UDC 622.28.042.44
DOI: 10.15587/2706-5448.2024.306879

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DETERMINATION OF THE TYPE OF ARCHED CARBON FIBER REINFORCED FASTENING OF THE PREPARATORY OPENING FOR THE CONDITIONS OF THE «DNIPROVSKA» MINE IN WEAKLY METAMORPHIZED ROCKS

The object of study is an arched carbon fiber-reinforced support of constant cross-section in a layered massif of weakly metamorphosed rocks. The article presents an analysis of the possible use of arched fiber-reinforced support of constant cross-section in a layered massif of weakly metamorphosed rocks for the conditions of the «Dniprovska» mine (Ukraine) around the preparatory opening. An analysis of the stability of mine openings in Western Donbas mines has shown that it is necessary to modernize the support system by introducing carbon fiber. The main reason for the low stability of the opening is the insufficient load-bearing capacity of the support, while its technical characteristics do not take into account the complex mining and geological conditions. The increase in stresses at mining depth is associated with impact safety, which is a serious problem during mining. Metal arch supports are deformable and have high rock loads and require a high level of energy absorption, i. e., to be very strong and flexible to withstand significant loads and avoid large displacements of the opening walls.

Carbon fiber-reinforced plastic is able to ensure the stability of the fastening system and eliminate the existing disadvantages of typical metal arch fasteners, namely, high labour intensity, low production speed and high weight of the structure. In this article, the stress-strain state for the specified conditions and the carbon fiber-reinforced plastic arch support of constant cross-section was analyzed using the SolidWorks software product, taking into account the physical and mechanical properties of carbon fiber-reinforced plastic and layered rocks. Taking into account the results of laboratory tests of an equivalent layered array on a press made of PLA and carbon fiber, the dependence of deformations of the equivalent array with increasing load was established.

The use of arched carbon fiber supports of various cross-sections can ensure the opening stability by reducing the intensity of stresses around its contour. On the basis of this study, a rational arched composite support of constant cross-section was proposed for the conditions of the «Dniprovska» mine. The obtained results indicate the need for further research, which will be considered in the author's future works.

Keywords: *mine opening, opening stability, layered massif, carbon fiber, carbon fiber-reinforced plastic, rational parameters.*

Received date: 06.05.2024
Accepted date: 25.06.2024
Published date: 27.06.2024

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How to cite
Tsivka, Y. (2024). Determination of the type of arched carbon fiber reinforced fastening of the preparatory opening for the conditions of the «Dniprovska» mine in weakly metamorphized rocks. Technology Audit and Production Reserves, 3 (1 (77)), 35–40. doi: https://doi.org/10.15587/2706-5448.2024.306879

1. Introduction

Type and the selection of the optimal fastening parameters to support the preparatory opening in difficult operating conditions, is critical for any mine in the world. The correct solution of this issue determines the safety of work and the establishment of further technical and economic indicators for increasing the productivity of coal mining.

The problem of ensuring the stability of preparatory openings is considered on the example of the coal mines of Western Donbas (Ukraine), since it is one of the most relevant for them, due to the rapid increase in the depth of the works and the deterioration of the mining and geological conditions of coal mining.

One of the most promising ways of improving the fastening of mine openings is the use of modern innovative materials for fastening systems of these openings in interaction with layered rock massifs. Around the supported openings, a zone of damaged rocks is formed, where the intensity and character of the rock pressure changes. The expansion of this zone is associated with large displacements of rocks near the opening contour, which often exceed the technical flexibility of the fastening.

ISSN 2664-9969

There are effective methods of ensuring the opening stability, based on the creation of an unloaded zone around them, but they were not always widely used in the mines of Ukraine due to the high labor intensity of the work and the large consumption of materials required for the simultaneous strengthening of artificially disturbed surrounding rocks. Nevertheless, the direction of ensuring the opening stability [1] by increasing the bearing capacity of the host rocks is very promising and requires further development.

The physical and mechanical characteristics of innovative materials, in particular, composite materials, which turned out to be the best in terms of their properties, were considered and studied. Carbon fiber [2] is the most suitable material for supporting mine openings. This material has advantages over steel, so the replacement or partial combination of these materials is quite promising for the modernization of fasteners.

Taking into account the main physical and mechanical properties (Table 1), it is possible to say that carbon fiber is not only not inferior, but even superior to steel. Its main advantage is high strength with extremely high modulus of elasticity and low density and creep. The tensile strength of this composite material is 1400 MPa, which is the same as that of the steel from which the fastener is made. The density of carbon fiber-reinforced plastic is 1500 kg/m^3, while the density of metal is 7500 kg/m^3. This means that this innovative material will be 5 times lighter than steel.

Table 1

Physical and mechanical properties of carbon fiber-reinforced plastic

Physical and mechanical properties	Carbon fiber-reinforced plastic
Density, kg/m^3	1500
Tensile strength, MPa	1400
Young's modulus, MPa	125000
Specific strength, $e \cdot 10^3$, km	83
Specific module, $E \cdot 10^6$, km	14
Bending strength limit, MPa	1190
Compressive strength limit, MPa	990

The proper strength of products largely depends on the characteristics of the materials used. The use of arched carbon-plastic fasteners allows to transfer the load from the weight of the collapsed rock and helps reduce stresses along the opening contour due to the physical and mechanical properties of carbon fiber.

During the analysis, it was found that the stability of the preparatory openings [3, 4] depends mainly on the methods of carrying out, guarding and locating them next to the mining openings, as well as on the type, design and characteristics of the installed fastening.

Today, in Ukrainian mines, up to 90 % of pits are supported by metal arch support, but at least 30 % of them are damaged and need repair. One of the key reasons for the inefficient use of these structures is the insufficient bearing capacity of fasteners, as well as technical characteristics that do not take into account mining and geological conditions.

Therefore, solving the problem of reducing the intensity of stresses around the preparatory opening in a layered massif of weakly metamorphosed rocks requires the selection of the optimal type of fastening, which is based on the analysis of various factors ensuring reliability, bearing capacity, operational capacity, manufacturability of installation, economy and resistance to deformations. One of the most effective approaches to improving production and rational use of material resources is the use of combined fastening methods or the use of carbon-plastic materials.

The aim of this study is to justify the use of arched carbon-plastic fasteners in weakly metamorphosed rocks of the «Dniprovska» mine to increase the stability of the layered massif around the preparatory opening. For this it is necessary to:

– analyze the stability of the mining openings of Western Donbas mines;
– analyze composite materials and their physical and mechanical properties;
– analyze the stress-strain state of the layered massif of weakly metamorphosed rocks and the arched carbon-plastic fastening of the permanent section of the Dniprovska mine;
– conduct laboratory studies of displacements of the layered massif around the opening contour on the press.

2. Materials and Methods

In this research, mathematical and laboratory studies aimed at the application of arched carbon-plastic fasteners in a layered rock massif were carried out. For this, an analysis and a series of studies aimed at justifying the use of this type of fastening were conducted.

To select the appropriate mathematical model [5, 6], a wide range of geomechanical and technological factors that arise during coal mining were taken into account. A stress-strain study using SolidWorks software provided a complete overview of the pressure distribution around the preparatory opening. The dependences of displacements of the massif during preparatory opening using steel and carbon fiber-reinforced plastic for fastening structures were obtained.

The validity of the results obtained in this study was confirmed by laboratory tests. Their aim was to confirm the correctness of the mathematical modeling and to establish the optimal fastening parameters for the equivalent plastic model. The experiments were carried out on a press, where the load on the model was gradually increased over a certain period of time. The dependences of the deformation of the array and the attachment were obtained using the theory of similarity and plastic deformations.

3. Results and Discussion

Taking into account the assessment of the stability of the array according to the RMR classification [7], the main principles of opening stability and the results of previous studies [8, 9], it was established that the studied openings do not meet the stability requirements. In this regard, a decision was made to select in detail the optimal fastening parameters using carbon fiber-reinforced plastic. This made it possible to choose the cross-section and cross-section diameter of the fastener to ensure the stability of the preparatory opening under the given conditions.

The research task was solved by modeling a layered array of weakly metamorphosed rocks under the conditions of the «Dniprovska» mine in the SolidWorks software and experimental studies of an equivalent model on a press.

The research conducted in this direction showed that the stress-strain state graphs were asymmetric, and the stresses around the opening when using conventional fastening systems were uneven, which confirms the adequacy of the performed calculations for the selection of optimal parameters.

For the study, the c^5 layer with a mining depth of 400 m with the appropriate mining and geological conditions of the mountain massif was chosen and presented in Fig. 1. It includes 18 layers of rocks: 1 – argillite 0.8 m; 2 – sandstone 1.45 m; 3 – argillite 2 m; 4 – siltstone 1.7 m; 5 – coal seam 0.36 m; 6 – siltstone 0.6 m; 7 – sandstone 3.2 m; 8 – argillite 1.7 m; 9 – siltstone 3.4 m; 10 – argillite 2.9 m; 11 – argillite 2.5 m; 12 – coal seam 1.05 m; 13 – argillite 2.25 m; 14 – siltstone 2.55 m; 15 – coal seam 0.27 m; 16 – siltstone 3.4 m; 17 – argillite 7 m; 18 – siltstone 5.8 m.

The height and width of the model is 20 m with a thickness of 5 m. The angle of incidence is 1°. The depth at which the simulation is carried out is 400 m.

The accepted height and width of the model made it possible to conduct a reliable calculation of the stress-strain state of the layered massif of rocks in complex mining and geological conditions using the SolidWorks software product. According to the data (Table 2, Fig. 1), the studied layered rock massif and carbon-plastic reinforcement were built in an elastic-plastic formulation of the problem, which reflected the typical conditions of the mines of Western Donbas.

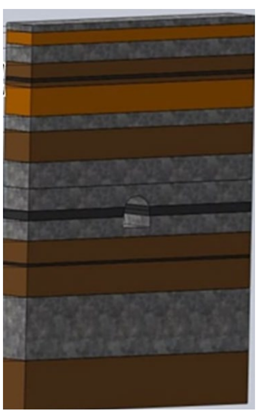


Fig. 1. The layered massif built according to the stratigraphic column for layer c^5 of the «Dniprovska» mine

Table 2

Physical and mechanical properties of rocks

Property	Rocks			
	Silt-stone	Argil-lite	Sand-stone	Coal
Modulus of elasticity, MN/m^2	1970	2000	2500	3600
Poisson's ratio	0.25	0.21	0.26	0.25
Shear modulus, MN/m^2	6000	6000	9500	1500
Mass density, kg/m^3	2510	2370	2600	1240
Tensile strength limit, MN/m^2	3	2.8	5.6	5
Limit of compressive strength, MN/m^2	25	18.5	28	30
Yield strength, MN/m^2	25	18.5	28	30

The main stage of this study was the analysis of the stress-strain state of the layered massif of weakly metamorphosed rocks under the conditions of horizontal and vertical stresses and arched carbon-plastic fastening of a constant cross-section in terms of intensity.

The effectiveness of this type of fastening is confirmed by careful analysis and research of the stress-strain state in difficult conditions. The key factor for an adequate analysis is the stress intensity distribution σ.

When calculating the stress-strain state of a carbon-plastic fastener of constant cross-section, the stress intensity was taken to be equal to 300 MPa (Fig. 2).

The analysis of the stress intensity plot around the preparatory opening using an arched carbon-plastic fastener of constant cross-section showed a number of changes compared to the basic metal fastener. In the opening roof, an unloading zone σ was formed, which differs in shape and size. Thus, unloading practically did not affect the rocks of the immediate roof, and on the other hand, a local zone with the value of σ is formed.

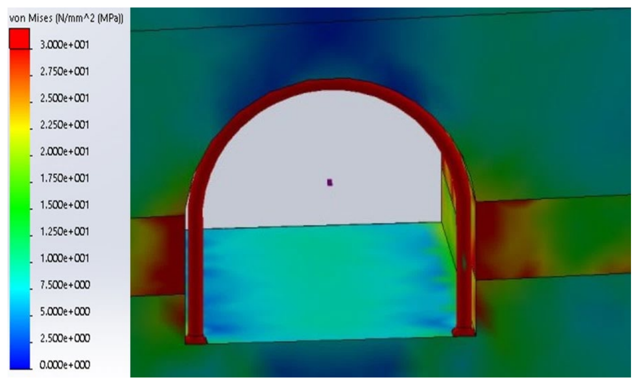


Fig. 2. Stress intensity diagram σ in the layered massif around the opening using carbon-plastic arch fastening of constant cross-section

Above the central part, a region with a concentration of σ appears in the rocks, which is 1.6–2.0 times higher than the initial state of the pristine massif.

In absolute terms, this concentration σ is not dangerous, since it is 3.0–3.8 times lower than the limit of compressive strength of the sandstones of the immediate roof. This fact should be noted for the following reason. Usually, including in metal arch fastening, an unloading zone is formed in the immediate roof above the opening, where the given value of σ characterizes the deflection of the roof rocks with corresponding horizontal displacements.

The top of the arched carbon-plastic fastener is in an unloaded state, which is often fixed when conducting computational experiments for the conditions of the mines of Western Donbas.

When analyzing the intensity of stresses (Fig. 3) of an arched carbon-plastic fastening of a constant section, the stresses range from 0 to +300 MPa.

Stresses of 20 to 50 MPa were observed in the top of the frame, with the highest values in the heels of the risers, which is normal for this type of fastening. The range of stresses in the compliance locks was from 5 to 15 MPa, which is due to the new technology of flexible fastening.

An unloaded state was observed in the upper part of the carbon-plastic fastener. The degree of unloading of the upper part is different from the metal arch fastening, and the peripheral cross-section of the upper part is in the zone of yielding locks with stresses from 20 to 25 MPa, which is normal for their operation [10].

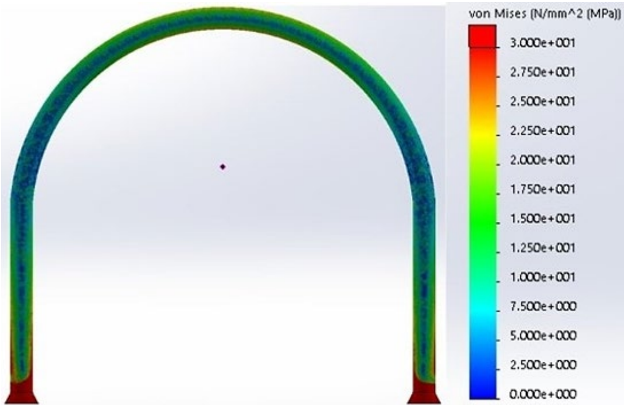


Fig. 3. Graph of stress intensity σ of carbon-plastic arch fastening of constant section

The results of the analysis of the stress-strain state of the massif and analytical studies showed that in the conditions of the «Dniprovska» mine, it is advisable to use arched carbon-plastic fasteners of constant cross-section with a cross-sectional diameter of 200 mm for layer c^5.

Changing the diameter and reducing the weight of the fastener is possible due to the high physical and mechanical properties of carbon fiber-reinforced plastic for creating structures of various geometric shapes, which is the basis of this relationship.

The advantages and disadvantages of this type of fastening in these conditions should also be highlighted. The advantages include ease of assembly and disassembly, the possibility of repeated use, and occupational safety. One of the disadvantages is the high cost. This is due to the large amount of carbon fiber used in these conditions.

The next stage was a laboratory study to determine the movements of equivalent rock layers under load to confirm the results of mathematical modeling of an arched carbon-plastic fastener with a constant cross-section in the layered massif of weakly metamorphosed rocks of the «Dniprovska» mine.

In order to obtain adequate results of the laboratory study, a geometric modeling scale of 1:60 was chosen. In this case, the cross-section of the produced space will have a maximum size of 9 cm. The effect of the produced space on the surrounding massif is local.

Its small volume, subject to compliance with the boundary conditions, allows to form and test a large number of models in a fairly short period of time with minimal material costs. The main criteria for choosing an equivalent material were its compressive strength limit, modulus of elasticity and Poisson's ratio. For a correct test on the press, the physical and mechanical properties of the equivalent material (Table 3) were determined based on the theory of similarity.

The deformation properties of the equivalent material have a linear dependence on the increase in external load. To determine the deformation process of an equivalent material, the average deformation of a series of materials is taken.

After the model was fully formed, loads were gradually applied to it that corresponded to the actual loading conditions over a period of time.

In order to record the results of the movements of the equivalent model, a rectangular grid with a cell size of 20×20 mm was applied to the glass surface. In the center of the model, the opening was displayed in interaction with a carbon-plastic arch attachment of proportional size.

The load was set according to the location of the geometric center with an interval of 700 N (Fig. 4). Every 30 minutes, the development of deformations was observed on the grid, and cracks and displacements were recorded on the camera. It was installed in the same position for the entire duration of the experiment.

The diagram (Fig. 5) of the distribution of stresses around an arched carbon-plastic fastener of constant cross-section shows a dependence, which indicates a decrease in the intensity of stresses in the layered massif of weakly metamorphosed rocks, which is typical for the conditions of the mines of Western Donbas. The discrepancy between laboratory and mathematical studies was 15 %, which confirms the feasibility of using this type of fastening for the conditions of the «Dniprovska» mine.

Thus, the results of the study are as follows:

– the displacement of the opening contour is not detected immediately after the installation of the arched carbon-plastic fastening, but after a certain period of time, which is determined, first of all, by the stability of the fastening and the strength of weakly metamorphosed rocks;

– the equivalence of the model is confirmed by the fact that in some points the research contradicted the numerical geomechanical data in this direction;

– obtained regularities of the distribution of the stress-strain state of the weakly metamorphosed layered massif using arched carbon-plastic fasteners of constant cross-section showed a decrease in the intensity of stresses around the contour of the preparatory opening for the conditions of the «Dniprovska» mine and confirmed the need to use this type of fastener.

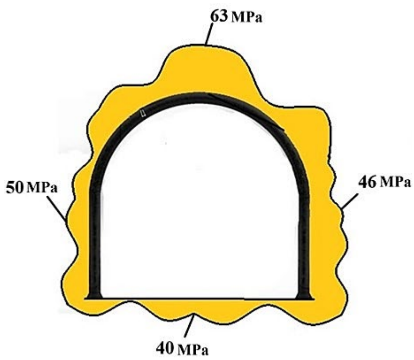
Table 3

The main physical and mechanical parameters of nature and equivalent material obtained on the basis of Newton's similarity

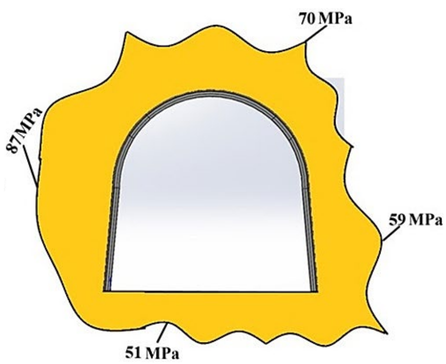
Characteristics of the material	Natures				Similarity coefficient	Models			
Mountain rock	Siltstone	Argillite	Sandstone	Coal		Siltstone	Argillite	Sandstone	Coal
Strength limit for uniaxial compression, MPa	16	17	15	13	0.046–0.044	0.7	0.75	0.65	0.6
Young's modulus, E, MPa	$3.22 \cdot 10^5$				0.013–0.093	0.042	0.05	0.060	0.03
Volumetric mass, γ, t/m^3	3	2.7	4	2	0.62–0.73	1.6	1.8	1.7	1.9
Poisson's ratio, μ	0.25	0.21	0.26	0.25	1	0.25	0.21	0.26	0.25

a b c

Fig. 4. Deformation of the equivalent model of the layered array under the action of the load: *a* – 4 kN; *b* – 9 kN; *c* – 12 kN



a



b

Fig. 5. Dependence of pressure distribution around the contour: *a* – arched carbon-plastic fastening of constant cross-section; *b* – arched metal fastening of the SVP 27 profile

Practical meaning. The use of arched carbon-plastic fasteners of various cross-sections is possible in any difficult mining and geological conditions. Its high levels of strength and flexibility allow to create a strong and flexible structure of various geometric shapes on a 3D printer. This ensures the integrity of the mine by reducing the stress intensity.

Limitations of the study. In order to implement the use of arched carbon-plastic fasteners in the mining industry, it is necessary to modernize enterprises for the manufacture of fastening structures with the necessary equipment.

The influence of martial law conditions. The martial law conditions in Ukraine did not affect the obtained results.

Prospects for further research. The obtained results allow to proceed to the next stage of testing arched carbon-plastic fasteners in mine conditions and introducing them into production.

4. Conclusions

The following pattern was established on the basis of studies of deformation processes around preparatory openings in a layered massif with an arched carbon-plastic fastener: when the stresses around the opening contour (P, MPa) increase, the cross-section diameter of the fastener ($D_{cross\text{-}section}$, mm) increases. This made it possible to determine the rational parameters of a new type of fastening for the conditions of the «Dniprovska» mine in order to reduce the intensity of rock pressure. The rational parameters of the arched carbon-plastic fastening of a constant cross-section ($D_{cross\text{-}section}$=200 mm, $h_{reinforcement}$=3600 mm) are sufficient to maintain the stability of the preparatory openings in the layered massif of weakly metamorphosed rocks.

Under the studied conditions, with the selected type of fastening around the preparatory opening in weakly metamorphosed rocks, it was possible to reduce the stress intensity from the level of σ=0.4 to the level of σ=2.0 due to the flexibility locks and high strength characteristics of carbon fiber-reinforced plastic.

Conflict of interest

The author declares that he has no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the study and its results presented in this paper.

Financing

The study was conducted without financial support.

Data availability

The manuscript has no associated data.

Use of artificial intelligence

The author confirms he did not use artificial intelligence technologies when creating the presented work.

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UDC 666.1.031.2/.6:004.94](045)
DOI: 10.15587/2706-5448.2024.307613

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SIMULATION OF THE WORK OF GLASS FURNACES WITH THE PURPOSE OF SEARCHING FOR RESERVES AND INCREASE THEIR EFFICIENCY

The object of research is the operation of a glass furnace. The work involved modeling the operation of a glass furnace by changing the technical and economic indicators of its operation in order to optimize the technological processes of manufacturing glass products, increase the energy efficiency of the process, and reduce the ecological burden on the environment. Glass furnaces are complex heat engineering units that require a large amount of energy to operate. Therefore, increasing their effectiveness is the main task of our research. In the work, computer modeling of thermal processes in the furnace was carried out, heat balances were calculated and analyzed, and the performance of the furnace was analyzed after changing and improving the technological regimes of combustion processes, glass boiling and furnace construction. Studies have shown that in order to increase the technical and economic performance of glass furnaces, it is advisable to conduct additional thermal insulation of the furnace enclosures. The thermal insulation of the vault increases the efficiency of the furnace by 2–3 %, and the thermal insulation of the remaining areas of the furnace in total allows to increase the efficiency of the heating unit up to 3 %. Such measures improve the sanitary and technical working conditions of the staff in the machine-bath shop. Studies have shown that additional heating of the air used for burning fuel significantly increases the efficiency of the furnace. Thus, an increase in air temperature by 100 °C increases the efficiency of the furnace by approximately 2.5 %. However, such a measure is possible with a corresponding increase in the volume of regenerator nozzles. A significant increase in the efficiency of the furnace was achieved when additional electric heating was installed. This allows to reduce the total energy costs, and at the same time, the introduction of every 10 % of additional electric heating increases the efficiency of the furnace by up to 3 % and improves the quality of the glass mass. Such additional heating can be recommended in the amount of 20–30 % of the total heat consumption for the operation of the furnace. The analysis of the obtained results showed a fairly good convergence of the results, which indicates the acceptable adequacy of the models. The obtained process simulation results allow choosing the optimal design and operation parameters of the glass furnace. The results of the work can be used in practice for the design of efficient glass furnaces of various purposes and performance.

Keywords: *glass furnace, regenerators, combustion, electric heating, computer simulation of technological processes.*

Received date: 23.04.2024
Accepted date: 29.06.2024
Published date: 30.06.2024

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How to cite
Zhdaniuk, N., Plemyannikov, O. (2024). Simulation of the work of glass furnaces with the purpose of searching for reserves and increase their efficiency. Technology Audit and Production Reserves, 3 (1 (77)), 40–46. doi: https://doi.org/10.15587/2706-5448.2024.307613

1. Introduction

Glass boiling is a high-temperature process that requires a significant amount of energy. Thus, the boiling of industrial silicate glass takes place at a temperature of about 1500 °C. Traditionally, the energy used to operate the glass furnace was provided mainly by fossil fuels [1]. At the same time, more than 75 % of the total energy required for the production