Behavior of asphalt concrete mixture during relaxation

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Abstract. The article discusses the asphalt concrete mixture compaction process with a road roller. The rheological model of a smooth drum and material interaction is adopted. The relaxation process that occur in the asphalt concrete mixture during compaction has been studied. During dynamic modeling, the physical and mechanical characteristics of the compacted material influence on the behavior of the latter during compaction was established. The article reveals the relaxation process physical essence, which plays an important role in the material compaction. The law of asphalt concrete mixture behavior during relaxation was determined. The obtained dependencies make it possible to evaluate the effectiveness of the force effect of a smooth drum on each pass of the roller.

1. Introduction
A smooth drum roller is one of the main means to compact the asphalt concrete pavement of highways. Asphalt concrete mixture is an elastic-viscous-plastic material, therefore, a theoretical description of its behavior under load is a rather complicated task. Various processes take place in the material to be compacted under loading [1].

This paper presents an investigation of the stress relaxation process that occur in asphalt concrete mixture.

A common tool for the study of the process of material loading is rheological modeling [2]. We will use a rheological model, which includes elastic, viscous and plastic elements, to describe the asphalt concrete mixture (Figure 1).

![Rheological model of asphalt concrete mixture.](image1.png)
2. Study of the stress relaxation process

The force on the material is excessive due to the high loading speed when compacting the asphalt concrete mixture with a road roller drum [3, 4]. Therefore, we can talk about the relaxation phenomenon observed in the asphalt concrete mixture.

To study the relaxation process we exclude the dry friction element from consideration in the accepted rheological model (Figure 1), since it does not affect the specified process [5, 6]. The relaxation process is schematically shown in Figure 2.

![Figure 2. Scheme of the relaxation process: a – initial position; b – instant loading; c – relaxation.](image)

The initial position of the considered model is shown in Figure 2, a. A load of $\sigma_{\text{max}}$ value is instantly applied to the model at the moment of time $t = 0$, after which it is fixed. In this case, the deformation of the elastic element $b$ is equal to $h_{\text{max}}$, and the deformation of the elastic element $c$ is equal to zero. The following relation is true for the moment of time $t = 0$

$$\sigma_{\text{max}} = bh_{\text{max}}.$$  \hspace{1cm} (1)

Over time, there will be a gradual tension of the elastic element $b$ and compression of the elastic element $c$. At the moment $t \to \infty$, the deformation of the elastic element $b$ will be $h_b$, and the deformation of the elastic element $c$ will be $h_c$. For the moment of time $t \to \infty$ the following relation is true

$$\sigma_r = bh_b = ch_c.$$  \hspace{1cm} (2)

where $\sigma_r$ is the stress in the material after relaxation [7].

Since the total deformation of the considered model for the times $t = 0$ and $t \to \infty$ is invariable, then

$$h_{\text{max}} = h_b + h_c.$$  \hspace{1cm} (3)

Taking into account (1) and (2), equation (3) takes the following form

$$\sigma_{\text{max}}b^{-\gamma} = \sigma_r\left(b^{-\gamma} + c^{-\gamma}\right).$$  \hspace{1cm} (4)

Expressing $\sigma_r$ from (4), we obtain

$$\sigma_r = \sigma_{\text{max}}c\left(b + c\right)^{-\gamma}.$$  \hspace{1cm} (5)

Stress relaxation refers to the decrease over time of the stresses that initially arise in the body during its rapid deformation [8, 9]. In equation (5) the coefficient $c\left(b + c\right)^{-\gamma}$ is always less than one, which means that $\sigma_r < \sigma_{\text{max}}$. Consequently, equation (5) describes the relaxation phenomenon.

In the model in Figure 2 elastic elements are connected in series (Figure 3, a). With such a connection, the following relation is valid

$$\sigma_{\text{max}} = bh_b = ch_c.$$  \hspace{1cm} (6)
Figure 3. Connection of elastic elements: a - two elements; b - equivalent replacement by one element.

Taking into account (6), equation (3) takes the following form

\[ h_{\text{max}} = \sigma_{\text{max}} \left( b^{-1} + c^{-1} \right). \]  

(7)

We replace two series-connected elastic elements with one equivalent (Figure 3, b), for which the following equation is true

\[ \sigma_{\text{max}} = k h_{\text{max}}. \]  

(8)

Taking into account (8), equation (7) takes the following form

\[ k^{-1} = b^{-1} + c^{-1}. \]  

(9)

From the equation (9) analysis it follows that with a series connection of elastic elements, the total stiffness of the system will be less than the stiffness of any element of this system. This property is the cause of stress relaxation in an elastic-viscous body [10, 11].

It follows from the analysis of expression (5) that the larger the value of b in comparison with the value of c, the more pronounced the relaxation. We will establish the validity of this statement for the adopted rheological model. Since the material temperature and density during relaxation can be considered constant, the rheological model parameters b, c and \( \mu \) are also assumed to be unchanged, and the equation of the rheological model (Figure 2) has the following form

\[ \frac{d \sigma}{dt} + \frac{b + c}{\mu} \sigma = \frac{bc}{\mu} h_{\text{max}}, \]  

(10)

where \( h_{\text{max}} \) is the model deformation achieved during loading.

Based on equation (10), a dynamic model was obtained, shown in Figure 4.

Figure 4. Dynamic model of the stress relaxation process.
The developed dynamic model makes it possible to obtain a stress-time diagram after fixing the model under instant loading (Figure 5).

![Figure 5. Strain-time and stress-time diagrams during relaxation.](image)

Under the initial conditions $t = 0, \sigma = \sigma_{\text{max}} = bh_{\text{max}}$ the solution to the differential equation (10) will have the following form

$$\sigma = \frac{bc}{b+c} h_{\text{max}} + \left( \sigma_{\text{max}} - \frac{bc}{b+c} h_{\text{max}} \right) e^{\frac{bc}{b+c} t}. \quad (11)$$

As $t \to \infty$, equation (11) takes the following form

$$\sigma = \sigma_r = \frac{bc}{b+c} h_{\text{max}}, \quad (12)$$

where $\sigma_r$ is the stress value after the end of the relaxation process.

Taking into account (11), equation (12) takes the following form

$$\sigma = \sigma_r + (\sigma_{\text{max}} - \sigma_r) e^{-K_r t}, \quad (13)$$

where $K_r = (b+c) \mu^t$ is the relaxation intensity factor.

Expression $(\sigma_{\text{max}} - \sigma_r)$ in equation (13) characterizes the relaxation resistance of the material.

The results of dynamic modeling are shown in Figures 6 and 7.
Figure 6. The relaxation resistance versus asphalt concrete mixture elasticity factor b graph 

Figure 7. The relaxation resistance versus asphalt concrete mixture elasticity factor c graph

The analysis of the graphs in Figures 6 and 7 shows that with the increase in the difference between the values of $b$ and $c$, all other things being equal, the difference between the initial and final stresses also changes. This confirms the adopted rheological model adequacy in describing the relaxation of the asphalt concrete mixture.

The equation (13) analysis allows concluding that the increase in the asphalt concrete mixture viscosity $\mu$ leads to the material relaxation time increase (Figure 8).

Figure 8. The relaxation process intensity graph at different values of $\mu$.

3. Conclusion
It is found that for viscous-elastic bodies, not only the magnitude of changes in the attached load or deformations is important, but also the rate of these changes. Relaxation can proceed at different rates, and the material final stress can reach different values. The relaxation process intensity is influenced not only by the maximum value of the loading stress, but also by the mixture viscosity. The material elastic properties affect its relaxation resistance.

The results of the studies carried out can be used to describe the asphalt concrete mixture vibration compaction. In this case, it is necessary to determine relationship between the physical and mechanical characteristics of the material to be compacted and the drum vibrator parameters. This relationship can be determined in a laboratory experiment.
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