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MODELING THE EVOLUTION OF DEFORMATIONS AND STRESSES IN ROAD-BUILDING MATERIALS BASED ON RHEOLOGICAL APPROACH

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Statement of the problem. The correct choice of sealing means for the construction of highways as a fundamental factor in the qualitative compaction of road building materials requires correct consideration of the operating stresses and rates of their change under the working bodies, as well as changes in stress within the material layer, with the corresponding kinetics of deformation development of the material. Different approaches and methods that exist in this direction show the ambiguity and inconsistency of some data, which is explained by the lack of consideration of factors that had not previously been given due attention.
Results. The problems of the analytical description of deformation development of road-building materials under load and stresses in them under certain deformation laws are considered, which is an important factor in the development of compaction technologies. It is shown that the application of the theory of hereditary creep for such a description allows us to take into account additional factors that were not previously treated with due attention, which led to significant inaccuracies in determining the stresses in time and the development of deformation of materials.
Conclusions. The problem of improving the quality and efficiency of compaction of road building materials can be solved by applying new progressive methods for studying the characteristics of the materials of the compaction layers of roads. The development of deformations and distribution of stresses in the compaction layer of the road-building material should be determined, taking into account its rheological properties, through the relaxation processes occurring in time. At the same time, using the interrelation between creep and relaxation processes, it is possible to determine by calculation the magnitude of deformations and acting stresses at any time in accordance with the various laws of loading and deformation of the material.

Keywords: road-building materials, design model, deformation, stresses, rheological properties.

Introduction. An important factor in the development of technologies for compaction of various road construction materials (subbase soil, asphalt and concrete mix, etc.) is consideration of the existing strains and rates of their changes influencing the development of deformations as well as changes in the strains inside a material layer for a particular kinetics of the deformation development in a material. These are two mutually connected processes which should be described based on certain parameters of rheological materials using a time factor. The first group of the issues has been dealt with at different points by various researchers both in this country and abroad [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 13, 22, 23, 24, 25, 26, 27, 28, 29, 30]. The development of a range of methodological approaches in the field generated a number of contradictory results, which, first of all, indicates how invariant the investigated parameters of road construction materials are. A correct choice of a calculation model of a compacted road construction material depends on whether the previously obtained data allow a correct model to be designed that would reflect its major features that are essential in investigating its compaction. Modern trends in the development of various compaction technologies as well as the resulting body of scientific knowledge on the interaction of compaction machines with road construction materials enable the *principles of designing calculation models* of soils and road asphalt concrete mixes to be formulated.

1. *Principle of succession* of calculation models for specialists working in different fields (construction, machinery, communal household, etc.).
2. *Principle of association* of specialists-researchers working on construction and operation of highways, designing and operation of transporting and technological machinery as well as material specialists investigating the features of the operational properties of compacted materials.
3. *Principle of a necessary combined consideration* of the time factor, features of compacted materials and adjustments for adequate reactions to the character of current loads of compactors.
4. *Principle of quantitative evaluation* of compaction based on actual operational conditions of employed compaction materials with certain parameters and operation modes.
5. *Principle of suitability* for manipulations with various analytical expressions and use of various mathematical calculation methods.
6. *Principle of implementability* in software products for a range of tasks involving modern PCs.
7. *Principle of accuracy of calculations* for short time periods (less than 1 sec.) of the interaction of a deformed environment with compactors.

Analyzing the above principles of designing calculation models of compacted road construction materials that are generated by the current issues [10], in this paper we are suggesting that one of traditional approaches to studying the rheological properties of deformed environments is employed in combination with the theory of hereditary creep of elastic-viscous-plastic materials that enables one to launch various mathematical models and methods of improving technological processes of compaction of subbase soil and road asphalt concrete mixes.

Theoretical foundations of the process under discussion. In order to describe processes of creep, let us use the simplest ratios of the non-linear theory of viscosity and plasticity. Then the creep equation will take the following form [12]:

$$\varepsilon(t) = \psi[\sigma(t)] + \int_0^t K(t-\tau)\psi[\sigma(\tau)]d\tau\,, \quad (1)$$

then in this case the similarity of the creep curves is observed for different loading conditions. The function $\psi[\sigma(t)]$ is called a similarity function. Any of the creep curves can be combined if its ordinates $\varepsilon(t)$ are changed into some number called a similarity coefficient. Based on the similarity coefficients, we can also assume that knowing the deformations of a basic creep curve and identifying similarity coefficients, the deformation of a compacted layer with various parameters of conditions and for all the investigated loads can be determined.

The expression (1) describes the similarity of creep curves only for different σ = const. In this case in order to give a complete description of the behavior of a compacted layer under a load that corresponds with a certain character of its interaction with a compactor, it is necessary to know the dependencies of the properties of a material expressed with the speed and value of deformation on many factors, which are, more importantly, loads, oscillation frequency, relative constraining force, temperature, humidity, thickness of a layer and density of soil, etc. Therefore the similarity function should take into account all the factors that determine a deformation capacity of a compacted layer and thus its properties:

$$\psi = \psi[x_1; x_2; \ldots; x_i; \ldots; x_n] = \psi[\vec{x}]\,,$$

where x_i are independent factors determining the deformation properties of a compacted layer and making up a space of independent factors (a factorial space).

Studies of creep and relaxation of strains in a material, changes of its properties under various loads or deformations in time are on a whole new level these days. One of the key issues is correct and well-informed choice of nuclei of integral equations of hereditary creep [15].

A satisfactory description of relaxation of strains as well as creep is possible using a simple but a fairly general weak singular nucleus

$$S(t) = A \cdot e^{-\beta \cdot t} \cdot t^{\alpha - 1}. \quad (2)$$

A resolvent of this nucleus (function of the creep rate) is

$$K(t) = e^{-\beta \cdot t} \sum_{n=1}^{\infty} \frac{[A\Gamma(\alpha)]^n \cdot t^{n\alpha-1}}{\Gamma(n\alpha)} \quad , \tag{3}$$

where A, α, β are the parameters of the nuclei of creep and relaxation; $\Gamma(\alpha)$ is the Euler gamma function; approximation showed that it agreed with the experimental data for describing restrained, settled and unsettled creep [12, 14, 15].

The functions (2) and (3) contain a sufficient number of the parameters: A, α, β so that almost any experimental curves of the deformation rate under a constant load or the rate of strain drops at a constant deformation could be approximated using them. Therefore knowing the parameters A, α and β, the deformation or strains can be determined for corresponding loading and deformation laws with a high degree of accuracy at any moment of time.

Laws of the development of deformation and strains. It is obvious that while evaluating the deformation characteristics of subbase soil and road asphalt concrete mixes, it is necessary to know both the initial characteristics of their corresponding properties [18] and the character of their change under external force of compactors [14, 16, 17, 33].

In these changes the features of the interaction of certain types and shapes of compactors with an environment of a compacted layer as well as typical redistribution of strains during its deformation have a big role to play. The main effect that emerges under the effect of a load on a compacted layer is a relative displacement of the particles of its material with the value and character of current deformations significantly depending on such physical characteristics as porosity, density, temperature, humidity, etc. If there is only compaction of the material of a compacted layer under a load of a compactor, the corresponding deformations are always damping and the resistance of a material to these deformations rapidly increases as so do the latter. If the deformations are associated with changes in the shape of soil, they can be both damping and non-damping. If the latter is the case, there are disruptions in the continuity of soil and loss of its strength.

Let us only consider such a state of the material of a compacted layer when its deformations are damping thus compacting road construction material without disrupting its continuity. This fairly considerable assumption is widely used in studies of the stress-strain of deformed environments, in particular in soil studies.

The main characteristics of deformation properties of subbase soil and road asphalt concrete mixes are a module of linear deformation E, module of shear deformation G and coefficient of transverse deformation μ. Unlike the module of elasticity, the shear module and Poisson coefficient used in the theory of deformation of elastic materials, the deformation modulus E and G as well as the coefficient of transverse deformation μ consider not only elastic but viscoplastic parts of deformation that emerge during loading. That is exactly why during interaction of compactors with subbase soil or road asphalt concrete mix the parameters E, G and μ can be presented as their *rheological characteristics* [19].

In order to evaluate the interaction of compactors with subbase soil or road asphalt concrete mix, the laws of compression and shear are commonly used bearing in mind that depending on a chosen model, the first one characterizes the formation of a trace (rut) and the second one — that of a driving force (adhesion). For implementing models of a higher level, it is beyond any doubt that a these laws should be employed in combination bearing in mind that any character of the interaction can be implemented.

Numerical values of the characteristics of road asphalt concrete mixes and soils should be invariant to the methods used to determine them. Based on almost century-long experience, the laws of compression and shear are identified using corresponding displacements of deformators (stamps). In cases when subbase soil or an asphalt concrete mix operate in complex stress-strains, according to the theory of hereditary creep, the deformation law can be presented as a shear and volumetric deformation equation [12]:

$$e_{ij}(t) = \frac{S_{ij}(t)}{2G} + \frac{1}{2G} \cdot \int_0^t K_c(t-\tau) S_{ij}(\tau) d\tau\,;$$

$$\theta(t) = \frac{\tilde{\sigma}(t)}{B} + \frac{1}{B} \cdot \int_0^t K_V(t-\tau) \tilde{\sigma}(\tau) d\tau\,,$$

where e_{ij} *(t)* are the components of a deviator of a deformation tensor; S_{ij} *(t)* are the components of a deviator of deformation tensor; *θ(t)* is a contraction (volumetric deformation during compaction); $\tilde{\sigma}(t)$ is a ball strain tensor шаровой тензор напряжений; $K_C(t)$ is a function of the shear creep rate; $K_V(t)$ is a function of the volumetric creep rate; G and B is a shear and volumetric elasticity modulus. For a compressed cylindrical sample we have

$$K_c(t-\tau) = \frac{K_{11}(t-\tau) + \mu_0 \cdot K_{21}(t-\tau)}{1+\mu_0}\,,$$

where $K_{11}(t - \tau)$ and $K_{21}(t - \tau)$ are functions of the creep rates of transverse and longitudinal deformation; μ_0 is an instant coefficient of transverse deformation, i.e. the shape of compression shear, i.e. the shape of shear is identical to that of stretching shear.

The coefficient of transverse deformation expressed with the rheological characteristics (a function of volumetric $\Pi_V(t)$ and shear $\Pi_C(t)$ creep) is

$$\mu(t) = \frac{-3\Pi_C(t) + \Pi_V(t)}{-6\Pi_C(t) - \Pi_V(t)},$$

and the connection between the functions of volumetric and shear creep is presented as

$$\Pi_V(t) = \frac{3(1-2\mu)}{1+\mu} \cdot \Pi_C(t).$$

The function of the volumetric creep rate [19] is as follows

$$K_V(t-\tau) = \frac{2\mu_0 K_{21} - K_{11}}{1-2\mu_0} = -\frac{K_{11} - 2\mu_0 K_{21}}{1-2\mu_0},$$

i.e. the volumetric deformation decreases as a result of compaction and thus the shape of volumetric deformation here is different from when the sample is stretched.

Therefore using the measured transverse and longitudinal deformations, we can design the functions of transverse and longitudinal creep knowing which it is not difficult to obtain functions of shear and volumetric creep. In the process the parameters of the material of a compacted layer are obtained that are invariant to the method employed to determine them for a universal model suitable for modeling interaction of subbase soil and road surfacing with compactors.

Using various simplified laws of loading of a compacted layer that are most precise in describing its interaction with compactors (Fig. 1), based on them, determining the development of the deformation and employing computational technologies, it is possible to identify the parameters of the creep nuclei and choose the optimal technological operation modes of the employed machinery during compacting of subbase soils and road asphalt concrete mixes [14, 19, 32].

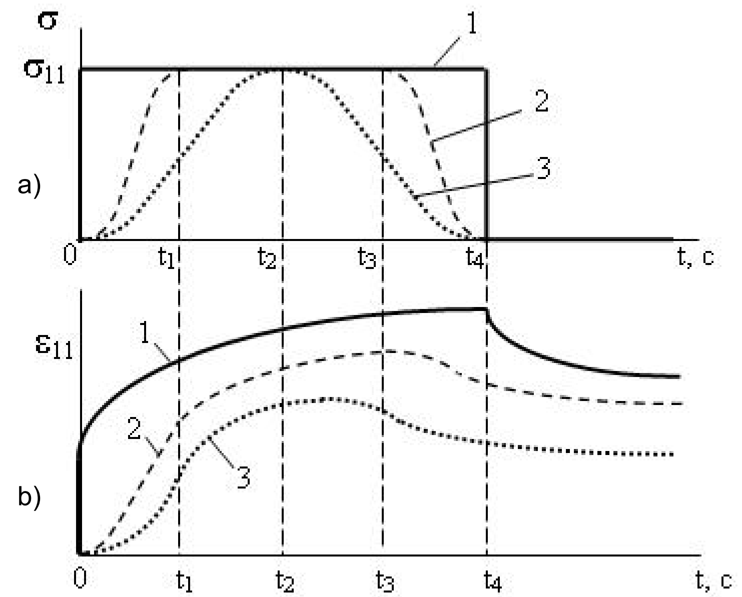


Fig. 1. Laws of loading a compacted layer:
1 is a rectangular one;
2 is a flattened parabola;
3 is a parabola

Hence, e.g., if we assume that the vertical contact pressure is evenly distributed under a caterpillar machinery (line 1 in Fig. 1, a), the development of complete deformation is computed according to the law (line 1 in Fig. 1, b)

$$\varepsilon_{11} = \frac{1}{E}\left[\sigma(t) + \int_0^{t_4} K_{11}(t-\tau)\sigma(\tau)d\tau\right] = \frac{\sigma_{11}}{E}\left[1 + \int_0^{t_4} K_{11}(t-\tau)d\tau\right].$$

If during the interaction of a poorly pumped pneumatic wheel of a roller with a compacted material during a free rolling mode when the resulting interaction of the wheel with the soil layer is normal in the direction of the force, the law of changes in a vertical load on the layer from the machinery is a flattened parabola (line 2 in Fig. 1, a), it can be replaced with a trapezoidal loading law in a certain degree. Accepting that $t_1 = t_4 - t_3$, for complete deformation we have (line 2 in Fig. 1, b)

$$\varepsilon_{11} = \frac{\sigma_{11}}{E \cdot t_1}\left(\int_0^{t_1} K_{11}(t-\tau)\tau d\tau + t_1\int_{t_1}^{t_3} K_{11}(t-\tau)d\tau + t_4\int_{t_3}^{t_4} K_{11}(t-\tau)(1-\frac{\tau}{t_4})d\tau\right).$$

During the interaction of a rigid drum of a roller or the pumped wheel the law of vertical contact pressures is accepted at its maximum (line 3 in Fig. 1, a), then it can be replaced with the triangular loading law in a certain degree. Accepting that $t_2 = t_4 / 2$, for complete deformation we have (line 3 in Fig. 1, b)

$$\varepsilon_{11} = \frac{\sigma_{11}}{E \cdot t_2}\left(\int_0^{t_2} K_{11}(t-\tau)\tau d\tau + t_4\int_{t_2}^{t_4} K_{11}(t-\tau)(1-\frac{\tau}{t_4})d\tau\right).$$

The deformation modulus is as follows

$$E = \frac{1 + \int_0^{t} K_{11}(t-\tau)d\tau}{\varepsilon'_{11}(t) / \sigma_{11}} \quad ;$$

$$K_{11}(t-\tau) = \frac{e^{-\beta_1 \cdot t}}{t} \cdot \sum_{n=1}^{\infty} \frac{\left[A_1 \cdot \Gamma(\alpha_1)\right]^n \cdot t^{\alpha_1 n}}{\Gamma(\alpha_1 n)} \quad ,$$

where ε_{11} is a vertical relative deformation of the layer; ε'_{11} is a vertical relative deformation of the layer at any time t and step-by-step loading law (the Heaviside step function); E is a momentary module of a vertical deformation (at $t = 0$); σ_{11} is a maximum pressure under the wheel; $K_{11}(t - \tau)$ is a function of the speed of a vertical creep curve; α_1, A_1 and β_1 are the parameters of an experimental curve of vertical creep; $\Gamma(\alpha_1)$ is a corresponding Euler gamma-function; t_1, t_2, t_3 and t_4 are the moments of time when there is a fluctuation of speed of a soil layer for different loading laws (see Fig. 2.4); τ is a current value of time.

For the most general case when a material of a compacted layer operates under complex strains, each of the components $\varepsilon_{ij}(t)$ of the deviator of the tensor of deformations $e_{ij}(t)$ are determined individually in each direction and laws of changes in a corresponding loading component from the compactor machinery.

Note that the deformation of a compacted layer is a superficial response of the processes and phenomena that develop in a layer under the effect of the compactors. What is happening inside the layer is not of much importance if the methods being developed can be used to predict interactions with road asphalt concrete mixes and soils of different compactors and based on that, their technological operation modes and parameters are determined thus improving the compaction technologies. For that, only a generalizing theory of compaction of road construction materials is required [21].

A feature of this rheological approach is complex evaluation of the rheological characteristics of a compacted layer that enables one to start determining the stress-strain considering the time and character of the loads from the compactors.

The connection between creep and relaxation allows the latter to be described when according to the creep tests run on the material, the parameters of the creep rate function whose values are part of the function of the rate of the relaxation strains.

Therefore according to the law of the deformation of the foundation layer under each point of the compactor, current strains in the compacted layer of the road construction material changing in time can be identified.

For the triangular law of the development of the deformation (Fig. 2,a), the strains are determined using the following expressions [14, 20]:

at $0 < t < t_1$

$$\sigma(t) = E \cdot \dot{\varepsilon}_\kappa \cdot t - E \cdot \dot{\varepsilon}_\kappa \cdot \int_0^t S(t-\tau)\tau d\tau = E \cdot \frac{\varepsilon_\kappa}{t_1} \cdot t - E \cdot \frac{\varepsilon_\kappa}{t_1} \cdot \int_0^t S(t-\tau)\tau d\tau ;$$

at $t_1 < t < t_2$

$$\sigma(t) = E \cdot \frac{\varepsilon_\kappa}{t_2 - t_1} \cdot (t_2 - t) - E \cdot \frac{\varepsilon_\kappa}{t_1} \cdot \int_0^{t_1} S(t-\tau)\tau d\tau - E \cdot \frac{\varepsilon_\kappa}{t_2 - t_1} \cdot \int_{t_1}^{t} S(t-\tau)(t_2 - \tau) d\tau .$$

The changes of the strains at the point t' in the diagram indicate that at this moment the strains at the point dropped down to zero unless the weight of the compactor is considered.

For the trapezoid law of the development of the deformation (Fig. 2,b) the strains in the compacted layer are given by means of the following expressions:

at $0 < t < t_1$

$$\sigma(t) = E \cdot \dot{\varepsilon}_{\kappa} \cdot t - E \cdot \dot{\varepsilon}_{\kappa} \cdot \int_0^t S(t-\tau)\tau d\tau = E \cdot \frac{\varepsilon_{\kappa}}{t_1} \cdot t - E \cdot \frac{\varepsilon_{\kappa}}{t_1} \cdot \int_0^t S(t-\tau)\tau d\tau \,;$$

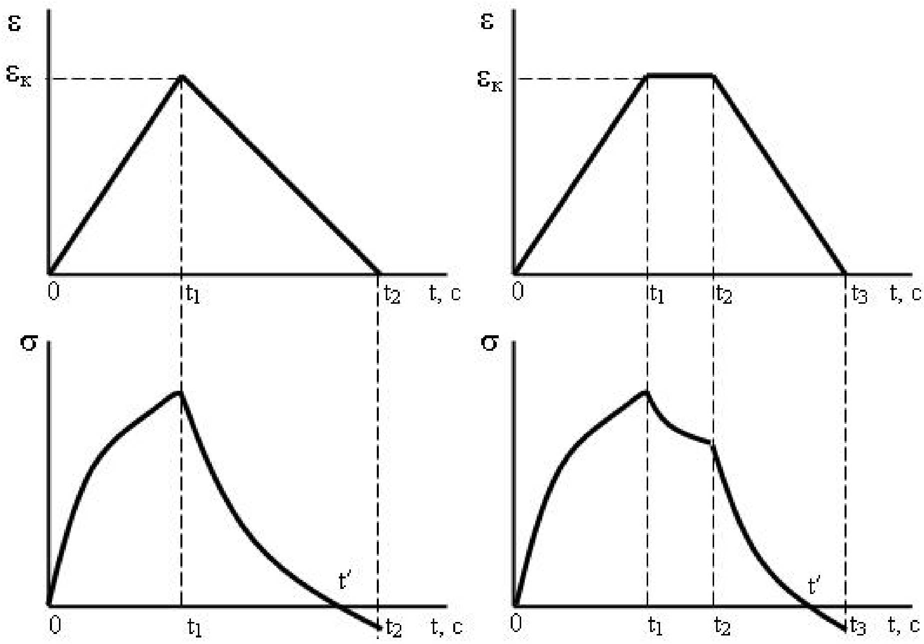
at $t_1 < t < t_2$

$$\sigma(t) = E \cdot \varepsilon_{\kappa} - E \cdot \frac{\varepsilon_{\kappa}}{t_1} \cdot \int_0^{t_1} S(t-\tau)\tau d\tau - E \cdot \varepsilon_{\kappa} \cdot \int_{t_1}^{t} S(t-\tau) d\tau \,;$$

at $t_2 < t < t_3$

$$\sigma(t) = E \cdot \frac{\varepsilon_{\kappa}}{t_3 - t_2} \cdot (t_3 - t) - E \cdot \frac{\varepsilon_{\kappa}}{t_1} \cdot \int_0^{t_1} S(t-\tau)\tau d\tau - E \cdot \varepsilon_{\kappa} \cdot \int_{t_1}^{t_2} S(t-\tau) d\tau -$$

$$- E \cdot \frac{\varepsilon_{\kappa}}{t_3 - t_2} \cdot \int_{t_2}^{t} S(t-\tau)(t_3 - \tau) d\tau \,.$$



a) b)

Fig. 2. Changes in the strains under the deformator for the triangular (a) and trapezoid (b) laws of the deformation of the material

Conclusions. The mathematical models of the interactions of subbase soil and road asphalt concrete mixes with different compactors developed based on the suggested methodological approach allow quick calculations for choosing the optimal technological operation modes and parameters of the employed compaction tools providing high-quality compaction.

According to the developed principles of designing the rheological models of subbase soil and road asphalt concrete mixes and classification properties of compacting effects, it was found that improving the quality and efficiency of compaction of road construction materials can be addressed by employing new cutting-edge methods of studying the characteristics of compaction materials of highway layers using one of the traditional approaches to investigating the rheological properties of deformed environments by means of the theory of hereditary creep of elastic-visco-plastic materials. Unknown laws of structural changes of a compacted material are involved in the similarity function based on the regression equations and exponential and degree nuclei should be used as functions of the rates of creep and relaxation.

It was shown that modeling loading of a layer of a road asphalt concrete mix or soil by means of a flat stamp, it is highly likely that a transition is made to describing deformation during its interaction with different compactors of chosen compaction tools. The equations of shear and volumetric deformation including the components of deviators of tensors of deformation and strain presented as a matrix as well as the functions of the rates of shear and volumetric creep allow the transition to the coefficients of transverse deformation using the functions of volumetric and shear deformation during the deformation of a compacted layer by means of a stamp when the functions of the rates of transverse and longitudinal creep can be determined. The calculation parameters of the material of a compacted layer, i.e. modulus of shear and linear deformation as well as the coefficient of transverse deformation, are invariant to the methods employed to determine them for a universal model suitable for modeling the interactions of subbase and road surfacing with compacting elements of the machinery.

Based on the use of the non-linear theory of hereditary creep of elastic-visco-plastic materials, a connection between developing deformation and the major laws of loading of a compacted layer of soil or an asphalt concrete mix can be replaced with a rectangular, trapezoid and triangular one with a sufficient degree of accuracy.

It was found that the distribution of strain in a compacted layer of a road construction material should be identified considering its rheological properties, relaxation processes occurring in time. Using the connection of creep and relaxation, it seems possible to determine the values of current strains at any point in time by means of calculations according to different laws of the deformation of a material.

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