# Development of new generation composite materials: a fractal approach

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**Abstract:** The research aimed to investigate the properties of glass-basalt composite tubes, specifically examining the relationship between structural fractal dimensions, composition, and mechanical properties. Physical experiments were carried out to assess the properties of glass and glass-basalt composite tubes. These tests included measurements of tensile strength, modulus of elasticity, fracture resistance, flexural strength, and additional mechanical characteristics. Fractal analysis of rovings and epoxy binder was performed at the microstructural level to evaluate the impact of structure on mechanical performance. Through predictive modeling of the physical and mechanical properties of glass-basalt composite tubes, an optimal range of properties was identified. This range is defined by specific technological parameters: rovings content of 68–74%, basalt fiber diameter of 7–12 μm, and epoxy binder content of 21–27%. Within this framework, the production of tubes with the following target properties was predicted: tensile strength $\sigma_p = 460 - 480 MPa$, compressive strength $\sigma_c = 350 - 370 MPa$, and modulus of elasticity $E = 17 - 19 GPa$.

**Keywords:** fractal modeling, microstructure, matrix fibers, glass-basalt plastic, composite material, forecasting, strength, fractal dimension, heterogeneity, mechanical properties, composite pipe, glass fiber, basalt, correlation analysis.

## 1 Introduction

The technologies for manufacturing various materials and methods for their investigation are complex [1] and labor-intensive [2]. This issue is particularly relevant when researching carbon nanotubes [3] and composites [4].

Composites also include glass-basalt plastic structures [5] and materials [6] used for construction in temperate and Arctic climatic zones. These materials must possess a necessary set of properties to make them suitable for operation in the extreme northern regions. Most properties that characterize the operability and efficiency of the technology for manufacturing glass-basalt composite materials are determined by the customer within acceptably small intervals. Within these intervals, a specific criterion, under the influence of control parameters, changes without violating technological requirements and regulatory standards. For this purpose, developers establish operational ranges for technological parameters that comply with existing national standards, which limit the numerical values of properties [7].

This paper, based on the study of the operational range of parameters for the technology of manufacturing glass-basalt composite pipes, explores the compromise region of properties, where their rational values are obtained.

## 2 Materials and Methods

The samples for testing were manufactured as follows: rings and strips cut in the axial direction (the average cross-sectional area was 15×15 = 225 mm²) from a pipe with dimensions of DN 297×15. The appearance of the pipes after failure is shown in Figure 1.

Fig. 1. – Photographs of fractures in hybrid glass-basalt-plastic pipes

The following materials were used in the pipe manufacturing process:

– Glass roving (fiber) 1200 TEX (E-glass) (China);
– Epoxy resin KER 828 (South Korea);
– Hardener IZOMTGFA (China);
– Accelerator Alkofen (China).

The approximate weight ratio of the materials was 70% roving, 30% binder, and a negligible amount of Alkofen. The weight ratio of resin to IZOMTGFA in the binder was 100/80.

## 3 Results and Discussion

The quality criteria of glass-basalt composite pipes are shown in Fig. 2, which presents surfaces describing the relationships between the composition parameters and the quality criteria of the pipes.

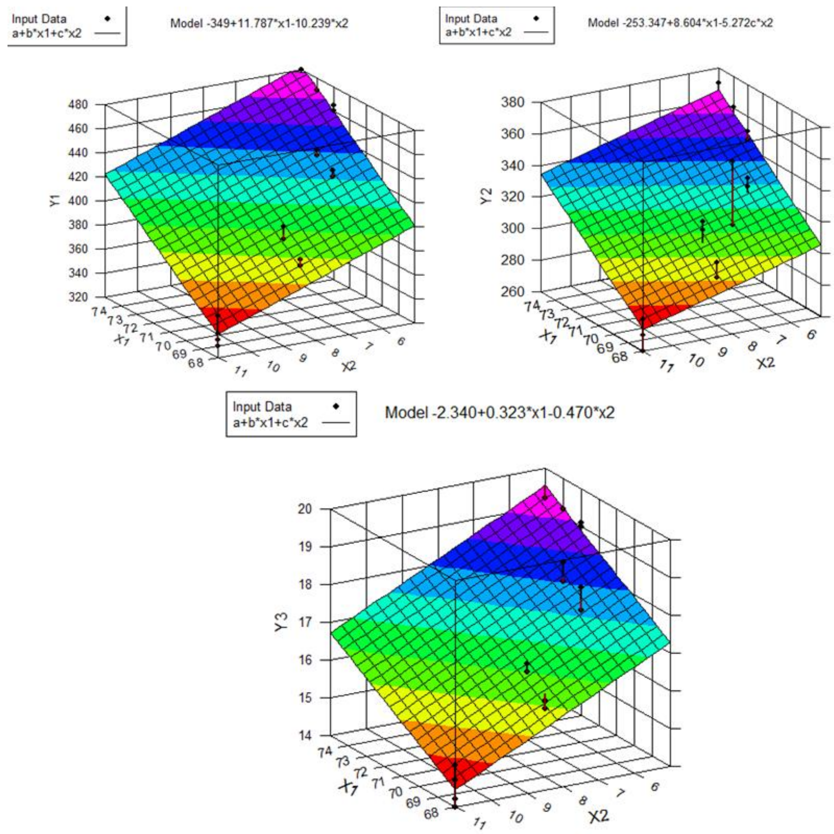


Fig. 2. – Dependence of tensile strength (a), compressive strength (b), elastic modulus (c) on roving content – X1 (%), basalt fiber diameter – X2 (μm)

The results presented in the graphs of Fig. 2 reflect the mechanism by which the content of glass-basalt fibers influences the mechanical properties of the pipes. Increasing the fiber content in the pipe composition leads to improved strength properties. Additionally, reducing the fiber diameter also enhances the strength properties [8], as the reduction of fiber size to nanoparameters reduces defects in the fiber structure [9], thereby improving the properties of the final product. This indicates that the structure of composite pipes [10], their composition [11], technological modes [12], and modifications [13] significantly influence the quality criteria of the pipes.

To investigate the impact of the structural elements of the pipes on their properties, the fractal dimensions of the roving (X4) and binder (X5) were calculated (Fig. 3). This is due to the fact that fractal geometry [14], based on intermediate asymptotics, is effectively applied to solve many current materials science problems: assessing fracture surfaces [15], evaluating the influence of technological parameters on properties [16], and quality prediction [17].

The fractal dimension was calculated using both the cellular and point methods. Then, by searching for the dimension values at the n-th iteration step, the fractal dimension of the structural elements was determined. The fractal dimension was calculated using the Hausdorff formula [18]:

$$D = -\lim_{\delta \to 0}\left(\frac{\ln\left(N\left(\delta\right)\right)}{\ln\left(\delta\right)}\right), \tag{1}$$

where $lnN(\delta)$ is the logarithm of the number of cells with linear dimensions $\delta$ that cover the object of study.

The cellular dimension was determined by the following formula (2):

$$\tilde{N}(L) = \sum_{m=1}^{K}(1/m)\cdot P(m,L) \sim L^{-D}, \tag{2}$$

where $N$ is the number of cells of size $L$ containing $m$ points.

A photo of the microstructure (Fig. 3a) in a 256-color format with shades of gray (Fig. 3b) was progressively covered with cells of size $\delta$.The cellular fractal dimension of the microstructure photo was calculated as the tangent of the slope of the line on the function graph. On the graph, the logarithm of the cell length is plotted on the horizontal axis, and the logarithm of the number of filled cells is plotted on the vertical axis (Fig. 3c). At the 5th iteration step, the convergence of the fractal dimension values of the glass-basalt matrix fibers was determined as $Dt = 1.992$, and at the 11th iteration step, the convergence of the fractal dimension values of the epoxy component was determined as $Df = 1.634$ (Fig. 3c).

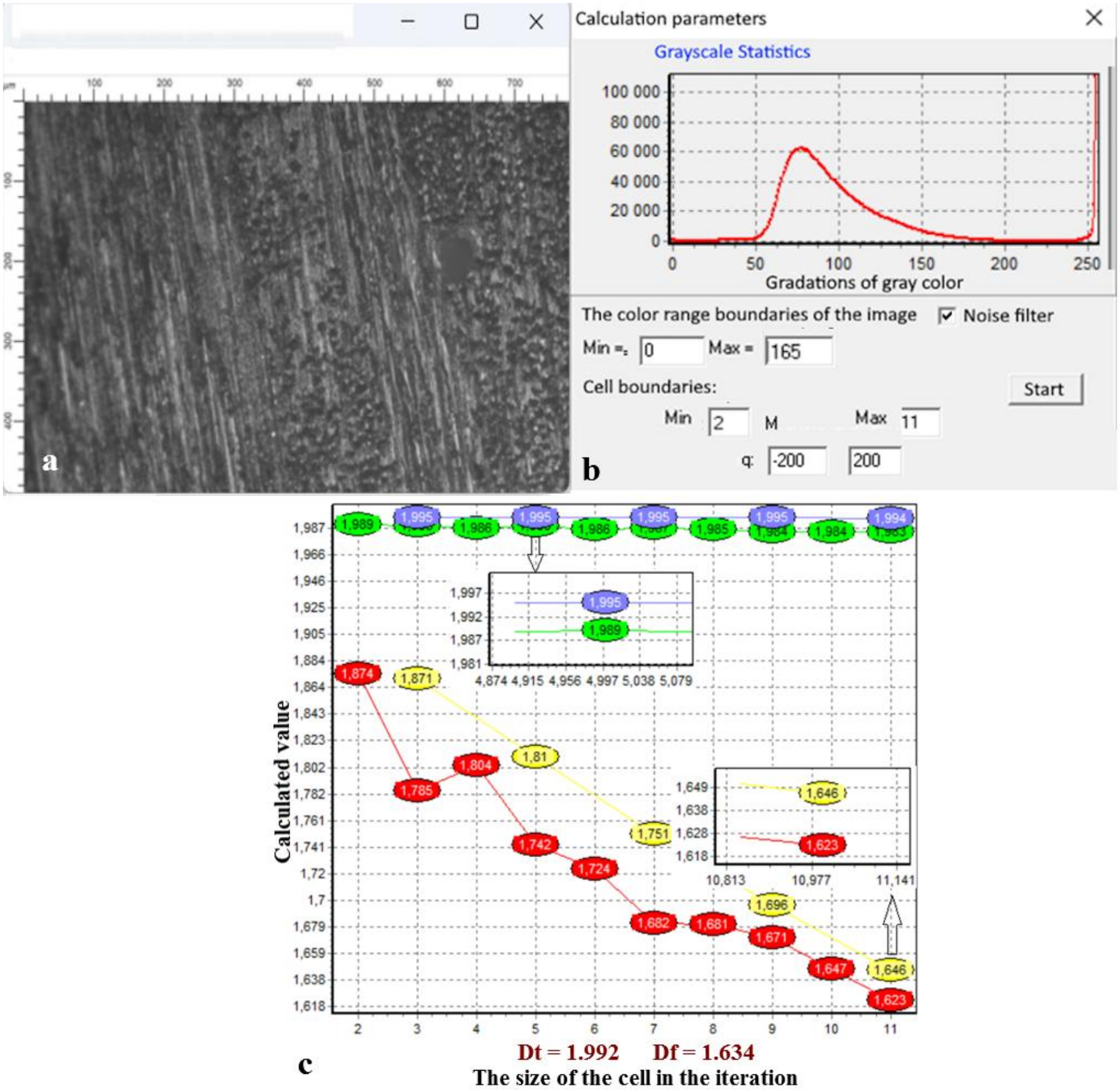


Fig. 3. – Software implementation of determining the fractal dimension of pipe structure elements: a – image in 256-color format; b – distribution of the image color gamut and selection of boundary cell sizes from 2 to 11 pixels; c – search for convergence of the fractal dimension values of basalt matrix fibers calculated by the cellular $D_{tonk}$ and point $D_{tont}$ methods and the fractal dimension of the epoxy component $D_{fonk}$ and $D_{font}$

By analyzing the influence of roving content (X1), basalt fiber diameter (X2), binder content (X3), and the fractal dimensions of the roving (X4) and binder (X5), mathematical models were developed to predict the tensile strength $\sigma_p$ (3), compressive strength $\sigma_c$ (4), and elastic modulus $E$ (5):

$$\sigma_p = -585.75 \cdot X_0 + 12.50 \cdot X_1 + 6.88 \cdot X_2 + 1.96 \cdot X_3 + 23.96 \cdot X_4 - 25.689 \cdot X_5 \\ R^2 = 0.99 \tag{3}$$

$$\sigma_c = -295.24 \cdot X_0 + 7.41 \cdot X_1 + 5.31 \cdot X_2 + 1.52 \cdot X_3 + 1.99 \cdot X_4 - 2.14 \cdot X_5 \\ R_2 = 0.92 \tag{4}$$

$$E = -19.30 \cdot X_0 + 0.46 \cdot X_1 + 0.24 \cdot X_2 + 0.08 \cdot X_3 + 0.88 \cdot X_4 - 0.94 \cdot X_5 \\ R^2 = 0.98 \tag{5}$$

To construct the compromise area of the physicomechanical properties of glass-basalt-plastic pipes, experimental data and the mathematical models from equations (3) to (5) were used. In this process, one argument was varied from the minimum to the maximum values within the designated working parameter range, while the other quality criteria were held constant at the average level. A mathematical model was then constructed based on the analysis of the obtained experimental points.

The graph-analytic method was employed, where the investigated area of points was not described traditionally by a trend line (Fig. 4a), but as an area representing the working range of numerical values for the parameters within the limits of the applicable standards, the standard technology, and other regulatory documents (Fig. 4b). In most cases, when processing experimental data and constructing various dependencies, not all experimental points fit the approximating function, which indicates the complexity of the technology and the influence of many factors on the final goal function (the quality criterion being studied).

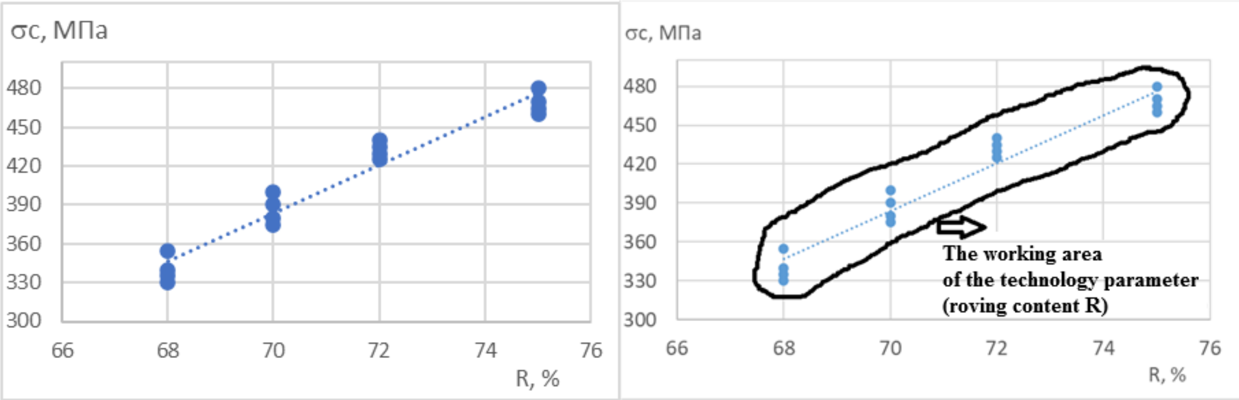


Fig. 4. – Construction of the working area of the pipe tensile strength values depending on the roving content

Figure 5 presents the compromise area of the physicomechanical properties of glass-basalt-plastic pipes, which is determined by overlaying the working areas of the selected parameters. The numerical values of the selected properties of the pipes remain within the limits of their standard production technology. By drawing a vertical line through the compromise area (for example, line AB passing through the indicated areas of numerical values of the selected parameters), the pipe composition can be determined and the range of their physicomechanical properties can be predicted. For a given roving content of 71%, basalt fiber diameter of 9%, and binder content of 24%, the predicted properties will fall within the following numerical ranges:

$$\sigma p \approx 360-381 MPa,$$
$$\sigma c \approx 285-303 MPa,$$
$$E \approx 14.2-15.1 GPa.$$

This approach allows for the management of pipe properties at the pre-design stage of production, which is advisable when predicting the composition and physicomechanical properties of pipes under industrial conditions. The work [19] confirms the feasibility of analyzing the working area of the composition and structure parameters to assess the rational properties of materials.

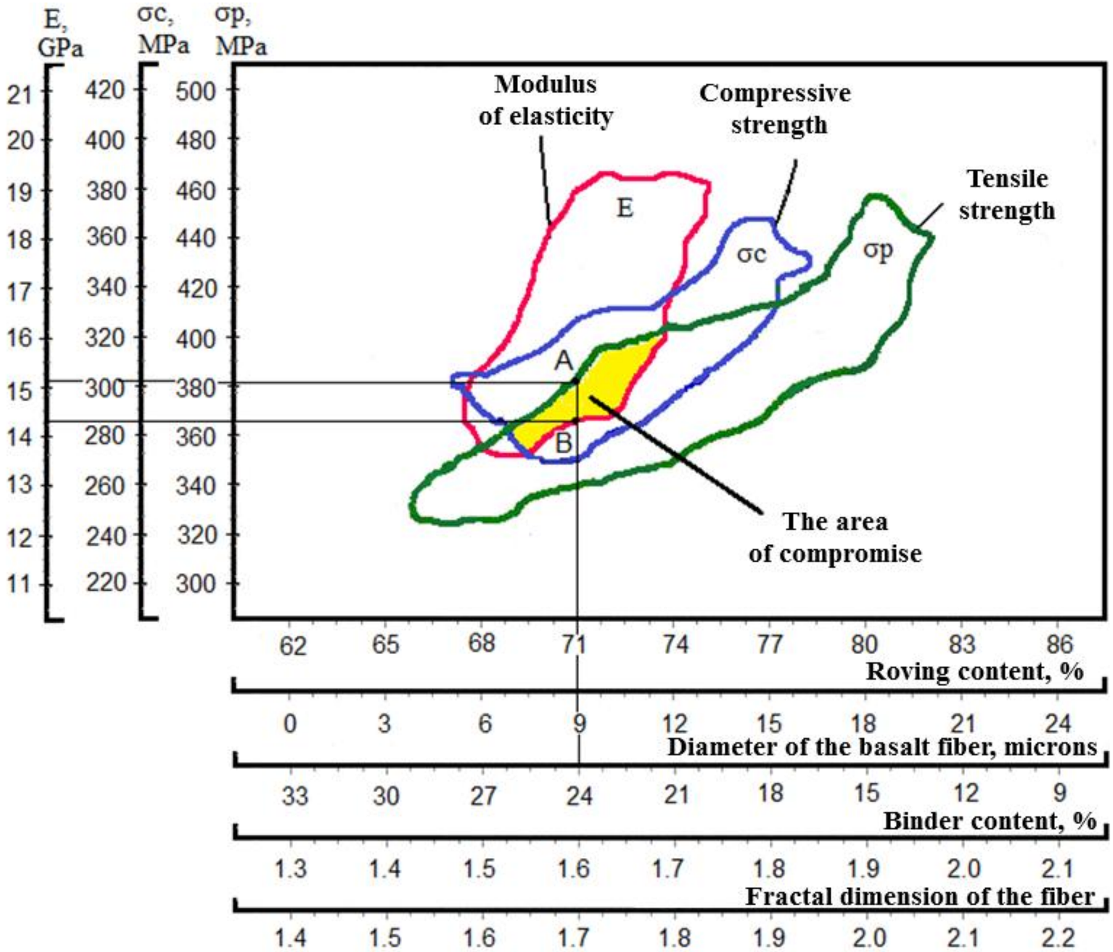


Fig. 5. – The compromise area of quality criteria for glass-basalt-plastic pipes: roving content 68-74%, basalt fiber diameter 7-12 μm, epoxy binder content 21-27%.

The selected criteria resulted in the following values:

$$\sigma p = 460 - 480 MPa,$$
$$\sigma c = 350 - 370 MPa,$$
$$E = 17 - 19 GPa.$$

The practical application of the compromise area of physicomechanical properties of glass-basalt-plastic pipes lies in the ability to select the primary criterion, as dictated by the customer, and ensure the attainment of its necessary numerical values by managing the technological parameters.

## 4 Conclusions

1. A compromise area for the physicomechanical properties of glass-basalt-plastic pipes has been determined using the graph-analytical method, with rational performance indicators of the pipes, including:

$$\sigma p = 460 - 480 MPa,$$
$$\sigma c = 350 - 370 MPa,$$
$$E = 17 - 19 GPa.$$

2. The use of the compromise area enables the production of pipes with predefined properties by controlling the percentage content of roving and epoxy binder, as well as the diameter of the roving fibers within strictly defined limits.
3. This approach provides a systematic method for managing the key technological parameters involved in the production of glass-basalt-plastic pipes, facilitating the prediction and optimization of their physicomechanical characteristics in accordance with specified requirements.
4. The proposed method demonstrates the potential for achieving the desired performance of composite pipes at the pre-design stage by effectively manipulating the composition and technological processes involved in their manufacture.

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