimental results

Environment	Aging Temperature (°C)	Number of Specimens	Saturation Time (Days)
Water	25°C	9	212
Sea Water	25°C	9	185
Water	2°C	9	285

Microscopic Analysis

Scanning electron microscopy was used to compare the microstructural changes of the unsaturated and saturated specimens. Figure 1 illustrates the fracture surfaces of a glass fiber-reinforced vinyl ester composite at two typical stages before and after saturation: the initial dry condition (Figure 1(a)), and the specimen that was subjected to seawater at its saturation level as an example of the saturated condition (Figure 1(b)).

The adequate cohesion between fibers and matrices of the virgin specimen is shown in Figure 1(a). It should be noted that when the specimen was exposed to a humid environment, the fiber-resin interface weakened. This phenomenon worsened when the specimen reached its saturation level, considerably degrading the interfacial bond (Figure 1(b)).



(a) (b)

Figure 1: Comparison between fracture surfaces of an (a) initial dry specimen and (b) a saturated specimen in seawater

SIMULATION OF MASS DIFFUSION PROCESS BY FINITE ELEMENT METHOD

The moisture absorption of a glass fiber/vinyl ester composite pipe was modeled through finite element analysis using ABAQUS version 6.12. A mass diffusion analysis was used in order to simulate the process. ABAQUS applied an extension of Fick's law for the governing equation of the mass diffusion step.

Fick's equation often defines the mass diffusion process as follows [17]:

$$J = -D.\frac{\partial c}{\partial x} \tag{4}$$

ABAQUS uses Fick's law as a particular case of the general chemical potential solution. The following formula demonstrates the connection between Fick's law and the general chemical potential [17]:

$$J = -D.\left(s\frac{\partial \phi}{\partial x} + \phi\frac{\partial s}{\partial x} \right) \tag{5}$$

In most real cases where $s=s\ (\Theta)$, the above equation could be written as [17]:

$$J = -sD.\frac{\partial \phi}{\partial x} - D.\frac{c}{s}\frac{\partial s}{\partial \theta}\frac{\partial \theta}{\partial x} \tag{6}$$

Normalized concentration and temperature-driven diffusion are defined by two terms of the above relation, respectively.

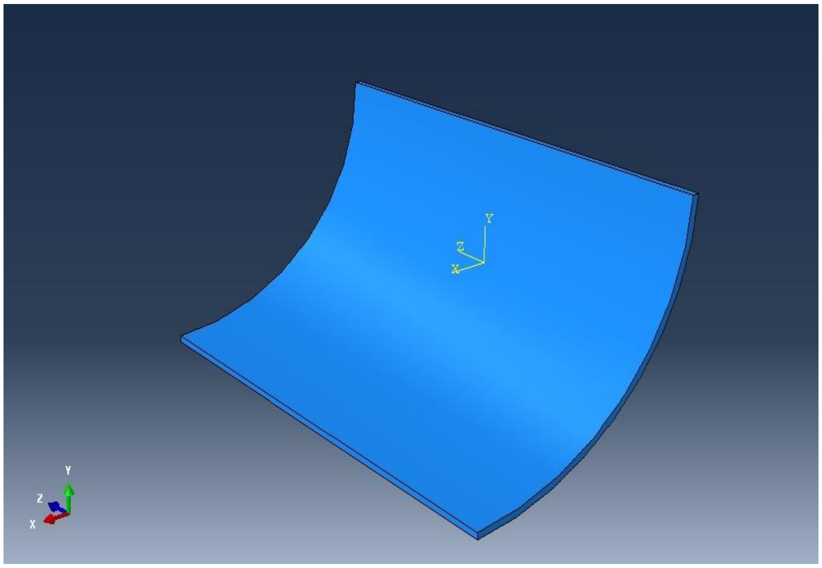


Figure 2: A quarter of the modeled specimen used in mass diffusion analysis

A quarter of the modeled specimen was used in the moisture diffusion simulation due to the symmetry of the model (Figure 2). Variations in the variables could be observed through the thickness of the specimen. In order to use mass diffusion analysis, diffusivity and solubility must first be defined. Diffusivity describes the motion of a substance through another material; in mass diffusion analysis, the normalized concentration of the diffusing material is determined by its solubility [17]. Solubility is calculated in terms of the maximum content of solute dissolved in a solvent at equilibrium, which is called the saturated condition.

In order to specify the concentration value of the regions surrounding the modeled specimen, the mass concentration boundary condition should be defined. Thus, the magnitude of one was applied to the modeled specimen wall, according to [18].

In this FEM simulation, a mesh of the model included 38,400 elements. Moreover, the linear heat transfer/mass diffusion element was selected from an element type family.

Figure 3 indicates the predictions of the FE analysis around the time that the composite specimens become saturated in various circumstances. These are in comparison with the saturation times of the specimens obtained through experimental research. It can be seen that the saturation times of the model can be computed by ABAQUS through the mass diffusion analysis, with a good approximation.

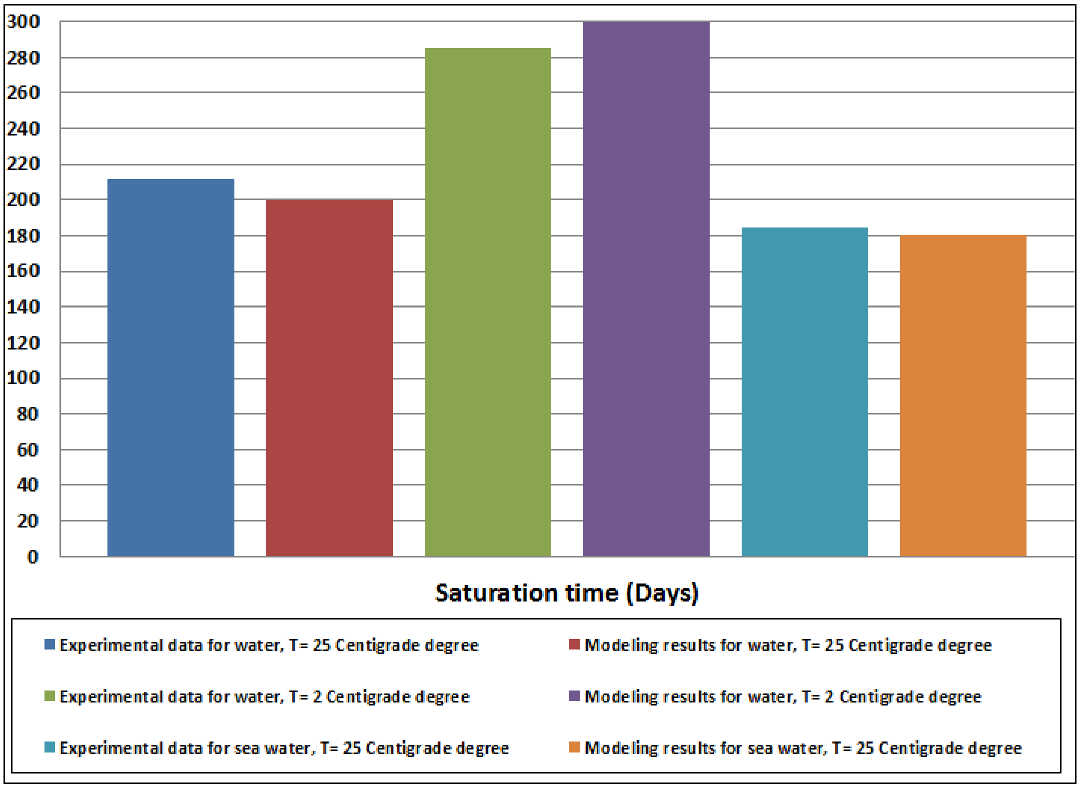
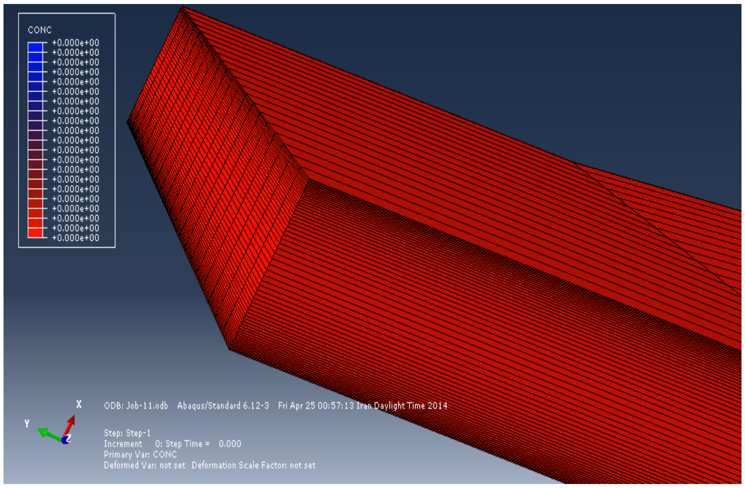
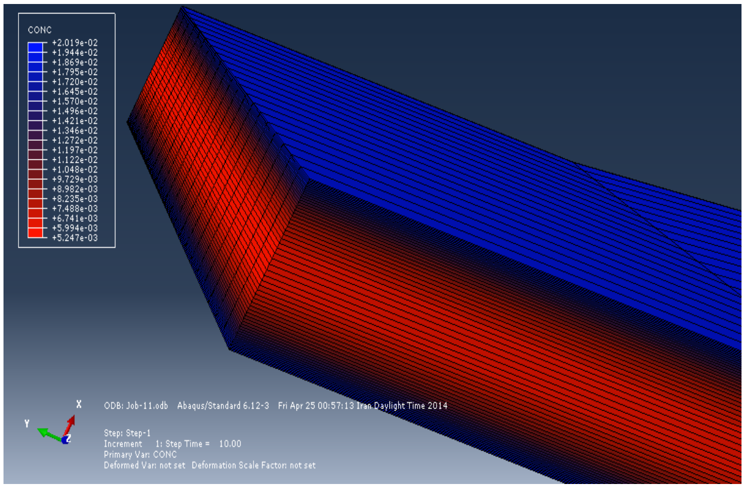


Figure 3: Comparison of saturation time results obtained from experiments and ABAQUS simulations

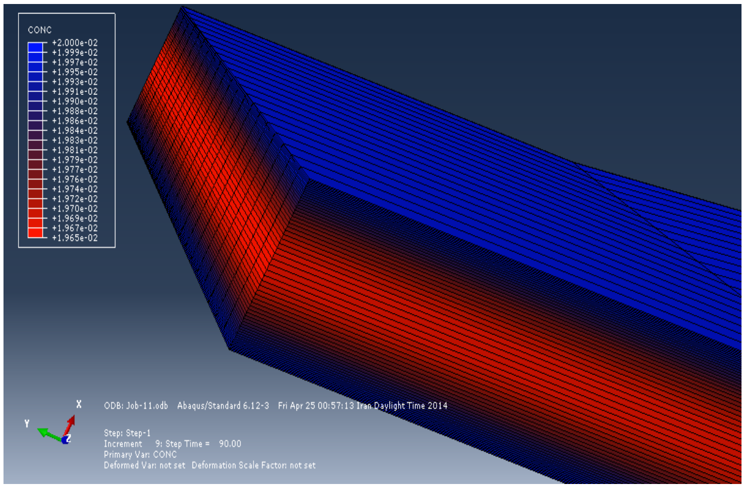
Mass concentration (CONC), mass flow rate (MFL) and amount of solute at an integration point (ISOL) are important outputs of the mass diffusion analysis. Figure 4 demonstrates the distribution of absorbed moisture after various aging times, in the specimen subjected to seawater at room temperature. It can be seen that the absorbed water at the surface layers is at its highest levels, whereas while it passes through the thickness, it decreases and then reaches its lowest at the core. The values of the mas flow rate as a function of the distance along thickness for the saturated specimen aged in seawater at room temperature are indicated in Figure 5, which shows that the mass flow rate decreases as water diffuses deeper though the thickness. The amount of solute at an integration point (ISOL) for the specimen immersed in seawater at its saturated condition is illustrated in Figure 6.



(a) Initial dry specimen



(b) Aged specimen after 10 days



(c) Aged specimen after 90 days

Figure 4: Distribution of absorbed moisture after various aging times in the specimen subjected to seawater at room temperature

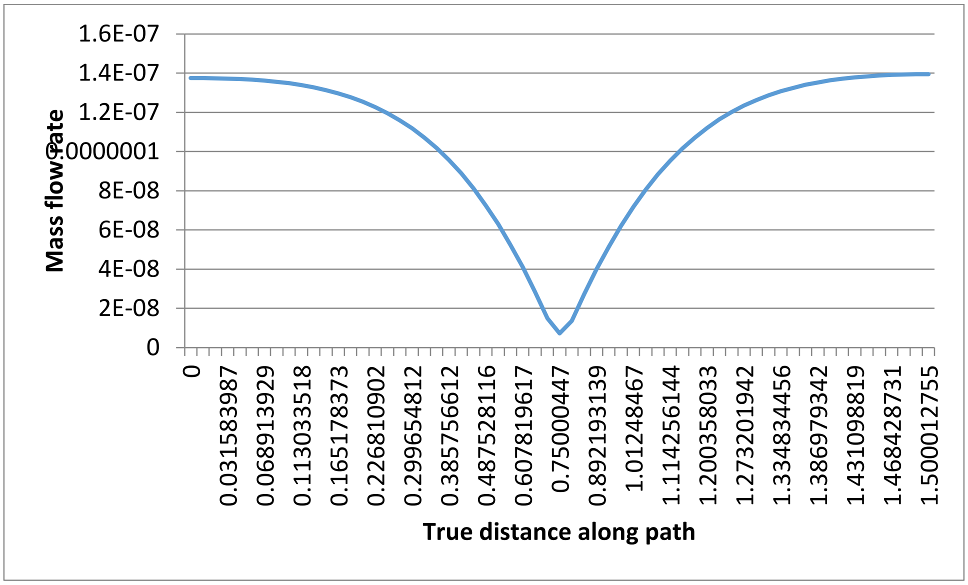


Figure 5: Mass flow rate as a function of the distance along thickness for the saturated specimen aged in seawater at room temperature

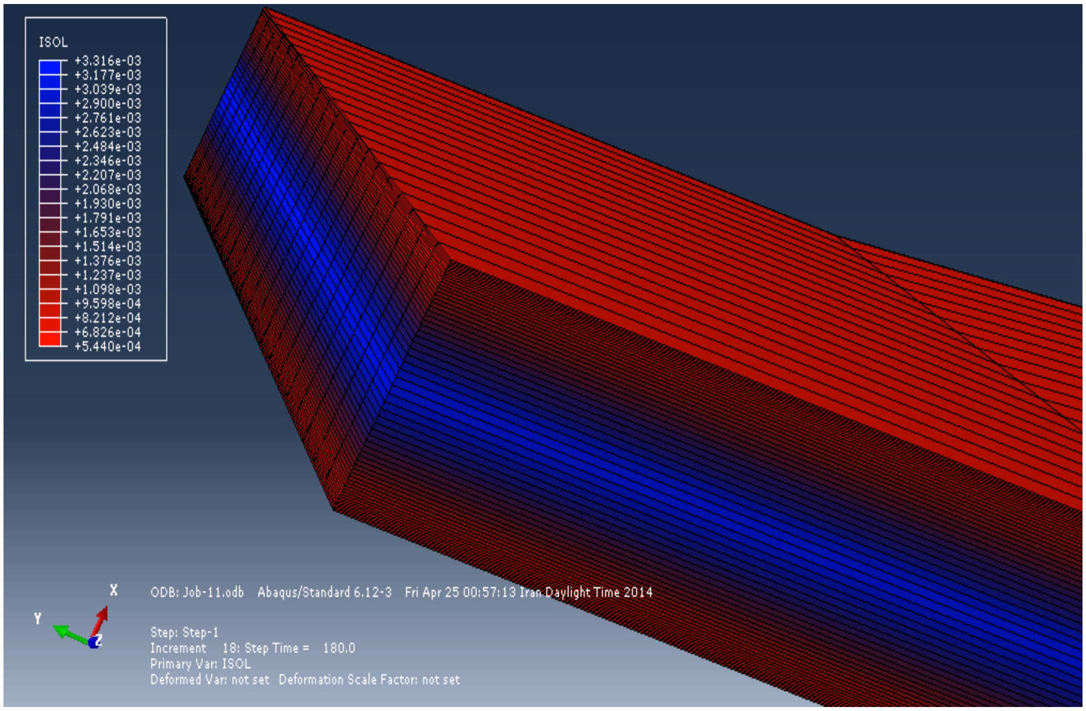


Figure 6: The amount of solute at an integration point (ISOL) for the specimen immersed in seawater at its saturated condition

CONCLUSION

The reliability of Glass fiber-reinforced Vinyl Ester composite pipes in harsh environments was examined in this investigation. Tubular specimens were placed in various humid conditions and their moisture uptake behavior was assessed. Subsequently, SEM images were used to compare the fracture surfaces of the virgin specimen and aged specimen at saturation. Additionally, the moisture diffusion process through E-glass/vinyl ester composite tube was simulated by a finite element method.

The investigations demonstrated that lower temperatures necessitated a longer saturation time than higher temperatures, and that normal water took longer than sea water to achieve saturation.

Furthermore, a comparison between the SEM pictures illustrated that there were essential differences between the strength of the fiber-resin interfacial bonding at the initial dry state compared to the saturated condition.

In conclusion, the results of the saturation times obtained from ABAQUS were shown to be in good agreement with the experimental results. Hence, it has been proved that the FE method could be used to calculate the time that specimens require to reach the saturation point.

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