Effect of asphalt concrete strength properties on energy intensity of milling

D V Furmanov, N E Lysako, L M Shamahov
Yaroslavl State Technical University 88, Moskovskiy prospekt, Yaroslavl, 150023, Russia

Abstract. Asphalt removal is a complex, energy-intensive technological operation. The paper is devoted to the research of power and energy properties of cutting by the cutting elements of road milling machines. We have analyzed works devoted to the development of different road-building materials; based on the analysis, we deem it possible for the correlation to exist between the strength properties of asphalt concrete and the cutting resistance forces produced by the working units of road milling machines. The most suitable strength property is the contact strength of asphalt concrete determined by the static penetration method. The paper describes the methodology of experimental research in this area and presents the results of experimental studies. We prove a direct correlation between the tangential component of the cutting resistance force and limit contact stresses for three types of asphalt concrete. This makes it possible to quickly and reasonably determine the cutting resistance forces when milling asphalt concrete of different grades at different temperatures without having to conduct complex, expensive research. The established relationship between the asphalt concrete contact strength property and the tangential component of the cutting resistance force suggests that the asphalt concrete strength properties previously determined by temperature, composition, and structure can be replaced by one, namely, its contact strength. This can replace the huge list of existing materials with a single parameter — contact destruction strength.

Keywords: milling machine, asphalt concrete, static penetration, cutting resistance forces, cutting element, contact stress, strength property.

1. Introduction

Development of road-building materials is a complex of technological operations such as the destruction and movement of natural or man-made construction materials with special machines. Efficient, economical and reliable machines depend on how well this process is understood. Currently, frozen and thawed soils are quite well studied in terms of cutting and digging. This makes it possible to build efficient bulldozers, excavators, motor graders, and other earthmoving machines. Mathematical models which describe cutting allow to create the methods of calculation and rationale for the parameters of machines and equipment, optimize the design of working units, and improve the lineup of machines.

However, not all materials are as lucky as soils. Despite many existing works on destruction, crushing, or disposal of such road-building materials as wood [1, 2], basic concrete, and reinforced concrete [3, 4], the vast majority of works study a narrow range of parameters and cannot be the basis for process simulation of a large enough group of machines and equipment.

Asphalt concrete is also one of these poorly researched materials. As an study subject, asphalt concrete is a more difficult material than frozen and, even more so, thawed soil. Being a complex dispersion-filled composite [5, 6], asphalt concrete displays a complex set of properties during cutting depending on the strength of the filler, temperature, viscosity of bitumen, and structural specifics of composition.
[7, 8]. The existing works determine cutting resistance forces of asphalt concrete by cutting elements of different shapes [9], the science basis of milling machine design [10] and their control systems [11], simulation of cutting asphalt concrete by different methods [12], and, for example, science basis of milling machine operation modes to achieve the required milled material quality to use it again. We should also note that the accumulated research of milling asphalt concrete is quickly becoming outdated due to continuous improvement of both the material and design of the working units of machines. Therefore, some mentioned works, especially older ones, provide only a qualitative view of the process and are of methodological value for further research. In addition, different parts of the world use completely different grades and types of asphalt concrete, which differ in composition, strength, and structure. This is due to both climate specifics of different regions and the availability of local materials with different strength properties as well as the legal framework determining the quality parameters of asphalt concrete for various purposes.

2. Problem statement
To figure out the scientific basis for the parameters of new machinery and equipment used to produce road construction materials, one must determine the cutting resistance forces on the cutting elements of the machinery based on the strength of the material, the geometric properties of the cut chips and cutting elements, the feed size, thickness, and width of the cut layer. This is required to find the energy parameters of the machine, calculate the strength of the main power elements, specify the required mass of the machine and traction characteristics, the choice of transmission and drive elements. The positive experience of studying the cutting of soils can serve as a qualitative methodological basis for studying the cutting of asphalt concrete. Besides, soil is a material similar in composition and structure to asphalt concrete. In some works, the soil is also considered a natural dispersion-filled composite consisting of separate grains of different size and shape, bound together by a binder, which is water in the liquid or solid phase [13]. Let us briefly consider the most significant works on soil cutting that allow to directly or indirectly determine the cutting resistance forces.

In the studies of N. G. Dombrovsky horizontal component of cutting resistance force at cutting edge is simplified, as product of area of the cut chip formed by width of the cutting element b and thickness h, and resistance factor kp [14]:

$$P_p = k_p \cdot b \cdot h$$

(1)

The author notes a relative error of 17 to 70% in the calculations. The formula is quite simple and does not take into account many factors. However, the experimental coefficient kp allows us to generalize this approach for totally different soils. For asphalt concrete, this approach has been used in [15], however, more recent studies [16] show the non-linear nature of the growth of cutting resistance forces as a function of the chip thickness.

In the studies of A. N. Zelenin horizontal component of the thawed soil cutting resistance force is defined as non-linear, depending on the thickness of the cut chip h, and resistance factor k_p [17]:

$$P_p = C \cdot h^{1.35} \cdot (1 + 2.6 \cdot b) \cdot (1 + 0.0075 \cdot \alpha \cdot z \cdot \mu)$$

(2)

where b is cutting width, α is cutting angle, z and μ are coefficients characterizing the cutting specifics.

The strength property C is important here. It is also determined experimentally and is numerically equal to the number of strikes until a specified depth of a special standard striker. There is satisfactory convergence of the results, the relative error does not exceed 25%.

The work of Yu. A. Vetrov shows that the horizontal soil cutting force is the sum of the frontal cutting components and two components that determine the forces on the side surfaces of the blade [18]:

$$P_p = \varphi \cdot m_{cv} \cdot b \cdot h + 2 \cdot m \cdot \delta \cdot h^2 + 2 \cdot m \cdot \delta_{avg} \cdot h$$

(3)

where m_{cv} and m also serve as strength properties of soil obtained experimentally for different cutting cases.

It is possible to skip researching specific cutting elements using the shown approach. The approach also provides a way to determine cutting resistance force of a material based on its strength properties.
Thus, the problem is to correctly select the strength property of the material $\sigma$ and the subsequent comparison of the values of these indexes with the forces of cutting resistance.

$$P_p = f(\sigma, h, a, b, c \ldots)$$

where $a, b, c \ldots$ is a set of geometric properties depending on the specifics of the cutting and the design of the cutting element.

In contrast to soil, asphalt concrete is a more complex multi-dimensional material whose strength is significantly affected by temperature. Therefore, the selected property must be easy and inexpensive to determine at different material temperatures and match as closely as possible to the asphalt milling.

The standard uniaxial compression failure methods (GOST 12801-98) or Marshall scheme [19], Hubbard-Field method [20] and other standard methods are not recommended to determine the cutting resistance of asphalt concrete. The point is that these methods are developed specifically to find the operational strength and do not reflect, for example, the destruction of structure-forming components of the material, as it occurs during the cutting. The closest to this are the penetration methods for strength determination [21]. The method of dynamic penetration became the basis for determining the cutting resistance forces in the work of A. N. Zelenin.

On the other hand, obtained strength properties should be compared with cutting resistance forces, and these forces should be calculated taking into account maximum conformity with milling, that is — taking into account typical cutting elements used, moving with necessary cutting speed.

3. Materials and methods

We have selected three grades of asphalt concrete for an experiment — granular A1, B2, and sandy D3 (GOST 9128-2009). They were used to determine correlation between strength properties and real cutting resistance forces. We have evaluated the uniaxial compressive strength properties of standard samples (fig. 1a) and penetration methods (fig. 1b) on laboratory presses. In this case, we have used a cylindrical die with a diameter of 13 mm and a die with a linear profile with a thickness of 3 mm and a length of 60 mm for penetration tests. The method for evaluating the strength performance of asphalt concrete in uniaxial compression when destroying standard samples was used in accordance with the relevant standard (GOST 12801-98). Therefore, the corresponding graphs show the strength values obtained at 0, 20, and 50 degrees Celsius.

![Laboratory press for determining the uniaxial compressive strength of asphalt concrete (a) and laboratory complex for penetration testing of asphalt concrete (b).](image)

It is very important that the same samples of asphalt concrete of the same grade are used for the cutting and indentation tests. Since the asphalt concrete grades should be standard, the strength of
individual asphalt concrete components, bitumen content and viscosity, as well as their degree of compaction can vary significantly.

The most effective and, at the same time, the least expensive method to determine cutting resistance forces is to use a pendulum stand, well-proven in the study of cutting processes of peat materials [22]. Similarly, this scheme is widely used in strength studies of metals (GOST 9454-78) and polymers (GOST 4647-2015).

Pendulum stand (fig. 2) is specially designed to determine the material cutting resistance forces for cutting elements of rotary machines at cutting speeds up to 5 m/sec. The law of energy conservation is used as the basis for the test bench operation. By measuring the loss of kinetic energy, the work of the tangential component of the cutting resistance force is determined:

\[ A = m_p \cdot g \cdot (h - h_0) \]  

(5)

where \( m_p \) is the mass of the pendulum at the point of cutting, \( g \) is the free fall acceleration, \( h \) and \( h_0 \) is drop height and rebound height accordingly (fig. 2b) determined by the position of the cutting edge of the tool.

![Figure 2. General view (a) and scheme (b) of the pendulum stand.](image)

The work of the tangential component of the cutting force can also be used to determine the average of the cutting resistance force itself. It should be noted that the obtained value should be defined as an integral that determines the average of the tangential component of the cutting resistance force along the cutter path of length \( b \):

\[ P_p = \frac{A}{b} \]  

(6)

Here is the order of operation of the pendulum stand:

– in the lower part of the stand a sample of asphalt concrete of a given grade and temperature is fixed at the required height, which corresponds to the specified thickness of the cut chip.

– the pendulum is lifted to the set height with a crane beam, the height corresponds to the required cutting speed of the material.

– with a special drop device, the pendulum is released and starts cutting the material after gaining the desired cutting speed.

– during cutting the pendulum loses speed, and after the cutting element leaves the cutting zone, the pendulum deflects to another, lower height.

– this height is fixed with a limb and is used to calculate \( h_0 \).
Despite the cutting resistance component indirectly determined in this way, the method offers good repeatability and accuracy. More details on this method can be found in [16].

4. Results
The results show that the effect of temperature on asphalt concrete strength is well described by a set of exponential functions (fig. 3). Regression equations in exponential form have high confidence coefficients (Table 1). It should be noted that the contact fracture stresses of asphalt concrete are considerably larger than the corresponding limit stresses in uniaxial compression of standard-sized samples.

![Figure 3. Stress-strain diagrams of asphalt concrete fracture obtained by static penetration and uniaxial compression fracture of standard samples.](image)

Table 1. Formatting sections, subsections and subsubsections.

| Property                                                                 | A1                             | Asphalt concrete grade         | D3                             |
|-------------------------------------------------------------------------|--------------------------------|--------------------------------|--------------------------------|
| Maximum contact stresses obtained by static penetration, MPa             | $\sigma = 289.6 \cdot e^{-0.033t}$, R$^2=0.93$ | $\sigma = 210.3 \cdot e^{-0.042t}$, R$^2=0.94$ | $\sigma = 121.8 \cdot e^{-0.037t}$, R$^2=0.975$ |
| Stresses obtained by standard uniaxial compression destruction method, MPa | $\sigma = 22.98 \cdot e^{-0.018t}$, R$^2=0.931$ | $\sigma = 18.94 \cdot e^{-0.027t}$, R$^2=0.99$ | $\sigma = 10.71 \cdot e^{-0.037t}$, R$^2=0.921$ |
| Horizontal components of cutting resistance, N                          | $P_p = 3048 \cdot e^{-0.02t}$, R$^2=0.83$ | $P_p = 2290 \cdot e^{-0.035t}$, R$^2=0.77$ | $P_p = 2086 \cdot e^{-0.065t}$, R$^2=0.97$ |

The maximum cutting depth of the cutting element is 6 mm. For the average cutting depth, which is 3 mm, we have obtained the tangential components of cutting resistance forces (fig. 4). The resulting graphs obey the exponential regression just as well.
To establish the correlation between the horizontal components of the cutting resistance force and the strength properties, we plot the graphs in the corresponding coordinates (fig. 5). At the same time, the points that correspond to a given temperature are transferred to the graph directly, and the points which temperatures do not correspond to the experimental data are calculated using the presented regression equations.

**Figure 4.** Dependence graphs of horizontal components of asphalt concrete cutting resistance forces on temperature at 3 mm thick cut chip.

**Figure 5.** Dependence of horizontal components of asphalt concrete cutting resistance forces on its contact strength.

The obtained graph establishes a good linear relationship between the contact stress values obtained by the static penetration method and the horizontal components of the asphalt concrete cutting resistance force. For the given conditions, the regression equation between the quantities can be expressed as a relationship:
As can be seen from the graph, the presented expression reflects the relationship well for granular asphalt concrete of grades A1 and B2 and somewhat worse for sandy asphalt concrete of grade D3. The above dependence can be used with some assumptions to simplify calculations.

5. Conclusions

Complex experimental research is required to determine the loads on the milling machine operating unit. The factors influencing the magnitude of these loads can be conventionally divided into four components — asphalt concrete temperature, composition and structure of asphalt concrete, geometrical properties of cutting (dimensions of cutting element, thickness of cut chips, cutting conditions), and cutting speed. The established relationship between the asphalt concrete contact strength property and the tangential component of the cutting resistance force suggests that the asphalt concrete strength properties previously determined by temperature, composition, and structure can be replaced by one, namely, its contact strength. This can replace the huge list of existing materials with a single parameter — contact destruction strength. Additional research is required to fully justify the cutting resistance forces.

6. Reference

[1] Bukhtoyarov L D, Force interaction of the cutting element of the flexible inertia-cutting brush-cutting working body with brushwood // Lesnoe khozyaistvo Povolzh'ya. Issue 7: Inter-institutional paper compilation. / Sarat. SKI. Saratov – 2003 p
[2] Drapalyuk M V 2003 Influence of geometrical and physical-mechanical factors on wood cutting // Les. Nauka. Molodezh VGLTA 2003: Paper compilation. / Edited by RAEN prof. L.T. Sviridova, Voronezh: VGLTA, pp 240–244.
[3] Gusev B V, Zagurskii V A, Concrete recycling, Moscow, Standartinform, 1988
[4] Boesmans B Crushing and separating techniques for demolition material EDA/RILEM Conference "Re-use of concrete and brick materials", June, 1985
[5] Bazhenov S L 2014 Mechanics and technology of composite materials: Scientific edition / Dolgoprudny: Publishing House ‘Intellect’, 328 p.
[6] Matthews F L, Rawlings R D, Composite materials: Engineering and Science. Woodhead Publishing, 1999, 408 p.
[7] Rybyev I A, Construction materials based on binders. Moscow: Vysshaya Shkola. 1978 309 p.
[8] Geznevzey L B 1976 Road asphalt. Moscow: Transport publ. house, 336 p.
[9] Kulepov V F 1983 Experimental study of loads on disc cutting working member during the opening of asphalt concrete pavements // Gorky regional scientifich and technical conference. – Gorky, p. 27. (NSTU, library).
[10] Karoshkin AA, Krasnoludskiy AV, Odcredenie Determination of power consumption of milling process with a cutter with complex tooth movement.// Izvestiya Tula State University, 2003. Pp. 167-173.
[11] Ignatov S D, Sherstnev N S, Analysis of mathematical model of road milling machine working process at asphalt concrete destruction. // SibADI Bulletin. 2017; (3(55)):120-125. https://doi.org/10.26518/2071-7296-2017-3(55)-120-125 (in Russian)
[12] Kuznetsova VN, Kiryushkina NA, Analysis of mathematical description of interaction process of milling working body with the developed medium. // SibADI Bulletin. 2015; (6(46)):102-106. https://doi.org/10.26518/2071-7296-2015-6(46)-27-31. (in Russian)
[13] Tsytovich N A 1979, 1983 A Short Course in Soil Mechanics / Moskva, (in Russian)
[14] Dombrovskii N G 1961 Earthmoving machines – Moscow : Gosstroizdat (in Russian)
[15] Baratashvili M P, Determination of factors influencing the operation modes of a machine and their importance for destruction of the surface asphalt layers // Scientific digital archive. URL: http://econf.rae.ru/article/6606 (access date: 11.02.2019). (in Russian)
[16] Furmanov, DV, Chizhov VS., Lysakov NE, Experimental determination of cutting resistance forces at destruction of asphalt concrete by a single cutting element // SibADI Bulletin. 2020;17(2):196-207. (in Russian) https://doi.org/10.26518/2071-7296-2020-17-2-196-207

[17] Zelenin A N, Balovnev V I, Kerov I P 1975 Excavation machines (Moscow: Mashinostroenie) 422 p.

[18] Vetrov J A, Baladinskiy V L, Barannikov V F, Kuksa V P 1972 Solid soil destruction (Kyiv: Budivelnyk) 351 p.

[19] Huschek S 1976 Der Kriechversuch Einanfaches Mittelzur Beurteilung der plastischen Verformbarkeit von Asphaltmischungen (Strasse und Verker) No. 4.

[20] Asphalt cold mix manual // Manual series № 14// Asphalt institute. – Lexington, KY, 1997.

[21] Eryomin V G, Eryomin A V, Volokitin V P 2003 The results of the study of deformation and durability properties of asphalt by pressing-in of a spherical indenter // Scientific Herald of the Voronezh State University of Architecture and Civil Engineering. Road and Transport Construction series. No. 1.

[22] Samsonov L N 1985 Milling peat deposits (Moscow. Nedra) 211 p.