To the question of determining indicators for evaluating quality compaction and efficiency for pavers

A P Prokopev, Zh I Nabizhanov, R T Emelyanov and V L Sabinin

Siberian Federal University, 79, Svobodny ave., Krasnoyarsk, RU-660041, Russia

E-mail: prok1@yandex.ru

Abstract. The results are considered of a study on the development of indicators of the quality of road materials compaction and efficiency for pavers. On the basis of the dimensionality analysis method, a dimensionless complex for the size of the ramming bar stroke is obtained, for use in the synthesis of systems of continuous non-destructive testing, automatic control and evaluation of the efficiency of stackers. The indicators for evaluating the efficiency of existing and newly created pavers are obtained, which have a close correlation with the compaction coefficient of the asphalt concrete mixture. The results are presented of calculation of specific and generalized performance indicators of various models of pavers.

1. Introduction

The quality of asphalt road surfaces largely depends on the technical operation of compacting the mixture during construction. Under-compaction of layers of road pavement leads to premature numerous damages during operation. According to the code of rules of CR 78.13330.2012 "Highways" (updated version of SNiP 3.06.03-85), at the final stage of construction of road surfaces a set of machines is used – stackers, a link of rollers. The link of rollers consists of light (weighing 5-6 t), medium (8-10 t) and heavy (10-15 t). The paper [1] presents data from studies of the compaction capacity of stackers and road rollers.

Studies [1] have shown "that light rollers provide a compaction coefficient ($K_c$) of 0.85-0.88, medium – $K_c = 0.92-0.94$ and heavy – $K_c = 0.97-1.0". Taking into account these data and the results of other scientific works [2-5, et al.], we can conclude that a promising direction is to significantly improve the quality of road surfaces, reduce the types and number of road rollers, and increase the economic efficiency of construction, through the use of modern stackers with high-compaction working bodies.

The paper [6] provides data on the high compacting capacity of asphalt pavers with such working bodies: degree of compaction close to the normalized is provided when laying asphalt coarse-grained mixtures (type A and B, with a crushed stone content of at least 40 %), the stacker at a speed of 1.0-1.5 m/min, the frequency of the ramming bar 1400-1650 min$^{-1}$ [6]. In this case, no additional compaction of the mixture is required. High efficiency is confirmed in research publications [3, et al.]. An important factor in the effectiveness of such an application of stackers is the temperature of the mixture in the operating range of 140-110 °C, since because of continuous changes in the temperature and density of the mixture, a constant increase in strength and deformation characteristics occurs. The ultimate strength and the modulus of deformation increase progressively with a decrease in temperature. Moreover, the modulus of deformation, which is a measure of the stiffness of the material, increases faster than the ultimate strength. Thus, when the temperature of the mixture decreases from 140 °C to 90 °C, the...
The modulus of deformation increases sixfold, while the ultimate strength only triples [7]. Therefore, it is very important to compact the asphalt mixture in the optimal mixture’s temperature range of the 140 °C - 110 °C.

2. Methods and results
The effectiveness of pavers can be objectively determined by analyzing them under the same operating conditions. The generalized indicator $P_{NG}$, used at the design stage with known technical characteristics, makes it possible to evaluate pavers belonging mainly to one type-sized group in the range of limited changes in the main parameter. The generalized indicator is the product of the specific energy intensity $N_s$ by the specific metal content $G_s$ [8].

The definition of the values N and G included in the $P_{NG}$, $N_s$, $G_s$ expressions is not difficult, as for domestic and foreign stackers they are always given in the prospectuses and technical specifications. The main task is to determine the productiveness of stackers.

The productiveness of stackers can be determined by the following dependency [8]:

$$P = 3600 \cdot B \cdot h \cdot V \cdot \rho,$$

where $B$ – width of the roadbed to be laid, m; $h$ – thickness of the layer to be laid, m; $V$ – working speed of the stacker, m/s; $\rho$ – density of asphalt pavement compacted by the working body of the stacker, t/m$^3$.

However, the direct application of this formula for evaluating the effectiveness of stackers is difficult due to the lack of clear data on the parameters $V$ and $\rho$, which depend not only on the parameters of the pavers, but also on the type of compacted material.

Let’s consider the workflow of the stacker and the parameter included in the productiveness formula. The stacker accepts the asphalt mix, transports it, distributes it, and compacts it. The useful work of the stacker can be attributed to the work on the distribution and compaction of asphalt concrete mixture. This work is carried out by compacting working bodies.

Stackers are used for laying asphalt concrete mixes of different types. When evaluating the effectiveness of stackers, it is possible to exclude parameters that characterize the properties of the compacted material, as it is possible to establish dependencies between the values included in the productiveness formula and the parameters of the stacker.

The density of the asphalt concrete mixture, taking into account the parameters of the compacting working body of the stacker and the road material, can be represented by the following function:

$$\rho = \varphi(e, f_r, V, h),$$

where $e = 2 \cdot r_e$ – bar stroke, m; $r_e$ – eccentricity of drive shaft of the ramming bar, m; $f_r$ – vibration frequency of the ramming bar, Hz.

In paper [6] to determine the parameters of stackers it is proposed to use the parameter $n$ – the number of impacts on a surface element of the material:

$$n = \frac{f_r \cdot l_r}{V},$$

where $l_r$ – length of the ramming bar, m; $V$ – m/s.

According to the manufacturers the length of the ramming bars of modern stackers is from 0.023 to 0.043 m. There is a need of additional factors, which have a significant impact on the efficiency of the compaction process of road materials, to develop a system for controlling the operating parameters of stackers. Based on the results of experimental studies [2, 11], we can identify a variable corresponding to this task. The stroke of the ramming bars is set when preparing the stackers for work on the object from 0.004 to 0.012 m [12]. The choice of the size of the bars stroke is carried out depending on the thickness of the layer and the type of road material.
Taking into account the functional dependences of the compaction coefficient on the variable parameters of the working process of stackers obtained in scientific works [2, 11, et al.], a dimensionless group for the size of the ramming bar stroke is proposed on the basis of the dimensional analysis method considered in the work of Schenk H. Jr. [13]:

\[ n_{te} = \frac{f_t \cdot e}{V}. \]  

(3)

On the basis of the dimensionless group proposed in this article, it is possible to obtain expressions for determining the compaction coefficient of an asphalt concrete mixture:

\[ K' = K \cdot \frac{f_t \cdot e}{V}, \quad K'' = \frac{\rho}{\rho_{st}}, \]

where \( K \) – proportionality coefficient; \( \rho \) – density of asphalt concrete mixture compacted by the working body of the stacker, \( \text{t/m}^3 \); \( \rho_{st} \) – the density of the same reshaped sample, compacted in the standard way, \( \text{t/m}^3 \).

Hence, the working speed of the paver is

\[ V = K \cdot \frac{f_t \cdot e \cdot \rho_{st}}{\rho}. \]  

(4)

Substituting expression (5) into formula (1), we get the following dependence:

\[ P = 3600 \cdot B \cdot h \cdot f_t \cdot e \cdot \rho_{st} \cdot K. \]  

(5)

Assuming \( h, \rho_{st}, K \approx \text{const} \), the performance can be represented as follows:

\[ P = 3600 \cdot B \cdot f_t \cdot e. \]  

(6)

Considering that the compacting working bodies of stackers can have several ramming bars, the expression (6) can be represented as follows:

\[ P = 3600 \cdot B \cdot f_t \cdot \sum_{i=1}^{n} e_i, \]

where \( n \) – number of compacting ramming bars.

The dependencies obtained above make it possible to switch to specific indicators. For stackers equipped with working bodies with ramming bars the specific energy intensity, specific metal content and the generalized indicator [8, 10], respectively, are determined by the following dependencies:

\[ N_s = \frac{N}{3600 \cdot B \cdot f_t \cdot \sum_{i=1}^{n} e_i}, \]  

(7)

\[ G_s = \frac{G}{3600 \cdot B \cdot f_t \cdot \sum_{i=1}^{n} e_i}, \]  

(8)

\[ P_{NGI} = \frac{G \cdot N}{\left(3600 \cdot B \cdot f_t \cdot \sum_{i=1}^{n} e_i\right)^2}. \]  

(9)
Based on the obtained formulas (7)-(9), the calculation of specific and generalized efficiency indicators was performed to compare different models of pavers. The calculation results are shown in table 1.

**Table 1. Performance indicators of pavers.**

| Paver model    | B (m) | G/N (t/kW) | P (m³/h) | G₀/N₀ (t h/m²) / (kW h/m²) | P₉₉ (t kW h²/m⁴) |
|---------------|------|------------|----------|-----------------------------|------------------|
| Titan-420     | 12.5 | 29.5/167   | 5513     | 0.0053/0.030                | 1.6·10⁻⁴         |
| Titan-410S    | 12.0 | 22.3/88    | 7409     | 0.0030/0.0119                | 3.6·10⁻⁵         |
| DR-150S       | 12.5 | 23.5/165   | 5625     | 0.0042/0.0293                | 1.2·10⁻⁴         |
| Super-2000    | 12.5 | 25.0/150   | 10773    | 0.0023/0.0140                | 3.2·10⁻⁵         |
| Titan-280     | 7.5  | 15.1/65    | 3308     | 0.0046/0.020                 | 9.2·10⁻⁵         |
| DR-120S       | 8.5  | 19.7/82    | 4131     | 0.0048/0.020                 | 9.6·10⁻⁵         |
| Super-1700    | 8.5  | 18.0/94    | 6120     | 0.003/0.015                  | 4.5·10⁻⁵         |
| 11011 K       | 7.0  | 15.5/54    | 2520     | 0.006/0.021                  | 1.2·10⁻⁴         |
| DS-179, two tampers | 7.0 | 18.0/77   | 5103     | 0.0035/0.015                 | 5.2·10⁻⁵         |
| DS-179, one tamper | 7.0 | 18.0/77   | 3402     | 0.0053/0.023                 | 1.2·10⁻⁴         |

Thus, based on the results of calculating the performance indicators of pavers according to technical parameters \( B, e, f, \) it can be concluded that among the considered models the most effective for \( G, N, P_{NG} \) are the models "Super-1700" (Germany), DS-179 with two bars ("Dormashina", plant) (screed width of 7...8.5 m), and "Titan-410S" (Germany), "Super-2000" (Germany) (screed width of 12...12.5 m). Table1 shows that to improve the efficiency of the domestic asphalt paver DS-179, it is necessary to reduce the metal consumption and increase the stroke of the bars.

It is advisable to make unambiguous assessments of the technical level of pavers using the method of calculating the technical level coefficient [10]:

\[
K_{t,l} = \frac{P_o}{P_m},
\]

where \( K_{t,l} < 1 \) – average level; \( K_{t,l} > 1 \) – for the best options of paver models; \( P_o \) – basic (standard or average) indicator; \( P_m \) – performance indicator.

Then, using the obtained dependencies, you can proceed to specific calculations, for example, on generalized indicators:

\[
K_{t,l} = \frac{G_o \cdot N_o \cdot \left( B_o \cdot f_{m} \cdot \sum_{i=1}^{n} e_{wi} \right)^2}{G_m \cdot N_{m} \cdot \left( B_o \cdot f_{m} \cdot \sum_{i=1}^{n} e_{wi} \right)^2}.
\]

Indicators make it possible to evaluate existing and newly created machines, but they cannot serve as a basis for calculating specific parameters \( e, f, N, G, V, \) etc. These parameters of asphalt pavers
should be calculated according to known dependencies and be within certain restrictions that ensure optimal quality of work (compaction coefficient, evenness, etc.) in the construction of asphalt roads.

3. Conclusion

On the basis of the dimensionality analysis method, we proposed a dimensionless complex for the size of the stroke of the ramming bars of the working body of the paver $n_{\text{e}} = f \cdot e/V$, which can be recommended for use in the design of systems for continuous non-destructive quality control of compaction and automatic control of compaction of road materials by pavers. The dimensionless complex can be used to create a neural network (intelligent) system for monitoring and controlling the compaction of road materials.

Specific and generalized indicators for evaluating the effectiveness of pavers are obtained as a result of transformations of the dimensionless complex for the size of ramming bars stroke and analytical dependencies.

A formula for evaluating the technical level of pavers by the coefficient of technical level is obtained, which is useful at the stages of creating new models, upgraded versions, as well as for justifying a commercial contract for the purchase of specific models of pavers.

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