

Design, Finite Element Analysis, and Experimental Investigation of Basalt Fiber Reinforced Polymer (BFRP) Composite for Oil and Gas Applications

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Abstract

The pipelines used for transporting oil and gas need to have sufficient strength, durability, and resistance to any form of corrosion. The usual metallic pipes are prone to corrosion and weigh quite a lot. In this research, the use of Basalt Fiber Reinforced Polymer Composite Pipe has been studied using computer aided design and finite element analysis among others. A BFRP pipe with 200 mm length, 50 mm inner diameter, and 10 mm wall thickness was modeled using orthotropic material property assumptions and studied under an internal pressure of 55 MPa. The maximum equivalent stress predicted through FEA was 210 MPa and the maximum displacement was 0.45 mm. The hardness obtained from the experimental test was 84.2 HRB, axial compressive strength was 178 MPa, and lateral performance stability was noted up to 12 kN. There was an approximate difference of 3.8% between the experimental and simulation axial compressive strengths of 185 MPa. The results indicate that there is potential for BFRP material to be used as a light and corrosion-resistant material for pipeline structures.

Keywords: BFRP Composite Pipe, Finite Element Analysis, Non-Intrusive Monitoring, Basalt Fiber, Pipeline Leak Prevention, Oil and Gas Safety, Structural Analysis, Corrosion Resistance.

1. Introduction

Oil and gas transportation through pipelines is common practice due to the requirement of safety and durability of the structure. Leakage from pipelines may result in loss of products, pollution, danger of fires, and disruption of the process [1]. Traditional metal pipelines are known to have great structural strength but poor resistance to corrosion, thus requiring substantial maintenance. This limitation led to research being carried out on fiber reinforced plastic pipes.

Basalt Fiber Reinforced Polymer (BFRP) is defined as a composite material that is formed using basalt fibers as reinforcements in a polymer matrix. The basalt fibers have favorable mechanical properties, thermal stability, and environmental resistance [2], [3]. This material has been considered for use in structures and infrastructures where lightweight and environmental resistance are needed. The properties of BFRP make it an alternative to metals without having the same disadvantages as metal pipe structures.

Despite the extensive studies on the properties and performance of the basalt fiber-based composite materials, there have been insufficient studies conducted on using BFRP for pipes under pressurized conditions. Especially, the effect of geometry, anisotropic properties of the material, internal pressure, and mechanical behavior has to be analyzed. The numerical analysis cannot solely prove the practical performance of the designed composite pipe. Thus, it is necessary to combine the numerical and experimental methods in order to achieve a more comprehensive evaluation.

This current research focuses on the use of a BFRP composite pipe by designing it, using FEA modeling, fabricating it, and conducting experiments. This study is done to evaluate the structural performance of the pipe under internal pressure loading and the mechanical behavior of the pipe observed from experiments. The main objective of this study is to find out the feasibility of the proposed BFRP pipe.

2. Literature Review

Studies on basalt fiber composites have been mainly concentrated on the aspects of the mechanical property, environmental durability, thermal behavior, and performance. Studies on the use of basalt fibers as reinforcements have established that basalt fibers are suitable for engineering applications that require good mechanical property and durability [2]. Extensive

study on basalt fibers and their composites has been done, which has identified the mechanical, thermal, and chemical properties of basalt fibers and their composites [3]. Study on mechanical properties of basalt fiber reinforced plastic has revealed the mechanical behavior of BFRP materials [4].

The mechanical and thermal environment may affect the properties of fiber-reinforced materials. Research on the tensile strength degradation of basalt fibers through heat treatment has proven that temperature has an effect on their failure behavior [6]. Also, the high-temperature behavior of fiber-reinforced polymers has been determined as an important issue for those systems where thermal environments are involved [8]. Therefore, it becomes clear that the environment and operational conditions should be considered in the design of BFRP.

Other studies have also focused on long-term behavior of composites. The creep behavior of BFRP tendon materials has been studied for prestressing purposes [9]. Experiments conducted on basalt and glass fiber reinforced concrete have shown the suitability of using basalt fiber reinforcement in structures [12]. Moreover, durability studies of BFRP bars subjected to marine environments have also been conducted [13].

The recent studies have expanded the scope of BFRP to cover erosion resistance and sustainability. The comparative analysis of GFRP, BFRP, and CFRP considered the effects of erosion and residual strength, thus providing information about the performance of BFRP under abrasive loads [14]. Recent studies have also covered the structure, properties, sustainability, and life cycle aspects of basalt fiber composites [15]. An overview of basalt fiber applications highlighted its prospects as a reinforcement material for engineering applications [10].

These reviewed articles provide much insight into properties at material level, environmental stability, thermal behavior, creep behavior, erosion resistance, and sustainability. Nevertheless, these research works do not actually determine the structural behavior of the whole BFRP pipe under high internal pressure along with considering both numerical analysis and experimental test results. This suggests that a pipe-level study is required integrating finite element analysis and mechanical testing, which is the aim of this work.

3. Problem Statement and Objectives

The usage of traditional metals in pipes used in the transportation of oil and natural gas is fraught with problems due to corrosion, wear and tear, high weight, and maintenance. A suitable alternative should provide adequate mechanical strength while reducing susceptibility to environmental deterioration. BFRP provides a promising composite configuration for this purpose; however, its suitability as a pressurized pipe structure must be established through systematic structural evaluation.

The lack of both numerical and experimental evaluations for the pipe indicates the necessity to conduct research on the behavior of a BFRP pipe under certain internal pressure and mechanical loads. Thus, the current study is aimed at modeling of BFRP pipe, its finite element analysis, manufacturing of the required specimens and evaluation of mechanical properties of the latter.

The objectives of the study are:

- To develop a CAD model of a BFRP composite pipe with defined geometric and material parameters.
- To analyze the structural response of the pipe under 55 MPa internal pressure using finite element analysis.
- To fabricate BFRP pipe specimens using the selected composite manufacturing process.
- To experimentally evaluate the fabricated specimens through hardness, axial compression, and lateral compression tests.
- To assess the agreement between numerical predictions and experimental observations for evaluating the structural feasibility of the proposed BFRP pipe.

4. Proposed Methodology

4.1 Research Framework

In order to analyze the structural characteristics of the BFRP composite pipe, the proposed methodology uses computer-aided design (CAD), finite element analysis (FEA), composite pipe manufacturing, and mechanical testing. The entire research process can be broken down into

five main steps (refer to Figure 1): (i) designing the geometry of the BFRP pipe, (ii) assigning material properties and numerical modeling, (iii) finite element analysis under pressure, (iv) manufacturing of BFRP pipes and their experimental investigation, and (v) comparing the results obtained from both numerical and experimental analyses.

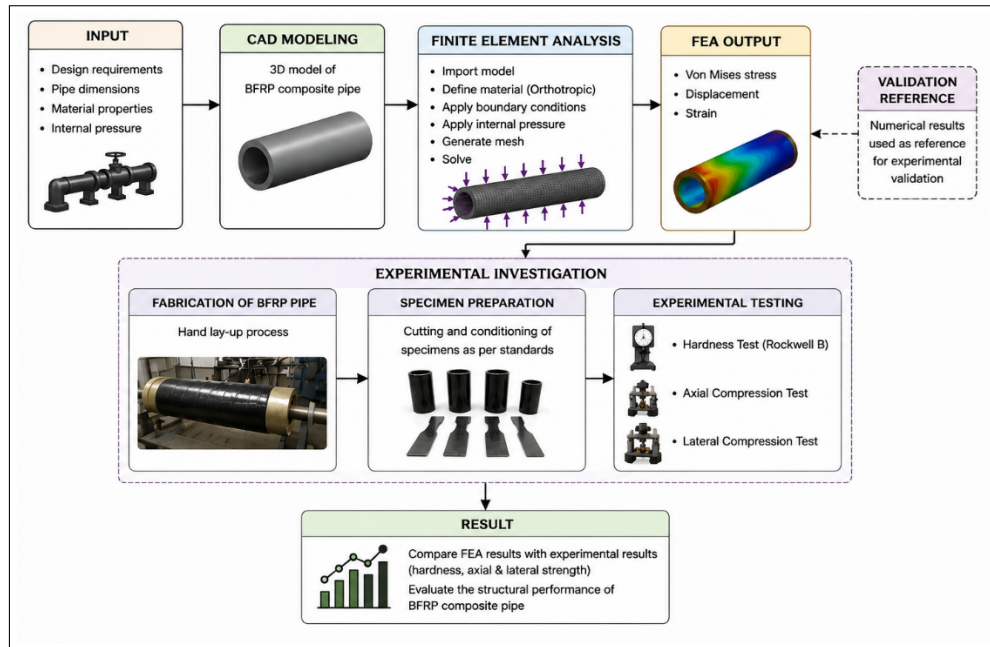


Figure 1. Research framework

The test procedure was specifically formulated to examine the resistance of the BFRP pipe to internal pressures and compression forces. The results obtained through the experiment were later analyzed to verify the accuracy of the numerical predictions. This is a comprehensive method to evaluate the practicality of BFRP as an alternative to traditional metals that are used for pipeline construction.

4.2 CAD Modeling and Geometric Configuration

BFRP pipe was designed in SolidWorks, total length of the pipe is 200 mm, internal diameter of the pipe is 50 mm, and thickness of the pipe is 10 mm. These dimensions were chosen in order to provide representative cylindrical shape of the pipe as well as its compatibility with the existing equipment for experiments.

Pipe was designed as composite cylindrical pipe with constant thickness of the pipe wall. Obtained CAD model of the pipe was used as the basis for FEA pre-processing and simulations. Figure 2 depicts CAD model as well as manufactured BFRP composite pipe.

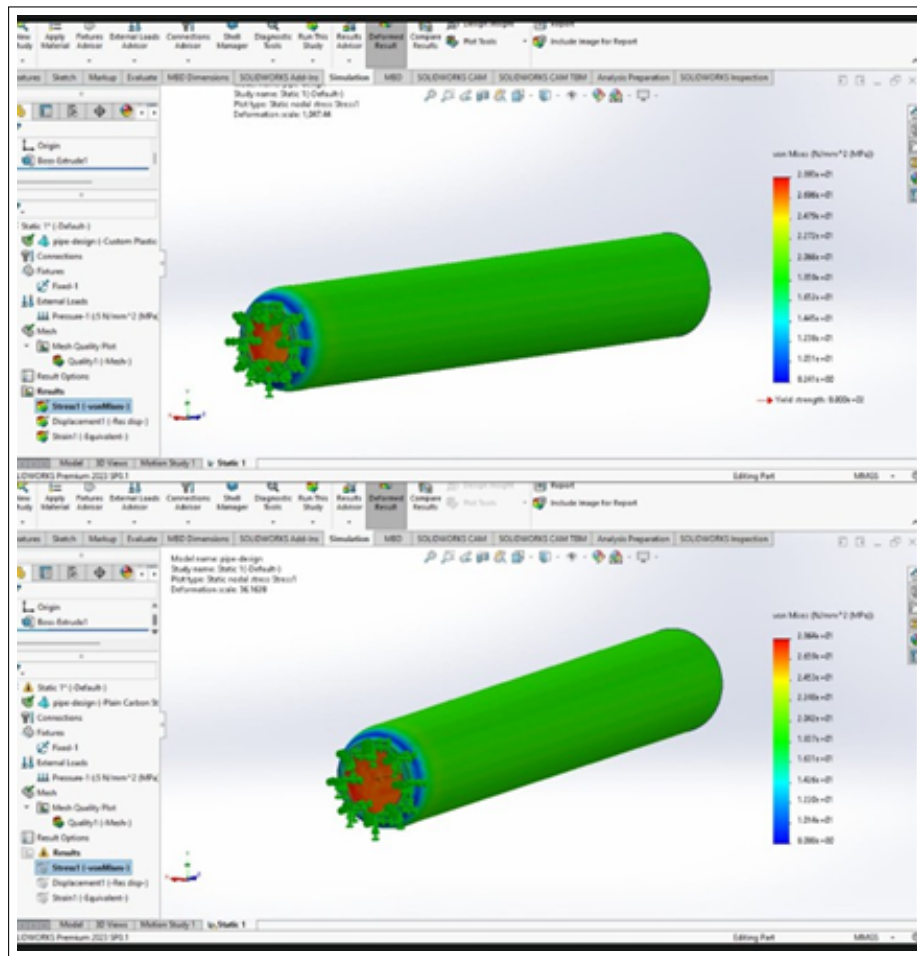


Figure 2. CAD model and fabricated BFRP composite pipe sample

4.3 BFRP Material Properties

Orthotropic elastic material properties were used to model the behavior of the BFRP composite considering the anisotropic nature of the composite material. The modulus of elasticity for the hoop direction was considered to be 45 GPa, whereas for the axial direction, it was 18 GPa. The shear modulus was estimated to be 4.5 GPa, and Poisson's ratio is 0.28.

The principal geometric, material, and simulation parameters used in the study are summarized in Table 1.

Table 1. Hardware and simulation configuration

Parameter	Specification
Pipe Material	BFRP Composite
Length	200 mm

Inner Diameter	50 mm
Thickness	10 mm
Internal Pressure	55 MPa
Mesh Element Size	1.8 mm
Element Type	Tetrahedral
Hoop Modulus (E1)	45 GPa
Axial Modulus (E2)	18 GPa
Shear Modulus (G12)	4.5 GPa
Poisson's Ratio	0.28

4.4 Finite Element Modeling and Boundary Conditions

For the stress-strain analyses of the designed BFRP tube subjected to the applied internal pressure, the FEA methodology was utilized. The CAD geometry of the structure was meshed with the tetrahedral elements having the average size of about 1.8 mm. This particular mesh was chosen to have sufficient resolution of the stress distribution areas, especially near the restrained end of the pipe.

In order to consider the realistic constraint in a pipeline, one end of the pipe was made rigid and could be taken as the constrained or flanged connection. An internal pressure of 55 MPa was considered on the inside of the pipe wall. This is done to consider the extreme case of internal-pressure loading on the pipe for analyzing its structural behavior using the proposed composite design.

The important outputs of the FEA analysis were the equivalent stress (Von Mises), total deformation, and strain distribution. Special focus was made on maximum stress and deformation because these indicate critical locations within the pipe structure.

4.5 Fabrication and Experimental Implementation

The BFRP pipe specimens were produced through the method of filament winding. Then, the mechanical behavior of the produced specimens was evaluated through hardness, axial

compression, and lateral compression tests.

In the case of the axial and lateral compression tests, a Universal Testing Machine (UTM) was used, whereas a Rockwell hardness tester was used to measure the surface hardness. A data acquisition system was used to record the load and displacement in the mechanical tests.

For the axial compression test, the specimen was placed vertically with respect to the compression platens of the UTM and was subjected to a compressive load along the longitudinal axis. In the case of the lateral compression test, the specimen was placed horizontally and was subjected to a compressive load in the transverse direction.

Three different locations on the exterior surface of the specimen were considered to obtain the hardness values, and then the average value was considered.

4.6 Experimental Testing and Validation Procedure

The experimental investigation comprised three principal tests: hardness measurement, axial compression, and lateral compression. The axial compression test involved the application of load up to failure or the maximum capacity of the testing equipment. Lateral compression test was done to study the resistance of the cylinder to diametrical loads.

The numerical and experimental investigations were compared using the available load, stress, deformation, and failure observations. The validation procedure considered:

- comparison of numerical and experimental mechanical response;
- comparison of predicted and measured compressive strength;
- evaluation of the observed failure behavior; and
- identification of agreement between the predicted stress concentration region and the experimentally observed structural response.

5. Results and Discussion

5.1 Finite Element Analysis Results

From the FEA results, the maximum equivalent (Von Mises) stress found in the BFRP pipe is around 210 MPa. As seen in the FEA analysis, maximum stress occurs at the pipe's fixed end because of the applied boundary condition, which causes a localized stress concentration.

For regions other than the fixed end, the stress distribution is relatively uniform along the length of the pipe.

The maximum predicted displacement is about 0.45 mm and is found at the pipe's free end. From the small displacement magnitude, the pipe structure retains its cylindrical shape when subjected to internal pressure loading. From the FEA, the strain capacity of the modeled BFRP pipe structure is about 1.2%, implying that the structure can undergo considerable deformation prior to structural failure. It is an evidence that the BFRP pipe configuration can withstand 55 MPa internal pressure loading while retaining its stability. However, the FEA results should only be considered numerical prediction for the adopted geometry, materials, and loading parameters used in this study.

5.2 Experimental Results

The experimental results obtained from the fabricated BFRP specimens are summarized in Table 2.

Table 2. Experimental test results

Test Type	Result
Hardness (Average)	84.2 HRB
Axial Compressive Strength (Sim.)	185 MPa
Axial Compressive Strength (Exp.)	178 MPa
Lateral Stiffness	Stable up to 12 kN
Failure Mode	Gradual
Strain Capacity	1.2%

The average hardness value of 84.2 HRB refers to the actual hardness of the fabricated specimen. The value of the experimental compressive strength obtained from the axial compression test was 178 MPa, while the numerical compressive strength value was 185 MPa. Thus, the experimental compressive strength was approximately 96.2% of the numerically predicted compressive strength.

The difference between the simulated and experimental axial compressive strength was about 3.8%, which represents a good level of agreement between the numerical and experimental

results for axial compressive strength.

The BFRP pipe showed no deformation under lateral compression loads until a load of about 12 kN. It is evident from the results that the mode of failure was not abrupt but gradual, implying that progressive failure had occurred.

5.3 Numerical–Experimental Validation

The result analysis from numerical and experimental investigations is an important factor that helps evaluate the efficiency of the suggested method of modeling. The value of the axial compressive strength predicted by the model is 185 MPa, and the experimentally obtained value of axial compressive strength is 178 MPa. The discrepancy between these values equals approximately 7 MPa, which makes up 3.8%.

This high degree of variation indicates that the numerical model offers a reasonably accurate prediction of the experimentally measured behavior of the axial compressive loading of the fabricated BFRP pipe. However, the validation should be considered within the framework of the current experimental data. Specifically, the present research cannot claim an exact experimental reproduction of the case of 55 MPa of internal pressure in FEA. Thus, the current numerical-experimental correlation can be used for mechanical characterization and axial compression only.

The progressive nature of failure experienced during experimentation is also aligned with the reported strain capacity of about 1.2%. This suggests that the proposed design of BFRP has deformation capacity and that no sudden catastrophic behavior occurs in the compression loading scenario.

5.4 Comparison with Conventional Pipe Materials

Qualitative comparisons were made for the proposed BFRP pipe in terms of carbon steel, GFRP pipe, and CFRP pipe. Relative cost, corrosion resistance, weight, and tensile strength have been considered for qualitative comparison, as shown in Table 3.

Table 3. Comparison with existing pipe materials

Material	Cost	Corr. Res.	Wt.	Tens. Str.
Carbon Steel	Medium	Low	High	High

Glass Fiber (GFRP)	Low	Medium	Low	Medium
Carbon Fiber (CFRP)	Very High	High	Very Low	Very High
BFRP (Proposed)	Medium	High	Low	High

It is clear from the comparison that BFRP is a material that falls between GFRP and CFRP. From the comparative analysis provided in the original research paper, it is evident that BFRP is characterized by relatively lower weight, high corrosion resistance and tensile strength without being excessively expensive like CFRP.

Another key finding in the study is that there is about a 60% decrease in weight compared to a similar steel pipe. The lower weight could possibly provide some benefits in transportation and installation. Additionally, the fact that BFRP is corrosion resistant becomes more significant for applications involving pipelines in harsh conditions.

5.5 Engineering Significance and Practical Implications

From the analysis of the numerical and experimental work carried out, the use of BFRP composite pipes as lightweight pipeline materials has been validated. From the FEA analysis carried out, it was found that the designed pipe is able to withstand the pressure of 55 MPa with a maximum equivalent stress of about 210 MPa and a displacement of about 0.45 mm. In addition, from the experimental study, it was found that the average hardness was 84.2 HRB and the axial compressive strength of 178 MPa.

The major engineering benefit of the material being considered is its low weight as well as corrosion resistance. The weight reduction relative to steel that is mentioned above might lead to decreased handling and installation demands, whereas its corrosion resistance might prove to be useful in those cases when usual metal-based pipelines encounter aggressive environments. This makes the material suitable for use in such applications as offshore drilling platforms, chemical industries, oil fields, etc.

However, the current study was conducted on a lab scale basis using a pipe sample with a diameter of 200mm. Therefore, the results obtained cannot be extrapolated to real-world conditions without further validation since long-term creep, cyclic pressure, environmental conditions, high temperature effects, and joint connection performances are still critical concerns.

5.6 Limitations and Research Implications

A number of issues need to be considered while analyzing the findings from the study.

- The current experimental research was carried out using the pipe made of BFRP in laboratory scale with a length of 200 mm only. Testing of the structural performance of the BFRP pipe needs to be done using full-scale testing under actual pipeline operating conditions.
- There is no examination on the long-term creep and fatigue behavior of the BFRP pipe when there are cyclic changes in internal pressure. This is especially important in case of oil and gas pipelines, which operate under cyclic pressure.
- The problem of BFRP pipe-to-metallic pipeline connection needs to be examined in terms of joint strength and sealing ability.

6. Conclusion and Future Work

In this research work, the design, FEA, fabrication, and testing of a Basalt Fiber Reinforced Polymer (BFRP) pipe have been carried out for use in the oil and gas industry. From the developed BFRP pipe design, analysis has been done by applying 55 MPa internal pressure resulting in a maximum equivalent stress of about 210 MPa and maximum displacement of 0.45 mm. In the experimental investigation, an average hardness of 84.2 HRB, axial compressive strength of 178 MPa, and stable lateral deformation up to 12 kN have been obtained. There is a variation of about 3.8% in simulated axial compressive strength of 185 MPa compared to the experimentally determined value. This work shows the feasibility of BFRP for pipeline construction. Pressure test at full scale, fatigue behavior at cyclic loading, environment degradation and high temperature resistance, as well as joint development and leak detection system development, will be the focus of future investigations.

References

- [1] Korlapati, Naga Venkata Saidileep, Faisal Khan, Quddus Noor, Saadat Mirza, and Sreeram Vaddiraju. "Review and Analysis of Pipeline Leak Detection Methods." *Journal of pipeline science and engineering* 2022, vol. 2, no. 4: 100074.
- [2] Sim, Jongsung, and Cheolwoo Park. "Characteristics of Basalt Fiber as a Strengthening

- Material for Concrete Structures." *Composites Part B: Engineering* 2005, vol. 36, no. 6-7: 504-512.
- [3] Fiore, Vincenzo, Tiziana Scalici, Gianluca Di Bella, and Antonio Valenza. "A Review on Basalt Fibre and its Composites." *Composites Part B: Engineering* 2015, vol. 74: 74-94.
- [4] Lopresto, Valentina, Claudio Leone, and Isabella De Iorio. "Mechanical Characterisation of Basalt Fibre Reinforced Plastic." *Composites Part B: Engineering* 2011, vol. 42, no. 4: 717-723.
- [5] Rafat, Md Tanzim, Tanjim Zahin Shuchi, Faizur Rahman Evan, and Md Anisur Rahman. "Mechanical and Absorption Properties of Carbon-Basalt and Glass Fiber Reinforced Composites: A Comprehensive Study with Implications for Advanced Manufacturing Technology." *Results in Materials* 2024, vol. 23: 100615.
- [6] Militký, Jiří, Vladimír Kovačič, and Jitka Rubnerová. "Influence of Thermal Treatment on Tensile Failure of Basalt Fibers." *Engineering fracture mechanics* 2002, vol. 69, no. 9: 1025-1033.
- [7] Yan, Libo, Bohumil Kasal, and Liang Huang. "A Review of Recent Research on the Use of Cellulosic Fibres, Their Fibre Fabric Reinforced Cementitious, Geo-Polymer and Polymer Composites in Civil Engineering." *Composites Part B: Engineering* 2016, vol. 92: 94-132.
- [8] Bazli, Milad, and Milad Abolfazli. "Mechanical Properties of Fibre Reinforced Polymers Under Elevated Temperatures: An Overview." *Polymers* 2020, vol. 12, no. 11: 2600.
- [9] Wang, Xin, Jianzhe Shi, Jianxun Liu, Long Yang, and Zhishen Wu. "Creep Behavior of Basalt Fiber Reinforced Polymer Tendons for Prestressing Application." *Materials & Design* 2014, vol. 59: 558-564.
- [10] Singha, Kunal. "A Short Review on Basalt Fiber." *International Journal of textile science* 2012, vol. 1, no. 4: 19-28.
- [11] Dhakal, Hom N., ZY and Zhang, and Mel OW Richardson. "Effect of Water Absorption on The Mechanical Properties of Hemp Fibre Reinforced Unsaturated Polyester Composites." *Composites science and technology* 2007, vol. 67, no. 7-8: 1674-1683.
- [12] Kizilkanat, Ahmet B., Nihat Kabay, Veysel Akyüncü, Swaptik Chowdhury, and Abdullah H.

- Akça. "Mechanical Properties and Fracture Behavior of Basalt and Glass Fiber Reinforced Concrete: An Experimental Study." *Construction and Building Materials* 2015, vol. 100: 218-224.
- [13] Lu, Zhongyu, Lizhu Su, Guijun Xian, Baihang Lu, and Jianhe Xie. "Durability Study of Concrete-Covered Basalt Fiber-Reinforced Polymer (BFRP) Bars in Marine Environment." *Composite structures* 2020, vol. 234: 111650.
- [14] Ren, Wenhao, and A. Siha. "Comparative Study on Sand Erosion Damage and Residual Strength of GFRP, BFRP, and CFRP Composites." *International Journal of Impact Engineering* 2026: 105659.
- [15] Farghal, Hebatullah H., and Tarek M. Madkour. "Basalt Fiber Composites: Structure, Properties, Sustainability, and Life Cycle Analysis." *Journal of Composites Science* 2026, vol. 10, no. 5: 253.