Justification of parameters of a disk tool for cutting asphalt concrete

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Abstract. The paper reflects the results of the study conducted to determine how a free rotary instrument cuts narrow joints in asphalt pavements required for road construction. Based on the analysis of strength characteristics of different asphalt concrete grades, we developed a mathematical model of working process, and this model stands as the calculation basis. The mathematical model associates the main parameter — cutting resistance force — with the material strength values and geometrical characteristics of the working body and the working process. The results of experimental confirmation of mathematical model reliability are presented in the paper.

1. Introduction

When the asphalt pavement was just invented, people quickly realized that they need a way to remove it too. First disc cutter models for joint-cutting the asphalt concrete appeared in the form of self-propelled machines [1] or trailing mechanisms [2] in the early twentieth century. The disc cutters are still in use, mainly as hinged replaceable working equipment for mechanical shovels. However, despite the long historical experience of using such equipment, it is very difficult to identify the main parameters of disc cutters at the design stage. Most of the existing samples are subject to intuitive design or copying other samples. The characteristics of such mechanisms are not rational.

The destruction of asphalt concrete is the task opposite to the one established when it was first created, specifically to resist high static and dynamic loads over a long period of time. To date, there is enough scientific potential to find the approaches to solving the problem of mathematical modeling of the process of cutting asphalt concrete with a disc work tool.

As an object of destruction, asphalt concrete is a complex composite material, which, according to Ryblev's classification [3], is an artificial conglomerate based on organic binder. L. B. Gesenzvey [4] indicates coagulational structure of asphalt concrete, and the strength of it depends not only on the strength of bonds between individual grains, but on the strength of the grains themselves of different fractions.

The strength of asphalt concretes is measured by various methods. Thus, nowadays, the methods of determining the operational strength based on the destruction of standard sized samples under loads became widespread in the world. These methods include the Hveem [5] and the Marshall [6] methods, which were widely used in the twentieth century. Today, a complex method of asphalt binder evaluation Superpave [7] is being spread widely. The standard Marshall method of asphalt concrete strength evaluation [8] is also widely used in Russia.

Unfortunately, none of these methods reflect the specific aspects of the processes of destruction and deformation of asphalt concrete under disc cutter. When the standard samples are destroyed with the above methods, the bind of the particles becomes broken, mainly in the tension and shift zones.
The operation of a disc cutter is associated with highly compressive stresses which destroy the bonds between the material particles, but also the particles themselves. This leads to higher stresses in the material.

The closest to the operation of a disc cutter are penetration-based power evaluation methods. In [9], it is shown that the values of contact strength of asphalt concrete, obtained by static penetration, turned out to be 5...8 times higher than the strength values obtained by the destruction of standard samples with uniaxial compression.

Now, various designs of disc cutters are used in textile, food, metalworking, and agriculture. As a work tool of road and construction machinery, a disc cutter is used in rotary bits, rippers, work tools of bulldozers, excavators, and other equipment. This is why the study of cutting processes using disc cutters of the equipment listed above can provide the basis for a methodology of calculation of parameters of disc cutters.

The first studies on the interaction of a disc cutter with soil date back to the early twentieth century. The Italian scientist Nerlo Nerli [10] experimentally proved that the horizontal component of cutting force of a free disc cutter is 30% less than a cutter with locked rotation.

In Russia, the operation of a disc cutter was studied by F. M. Mamatov [11], L. I. Baron [12], G. P. Sineokov [13]. The interaction of a disc cutter with frozen soil and snow-ice formations was studied by R. B. Zhelukevich [14].

Thus, to determine the rational characteristics of a disc work body, there is enough practical experience to associate strength and deformation characteristics of a material with geometrical and kinematic characteristics of a cutting element.

2. Problem statement
To design a disc cutter, three problems need to be solved one by one:

- create a mathematical model that describes the relation of the horizontal and vertical components of cutting forces with geometric characteristics of the tool, material strength value, and one-pass cut depth;
- determine the rational sizes of the disc work tool for the given input data and constraints (type and method of use of the base machine, material grade, the required cut depth);
- determine the operating characteristics of the "base machine - disc cutter - material" system and a rational method of use.

The first problem is the most difficult because the chosen theory needs to be justified scientifically and confirmed experimentally.

The second problem can be solved by successive substitution of various sets of source data to the target function and finding the optimal solution.

The third problem is the calculation of productivity and efficiency of the already developed equipment depending on various operating conditions.

3. Theory
The disc cutter interacts with the material at the contact surfaces. When it happens, the material is deformed due to the stresses in contact zones. The chosen mathematical model is based on the following assumptions:

- contact stresses on the disc surfaces are equal and correspond to the contact strength of the material;
- the disc cutter rolls without slipping at the lowest point;
- the value of contact stresses does not depend on the strain rate.

Schematization of the cutting process (Figure 1) allows the elementary cutting forces on the blade dR₁ and the side chamfers dR of the cutter to develop as a result of the material deformation. In turn, the elementary force dR₁ is a vector sum of normal force dRₙ₁ and friction force dRₙ₁. The elementary forces dN₂ in a direction normal to the surface of the chamfers and the elementary friction force dF₁ are formed on the elementary area of a disc cutter dS.
The values of elementary cutting forces on the blade of a disc cutter are determined by the ratio:

- if $\alpha \leq \eta$:
  
  \begin{align*}
  dR_x^e &= \sqrt{dx^2 + dy^2} \cdot (\delta + \Delta) \cdot \left( \sin \alpha - \mu \cdot \cos \alpha \right); \\
  dR_y^e &= \sqrt{dx^2 + dy^2} \cdot (\delta + \Delta) \cdot \left( \cos \alpha + \mu \cdot \sin \alpha \right);
  \end{align*}

- if $\alpha > \eta$:
  
  \begin{align*}
  dR_x^e &= \sqrt{dx^2 + dy^2} \cdot (\delta + \Delta) \cdot \left( \sin (\alpha - \eta) - \mu \cdot \cos (\alpha - \eta) \right); \\
  dR_y^e &= \sqrt{dx^2 + dy^2} \cdot (\delta + \Delta) \cdot \left( \cos (\alpha - \eta) + \mu \cdot \sin (\alpha - \eta) \right);
  \end{align*}

where $dx$ and $dy$, the horizontal and vertical projections of the working area of the blade on the axis; $\delta$, the thickness of the disc blade; $\Delta$, geometric factor that takes into account the difference of the real size of the working surface of the blade and the width of the material deformation area; $\sigma_k$, the contact strength limit of the material determined by the static penetration method for various grades of asphalt concrete at different temperatures; $\alpha$, the angle of the vector direction of the elementary force $dR$; $\eta$, the angle of external friction between the material and the surface of the blade; $\mu$, the angle of internal material friction.

Total cutting force on the blade $R_l$ is determined by numerical integration over the working arc of the disc circumference.

The elementary forces concentrated on the chamfers of the disc cutter $dR$ is determined by the vector addition of elementary friction and deformation resistance forces of the material:

\[ dR_b = 2 \cdot dx \cdot dy \cdot K_d \cdot \sigma_k \cdot (\mu + \gamma^\nu); \]
4. Experiment results

The results obtained during the numerical solution were verified on experimental hardware — a disc cutter attached to the blade of a small excavator, while making it possible to record vertical and horizontal components of the cutting force (Figure 2). For this purpose, we developed a special device — a frame with a free disc on the suspension arm. The components of the cutting resistance force are recorded by strain gauge sensors, the readings of which are recorded to a personal computer via an analog-to-digital converter.

During the experiment, the temperature of the asphalt concrete was monitored with an infrared pyrometer. The asphalt concrete was cut with the caterpillar drive, the disc cutter was dug into the asphalt concrete in advance. The depth of cut was monitored by the high-accuracy depth gauge. The
system was pre-calibrated at the press. It included the strain gauge sensors, strain gauge amplifier, analog-to-digital converter, and personal computer.

Before the work started, we took samples of asphalt concrete and determined the maximum contact stresses in the temperature range from 5° to 50° by static penetration. The values of contact stresses were then used to calculate the force parameters of the disc cutter.

The equipment was specifically manufactured for experimental research and was not used for road construction and repair.

The values were measured by using flat discs and discs with sharpened cutting edges of different diameters. The asphalt concrete of the B2 grade [15] was cut to a depth of three to ten millimeters at the temperature of 30°…38°С.

The result was plotted onto several graphs, two of which are shown (Figure 3).

**Figure 3.** Cross-plots of cutting resistance forces obtained by the operation of discs with a diameter of 237 mm and a thickness of 3 mm with a sharpened edge (a) and edgeless (b).
5. Results discussion
The results of theoretical and experimental studies go along with each other. The difference between the theoretical and experimental results does not exceed 12% of the absolute value in pixels.

As can be seen from the graphs, the growth of the horizontal component of cutting force in both the sharpened and flat discs is linear depending on the depth of cut. The growth of the vertical component of cutting force, however, diminishes for both types of discs.

The values of components of cutting force for the flat disc is more than 30% higher than the corresponding values for the sharpened cutting edge. In addition, it was found that using the disc with the sharpened cutting edge the quality of the joint is significantly higher, the edges of the joints have significantly fewer chips and cracks.

Overall, the presented mathematical model and the method of calculating constructive and technological parameters of the equipment, which was created with this model as its basis, can be recommended for practical use.

6. Conclusion
In the course of theoretical and experimental studies the tasks at hand were completed. This allowed formulating the following conclusions:

- the successful verification of the mathematical model allowed us to create a method to calculate the parameters of the disc work bodies for cutting asphalt pavements;
- the results of calculations and experimental data go along with each other;
- it is established that the disc cutters with a sharpened cutting edge are more effective than flat disc cutters;
- the obtained mathematical model makes it possible not only to describe the working process, but also obtain optimum performance values of a disc cutter during the design stage and calculate the operating values for a given method of work execution.

References
[1] Pat. US 719.260/ Asphalt cutting attachment for steam rollers, J. Richards, 27.01.1903.
[2] Pat. US 755.157/ Device for cutting asphalt, T. F. Moran, 22.03.1904.
[3] Ryb'ev I A 1969 Asfal'tovye betony [Asphalt concrete] (Moscow: Vysshaya shkola) – 399 p.
[4] Gezenzvey L B 1976 Dorozhniy asfaltobeton. [Road asphalt] (Moscow: Transport publ. house). – 336 p.
[5] Radovskiy B S 2006 Metody proektirovaniya sostava asfal'tobetonevykh smesei v SShA [Asphalt composition design methods in the USA] Dorozhnaya Tekhniya No. 6: 68-81.
[6] The Asphalt Handbook: MS-4/ Asphalt Institute. – 1989.
[7] Superpave 2005 Final Report of the TRB Superpave Committee. TRB. pp.1 – 56.
[8] GOST 12801-98. Materials on the basis of organic binders for road and airfield construction. Test methods. M.: publ. MNTKs – 1999.
[9] Furmanov D V, Nikolayev V A and Klockho N N 2019 Asphalt Concrete as Object of Destruction by Operating Units of Milling Machines Proceedings of the 5th International Conference on Industrial Engineering (ICIE 2019) eds A Radionov, O Kravchenko, V Guzeev, Y Rozhdestvenskiy (Cham: Springer). P 719-726. https://doi.org/10.1007/978-3-030-22063-1.
[10] Nerli N 1930 Sulproblema dinamico dell aratro a disco estratto del bollettino del R. Instituto Superiere Agraro di Pisa. V 1.
[11] Mamatov F M 1977 Eksperimental'noe issledovanie razlichnychykh tipov ploskichh nozhei [Experimental study of various flat cutters] Sb. nauchn. trudov MIISP (Moscow: MIISP) Vol. 15, Issue 1: 5–7.
[12] Baron L I, Glatman L B and Zagorskii S L 1973 Razrushenie gornykh porod prokhodcheskimi kombainami. Razrushenie tangentsial’nymi instrumentami [Destruction of rocks with roadheaders. Destruction with tangential tools] (Moscow: «Nauka»). – 171 p.

[13] Sineokov G P and Panov I M 1977 Teoriya i raschet pochvoobrabatyvayushchikh mashin. [The theory and calculation of soil-cultivating machinery.] (Moscow: Mashinostroenie). – 328 p.

[14] Zhelukevich R B, Ganzha V A and Bezborodov Yu N 2011 Rabochii organ dlya udaleniya snezhno-ledyanogo nakata s poverkhnosti dorog i aerodromov [Working body for removal of snow and ice skid from surface of roads and airfields] Stroitel’nye i dorozhnye mashiny No. 1: 61.

[15] GOST 9128-2009 Asphaltic concrete mixtures for roads and aerodromes and asphaltic concrete. Specifications. Introduced from 1.01.2009 M., Standartinform – 2010.