DEVELOPMENT OF THE UNIVERSAL WORKING EQUIPMENT OF THE EXCAVATOR FOR PREPARATION OF MATERIALS BASED ON WASTE DURING THE ROAD BUILDING

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Resume

The article proposes a technological line for recycling the blast-furnace slag. This line makes it possible to obtain the crushed stone for road building, which has high water and frost resistance. The design of replaceable working equipment of a single-bucket excavator, with replaceable working tools for loosening frozen slag in dumps and preparing it for use in road building, is proposed. The results of testing the manufactured replacement working equipment are presented. The results of mathematical processing of experimental data using the approximation method are presented, as well.

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1 Introduction

Development of the road infrastructure and, in particular, the construction and reconstruction of highways, bridges and overpasses, is one of the most pressing issues in the field of transportation [1-8]. At the same time, one of the most material-intensive, financial and energy-consuming operations in the road construction, is the production of building materials and its transportation to the place of road building. This fact determines the relevance of the development of new cheaper materials for road building [9-25].

Organizations involved in the road building widely use artificial materials made on the basis of man-made waste, for example, based on the blast furnace slag, as an alternative to natural materials [9-11].

Blast furnace slag is one of the wastes of ferrous metallurgy, which is formed in a liquid state during the smelting of pig iron and solidifies when it is cooled. Blast-furnace slag consists mainly of gangue iron ore. There are about 500 kg of blast-furnace slag per each 1 ton of cast iron, which needs to be processed. About 1.1 billion tons of pig iron are produced annually in the world, therefore, the annual global production of the blast furnace slag is about 500-550 million tons [2].

Recycling and further use of solid metallurgical slags, instead of expensive natural materials, reduces the cost of road building, significantly reduces the environmental burden in the regions due to elimination of slag dumps, allows to preserve mining and chemical raw materials, mineral materials [9-11]. All this confirms the need to solve the environmental problem of disposal of solid blast furnace slag accumulated in dumps.

The results of research in the field of processing the blast-furnace slag for use in construction are presented in a large number of scientific papers by both the authors of this article [9-11] and many other authors, [26-38].

A preliminary literature analysis of these articles showed that the most common method of recycling the blast-furnace slag is its granulation. Granulation is a rapid cooling of liquid hot slag in a water jet, leading to formation of a fine-grained (less than 10 mm) bulk

Figure 1 *The blast-furnace slag dump of ArcelorMittal Temirtau JSC on a satellite image*

multicomponent material - granulated blast-furnace slag.

Granulation of the blast-furnace slag is carried out for its further use as an active mineral additive in the production of cement and concrete. Blast-furnace slag is also used for the production of the calcium-containing ferroalloy, paving slabs, curbs, fertilizers, asphalt concrete pavements and heat-insulating materials. Despite this, the demand for blast-furnace slag in regions with ferrous metallurgy enterprises is, as a rule, much lower than the volume of production of this material.

Due to the limited demand for the blast-furnace slag in regions with metallurgical production, despite the processing of most of the material in the ways described above, a significant part of the slag is still sent to dumps that occupy huge areas and require disposal. For example, according to the data for 2022, more than 30 million tons of the blast-furnace slag have been accumulated in the dumps of ArcelorMittal Temirtau JSC (Figure 1).

The main method of recycling the solid blast-furnace slag from dumps is production of the crushed stone for road building. However, today the use of the blast-furnace slag for roads building is limited due to its high water absorption (6 - 8%) and insufficient frost resistance.

The main reason for these disadvantages is the high porosity of a significant part of crushed stone grains made based on the blast furnace slag (Figure 2). The moisture absorbed by the pores of the blast-furnace slag in summer increases in volume when it freezes in winter and destroys crushed stone grains, as well as pavement built on its basis, causing the formation of cracks, subsidence and ruts on the asphalt pavement. [39].

To solve this problem, the work [39] proposes a technology for processing the slag crushed stone, which includes the following steps:

1) mixing pre-moistened crushed stone with a liquid mixture containing cement, microsilica and crushed (to a powder state) blast-furnace slag;
2) filling the pores of the obtained material with a powdered filler of a similar composition;
3) removal of excess powdered filler from the surface of crushed stone grains;
4) moistening the slag crushed stone for better setting of the filler in the pores;
5) drying of the slag crushed stone with filled pores;
6) impregnation of the obtained material with a water-repellent composition.

Kunaev proposed an experimental production line for the practical implementation of this technology (Figure 3), [39]. Let us consider the principle of operation of this production line.

Mixer 1 performs the pre-mixing of the pre-moistened (for better adhesion) crushed stone with a liquid mixture containing cement, silica fume and crushed (to a powder state) blast-furnace slag [9]. Next, the slag crushed stone enters into the mixer 2, which fills pores with a dry mixture of a similar composition.

Figure 2 *External pores on the surfaces of slag crushed stone grains*

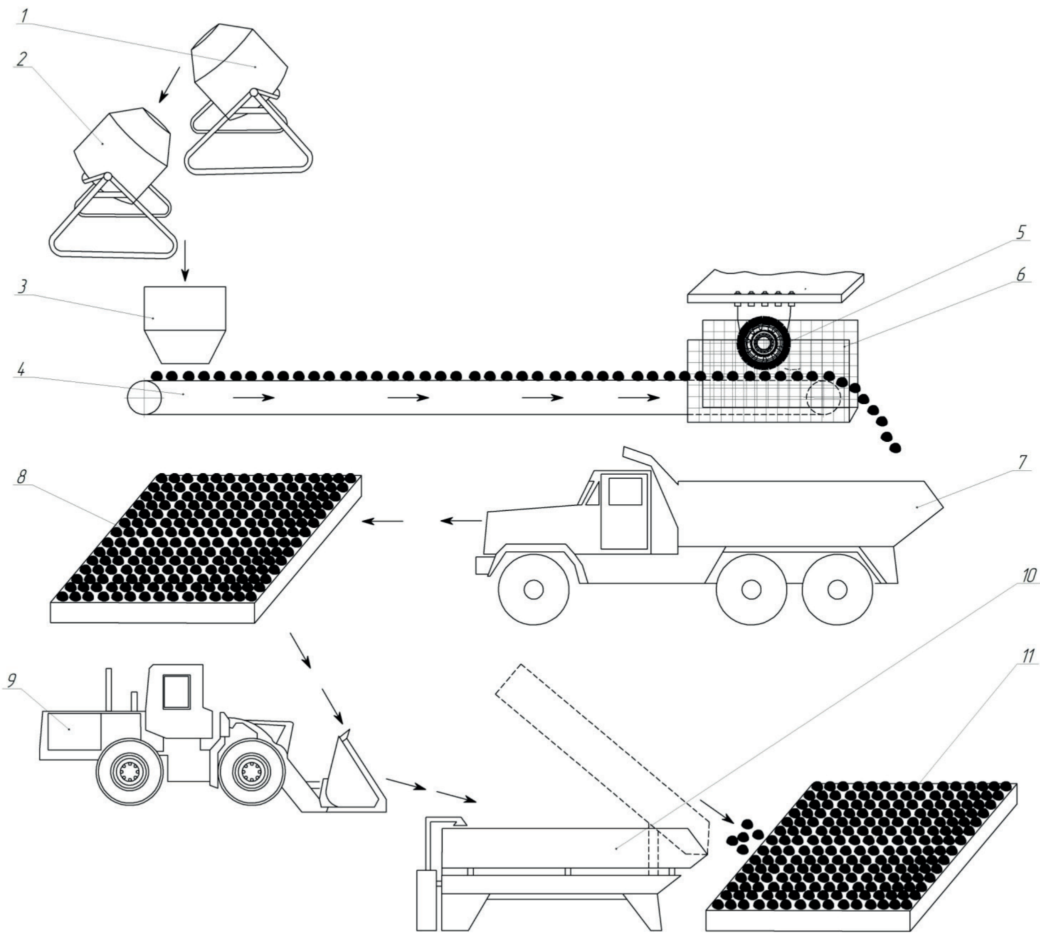


Figure 3 *Experimental technological line for hydrophobization of slag crushed stone: 1, 2 - mixers; 3 - dispenser; 4 - belt conveyor; 5 - rotating brush with synthetic bristles; 6 - metal gratings; 7 - dump truck, 8 section of moistening and pre-drying, 9 - single-bucket loader, 10 - bath for hydrophobization (impregnation with a water-repellent composition), 11 - finished product storage section*

After that, the crushed stone is directed through the dispenser 3 along the conveyor 4, to the rotating brush with synthetic bristles 5. The brush 5 during rotation ensures indentation of the powdered filler deep into the pore space and the removal of excess mixture from the surface of the crushed stone grains. Metal gratings 6, installed on both sides of the conveyor, prevent the crushed stone from spilling over the borders of the conveyor belt when in contact with the brush. The dump truck 7 transports the slag crushed stone with filled pores to the section of moistening and pre-drying 8, where the surface of the material is moistened for setting the powder mixture. The crushed stone is located at this site until the setting the powdery filler in its pores. Then, the single-bucket loader 9 loads the slag crushed stone into the impregnation bath for hydrophobization (impregnation with a water-repellent composition) 10. After impregnation for a predetermined time, the crushed stone is unloaded to the finished product storage section 11. For convenience, this technology of the slag crushed stone recycling is supposed to be used directly near the road under construction [39].

Prior to the delivery of the slag crushed stone to this technological line, the blast furnace slag must be removed from the dumps and crushed to the required fraction size. However, during the long-term (20 - 30 years) storage of slag in dumps, its elements are compressed, fastening together and forming a monolithic material, inconvenient for loading into dump trucks and crushing. This task is especially difficult in winter, when the blast-furnace slag in dumps becomes a frozen material. In conditions of a sharply continental climate, this period can be more than half of a calendar year. In order to avoid stopping the extraction of slag from dumps and further hydrophobization for the winter period, the preparation of this material for crushing into crushed stone and subsequent processing should include preliminary loosening [9]. Based on the foregoing, the purpose of this paper was formulated.

The purpose of research is to develop, manufacture and test equipment with interchangeable working tools for preparation of building materials based on industrial waste during the road infrastructure building, namely loosening frozen dump slag in the winter, as well as pressing powdered filler deep into the pore space of crushed stone grains and removing its excess from the surface of the processed material.

To achieve this purpose, the following tasks were solved:

- analysis of equipment constructions and methods for loosening the hard rocks and frozen soils;
- selection of materials and methods of research;
- development of a 3D model and drawings of a universal working body of a single-bucket excavator with interchangeable working tools;
- manufacturing and testing of a prototype of a universal working body of a single-bucket excavator.

2 Literature review

The first stage of the production of the slag crushed stone for road building is the extraction of raw materials (blast furnace slag) from dumps.

For loosening the blast-furnace slag during its extraction from dumps, it is recommended to use earth-moving machines designed to develop frozen and solid soils.

In order to develop the construction of equipment for loosening the frozen blast-furnace slag in dumps in winter, the existing equipment for loosening the frozen soils was analyzed.

A critical analysis of technologies and equipment for loosening frozen and solid soils, which can be used, among other things, in the loosening of frozen slag in dumps, showed that the most significant results in this area were achieved by authors of [9, 40-50]. The main types of machines used for loosening the frozen soils, discussed in works [40-50], are listed in Figure 4.

Let us consider the main methods and equipment for loosening the frozen soils, which are described in these works and, accordingly, hypothetically can be used for loosening the blast-furnace slag in dumps in winter.

Explosive (slit or hole) method is used in preparation of the frozen soils for further excavation. This method is mainly used in uninhabited areas. It is acceptable in inhabited areas, as well, however, with use of shelters and explosion localizers. Slots are cut at a distance of 0.9-1.2 m from each other by the trencher machines or slot cutters. Next, the slots are loaded through one with concentrated or elongated charges. After that, the slots are filled with sand. When loosening the frozen ground by this method, the site is preliminarily divided into several grips. At the first grip, holes are sequentially drilled, charged and blown up. At the second grip, the work is not carried out according to safety conditions, while at the third grip, the ground excavation is carried out directly.

The method of mechanical loosening of the frozen soils is advisable to apply at a freezing depth of 0.4 to 1.5 m and the excavation of small-sized pits and trenches. This method involves crushing or chipping the frozen layer by static or dynamic action of a special working body mounted on an excavator, tractor or other base machine.

Dynamic impact is provided by shock, vibration or their combined action using a ball or wedge hammer, diesel hammers, wedge tractor rippers and other equipment. It should be noted that the costs of mining by dynamic methods using diesel hammers and hydraulic hammers are 2 to 3 times higher than the costs of mining with rippers, performing mechanical loosening [48-50].

Analysis of the considered methods of loosening the frozen soils showed that the most of them fully meet the requirements for equipment for loosening the frozen dump blast-furnace slag, the replaceable working

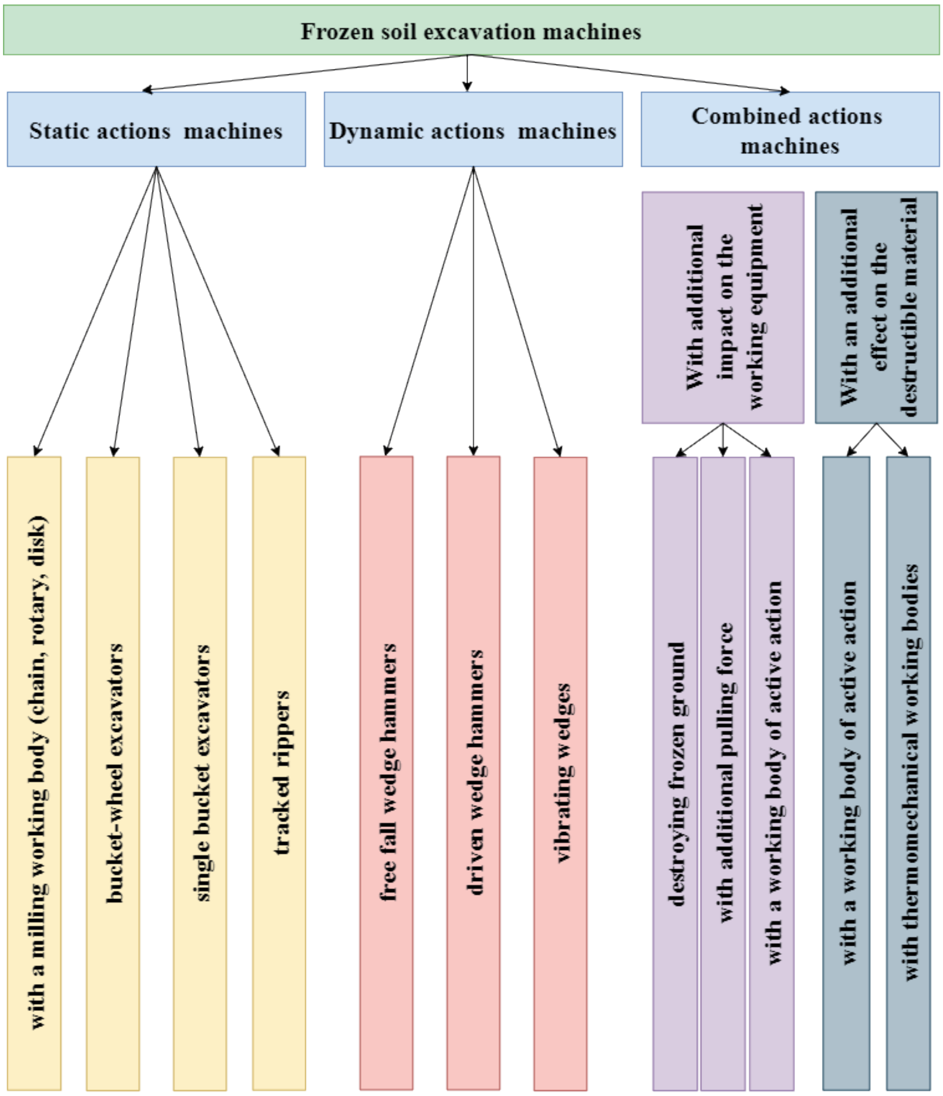


Figure 4 *The main types of machines for loosening the frozen soils*

equipment of a single-bucket excavator, proposed by Letopolsky et al. [50]. Authors proposed to use an excavator bucket combined with a hydraulic hammer as a replaceable working equipment.

In order to optimize the workflow and reduce the time spent on changing work equipment, an improved design of the working body of a single-bucket excavator has been proposed. The design solution combines a bucket and two hydraulic hammers located on the front side of the bucket.

At the first stage, the excavator works with hydraulic hammers, loosening the frozen and hard soil and at the second stage, it works with a bucket, collecting loosened soil and loading it into a dump truck body.

In the course of the theoretical studies, the authors of [50] calculated dependencies that allow to determine the parameters of the installed hydraulic hammers. The proposed design solution increases the performance and operational reliability of the working equipment of the excavator in the development of frozen and solid grounds. Developing their experience, and of other specialists in the field of soil mechanics, as well as based on our own practical experience of the research team, confirmed by analytical studies, our team of authors propose to use cheaper cutterhead ripper for loosening the frozen blast-furnace slag.

3 Materials and methods

To achieve the purpose and objectives of the research, both theoretical (literature review, 3D computer modeling, development of technical specifications for designing of experimental equipment and a flow sheet of the developed processes, approximation of experimental dependencies) and experimental (manufacturing and testing of an experimental construction of the cutterhead ripper, production and testing of an experimental sample of crushed stone based on the blast-furnace slag using the proposed equipment) methods were used.

According to the results of a literature review, the working group of the Karaganda Technical University

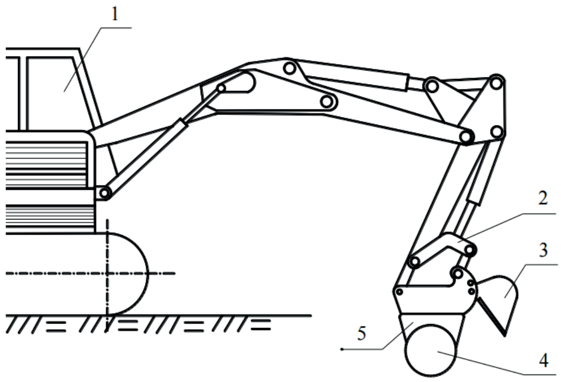


Figure 5 *General view of the cutterhead ripper: 1 - excavator, 2 - bracket, 3 - bucket 3, 4 - cutterheads, 5 - body*

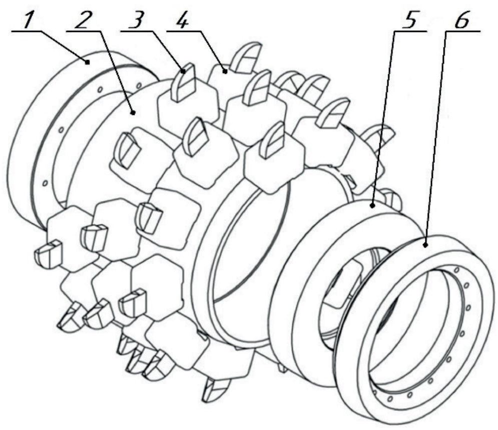
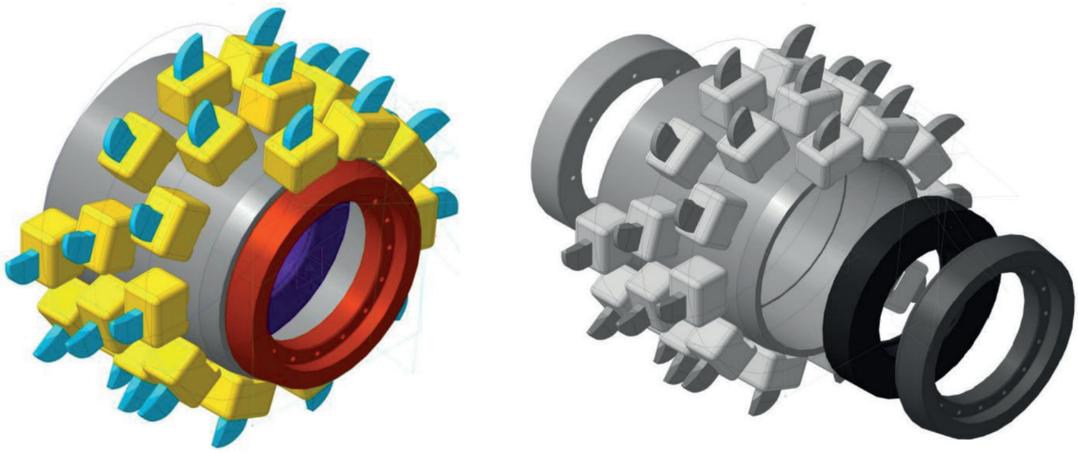


Figure 6 *The construction of the proposed cutterhead (in a disassembled state): 1 - bush, 2 - body, 3 - fist, 4 - cutterhead, 5 - bush, 6 - sidewall*



a) b)

Figure 7 *The 3D model of the cutterhead: a - cutterhead in the assembled state, b - cutterhead in the disassembled state*

under the leadership of professor Kadyrov (one of the authors of this article) decided to develop the construction of a universal cutterhead ripper with replaceable working tools. The cutters (for loosening frozen grounds) and the synthetic brushes (for pressing powdered filler deep into the pore space of crushed stone grains and removing its excess from the surface of the processed material) were proposed to use as working tools. The proposed construction of the cutterhead ripper is mounted on the basis of a single-bucket excavator and allows to crush and excavate the frozen grounds and rocks of high strength.

The cutterhead ripper is a replaceable working body, which is pivotally mounted on the handle of the base excavator 1 and consists of two coaxially located ground-destroying cutterheads 4, a body 5, a bracket 2, a bucket 3 and a drive (Figure 5). Holders with replaceable cutting elements (cutters) are placed on the surface of the cutterheads along a helical line.

To develop a prototype of a universal cutterhead, 3D models of all parts of this equipment and a general 3D model were preliminarily built. The construction of the cutterhead is shown as a 3D model in Figures 6 and 7.

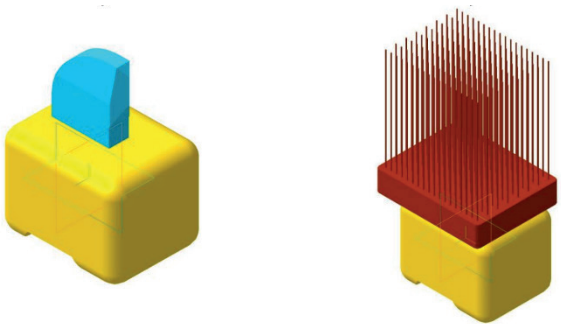
Structural parameters of the bracket satisfy the condition of interchangeability of the working equipment. A bucket (attached to the bracket) serves to extract the solid blast-furnace slag from the dump. The bucket has two positions relative to the bracket: neutral and working. The transmission of torque to the cutterheads is carried out through a planetary gearbox and a bevel gear from an axial-piston hydraulic motor. The power source of the hydraulic motor is the oil station of the base machine (excavator).

The work of an excavator with a universal cutterhead ripper provides for the layer-by-layer loosening of an array of the dump blast-furnace slag with its further excavation from the dump with a bucket.

Introduction of the working body into the array and its translational movement along the loosening strip located on the slag dump is carried out due to the pressure force of the hydraulic cylinders of the boom and the handle. The main technical characteristics of the universal cutterhead of the proposed construction are presented in Table 1.

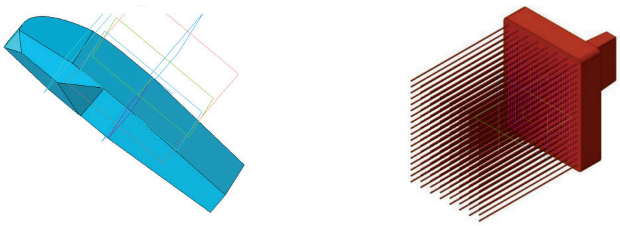
Table 1 *Technical parameters of the universal cutterhead of the proposed construction*

Parameter	Value
Loosening depth per pass (m)	0.2
Loosening strip width (m)	1.1
Performance (m^3/hour)	7.0
Hydraulic motor power (kw)	36.9
Torque of the working body (N·m)	6000
Universal cutterhead diameter (by cutters) (m)	0.68
Overall dimensions	
Width (m)	1.1
Height (m)	1.2
Weight (kg)	1000



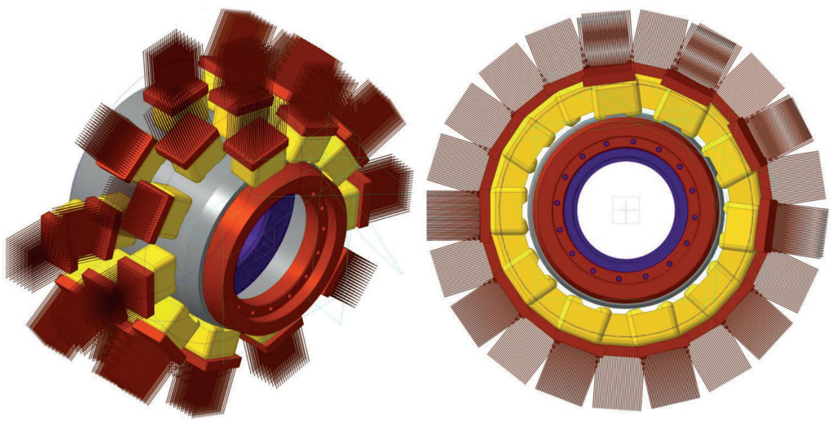
a) b)

Figure 8 *Replaceable working tools of a universal cutterhead assembled with a fist: a - cutter, b - brush*



a) b)

Figure 9 *Replaceable working tools of a universal cutterhead: a - cutter, b - brush*



a) b)

Figure 10 *The 3D model of the cutterhead with the installed synthetic brushes: a - isometry, b - right side view*

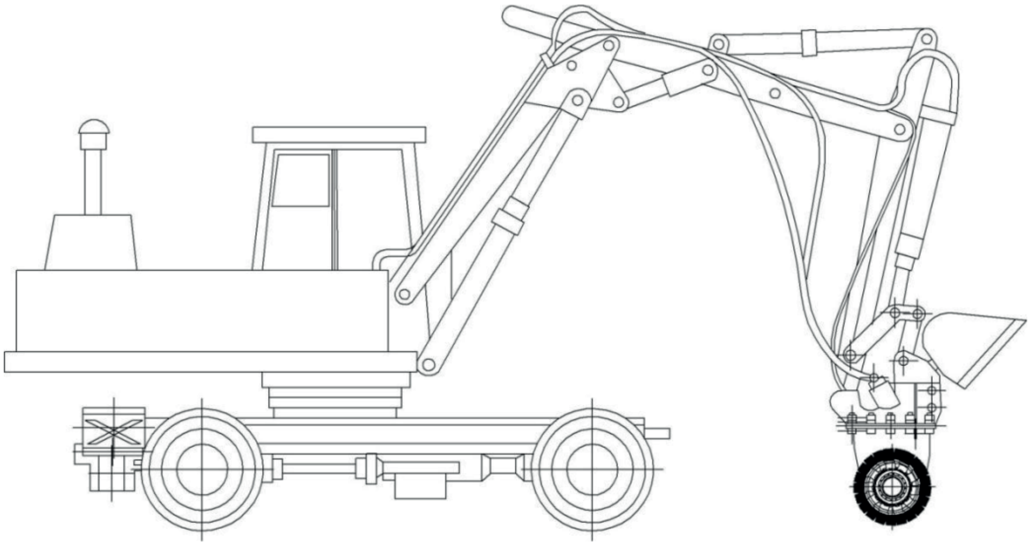


Figure 11 *Cutterhead ripper with replaceable tools - brushes with synthetic bristles*

The peculiarity of the proposed equipment is the presence of a bucket for removing the loosened blast-furnace slag, which allows loosening and moving the material without the involvement of additional machines and ensures the energy efficiency of this equipment [51].

Taking into account the seasonality of work on loosening the frozen ground and blast-furnace slag in dumps, in order to avoid downtime of the cutterhead ripper in the summer, the authors of this paper propose to use it as part of an experimental technological line for hydrophobization of the slag crushed stone, namely, for compacting the powdered filler in the pores of crushed stone grains and removing its excess from the material surface. To solve this problem, the replaceable working tools of a universal cutterhead ripper were developed. These replaceable working tools are the brushes with synthetic bristles (Figures 8, 9). Figure 8 shows two versions of the replaceable working tools of the cutterhead ripper assembly with a fist, for fixing in which a Morse cone connection is used (the cone angle is 3°).

This connection type is chosen as the most quickly detachable. Welding is used to attach the fists to the cutter body. Figure 9 shows the same working tools (cutter and brush), but separated from the fist. A 3D model of a universal cutterhead with installed brushes is shown in Figure 10.

4 Results and discussions

Based on the constructed 3D models, assembly drawings of a universal cutterhead installed on a basic machine (a single-bucket excavator) were developed. Figure 11 shows a general view of a single-bucket excavator with a universal cutterhead with synthetic brushes used as working tools.

In this case, a universal cutterhead with brushes with synthetic bristles, installed as a working body of a single-bucket excavator, can be used as a part of a mobile technological line for processing the crushed slag stone in road conditions in summer, replacing a rotating brush. This completely eliminates the downtime of the proposed equipment in the summer and saves money for the purchase of a separate rotating brush with a drive.

The technological line for processing the slag crushed stone, containing a single-bucket excavator with a universal cutterhead equipped with brushes (highlighted in green oval), is shown in Figure 12. Otherwise, this technological line operates similarly to the line shown in Figure 3.

Based on the developed drawings, a prototype of a universal cutterhead was made. The manufactured prototype of a universal cutterhead, mounted on a base machine (single-bucket excavator), shown in Figure 13, was tested for suitability for loosening (destruction) of various materials. The results of tests are presented in the diagram in Figure 14.

The second experiment was aimed to evaluate the applicability of a universal cutterhead, equipped with replaceable working tools (brushes), as a replacement for a separate rotating brush when used as a part of an experimental technological line to remove excess powdered filler from the surface of the slag crushed stone grains, as well as to determine the optimal time of processing the slag crushed stone by universal cutterhead, equipped with synthetic brushes.

The main task of this experiment was to assess the effect of the processing time of the slag crushed stone with a universal cutterhead t_{proc} equipped with synthetic brushes on the quality of filling the pores of experimental samples of the crushed stone. The quality of filling the pores was evaluated by reducing the water absorption W_{abs} of the slag crushed stone samples after processing with a universal cutterhead and impregnating with a hydrophobizer (water repellent). Thus, the objective function looks like:

$$W_{abs} = f(t_{proc}) \rightarrow min. \quad (1)$$

For the experiment, 10 experimental samples of the hydrophobized slag crushed stone were prepared. Each of these samples weighed from 2000 to 2100 g. During the experiments, the developed construction of a universal cutterhead was used to fill the pores of the slag crushed stone with powdered filler and remove its excess from the surface of the material. And the processing time was varied from 30 seconds to 300 seconds in increments of 30 seconds (Table 2).

Each sample was tested for water absorption. The water absorption was determined by comparing the mass of samples of the slag crushed stone in water-saturated condition and after drying. Samples of crushed slag stone were placed in the reservoir with water so that the water level in the reservoir was at least 20 mm higher than the top of the slag crushed stone samples. The samples were kept in the reservoirs with water for 48 hours, after which each sample was taken out of the reservoir and weighed on a scale with an error of no more than 1 g. Water absorption was calculated by the formula:

$$W_{abs} = \frac{m_1 - m_2}{m} * 100\,\%\,, \quad (2)$$

where:
m_1 - mass of a sample in the water-saturated condition, g;
m - mass of a sample in the dry condition, g.

The results are presented in Table 2.

The Microsoft Excel was used to process the experimental data. The graphic dependence presented in Figure 15 shows the effect of the time of processing

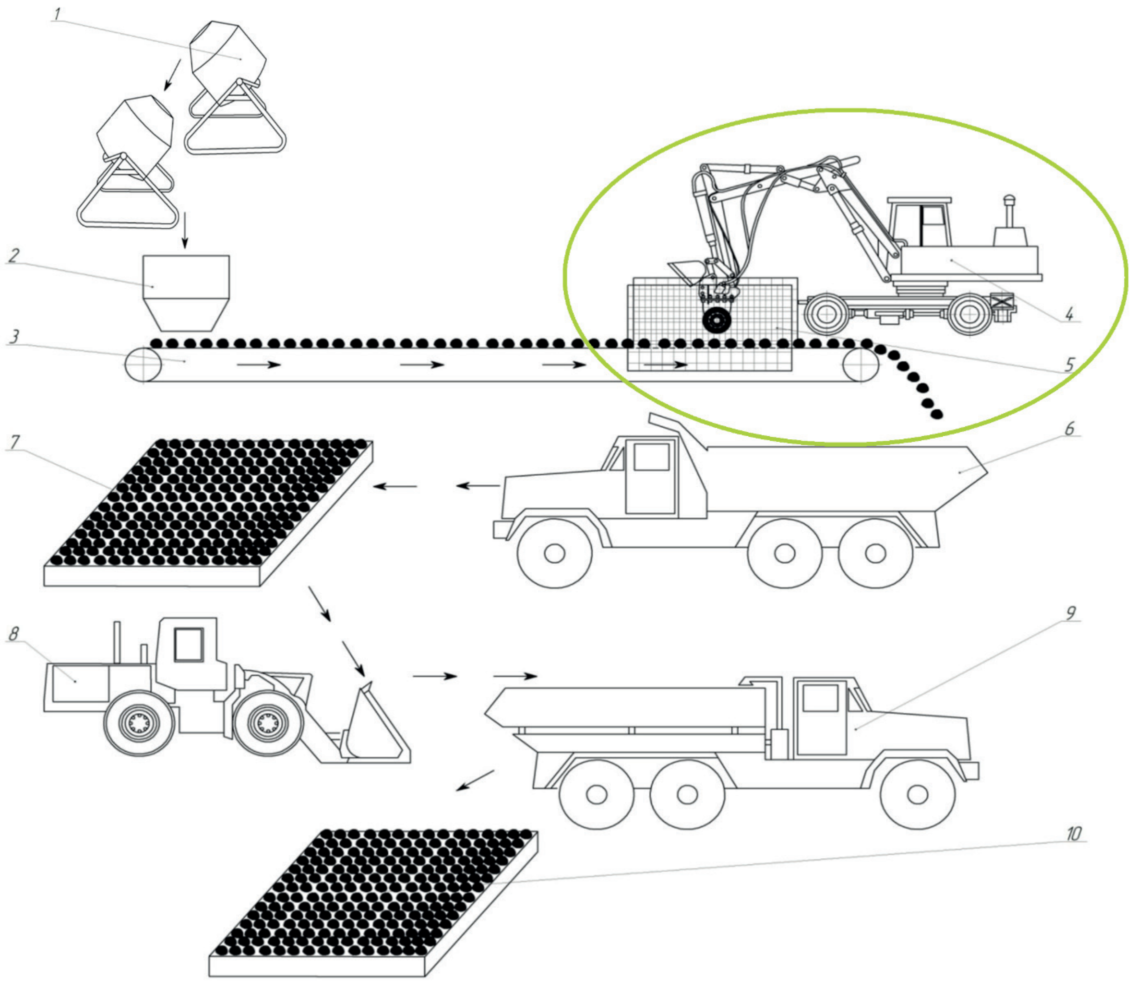


Figure 12 *Experimental technological line for processing the slag crushed stone after modernization: 1 - a complex of 2 mixers; 2 - dispenser; 3 - belt conveyor; 4 - single-bucket excavator with a universal cutterhead, equipped with replaceable brushes with synthetic bristles; 5 - metal gratings; 6 - dump truck, 7 - section for moistening and pre-drying of crushed stone, 8 - single-bucket loader, 9 - mobile equipment for hydrophobization of the slag crushed stone, 10 - section for unloading and storing finished products*

Figure 13 *A prototype of a universal cutterhead with cutters installed on the base machine (single-bucket excavator)*

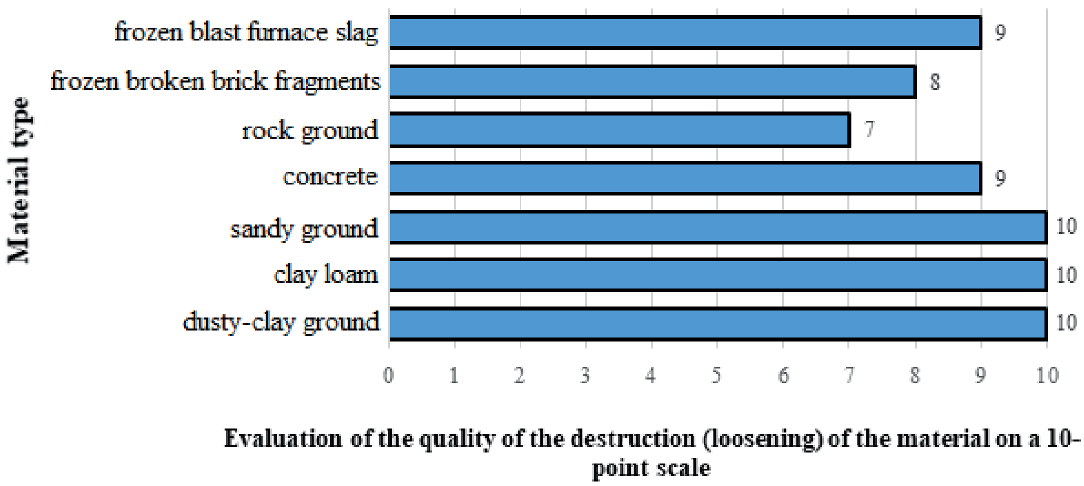


Figure 14 *The results of tests for loosening different materials with a universal cutterhead mounted on a single-bucket excavator*

Table 2 *Calculation of water absorption of the slag crushed stone*

Sample number	Time of processing with universal cutterhead t_{proc} (s)	Mass of a sample in the dry condition m (g)	Mass of a sample in the state water-saturated condition m_1(g)	Water absorption W_{abs} (%)
1	0	2030	2146	5.71
2	30	2085	2176	4.35
3	60	2013	2098	4.20
4	90	2024	2094	3.45
5	120	2006	2053	2.34
6	150	2048	2091	2.09
7	180	2031	2063	1.56
8	210	2044	2071	1.34
9	240	2056	2079	1.11
10	270	2037	2068	1.50

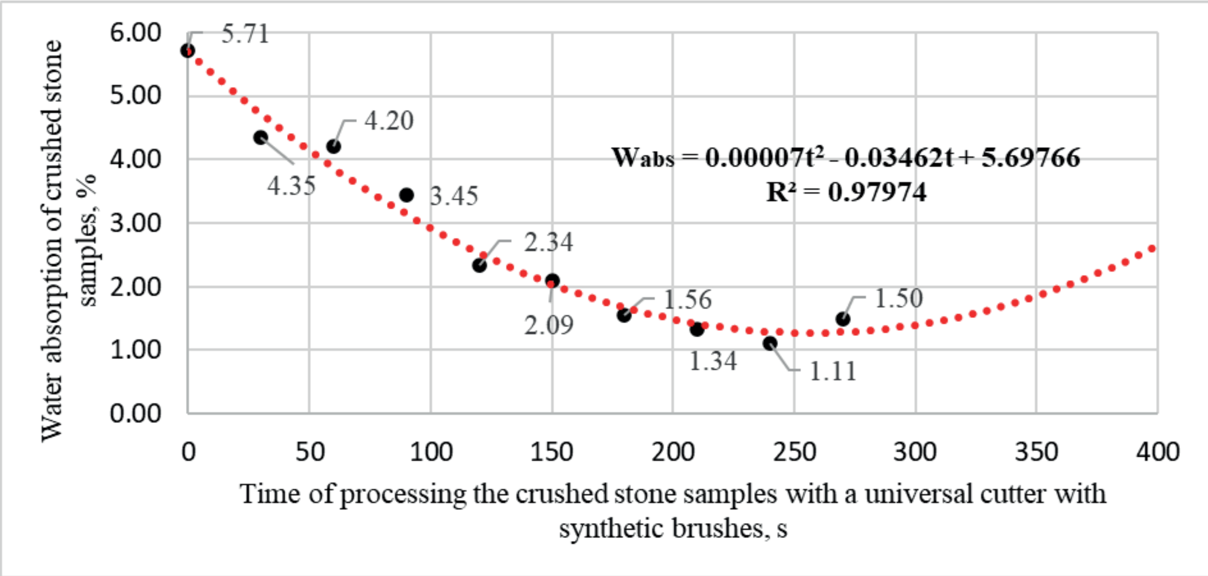


Figure 15 *Influence of the processing time of the slag crushed stone with a universal cutter on its water absorption*

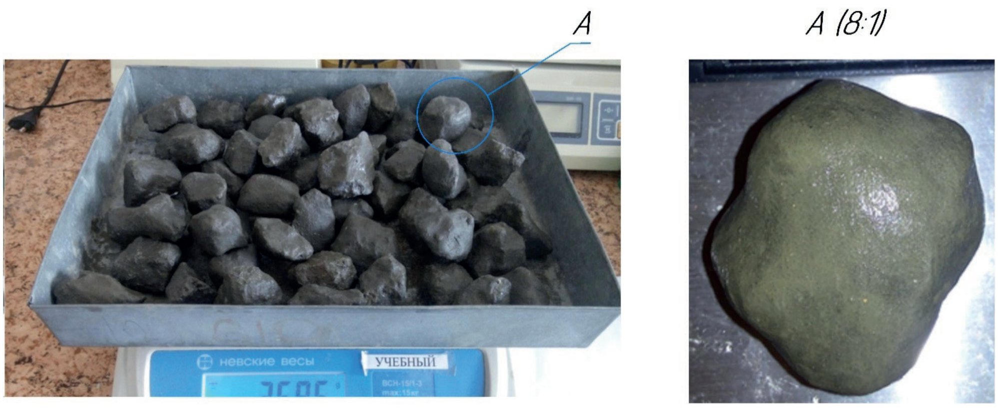


Figure 16 *The samples of the slag crushed stone after processing on the experimental technological line using a single-bucket excavator with a universal cutterhead equipped with replaceable brushes*

the slag crushed stone with a universal cutterhead on the water absorption of the sample.

As readers can see, the water absorption decreases with an increase in the time of processing the crushed stone with a universal cutterhead up to 240 seconds ($W_{abs} \rightarrow min$), after which it begins to increase. This is explained by the fact that with an increase in the processing time of the slag crushed stone to 5 minutes or more, a part of the powdered filler is removed from the pore space. This leads to worse filling of the pores and, accordingly, the absorption of more moisture. The Microsoft Excel allowed to obtain a polynomial trend line describing the relationship between the water absorption W_{abs} and the processing time of crushed stone t_{proc}. The obtained polynomial trend line is approximated by the following equation:

$$W_{abs} = f(t_{proc}) = 0.00007\, t_{proc}^{\ 2} - 0.03462\, t_{proc} + 5.69766. \quad (3)$$

This equation has a high reliability coefficient ($R^2 = 0.97974$). Using the Microsoft Excel functionality, a prediction trend line for graphic dependence in Figure 15 was built. This trend line allows to calculate how the water absorption of the slag crushed stone will change with a further increase in the processing time of this material with a universal cutterhead ripper. It is possible to track (Figure 15) the predicted values of water absorption with a change in the time of processing this material with a universal cutterhead along the trend line in the range t_{proc} = 270-400 s.

Figure 15 shows that with a further increase in the time of processing the slag crushed stone with a universal cutterhead for more than 240 s, the water absorption of the material increases and, for example, at t_{proc} = 400 s it is about 2.7%.

Based on the foregoing, it can be concluded that the optimal time for processing the slag crushed stone with a universal cutterhead with synthetic brushes is $t_{proc\ opt}$ = 240 s.

As readers can see in Figure 16, including with a significant increase, on the obtained samples of the hydrophobized slag crushed stone (at t_{proc} = 240 s), there are no excess powdered filler and all the existing pores are filled.

Thus, the use of a universal cutterhead equipped with brushes as a part of a mobile technological line for processing the slag crushed stone ensures complete penetration of powdered filler deep into the pore space and removal of excess filler from the surface of crushed stone grains.

5 Conclusions

1. The authors presented the literature review of methods for processing the blast-furnace slag. Based on the literature review, it was concluded that the most appropriate way to process the waste blast-furnace slag is to obtain the slag crushed stone on its basis. The main disadvantages of the resulting material (insufficient water resistance, frost resistance, low strength) are determined.
2. To eliminate these disadvantages, the authors proposed and substantiated the composition of the technological line for filling the pores of the slag crushed stone and impregnating it with a hydrophobizator (water-repellent composition).
3. A critical analysis of machines and equipment that can be used to loosen the frozen blast-furnace slag in dumps in winter showed that cutter equipment is the most suitable. Based on the results of this analysis, the working group of the Karaganda Technical University designed and manufactured the replaceable working equipment of a single-bucket excavator with replaceable working tools (cutters and brushes) for loosening the frozen blast furnace slag in dumps and removing excess powdered pore filler from the surface of the material during its further processing on the proposed technological line.
4. The advantage of using the replaceable working tools of mounted working equipment (in particular, cutters for loosening the blast-furnace slag in dumps and brushes with synthetic bristles) is to save money on purchase of the specialized equipment and prevent downtime of existing machines.
5. Tests of the manufactured equipment showed its high efficiency in loosening the frozen blast-furnace slag and other materials, as well as at use as part of a technological line for processing the slag crushed stone.
6. Further research in the field of mechanization of the obtaining materials for building of the road infrastructure facilities based on metallurgical waste will be aimed at developing an integrated technology for enrichment in strength of the crushed stone from the blast-furnace slag.

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Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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