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Effect of Aggressive Environments on the Strength Characteristics of Glass and Carbon Fiber Composites in the Oil and Gas Industry

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Abstract

The Russian oil and gas pipeline system spans over 290,000 km, transporting water, oil, gas, and petroleum products. While the estimated service life of these pipelines is 30 years, actual durability often ranges from 10 to 20 years due to harsh conditions, with failures occurring even earlier. Enhancing equipment efficiency is crucial, and using innovative materials like metallic and nonmetallic composites could extend operational lifespan. However, the adoption of these materials is hindered by insufficient knowledge of their environmental interactions and a lack of standardized regulatory documentation. In this paper, changes in the strength at break and strain at break of nonmetallic composite materials were investigated after holding of the samples in operating environments with different acidities and chemical compositions, the dependences equations were obtained.

Keywords: Layered nonmetallic composites; Fiberglass; Carbon fiber; Aggressive environment; Corrosion resistance

1. INTRODUCTION

Pipeline transport is one of the most economical and efficient modes of transportation of hydrocarbons. Russia ranks second globally in terms of the total network extension dedicated to fluid transport, encompassing systems for oil, natural gas, water, as well as both primary and subsidiary distribution lines. Also, due to the difficult political situation in Russia, the use of import-substituting technologies to optimize field operating costs and increase production and transportation efficiency has become vital for oil and gas companies. New approaches to the manufacture of equipment, as well as innovative materials capable of resisting aggressive environments, are used to create high-tech equipment.

Layered nonmetallic composite materials are becoming increasingly popular. Unlike structural steels, composites have unique strength properties, low mass (compared to steel), and other characteristics that allow them to be used in various industries [1,2]. Products made of layered composites have specific rigidity and increased endurance to cyclic loads [3,4]. The hydrophilic surface of layered composites makes it possible to prevent the deposition of asphalt-resin-paraffin deposits, salts, and reduce hydraulic resistance [5–7]. The low thermal conductivity of layered composites (on average 100 times lower than that of steels) allows these materials to be widely used in the conditions of the polar region and in permafrost soils [8–11]. Thus, the use of nonmetallic composite materials for the manufacture of tanks, housing of equipment, tubing, pumping rods, casing pipes, main and field pipelines, process pipelines, and working parts of rotodynamic pumps has great prospects [12–18].

Products made of layered nonmetallic composite materials consist of a matrix (epoxy resin, polyester resin), which is a binding material, and various fillers (glass, carbon, basalt fibers), which act as a reinforcing material [19]. The manufacturing process consists of layer-by-layer impregnation of the reinforcing material with resin, pressing to remove excess resin and air bubbles, and further polymerization of the resin [20–22].

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This work is aimed at studying the effect of aggressive operating environment on the strength characteristics of nonmetallic composite materials.

2. MATERIALS AND METHODS

The study was conducted by physical experiment with glass and carbon fiber samples with dimensions of 250×20×5 mm according to GOST (Russian national standard) for tensile testing of polymer composites [23]. The matrix used was epoxy resin ED-20 with hardener Etal-45M, and the filler consisted of carbon fiber and fiberglass of plain weave with a density of 200 g/m².

The process of manufacturing samples using the hand-lay-up process involved the following steps (Fig. 1):

a) cutting layers of fiberglass and carbon fiber to the correct dimensions according to the GOST [23];

b) layer-by-layer impregnation of the material with epoxy resin;

c) removal of any excess resin and air from each layer;

d) drying the samples at room temperature for 7 days under gravity pressure.

To obtain the average values of strength parameters, three samples were made from each material and for each environment. Before the aging process began, the mass of the samples was measured using analytical scales MIDL ML 0.2-I B1J.

Testing substances:

- CH_3COOH solution (pH = 3, 5, 7);
- 5% NaCl solution;
- prepared oil [24].

Time of sample exposure in the operating envi ronment was 10 days, after which the samples were dried at room temperature for 30 days. Before conducting static tests, the mass of the sample was measured. The tensile tests were conducted using a calibrated Shimadzu AGX-V2 universal testing machine, with a tensile speed of 5 mm/sec.

3. RESULTS AND DISCUSSION

According to the results of exposure and static tests, the dependences of the change in strength properties on the operation environment were obtained (Fig. 2).

Fig. 1. Process of sample manufacturing: fiber cutting (top left), impregnation and removing of resin (top right), drying of samples (bottom).

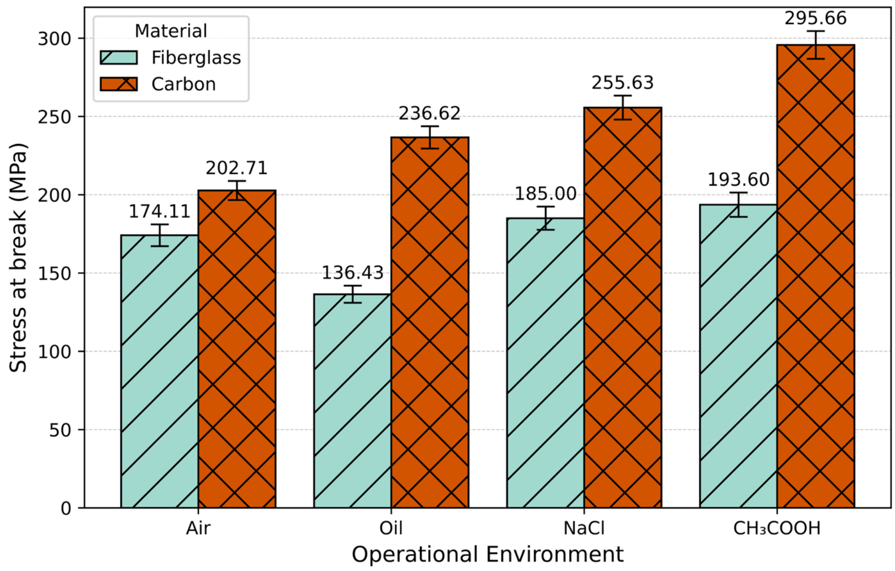

Fig. 2. Change in the stress at break for fiberglass and carbon fiber depending on the holding substances of sample.

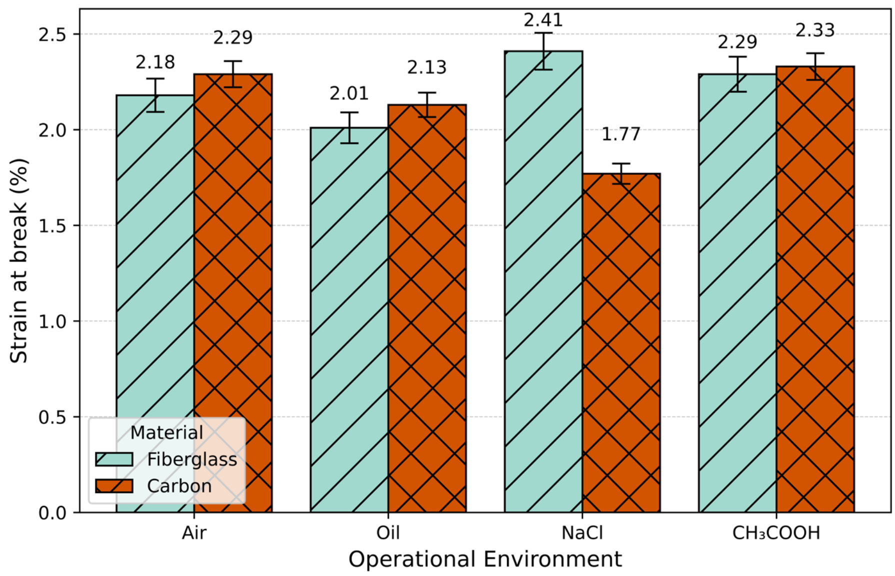

Fig.3. Change in strain at break for fiberglass and carbon fiber depending on the holding substances of sample.

Based on the obtained results, the authors concluded that the stress at break of carbon fiber increased by 16% after exposure to prepared oil, by 26% in NaCl solution, and by 46% in CH_3COOH solution. The stress at break of fiberglass increased by 6% after exposure to NaCl solution and by 11% in CH_3COOH solution; however, after exposure to prepared oil, the stress at break of the sample decreased by 28%.

Additionally, a dependence of the change in material plasticity was obtained, exemplified by the strain at break indicator for layered composites after exposure in various substances (Fig. 3).

The strain at break of carbon fiber increases by 2% after exposure to CH_3COOH solution and decreases by 8% after exposure to prepared oil, while in NaCl solution it decreases by 29%.

The strain at break of fiberglass increases by 10% after exposure to NaCl solution, by 5% in CH_3COOH solution, and decreases by 8% after exposure to prepared oil. The experiment showed that the dependence of changes in strength properties (stress at break and plasticity) has different characteristics for different types of fillers [25–30].

The authors conducted measurements of the change in mass of the samples after exposure to verify the adsorption capacity of layered nonmetallic composite materials (Fig. 4).

After exposure to prepared oil, the mass gain was 1.65% for carbon fiber and 1.23% for fiberglass; in NaCl

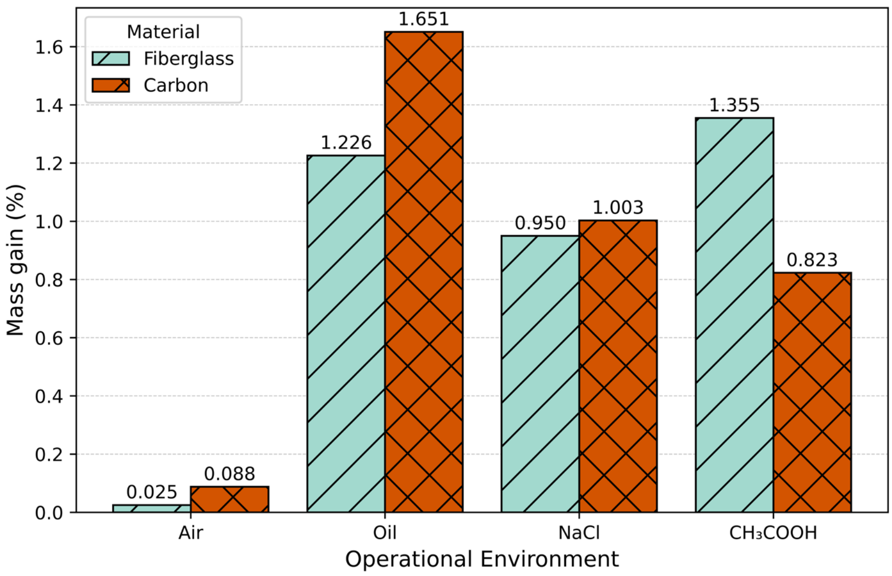

Fig. 4. The change in the mass of the sample (mass gain) due to the adsorption of substances.

Fig. 5. Samples with a fixed thermistor: fiberglass (top) and carbon (bottom).

solution, it was 1% for carbon fiber and 0.95% for fiberglass; and in CH_3COOH solution, it was 0.82% for carbon fiber and 1.35% for fiberglass.

As a result of the conducted experiment, it can be concluded that carbon fiber is the most sensitive to various operating environment, with its stress at break changing over a wide range, as well as its plasticity. This can negatively affect its operation since carbon fiber is characterized by high strength and low plasticity; further increases in strength will lead to increased brittleness of the material.

In contrast, the influence of operating environment on fiberglass positively affects both the stress at break and plasticity of the material, as all fiberglass types have greater plasticity that limits their application range.

The authors were unable to find a reliable source of information describing this change in elongation; therefore, the authors hypothesized that the strengthening of layered composites occurs due to incomplete polymerization prior to the experiment and its completion during exposure due to exothermic reactions.

The next stage involved studying the changes in strength characteristics of layered nonmetallic composite materials after exposure to an aqueous solution with varying acidity (pH = 3, 5, 7). The medium used was a solution of distilled water with acetic acid CH_3COOH.

To verify the hypothesis about the hardening of samples due to internal heat generation, a thermistor was attached to each sample for continuous temperature monitoring throughout the exposure (Fig. 5).

Temperature monitoring was conducted using a temperature measurement setup, the scheme of which is shown in Fig. 6.

Temperature monitoring was conducted using an Arduino UNO microcontroller (2) that recorded data from thermistors (3, 4) at a polling frequency of once every 0.5 seconds. It showed that the temperature of the samples matched the ambient temperature, with an error not exceeding 0.8%, which allows us to conclude that the changes in the strength properties of layered nonmetallic

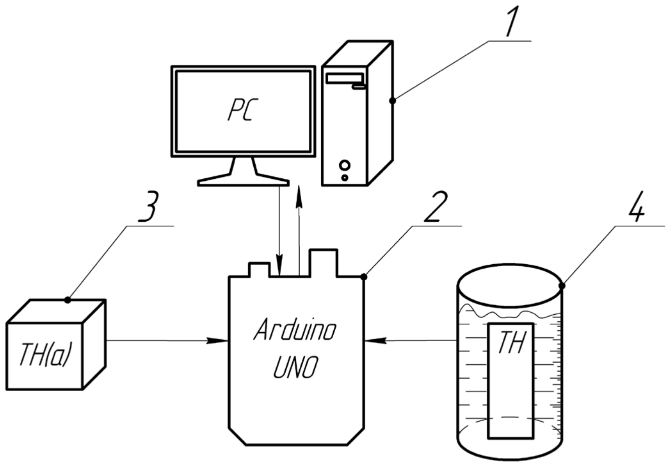

Fig. 6. Scheme of the temperature measurement unit during holding in substances (1 – personal computer, 2 – Arduino–based microcontroller, 3 – thermistor for measuring ambient temperature [TH(a)], 4 – thermistor for measuring the temperature of each sample [TH]).

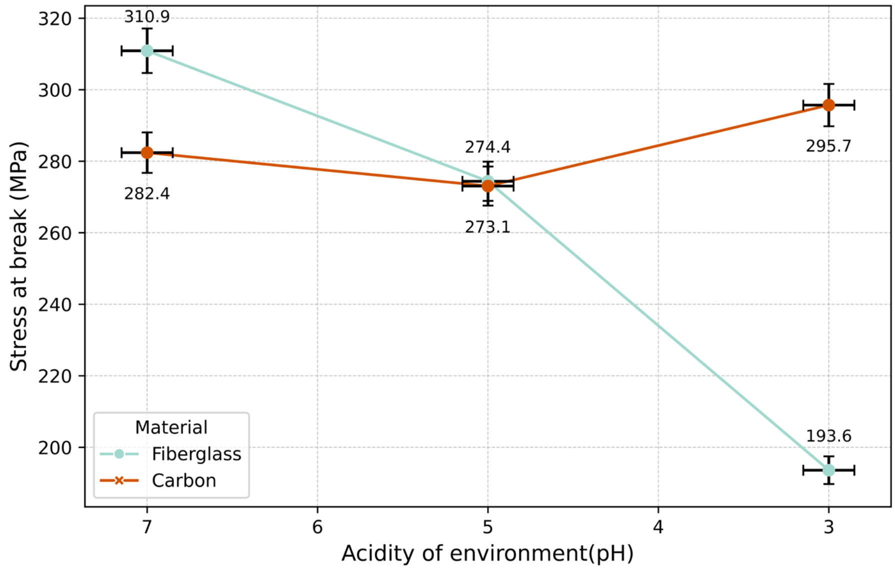

Fig. 7. Change in the stress at break of nonmetallic composites from acidity of holding substances of sample.

composite materials are not related to the release of internal energy due to a chemical reaction.

The exposure of samples in operating environment with different acidity levels was carried out for 10 days, followed by a drying period of 30 days. As a result, dependencies of changes in stress at break based on acidity were obtained (Fig. 7).

After exposure of fiberglass in a medium with pH = 7, the stress at break was recorded at 310.9 MPa; after exposure in a medium with pH = 5, it was 273 MPa; and after exposure in a medium with pH = 3, it was 193.6 MPa. Thus, with increasing acidity of the medium, the stress at break of fiberglass decreased by 37.8%.

After exposure of carbon fiber in a medium with pH = 7, the stress at break was recorded at 282.4 MPa; after exposure in a medium with pH = 5, it was 274.37 MPa; and after exposure in a medium with pH = 3, it increased to 295.7 MPa. Increasing acidity of the medium leads to a rise in stress at break for carbon fiber by 5%.

The dependencies for changes in stress at break for fiberglass (1) and carbon fiber (2) after exposure in operating environment with pH ranging from 3 to 9 units were derived:

$$\sigma_{B\ glass} = 14.66pH^2 - 65.27pH + 346.27, \tag{1}$$

$$\sigma_{B\ carbon} = -20.81pH^2 + 141.89pH + 72.52. \tag{2}$$

The error in the calculated stress at break compared to the empirically obtained value does not exceed 5%.

Changes in the acidity of the medium significantly affect the stress at break of layered nonmetallic composite materials. The change in strain at break for layered nonmetallic composite materials depending on the acidity of the medium is presented in Fig. 8.

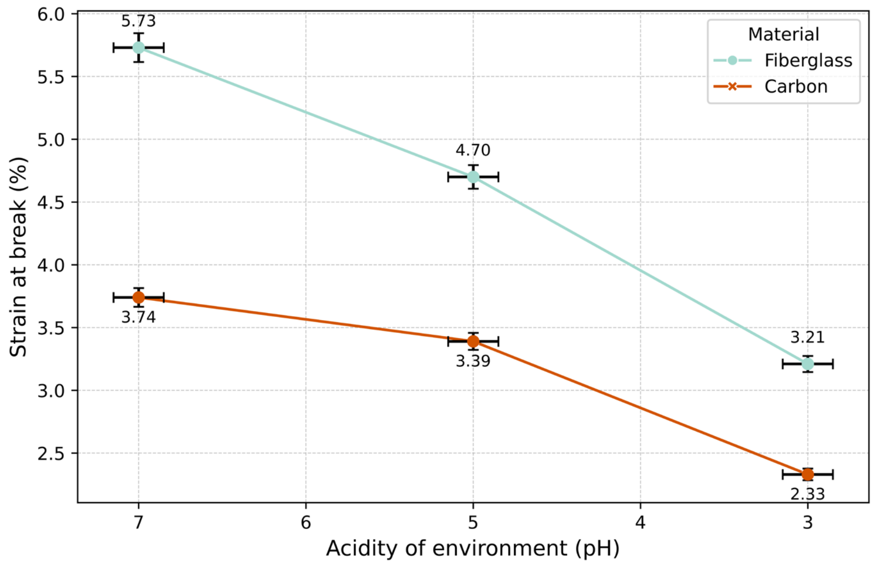

Fig. 8. Change in strain at break for fiberglass and carbon fiber depending on the acidity of holding substances of sample.

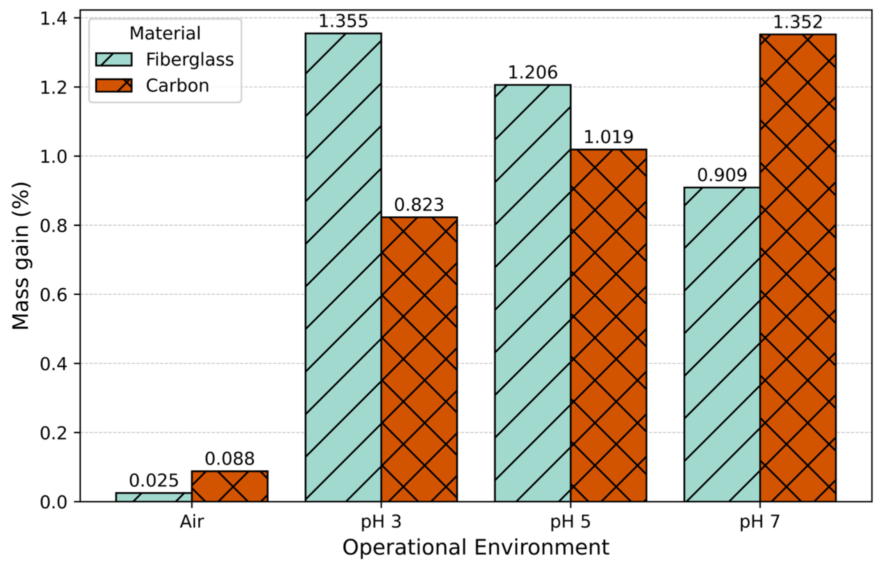

Fig. 9. Change in the mass of the sample (mass gain) due to the exposure process in various holding substances of sample.

Since the exposure of fiberglass to a solution with a pH = 7, the strain at break was measured at 5.73%. After exposure to a solution with a pH = 5, the strain at break was 4.7%. And after exposure to a solution with a pH = 3, the strength at break was 3.21%. Therefore, as the acidity of the solution increased, the strain at break of the fiberglass decreased by 44%.

Following the exposure of carbon fiber to a solution with a pH = 7, the strain at break was measured at 3.74%; after exposure to a solution with a pH = 5, it was 3.39%; and after exposure to a solution with a pH = 3, it decreased to 2.33%. The rise in the acidity of the environment results in a 38% reduction in the strain at break for carbon fiber.

The effects of changes in the strain at break of fiberglass (3) and carbon fiber (4) after exposure to operating conditions within a pH range of 3 to 9 have been determined:

$$\Delta l_{glass} = -0.355 pH^2 + 2.125 pH + 0.56, \quad (3)$$

$$\Delta l_{carbon} = -0.23 pH^2 + 2.18 pH + 1.26. \quad (4)$$

The error is also less than 5%.

The authors also measured the change in mass of the samples after exposure to verify the adsorption capacity of layered nonmetallic composite materials (Fig. 9).

The authors noted that after exposure in a medium with pH = 3, the mass gain was 0.82% for carbon fiber and 1.35% for fiberglass; in a medium with pH = 5, it was 1.02% for carbon fiber and 1.2% for fiberglass; and in a medium with pH = 7, it was 1.35% for carbon fiber and 0.9% for fiberglass.

The maximum strain at break is achieved after exposure in a medium with pH = 7. The maximum strengthening of the fiberglass sample occurs after exposure in a medium with pH = 7, while the maximum strengthening of the carbon fiber sample occurs in a medium with pH = 3.

The observed variations in the stress at break and strain at break of fiberglass and carbon fiber composites under different pH conditions can be attributed to the distinct degradation mechanisms of these materials in acidic environments. For fiberglass, exposure to acidic solutions leads to the leaching of ions such as Ca, Mg, and Al from the glass structure, resulting in a weakened fiber network and a subsequent decrease in tensile strength and strain at break. This degradation mechanism has been documented in studies examining the durability of glass fiber-reinforced polymers in harsh environments [31].

In contrast, carbon fiber composites exhibit a different response to acidic exposure. The carbon fibers themselves are generally resistant to chemical attack; however, the matrix material and the fiber-matrix interface can be susceptible to degradation. Studies have shown that environmental factors such as ultraviolet (UV) radiation and salt-fog can lead to matrix plasticization and erosion, which in turn affect the mechanical properties of carbon fiber-reinforced polymers [32]. While these studies focus on UV and salt-fog exposure, similar degradation mechanisms may occur under acidic conditions, potentially leading to changes in the composite's mechanical performance.

The quadratic regression models (1)–(4) employed in this study effectively capture the nonlinear relationship between the pH of the exposure environment and the mechanical properties of the composites. The choice of quadratic polynomials is supported by the complex nature of the degradation processes, which are influenced by multiple factors including ion leaching, matrix degradation, and fiber-matrix interface deterioration. The authors realize that the approximation of dependencies using quadratic functions based on only three experimental points has its limitations and may not fully reflect the complexity of the processes under study. In the future, it is planned to expand the experimental base by increasing the number of measurement points, which will allow using more complex approximation models and improving the accuracy of the obtained dependencies. However, at this stage of the study, taking into account the limited data available, the chosen approach seems reasonable and allows us to obtain a primary understanding of the nature of the dependencies between variables.

4. CONCLUSION

The study demonstrated that the mechanical properties of layered nonmetallic composites (carbon fiber and fiberglass) significantly depend on the type of filler and the operating environment.

The strength at break of carbon fiber increases by up to 46% in an acidic environment, 26% in a saline solution, and 16% in oil. For fiberglass, strength at break improves by up to 11% in an acidic environment and 6% in a saline solution but decreases by 28% in oil. The strain at break for carbon fiber decreases by 38% in an acidic environment and 29% in a saline solution, while for fiberglass, it decreases by 44% and 8%, respectively.

Mass changes in the samples reach up to 1.65% for carbon fiber and 1.35% for fiberglass, depending on the environment, with stronger samples showing minimal mass variations. This may lead to the assumption that composites become more brittle due to the absorption of aggressive substances.

These findings provide valuable insights into the effects of environmental factors on the strength and strain behavior of composites, enabling more informed design of equipment for use in aggressive conditions. However, the issue of degradation of composites over a long period of time remains open and requires a more detailed study.

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УДК 620.178:622.3

Влияние агрессивных сред на прочностные характеристики стеклопластиковых и углепластиковых композитов, используемых в нефтегазовой промышленности

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Аннотация. Протяженность российской нефтегазопроводной системы составляет более 290000 км; она используется для транспортировки воды, нефти, газа и нефтепродуктов. Несмотря на то, что расчетный срок службы этих трубопроводов составляет 30 лет, фактический срок службы часто колеблется от 10 до 20 лет из-за суровых условий эксплуатации, при этом поломки возникают еще раньше. Использование инновационных материалов таких как металлические и неметаллические композиты, в перспективе, может продлить срок эксплуатации нефтегазового оборудования. Однако недостаточная изученность их взаимодействия с агрессивной средой и отсутствие единых стандартов затрудняют масштабное внедрение данных материалов. В данной работе были исследованы изменения предела прочности и относительного удлинения неметаллических композиционных материалов после воздействия на образцы рабочих сред с различной кислотностью и химическим составом, получены уравнения зависимостей.

Ключевые слова: слоистые неметаллические композиты; стеклопластики; углепластики; агрессивная среда; стойкость к коррозии