DEVELOPMENT AND RESEARCH OF SPECIAL EXCAVATOR BUCKETS FOR MINING OIL-BITUMINOUS ROCKS

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Resume

Given the shortage of petroleum bitumen in the Republic of Kazakhstan, the use of local bitumen-containing rocks is becoming increasingly relevant, which requires the development of specialized mechanization tools. In this paper are discussed the special excavator buckets designed for year-round extraction of rocks with a bitumen content of up to 25%. The design features of the bucket that reduce resistance during digging and unloading are described. Calculations of resistance, chip thickness, operation duration, and productivity of the EO-4121 excavator at different temperatures and bitumen contents were performed. It is shown that unloading becomes more difficult when the bitumen content exceeds 18.2%. A comparison of the calculated and experimental data confirmed the high accuracy of the models used.

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1 Introduction

Production of means for mechanization development, transportation and use of bitumen-containing rocks in the Republic of Kazakhstan is still episodic [1]. At the same time, the road organizations of the country require 1.7 million tons of bitumen annually for construction, repair and maintenance of highways. They receive less than half of the required amount, because bitumen, a heavy residue of oil refining, is a scarce material.

Regardless of how much its production increases, practice shows that the lack of bitumen will remain acute. In large volumes bitumen is used in industrial, civil, agricultural and other construction sites, in the production of roofing, thermal and waterproofing materials, in nuclear power engineering as a means of protection against radioactive radiation, in the paint and electrical industry, as well as in other sectors of the economy. In general, the need for bitumen is now estimated at several million tons per year. The current deficit can be largely balanced by expanding the use of domestic bitumen-containing rocks [2].

Progress in the use of bitumen-containing rocks in various sectors of the national economy depends crucially on creation of the new special tools and machine systems for development, transportation and processing, in which the fundamental scientific and technical ideas are materialized.

Special means of mechanization lay the foundation for a wide access to fundamentally new, resource-saving technologies based on the bitumen-containing rocks, increase in labor productivity and product quality. Production persistently raises questions of improvement and creation of mechanization means, as success in the use of rocks is primarily determined by the efficiency and productivity of the tools used [3]. It should be noted that the rock properties make the existing tools inoperable and work with a sharp decrease in productivity precisely in the process of their interaction with the working bodies of the applied means of mechanization.

The performed work was aimed at creation of special excavator buckets, allowing extraction of bitumen-containing rocks with bitumen content up to 25% in year-round operation. The use of such equipment would allow to extract bitumen-containing rocks directly by excavators without powerful bulldozers.

It should be noted that the subject of this study is closely related to the field of "Mechanical Engineering in the Transport Industry" and the objectives of the automotive industry, since the development of specialized buckets and working parts for excavators is aimed at increasing the efficiency of extracting bitumen-containing raw materials, which are the basis for the production of road construction materials. Modern transport engineering considers construction and quarry machinery to be an important link in the technological chain of transport infrastructure development. Improving the productivity and reliability of earthmoving equipment directly affects the pace of construction and repair of motorways, the performance characteristics of road surfaces, and the economic sustainability of the motor transport system as a whole.

2 Materials and methods

Oil-bituminous rocks have high strength characteristics, especially at low positive temperatures, which makes it difficult to extract them mechanically using standard mining and construction equipment [4]. At sub-zero temperatures or in early spring and late autumn conditions, the strength of these rocks increases, making it impossible to break them down effectively without the use of specialized equipment. In view of this, to ensure stable extraction of these materials, it is necessary to use slow-moving or slow-moving transport machines equipped with hydraulic drives. This allows the speed of the working parts to be adjusted depending on the level of resistance encountered, thus ensuring more stable and energy-efficient operation.

Currently available single-bucket excavators are equipped with buckets with teeth that are well suited for breaking up dense and hard soils such as loam, gravel, frozen or rocky soil. In such cases, the force is concentrated on the teeth, which allows the load to be concentrated and the material to be broken up effectively [5]. However, the oil-bituminous rocks differ significantly in structure. They are elastic-viscoplastic materials that are not prone to brittle fracture like mineral rocks. When cutting these rocks with a bucket, the so-called drain-type chips are formed-an elongated, viscous, and sticky mass.

When using a bucket with teeth in such conditions, cutting efficiency is significantly reduced. This is due to the fact that the material is destroyed between the teeth by the blunt part of the bucket, known as the gum. The gum has a large contact area with the rock, creating excessive resistance and increasing the energy consumption of the mining process. Moreover, due to the accumulation of material on the inner surfaces of the teeth and gums, friction increases, which negatively affects the performance of the equipment, as well.

To increase the efficiency of cutting oil-bituminous rocks, it is recommended to use buckets with a continuous cutting edge sharpened along the entire length [6]. This design allows for a uniform and directed force across the entire width of the cut chips. The reduced thickness of the edge and sharpening achieve an oblique cutting effect, in which the forces are distributed more evenly and the resistance of the material is reduced. This not only improves the performance of the excavator, but reduces wear on the cutting elements, as well.

The standard excavator buckets were originally designed for working with loose or loose materials that have a small natural slope angle, typically up to 30-40°. In such cases, the bucket is made in the form of a vessel with one open side, through which both material intake and subsequent unloading are carried out. However, the oil-bituminous rocks have a significantly larger natural slope angle-up to 80°, which eliminates the possibility of material spillage. In this regard, there is no need for side walls on the bucket. Moreover, the presence of such walls only increases the contact area between the bucket and the rock, which leads to increased resistance during unloading.

It should be noted that oil-bituminous rocks tend to adhere strongly to metal surfaces, especially at elevated temperatures and when the bitumen content exceeds 18-20% [7]. This significantly complicates the process of unloading material from the bucket, often making it impossible without the use of auxiliary means such as vibrators, mechanical scrapers, or manual labor. In the design of the proposed buckets, the absence of side walls significantly reduces the area of contact between the material and the surface, thereby facilitating unloading even at high levels of stickiness.

In addition, the oil-bituminous rocks have the high moisture content, which contributes to formation of a monolith inside the bucket. This, in turn, simplifies the task of retaining material in the bucket even if there are slots or holes in its walls. Therefore, solid side and rear walls are not required. To reduce the weight of the equipment, increase maneuverability, and reduce energy consumption, it is proposed to manufacture the rear wall and side elements of the bucket perforated or with longitudinal slits oriented in the direction of chip movement [8]. Such slits not only serve to lighten the structure, but also create conditions for mechanical cleaning of the bucket from adhering material.

The proposed ladle consists only of a bottom and a back wall. To simplify manufacturing, they should represent a single surface of cylindrical shape. To ensure that the capacity of the proposed bucket is equal to that of a standard bucket, it should be slightly larger in width or height. Bucket designs are shown in Figure 1.

The bucket EO-AT-01 consists of the following main

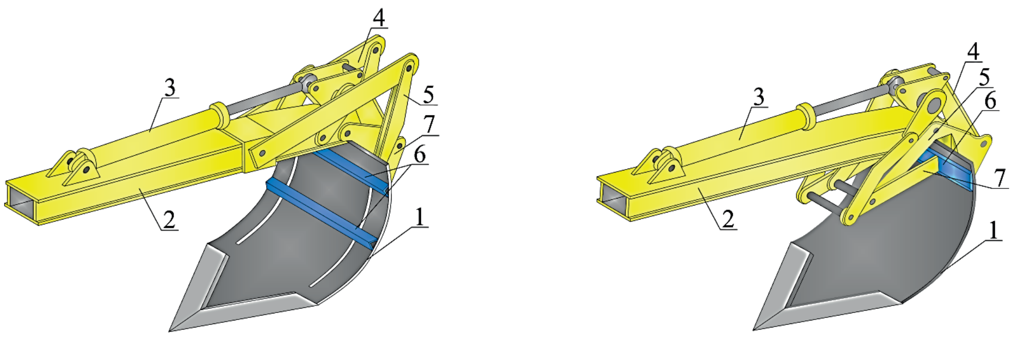

***Figure 1** Excavator working equipment: a) with two cleaning devices; b) with one cleaning device; 1 - bucket; 2 - handle; 3 - hydraulic cylinder; 4 - linkage system; 5 - tie rod; 6 - tie rod; 7 - cleaning frame*

parts (Figure 1, a). Bucket 1 is connected to the handle 2 and is driven by hydraulic cylinder 3 through the lever system 4. One end of the rod 5 is rigidly connected to the bucket body 1, and the rod 6 to the lever system 4. The other end of the link 5 and the link 6 are articulated with the cleaning frame 7. In the initial position, the cleaning frame is behind the bucket.

When turning the bucket for scooping the material, the link 5 turns together with the bucket, and the cleaning frame 7 turns with the link 6 in relation to the joints of the link 5 and in the final stage approaches the handle 2 (Figure 1, b). When unloading, the bucket is rotated in the opposite direction, the cleaning frame moves along the cylindrical bottom of the bucket and cleans it.

Working equipment of EO-AT-02 (Figure 2, a) includes a bucket 1 fixed on the handle 2 and driven by a hydraulic cylinder 3. Levers 4 are rigidly fixed on the handle by means of clamps, which are connected with the cleaning frame 6 through rods 5. The frame is attached to the rods through slots in the bucket bottom.

The working equipment of the excavator works as follows. When the bucket moves along the face, the cutting edge cuts the rock chips. As the bucket is filled with rock (Figure 2, b), it is rotated by hydraulic cylinder 3, and the cleaning device is moved in the direction of rock movement by means of rods 5. After the bucket is filled with rock, the excavator bucket is moved to the unloading position (Figure 2, c), rotated, and the bucket is unloaded under the action of gravity. Part of the rock, adhering to the inner surface of the bucket is cut off by cleaning frame 6, which, when the bucket is turned towards the cutting edge, slides along the inner walls to ensure the complete discharge of the sticky material. This mechanism prevents the accumulation of bitumen and maintains the high volumetric efficiency of the bucket throughout the working cycle. After that, the working equipment of the excavator is transferred to the initial position and the work cycle is repeated.

Oil-bituminous rocks adhere to the surface of the bottom and rear wall of the proposed bucket. Its cleaning is the most expedient to be carried out mechanically by movement of a special cleaning element [9]. To avoid an increase in the equipment costs, without reducing its reliability, it is advisable to move the cleaning element not by a special drive (hydraulic cylinder), but with the help of levers fixed on the handle. When turning the bucket for unloading, the lever located on the back side of the bucket should move the cleaning element, and for this purpose it is advisable to use longitudinal slots made to reduce the weight of the bucket.

3 Results and discussions

Increase of working capacity of developing machines is possible at reduction of resistances to movement of the working body, and also saving the technological operations performance time. Next is considered the possibility of application in the development of oil-bituminous rocks excavator EO-4121, which has the following indicators: cutting force 145 kN, bucket movement speed 0.03 - 0.4 m/s, unloading rotation time 4 s, capacity 1000 mm^3, cutting angle 30° [10].

The working capacity of the equipment is reduced due to difficulties in overcoming resistances during digging and releasing the working bodies from the rock. Resistances arising during the rock development can be calculated based on the parameters of working bodies and properties of the medium, using dependencies obtained from interaction models.

The combinations of parameters, at which the excavator operation is possible, are to be found next. As it was shown earlier, the resistance can be determined from [11]:

$$P = 1.24 \cdot b \cdot h \cdot \left(\frac{1}{2}\gamma \cdot h \cdot A_1 + K_{\nu 1} \cdot \rho_1 \cdot A_2 + \right. \\ \left. + K_{\nu 2} \cdot \rho_2 \cdot A_3\right), N, \quad (1)$$

where P - digging resistance, N; b - bucket width, mm; γ - material density, N/m^3; A_1, A_2, A_3- analytical ratios; ρ_1 - stickiness, Pa; ρ_2 - coupling, Pa; $K_{\nu 1}$ - coefficient of influence of load application speed on stickiness value; $K_{\nu 2}$ - coefficient of influence of the load application speed on the adhesion value.

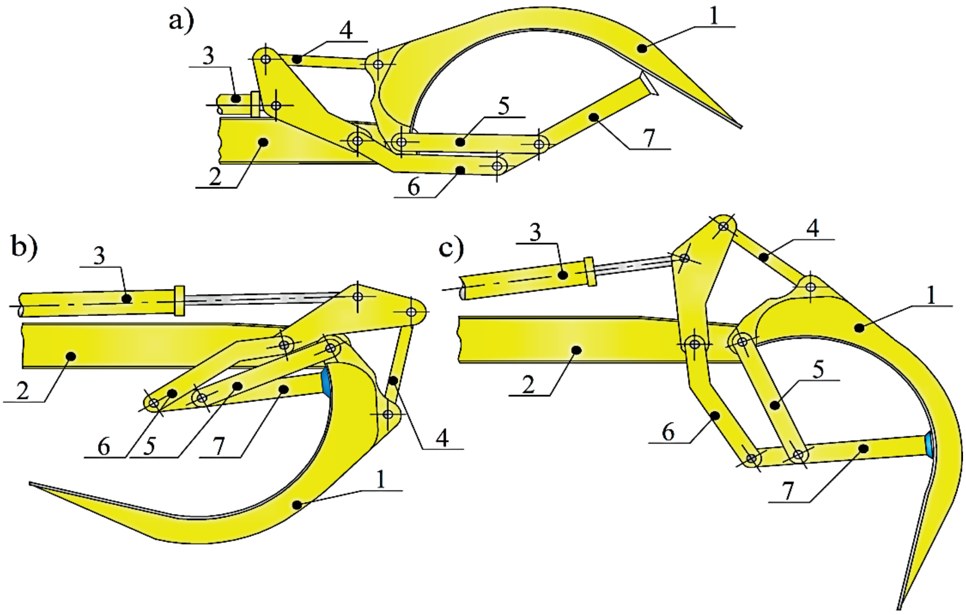

Figure 2 *Excavator working equipment: a) start of operation; b) bucket filling process; c) unloading position; 1 - bucket; 2 - arm; 3 - hydraulic cylinder; 4 - linkage system; 5 - link; 6 - link; 7 - scraper frame*

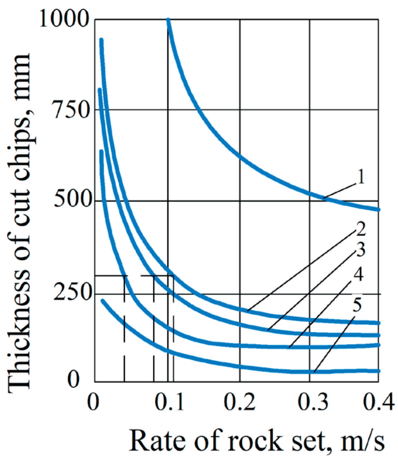

Figure 3 *Effect of speed on possible chip thickness: 1 - bitumen content 25%,temperature 20 °C; 2 - 18.5% and 20°C; 3 - 18.5% and 10°C; 4 - 10% and 20°C; 5 - 10% and 0°C.*

The maximum force on the cutting edge of the excavator bucket is 145 kN. Taking into account this (limit force) according to:

$$P_{01} = b \cdot h \cdot \left(\frac{\gamma \cdot h}{2} \cdot A_1 + K_{\nu 1} \cdot \rho_1 \cdot A_2 + \right. \\ \left. + K_{\nu 2} \cdot \rho_2 \cdot A_3\right), N \quad (2)$$

For the rock with bitumen content of 10 and 30% at temperatures of 0 and 40 °C the influence of cutting speed on the possible thickness of cut chips was established (Figure 3).

At the bucket set path length L, the required thickness of the cut chips can be found from [12]:

$$h = \frac{q \cdot K_n}{L \cdot b}, \text{mm} \quad (3)$$

where q - bucket capacity equal to 1 m^3; K_n - rock recruitment loss factor, K_n = 1.2; L- material path length, L = 4000 mm; b - bucket width (b = 1000 mm).

For the single scooping, the thickness of the cut chip is 300 mm. Based on this it is possible to find optimal cutting speeds of rock (Figure 3) for specific conditions. Thus, the optimum rock cutting speed with bitumen content at 0 °C is 0.003, with 30 % - 0.08, and at 40 °C - 0.11 and 0.6 m/s.

Based on the constant length of the rock picking path at the optimum speed of the implemented movement, the duration of this operation can be determined depending on the temperature and cohesion value (Figure 4). The limit value of adhesion, at which the equipment operation is irrational, depends on the bitumen content,

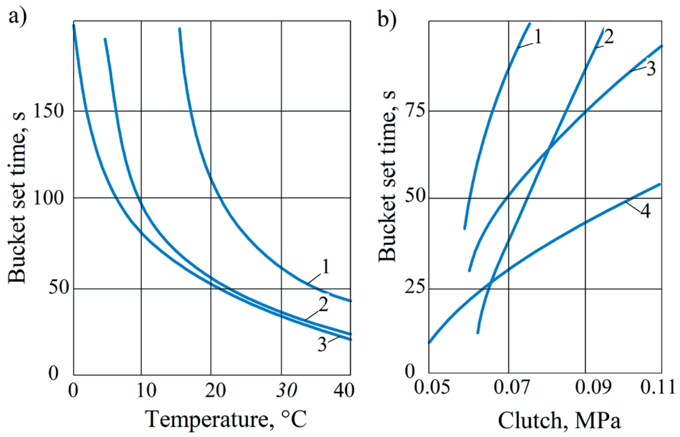

Figure 4 *Impact: a) rock temperatures: 1 - bitumen 10%; 2 - bitumen 18.5; 3 - bitumen 20; b) of the clutch on the bucket take-up time: 1 - bitumen 10%; 2 - bitumen 18.5%; 3 - bitumen 25%*

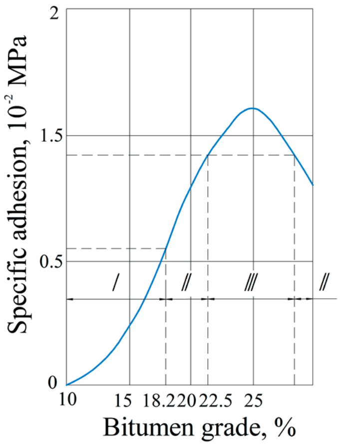

Figure 5 *Zones of workability of excavator EO-4121 on bucket unloading depending on bitumen content in rock: I - smooth unloading, II - longer operation, III - unloading is impossible*

temperature and the maximum possible duration of the operation [13].

The specific adhesion, depending on the bitumen content of the rock and temperature, is evaluated with respect to contact duration and pressure. The inner surface of the excavator bucket contacts the rock in the following way. During the rock recruitment, the cut chip exerts a pressure on the cutting edge and bottom that is larger than the static pressure of its gravity. As the bucket is filled, the pressure from the gravity of the material increases and is transmitted to the side walls, i.e., its magnitude in the rock contact zone changes as the bucket is filled. At the end of filling and after turning the bucket for unloading, the pressure stabilizes [14]. For practical calculations, it is assumed that the pressure value in the contact zone can be determined by Equation (4), and it acts during the bucket filling and bucket rotation for unloading.

The value of pressure in the contact zone can be determined as

$$N = (0.5 - 0.7) \cdot C \cdot S, \tag{4}$$

where C - soil developability index by DorNII impactor, blow count; S - half of the bucket projection area in the direction of travel when digging, mm^2.

Specific adhesion of oil-bituminous rock, which determines the equipment operability, depends on design and technological parameters. The influence of bitumen content in the rock on the workability of the EO-4121 excavator is of interest (Figure 5). At 20°C the rock of the Munaily-Mola deposit can be developed by the excavator with unobstructed bucket unloading if the bitumen content is less than 18.2%. At a higher amount of bitumen, unloading becomes difficult, and at 22.5% it becomes impossible.

Unloading of the rock with bitumen content more than 18.2% is possible, but it will be significantly stretched in time, which leads to a decrease in productivity and the use of manual labor to clean the working bodies. Duration of unloading operation of on rock with specific adhesion above the limit can be determined from the expression

$$t_2 = \frac{\rho_2 \cdot t_1}{2\rho_2 - \rho}, s, \tag{5}$$

where ρ_2 - specific adhesion at which the productivity is not reduced, N/mm^2; t_1 - bucket turning time for

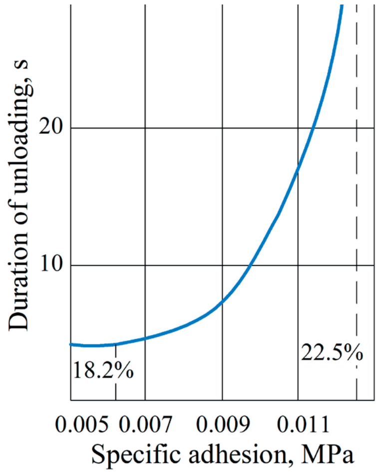

Figure 6 *Dependence of excavator bucket unloading time on specific adhesion of oil-bituminous rock*

unloading, s; ρ - specific rock adhesion for the conditions under consideration, N/mm^2.

The influence of specific adhesion of oil-bituminous rock with different bitumen content, at 20°C, on duration of unloading the excavator bucket is shown in Figure 6. The limiting value of specific adhesion, when unloading of the rock is impossible even when the bucket is held for a long time after its rotation, is 0.0124 N/mm^2.

From the data on duration of the operations, the productivity of the machine as a whole can be determined. Operating capacity of the excavator is:

$$P_{\varepsilon} = \frac{60 \cdot q \cdot K_H}{t_s - K_r} \cdot K_b, N , \tag{6}$$

where q - excavator bucket capacity equal to 1 m^3; K_H - bucket fill factor; K_r - rock loosening factor (1.1); K_b - excavator time utilization factor (0.85-0.9); t_s - duration of the excavator working cycle, equal to $t_s = t_k + t_n + t_b + t_{nz}$ (t_k, t_n, t_b, t_{nz} - duration of digging, turning to unloading, unloading, turning into the face, respectively), s.

It is assumed that taking into account acceleration and stops during normal operation of the excavator $t_n + t_{nz} = 0.6t_s$. When the excavator is rotated by 90° during the rock unloading, the minimum cycle duration is 18 s, i.e., the duration of rotation to unload and back to the face is 10.8 s.

The duration of the working cycle during extraction of oil-bituminous rocks is determined mainly by the duration of digging and unloading, which depends on the properties of the rock. The change in time spent on these operations affects the excavator productivity (Figure 7).

The standard productivity of the excavator is 91.3 m^3/h. The analysis of the change of excavator productivity at extraction of oil-bituminous rocks allows to note that with the growth of adhesion (at temperature decrease from 40 to 0°C) the excavator productivity at development of rock with bitumen content of 10% decreases due to the increase of bucket filling duration. At development of rock with bitumen content of 25% up to adhesion value of 0.077 N/mm^2 (15°C) the excavator operation is impossible, because the rock is not discharged from the bucket. As the temperature decreases, the stickiness of the rock decreases, which leads to an increase in productivity by reducing the duration of unloading. But since the duration of bucket recruitment increases simultaneously, productivity decreases after 0.0 95 N/mm^2.

Thus, the possibility of development of oil-bituminous rocks depends on strength indicators characterized by adhesion and stickiness. Moreover, material destruction can be ensured by reducing the speed of movement of the working body, while it is impossible to realize bucket unloading under unfavorable conditions without additional improvements of the working body.

The timing of work of excavator E0-4121 at extraction of oil-bituminous rock of Munaily-Mola deposit (Kazakhstan) with bitumen content of 19.4% at 33°C has shown that the duration of working cycle and productivity differ significantly from these indicators at soil development (Table 1).

The angle of internal friction is found by the following equation [15-16]

$$\varphi = 0.019 \cdot B^2 - 1.7 \cdot B + 0.0084 \cdot T^2 + \\ + 0.24 \cdot T - 44,^\circ \tag{7}$$

where B - bitumen content, %; T - temperature of oil-bituminous rock, °.

The clutch value is determined by [15-16]:

$$C = 0.000025 \cdot B^2 - 0.00265 \cdot B + \\ + 0.0000075 \cdot T^2 - 0.001 \cdot T + 0.086, \text{MPa}. \tag{8}$$

The stickiness value is found as [15-16]:

$$P_2 = 0.0000575 \cdot T^2 - 0.0038 \cdot T - \\ - 0.000075 \cdot B^2 + 0.00295 \cdot B + 0.107, \text{MPa}. \tag{9}$$

The average rock set path was 4200 mm, bucket travel speed was 0.13 m/s, the thickness of cut chips was 310 mm, and the duration of rock contact with the bucket surface was 42.1 s. Using the field device P10-SU1, the grip and angle of internal friction of the material were determined in the field, which are equal

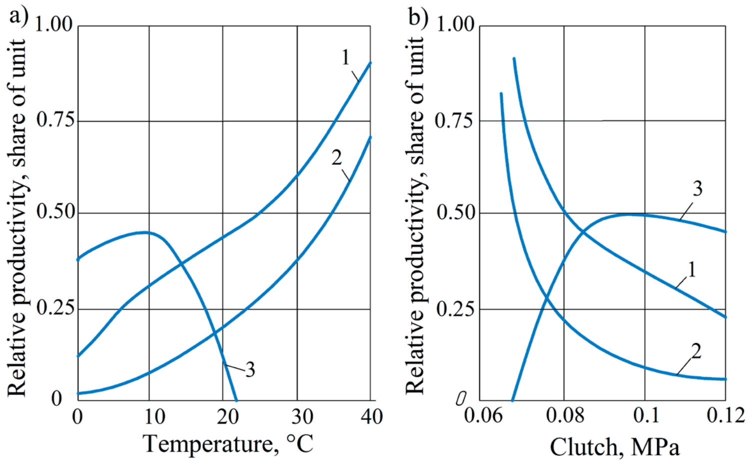

Figure 7 *Dependence of productivity of excavator E0-4121 on: a) rock temperatures: 1 - bitumen content 18.5%; 2 - bitumen content 10%; 3 - bitumen content 25%); b) of petroleum-bituminous rock adhesion: 1 - bitumen content 18.5%; 2 - bitumen content 10%; 3 - bitumen content 25%*

Table 1 *Timekeeping of working cycle of excavator EO-4121*

Operation	Average duration, s	Standard deviation	Coefficient of variation	Confidence interval
Rock set in the bucket	31.2	3.49	11.2	± 2.5
Turning the bucket for unloading	10.9	0.52	4.8	± 0.9
Unloading rock from the bucket	7.8	1.05	13.4	± 0.6
Turning the bucket into the face	7.3	0.31	4.3	± 0.6
Working cycle time	57.2	-	-	-

Table 2 *Correspondence between the production data and those derived from theoretical models*

Indicator	Unit of measurement	Significance		Absolute deviation	Divergence, %
		valid	estimated		
Duration of rock intake into the bucket	s	31.2	32.3	1.1	3.5
Unloading duration	s	7.8	6.2	-1.6	20.5
Cycle duration	s	57.2	56.7	-0.5	0.9
Capacity	m^3/h	55.1	55.4	0.3	0.5

to 0.072 MPa and 18.1°; calculated by Equations (8) and (9), respectively, 0.066 and 16.95° [17-19].

The value of specific adhesion, determined by calculation, at the moment of rock recruitment into the bucket (pressure 0.06 MPa, contact duration 10 s) was 0.0076 N/mm^2, for the moment of bucket unloading (respectively 0.06 and 42.1) - 0.0084 N/mm^2.

As a result of calculation of resistance to bucket displacement (cutting angle $\alpha = 30^\circ$) the following values were obtained: when using in the calculation the shear characteristics determined in the fields, 141805 N, when using the calculated values - 132149 N. Discrepancies with the passport characteristic of the force on the cutting edge of the bucket are respectively 2.2 and 8.9%.

The predicted duration of material unloading from the bucket is 6.2 s, which is 20.5% different from the timing data due to the unevenness of unloading. Comparison of calculated values of indicators of the working cycle elements and productivity of the excavator with the actual ones is given in Table 2 [20-22].

The calculated value of working cycle time is 0.9% lower than the actual value, and the calculated productivity is 0.5% higher than the actual value.

4 Conclusion

The conducted studies and calculations confirm the relevance and prospects of development and implementation of specialized excavator buckets for effective extraction of oil bituminous rocks in the conditions of the Republic of Kazakhstan. Taking into account the chronic deficit of oil bitumen in the country and the growing needs of road and construction sector, the use of natural bitumen-containing rocks can become a significant reserve to replace the scarce material.

The developed bucket designs adapted to the physical and mechanical characteristics of oil-bituminous rocks allow to significantly reduce the cutting forces and resistance during unloading, as well as to increase the productivity of excavator machines. An important advantage is the refusal to use an additional drive for bucket cleaning - the movement of the cleaning frame is realized by the kinematics of the bucket itself, which increases reliability and reduces the cost of equipment.

Modelling of the technological process of rock cutting and unloading allowed to reveal the dependence between the bitumen content, rock temperature and duration of operations. Limit values of rock stickiness and adhesion were determined, at which the use of a standard excavator becomes ineffective or impossible. In those cases it is necessary to use new technical solutions or change the machine operation mode.

Comparison of the calculated data to results of timing observations showed a high degree of coincidence - the differences do not exceed 1%, which confirms the reliability of the proposed model and the possibility of its application in the design and selection of operating modes of excavators.

Thus, the proposed technical solutions and approaches can become a basis for creation of a new generation of machines capable of efficient development of bitumen-containing rocks, reducing operating costs and increasing productivity in conditions of complex geological and climatic factors.

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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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