Comparative analysis of experimental methods to assess the resistance of milling road asphalt concrete

D V Furmanov
Yaroslavl State Technical University, 88, Moskovskiy prospekt, Yaroslavl, 150023, Russia
E-mail: furmanovdv@ystu.ru

Abstract. The paper is devoted to the comparative analysis of experimental evaluation of cutting resistance of road asphalt concrete to cutting elements with cylindrical carbide tips, which are widely used in rotors of road milling machines. The paper shows the comparison of the results obtained from the study of cutting of typical asphalt concrete with a single cutter on a pendulum stand and on a stand with a mechanical low-speed drive of the cutting element. The advantages and disadvantages of both methods are determined and provided in the paper. The conclusions obtained allow us to recommend reasonably the methods of research of strength indicators of asphalt concrete from the point of view of cutting resistance to cutting with working bodies of road machinery.

1. Introduction
It is difficult to choose and justify the rational parameters of new milling machines, as well as choose the rational technological parameters of existing machines without detailed studying of interaction of a cutting element with a material. With regard to cutting resistance, asphalt concrete of various grades shows a wide spectrum of the properties depending on the changes in external conditions. Such properties essentially make studying of this process more complex [1]. Being a dispersedly filled thermocomposite [2, 3], asphalt concrete has a set of complex strength properties, which depend on the strength of the filler, fractional composition and structure, properties of the binder, and temperature [4]. The structure of the asphalt concrete is formed as early as in the mixing chamber and changes during paving and operation [5].

Currently, these circumstances do not allow simulating the cutting of this material using only a set of analytical methods, and the correct choice of the experimental method will influence not only the volume and accuracy of information received, but also the degree of compliance of the method with the actual process.

2. Study methods
The first method that can be potentially used in the study of cutting is the method based on measuring the cutting energy of a single cutting element when using a freely dropped pendulum (Fig. 1). This method is widely used to determine the energy of ductile failure of standard samples of metals and polymer materials [6, 7]. With regard to determination of energy intensity of cutting, this method was effectively used in research of working processes of peat deposit milling [8].

The operation of the test bench is based on measuring the cutting forces based on changes in kinetic and potential energy during the cutting:
\[ A = m_p \cdot g \cdot (h - h_0) \]  
where \( h \) is pendulum drop height; \( h_0 \) is pendulum deflection height after impact; \( g \) is the gravity acceleration; \( m_p \) is the specified mass of the moving parts of the test bench at the impact point of the cutting force.

\[ m_p = \frac{T^2 \cdot M}{4 \pi^2 \cdot L^2} \]  
where \( T \) is experimentally determined pendulum period; \( M \) is the first moment of the pendulum, which is also determined experimentally by lifting the pendulum; \( L \) is the distance between the cutting zone and the rotation axis.

The following shows how the cutting resistance forces are calculated:

\[ A = \int_{0}^{l_{\text{max}}} F(l) \, dl \]  
where \( l_{\text{max}} \) is the sample length; \( F(l) \) is the horizontal cutting force that change functions.

Since the last value is unknown, the average of the horizontal cutting resistance force can be estimated:

\[ F_{\text{av}} = \frac{A}{l_{\text{max}}} \]

This value allows us to calculate the energy values of the working process, determine the drive power and the average torque of the milling cutter rotor. However, the following values remain unknown: the values of the vertical cutting resistance forces, the peak values of cutting forces, the pulse rate of cutting forces due to the uneven structure of the material.

Nevertheless, the undisputed advantage of this method is that it most accurately reproduces the real process: since a real cutter is installed on the pendulum, the required cutting speed is achieved by selecting the desired drop height, and it is also possible to install thermostatted samples with different temperatures.

The second method is based on the direct measurement of the cutting resistance forces by power sensors (Fig. 2). This method is most conveniently implemented when using a metalworking (milling)
machine equipped with special fixtures for sensors, cutting elements, and material. Such design provides high rigidity of mountings of main elements of the measuring complex, accuracy of positioning of the cutting tool relative to the workpiece, and uniformity of feed. The design allows obtaining oscillograms of vertical and horizontal components of cutting resistance forces (Fig. 3). Thus, the figure shows an oscillogram of the horizontal resistance force to cutting of asphalt concrete of grade B2 [9] with 2-mm thick chips to be cut. The data were obtained at a sample temperature of 22 °C.

Let us consider the basic advantages of this type of equipment. The undoubted advantage is that this equipment allows us to determine not only horizontal but also vertical cutting resistance forces, which provides us with a way to fully analyze the loads on the working body and the cutting element. In addition, the analysis of the oscillogram of the components of cutting resistance forces allows us to determine not only the average values, but also the amplitude of the components and the full cutting forces arising from the interaction of the cutting element with asphalt concrete components.

![Figure 2. A mechanically driven test bench for cutting asphalt concrete.](image)

The only disadvantage of this method is that it is not possible to achieve cutting speeds that correspond to actual speeds when milling asphalt concrete. Taking into account that the cutting speed of road milling machines reaches 3.5 - 4.5 m/s [10], and the feeds of existing universal milling machines reach 1 - 1.5 m/min, the components of cutting resistance forces measured by this method will be somewhat underestimated.

3. **Comparative analysis of the methods**

The experience gained with both methods allows us to compare the obtained values of cutting resistance forces and draw conclusions. In the paper published earlier [11], we obtained the following regression equation describing the average value of the cutting resistance force component using a pendulum test bench on asphalt concrete, grade B2:

\[
F = 1971 \cdot \Delta h^{0.45} \cdot t^{-0.445}
\]

where \( h \) is the chip depth, mm; \( t \) is the temperature, °C.
Figure 3. Oscillogram of the horizontal component of cutting resistance forces obtained by cutting asphalt concrete, grade B2 at a chip depth of 2 mm.

Figure 4. The dependencies of the horizontal component of the cutting resistance force of asphalt concrete of grade B2 obtained on the pendulum bench (indicated by the plot) and on the mechanical bench (indicated by points).

The cutting resistance force component obtained using this formula is 680.4 N. The oscillogram analysis in Fig. 3 shows that the average value of the horizontal component of cutting resistance force is 578.6 N.

Let us also consider the rest of the plot points (Fig. 4). The curve on the graph reflects the dependence on the chip thickness of the tangent component of the cutting force of asphalt concrete, obtained on the pendulum test bench and reflected in the paper mentioned previously. The curve represents a section of the approximating surface of the empirical function (5) in the temperature plane of $t = 22$ °C. Points on the plot show the results of the experiment, obtained on a mechanical test bench when cutting a sample of asphalt concrete of the same grade with the same cutting element.

Comparative analysis of the two plots shows the average divergence not exceeding 15%, which can be caused by factors related to the measurement error and spread of the strength values of structural
components of asphalt concrete and their bonds in two different samples. However, the most likely reason for the underperforming mechanical bench is the difference in cutting speeds.

4. Conclusion
Both methods demonstrate a satisfactory relative error and, consequently, the possibility of using both methods in practice. Both methods demonstrate workability and good mutual convergence.

The pendulum test bench is simple and cheap; the cost of experiments on such equipment is much lower than the use of more complex mechanical methods. In addition, when it comes to cutting asphalt concrete, the pendulum bench makes it possible to implement the working process at the same speeds as those implemented in real machines. Unfortunately, the pendulum bench is not fit to study dynamic phenomena arising in the contact of the material with the cutting element. The use of a pendulum bench should be recommended to study the energy capacity of milling various road construction materials (not only asphalt concrete).

The method based on the use of mechanically driven test benches can be recommended for detailed study of cutting of road-building materials, including determining peak values of cutting forces, the horizontal component, as well as the full cutting resistance force, with dynamic phenomena taken into account. It is to be noted, however, that not all workflow parameters can be implemented on such machines in the same manner as they are implemented on real machines. Cutting speeds on such equipment will be significantly lower, which may lead to lower cutting resistance forces.

The question of the impact of cutting element speed on cutting resistance for modern asphalt concrete is also subject to study.

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