Efficient Asphalt Concrete Mix Compaction Modes by Vibrating Road Rollers

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Abstract. The paper considers the asphalt concrete mix compaction process. The behavior of the material being compacted under load is described using the Kelvin-Voigt rheological model consisting of elastic and viscous elements. The interaction process of a vibratory roller with an asphalt concrete mixture is modeled using a single-mass oscillatory system. The model input parameters are the characteristics of the material being compacted and the vibrating equipment. The output parameters are the parameters of the roller vertical movement. As a simulation result, the temperature limits of the different rollers types efficiency are obtained. Also, rational vibration exciter frequency ranges were obtained for different types of rollers

1. Introduction
Asphalt is currently the most common road surface finish. This is due to the high bearing capacity and elastic properties of this material, as well as easy care and repair [1,2].

The asphalt concrete mix compacting is an important technological operation on which the whole structure quality, reliability and durability depend. A set of vibratory road rollers is used to compact the coating. The greatest difficulties are caused by the appointment of compacting machine rational operating modes in terms of the rolling process efficiency. To justify the machines operation modes, it is necessary to consider the process of road roller working body interaction with an asphalt concrete mixture.

2. Vibration compaction simulation
A smooth metal roller is considered as a vibrating road roller working body. To describe the behavior of the asphalt concrete mixture under cyclic loading, we will use the Kelvin-Voigt rheological model consisting of elastic and viscous elements installed in parallel. The analysis [3,4,5] found that the Kelvin-Voigt model can be used to describe the asphalt concrete mixture behavior under vibration loading. Let's imagine the process of the road roller vibration drum interaction with an asphalt concrete mixture in the form of a single-mass oscillatory system (figure 1).
Figure 1. The scheme of the vibratory drum interaction with the asphalt concrete mixture.

In figure 1 the point of system static balance is taken as the reference point for the drum displacements $h$. An eccentric weight $m_0$ rotating with a frequency $\omega_0$ that adds a dynamic load to the static load created by the roller weight $mg$ is used as the drum vibration mechanism.

The differential equation of the drum vibrational motion has the form [6]

$$\left( m + m_i \right) \ddot{h} + \mu \dot{h} + ch = m_0 \omega_0^2 r \cos \omega_0 t,$$

where, $m$ is the roller mass per drum, kg, $m_0$ is the debalance mass, kg, $\mu$ is the material viscosity coefficient, N·s/m, $c$ is the material stiffness coefficient [7], N/m, $\omega_0$ is the debalance speed, rad/s, $r$ is the debalance shaft eccentricity, m [8].

The solution to equation (1) was obtained using the dynamic simulation environment “Simulink” package “MATLAB”. Figure 2 presents a dynamic model of the considered single-mass oscillatory system.

The asphalt concrete mix viscous properties largely depend on the material temperature. In the course of experimental studies [9], a two-factor dependence was obtained

$$\mu(T, f) = 5.21454 \cdot 10^1 \cdot 0.958554536^T \cdot 0.904551639^f,$$

where $T$ is the asphalt concrete mix temperature, °C, $f$ is the vibration frequency, Hz.

Dependence (2) was taken into account in the dynamic model in the form of the “Viscosity” subsystem for calculating the viscosity coefficient of the asphalt concrete mix at a given temperature and vibration frequency.

The simulation results are displayed in the form of a diagram that shows time dependence of the vibration drum displacement $h$.

One way to determine the road surface compaction effectiveness with a vibratory roller drum is based on measuring the reaction of a material to a force [10,11,12]. To do this, an accelerometer is installed on the vibrating drum, which registers its acceleration at the moment of rebound from the material being compacted. The stiffer the material, the greater the acceleration of rebound. Then the spectrum of vibratory drum vertical accelerations for two cycles of vibration is analyzed. This way it is possible to evaluate the stiffness (or strength) of the material, as well as indirectly judge its density [13,14].

To implement this method, a subsystem “Acceleration Calc” for calculating drum vibration acceleration was introduced into the dynamic model (figure 3).
Figure 2. Dynamic model of a single-mass oscillatory system.

Figure 3. Block diagram of the subsystem “Acceleration Calc”.

The subsystem “Acceleration Calc” algorithm is based on the displacement second derivative \( \frac{d^2h}{dt^2} \) calculation at the moment of drum rebound from the material surface. The numerical value \( \frac{d^2h}{dt^2} \) is equal to the drum vibration acceleration at the moment in time [15,16,17,18]. During the simulation, the dependences of drum vibration acceleration of different masses on the asphalt concrete mix temperature were obtained, which are similar to those shown in figure 4. The order of the vibration accelerations obtained values corresponds to those obtained in the work [19].
3. Results

Graphs of changes in vibration acceleration with decreasing mixture temperature for each $10^\circ C$ for different rollers mass are shown in figure 5.

Analysis of the graphs shown in figure 5 allows you to set the temperature limits of the effectiveness of rollers different types. For example, curve 1 has an extremum at point A. Therefore, after the mixture reaches a temperature of $110^\circ C$, further use of the light type roller will be ineffective in terms of density increase, and it is necessary to begin to compact the material with a medium type roller.
When comparing the values of the boundary temperatures obtained during the simulation with the data of regulatory sources [20] satisfactory convergence was established (relative error within 12%). This allows us to conclude that the adopted model is adequate.

Also, as a result of simulation, the dependences of the drum vibration acceleration on the vibration frequency for different masses rollers were obtained (figure 6).

The analysis of the curves shown in figure 6 allows us to establish vibration exciter rational frequency ranges for different types of rollers. At a given vibration frequency, the highest increase in density is achieved by the roller with maximum drum acceleration. In figure 6, the abscissas of points A and B are the boundary frequencies for different types of rollers. Thus, the frequency range for light rollers is 55-60 Hz, for medium - 47-55 Hz, for heavy - 30-47 Hz. A comparison of the vibration frequencies values obtained during the simulation with the frequencies of existing models of rollers gives satisfactory convergence.

4. Conclusion
Using the proposed rational vibration compaction modes in practice will eliminate unnecessary roller's passes, which will reduce the compaction time and fuel consumption. Therefore, productivity will increase and the roller's work quality will increase.

Recommendations regarding rational vibration frequency ranges for rollers of different masses can be used in the design of new road rollers models.

5. References
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