DESIGNING AND CONSTRUCTION OF ROADS, SUBWAYS, AIRFIELDS, BRIDGES AND TRANSPORT TUNNELS

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INFLUENCE OF THE REMAINING LIFE OF CONCRETE AIRDROME AND HIGHWAY PAVEMENTS ON THE FORMATION OF ELASTIC ACOUSTIC EMISSION WAVES

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Statement of the problem. While determining the characteristics of operated cement concrete airfield pavements and highways, there is a problem of their service life for them to be used further.
Results. Determining the characteristics of a pavement is possible based on the evaluation their remaining life, measurement of the acoustic emission occurring in different stages of damage process related with specific physical structure and propeties of material, which influence the formation and distribution of elastic waves. While measuring the speed and attenuation passing through the multicomponent medium waves, the serviceability needs to be evaluated. The modeling allows for the above component to be connected with physical and mathematical character of material.
Conclusions. A physical and mathematical model of the formation of elastic acoustic emission waves of failing concrete material to make well-timed decisions based on its further operational suitability.

Keywords: airfield pavement, elastic waves, speed, acoustic emission, remaining life.

Introduction

One of the urgent issues faced by construction these days is improving strength and reliability of building structures. Their limit states are the result of accumulation of microdefects in the process of operation which causes macrocracks, degrading performance and failure [3].

Therefore this paper looks into the evaluation of the development of internal wear and its effect on deformative characteristics of composites. This is dealt with in two aspects:

1) designing a physical and mathematical model of damage susceptibility and describing mechanical behavior of media in wave processes;

2) developing an effective and viable method of identifying and assessing defects.

Most artificial airfield pavements these days are made of concrete cement with a great emphasis on viable structures, high quality and strength of the base course to secure safe takeoff and landing of aircraft. Throughout its service life pavements are subjected to incomplete failures that affect flying safety. For credible and hands-on information on the current operational condition of pavements and predicting its behavior further into their service lives, it is necessary that methods of monitoring complying with the specific criteria are applied [9].

Loads and impacts affecting stress strain, durability, maintainability of airfield pavements can be classified according to their physical nature: climatic and hydrogeological, industrial and technological, mechanical, technogenic (operational and technological), emergency and specific ones [3]. The bearing capacity of pavements is mostly impaired by mechanical loads, they are caused immediately by landing gears on pavements with vertical (takeoff, landing, taxiing and parking) and horizontal (taxiing) loads. Mechanical loads are certain and major initial parameters in construction [4].

1. Formation of elastic waves of acoustic emission in microfailure of the structure of an airfield pavement material. In order to provide flying safety, airfield pavements must withstand the following set of force impacts influencing the stress strain of their construction elements.

Firstly, loads emerging during the takeoff, landing, taxiing and parking of aircrafts. These statistical calculation loads correspond with the complete weight of calculation aircrafts. For most aircrafts these days the calculation load on a pavement is transmitted with a three-axle landing gear consisting of two major and one nose support, most of the load (80—90 %) is evenly distributed onto two major supports and the nose support takes up the rest. Besides vertical forces, horizontal forces also act on airfield pavements during touch-down on uneven surfaces and friction of pneumatic tires during taxiing. Taxiing gives rise to frictional forces which causes the wheel to start rolling until the peripheral velocity equals the forward speed of an aircraft. Sliding friction ad then rolling friction are applied to the lower compressed propellant opposite to the aircraft flying path. The counter force is a reaction force which is a horizontal longitudinal load that causes wear and damage of the upper pavement and a shear of cement concrete slabs [3].

Secondly, dynamic impact caused by non-calculated landing conditions give rise to shocks and local damages. Taxiing as well as the start and end of a takeoff lift when lifting force is not significant, there are oscillatory motions of aircraft causing inertia loads on a pavement. They cause oscillations (rolling) of pavements and base courses. These are vibrations and waving processes resulting in structural changes in a pavement material that cause hair cracks developing into open (visible) cracks that result in the base losing its stability when they are excessively saturated and thus slabs heaving [5].

Studies of impacts of mechanical loads of aircraft on rigid airfield pavements were conducted by V.F. Babkov, A.K. Birul, N.B. Vasiliev, A.P. Vinogradov, N.I. Volkhov, G.I. Glushkov, L.I. Goretsky, B.I. Demin and others [3, 4].

During the operation of cement concrete pavements there are continuous microcracks emerging which cause rigid waves read by external devices and made into acoustic emission waves for monitoring purposes. Increasing forces on a local area of a cement concrete surface of a runway or a highway cause concentrations of new sources of elastic waves in the cracks. These waves have certain characteristics influencing defects in a material structure and indicate these changes are happening. By measuring these characteristics, residual life cycle of a structure can be observed throughout a considerable amount of time [6].

Existing methods of monitoring do not allow for a comprehensive evaluation of the performance of a pavement. The authors are suggesting the acoustic emission method [9], based on reading elastic wave signals arising as microdefects occur in the structure of a material under loading. This method is more sensitive and capable of detecting defects as they start emerging.

The authors suggest that processes occurring in the structure of an airfield pavement material under the action of elastic waves arising as a result of mechanical impacts of wheel gears of aircraft during takeoff and landing operations and taxiing.

There is a lot to be studied experimentally and theoretically in the failure area under the effect of shock wave processes [13]. In order to predict changes in the properties of materials impacted by shocks processes occurring in these materials need to be further modeled [1], which seems impossible unless available equations of energy distribution in two-component media are comprehensively analyzed [4].

The theory of elasticity used in the linear case describes the process with a system of two wave equations of two functions [11] and two speeds. When solving a boundary problem of the theory of elasticity, non-stationary areas are of particular interest where some physical characteristics are disrupted. These creeping surfaces of these areas are shock elastic waves.

The structure and profile of an emerging elastic wave are intrinsically linked to attenuation of these waves as they propagate. The analysis of the attenuation must be conducted while considering the physical nature of a propagation medium, kinetics of its plastic deformation. Based on the models of a plastic elastic solid with phase transformations put forth by R.I. Nigmatulin, propagations of shock waves of varying intensity in copper were numerically analyzed. It was noted that shock waves are always accompanied by phase transformations of high intensity and failure [7].

Different models of a medium describing the attenuation of waves were investigated by L.Ya. Kosachevsky, G.I. Bykovtsev, N.D. Verveiko [2], Yu. A. Rossikhin [8], M. A. Artemov, V. A. Baskakov, L. I. Slepyan. They make a conclusion that Maxwell attenuation (as a result of relaxation of tangential stress) is the most viable models for describing attenuation. The authors conducted numerical experiments, provided mathematical reasoning on mutual collision of slabs, present possibilities of mathematical description of the behavior of a medium in dynamic deformation both for plastic elastic and non-linear viscoelastic plastic models.

As the analysis suggests, the front of the density wave of mobile dislocation increases as so do loading and unloading waves. The authors conclude that attenuation of an elastic source is accounted for with the interaction of an elastic compression wave with an unloading wave arising immediately following the elastic source due to relaxation of stresses. Owing to the effect of a yield delay, plastic transition of a medium is made more difficult as the stress following the elastic source is larger than a yield point and changes in time.

It is rather daunting to describe actual physical processes in materials under the effect of an applied pressure pulse mathematically and thus models are designed that are more or less capable of representing the behavior of materials under specific conditions. Deformation and rheological properties of porous media are also modeled.

2. Physical and mathematical models of propagation of elastic waves in cement concrete.

Let us consider a cement concrete airfield pavement which is constantly subjected to static and dynamic loads during monitoring, takeoff and landing of aircraft. Physically cement concrete is a two-component porous gas-saturated medium.

Propagation of waves in a non-limit gas-saturated homogeneous elastic porous medium is given by a system of equations [1, 2, 8, 11]:

$$\begin{gathered}\rho_{11}\frac{\partial^2 u_i^{(1)}}{\partial t^2}+\rho_{12}\frac{\partial^2 u_i^{(2)}}{\partial t^2}=\frac{\partial}{\partial x_i}(\lambda\frac{\partial u_j^{(1)}}{\partial x_j})+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i^{(1)}}{\partial x_j}+\frac{\partial u_j^{(1)}}{\partial x_i}\right)\right]+\frac{\partial}{\partial x_i}\left(Q\frac{\partial u_j^{(2)}}{\partial x_j}\right),\\ \rho_{12}\frac{\partial^2 u_i^{(1)}}{\partial t^2}+\rho_{22}\frac{\partial^2 u_i^{(2)}}{\partial t^2}=\frac{\partial}{\partial x_i}\left(Q\frac{\partial u_j^{(1)}}{\partial x_j}+R\frac{\partial u_j^{(2)}}{\partial x_j}\right),\end{gathered} \tag{1}$$

where $u^{(\alpha)}$ are components of the displacement vectors of phases (elastic and gas); $R = mR_0$, $Q = (1-m)R_0$ are coefficients depending on the porosity of a medium m and compressibility of a gas (air) R_0; λ, μ are Lamé coefficients; ρ_{11}, ρ_{22} are effective densities of the phases; ρ_{12} is a dynamic coefficient of the connection of phases.

Using the denotation $\frac{(1-m)^2}{m} R_0 = G$ equations of attenuation of longitudinal and transverse waves in breakages takes the following form

$$\begin{aligned} (\lambda + G)[U_{k,k}^{(1)}]\nu_i + \mu[U_{i,j}^{(1)}]\nu_j + \mu[U_{j,i}^{(1)}]\nu_j + Q[U_{k,k}^{(2)}]\nu_i + \rho_{11}c[V_i^{(1)}] + \rho_{12}c[V_i^{(2)}] = 0, \\ Q[U_{k,k}^{(1)}]\nu_i + R[U_{k,k}^{(2)}]\nu_i + \rho_{12}c[V_i^{(1)}] + \rho_{22}c[V_i^{(2)}] = 0, \end{aligned} \tag{2}$$

where ν_i, ν_j are coordinates of a unit vector directed at an unexcited part of a porous medium; c is the velocity of a wave surface; $V_i^{(\alpha)}$, $(\alpha = 1,\ 2)$ are components of the velocity of phase displacements.

As $\Sigma(t)$ goes through the wave surface, geometric and kinematic conditions of compatibility of the first order are met:

$$\left[\frac{\partial U_i^{(\alpha)}}{\partial x_j}\right] = \left[U_{i,j}^{\alpha}\right] = \omega_i^{(\alpha)}\nu_j, \quad \left[\frac{\partial U_i^{(\alpha)}}{\partial t}\right] = \left[V_{i,j}^{(\alpha)}\right] = -c\omega_i^{\alpha}, \tag{3}$$

where $\omega_i^{(\alpha)}$ are surges of the first derivatives of the velocity of the phase transformations.

As a result of using geometric and kinematic compatibility of the first order and a few transformations, the system of equations (2) takes the following form:

$$\begin{aligned} (\lambda + G)\omega_j^{(1)}\nu_j + \mu\omega_i^{(1)}\nu_i + \mu\omega_j^{(1)}\nu_j + Q\omega_j^{(2)}\nu_j - \rho_{11}c^2\omega_i^{(1)}\nu_i - \rho_{12}c^2\omega_i^{(2)}\nu_i = 0, \\ Q\omega_j^{(1)}\nu_j + R\cdot\omega_j^{(2)}\nu_j - \rho_{12}c^2\omega_i^{(1)}\nu_i - \rho_{22}c^2\omega_i^{(2)}\nu_i = 0. \end{aligned} \tag{4}$$

In order to obtain a homogeneous system of equations of the propagation of longitudinal waves in relation to ω_α, let us introduce the denotations $\omega_j^{(\alpha)}\nu_j = \omega_\alpha \left(\omega_i^{(\alpha)}\nu_i = \omega_\alpha\right)$, $a = 1, 2$.

$$\begin{aligned} (\lambda + G + 2\mu - \rho_{11}c^2)\omega_1 + (Q - \rho_{12}c^2)\omega_2 = 0, \\ (Q - \rho_{12}c^2)\omega_1 + (R - \rho_{22}c^2)\omega_2 = 0. \end{aligned} \tag{5}$$

Lamé coefficients λ and μ are expressed using the Poisson coefficient ν and Young modulus E as follows [10]:

$$\lambda = \frac{E\nu}{(1+\nu)(1-2\nu)}, \quad \mu = \frac{E}{2(1+\nu)}. \tag{6}$$

Solving the system of equations (5) considering (6) we get:

$$c^4\left(\rho_{11}\rho_{22} - \rho_{12}^2\right) - c^2\left(R\rho_{11} + \left(\frac{E\nu}{(1+\nu)(1-2\nu)} + G + \frac{E}{(1+\nu)}\right)\rho_{22} - 2Q\rho_{12}\right) + \\ + \left(R\left(\frac{E\nu}{(1+\nu)(1-2\nu)} + G + \frac{E}{(1+\nu)}\right) - Q^2\right) = 0. \tag{7}$$

In a two-component elastic gas-saturated porous medium there are two types of longitudinal waves. The velocities of propagation of longitudinal waves are given by the formulas

$$c_{p1,2} = \sqrt{\frac{\left(R\rho_{11} + k\rho_{22} - 2Q\rho_{12}\right) \pm \sqrt{\left(R\rho_{11} + k\rho_{22} - 2Q\rho_{12}\right)^2 - 4\left(\rho_{11}\rho_{22} - \rho_{12}^2\right)\cdot\left(Rk - Q^2\right)}}{2\left(\rho_{11}\rho_{22} - \rho_{12}^2\right)}}, \\ k = \left(\frac{E\nu}{(1+\nu)(1-2\nu)} + G + \frac{E}{(1+\nu)}\right). \tag{8}$$

From Equations (4) we get a system of equations of propagation of shear waves in relation to $\omega_i^{(\alpha)}$ on condition that $\omega_j^{(1)}\nu_j = 0$, $\omega_j^{(2)}\nu_j = 0$.

$$\left(\frac{E}{2(1+\nu)} - \rho_{11}c^2\right)\omega_i^{(1)} - \rho_{12}c^2\omega_i^{(2)} = 0, \\ -\rho_{12}c^2\omega_i^{(1)} - \rho_{22}c^2\omega_i^{(2)} = 0. \tag{9}$$

Instead of μ in (9) the expression (6) was used.

Let us solve a system of equations (9):

$$c^4\left(\rho_{11}\rho_{22} - \rho_{12}^2\right) - c^2\frac{E}{2(1+\nu)}\rho_{22} = 0. \tag{10}$$

In an elastic gas-saturated porous medium there is a transverse wave. The velocity of propagation of a transverse wave is

$$c = \sqrt{\frac{\frac{E}{2(1+\nu)}\rho_{22}}{\rho_{11}\rho_{22} - \rho_{12}^2}}. \tag{11}$$

Analyzing the expressions (8) and (11), we conclude that propagation of longitudinal and transverse waves account for physical characteristics of a medium. Using the Poisson coefficient and Young modulus for cement concrete, we get the velocity of propagation of waves in a cement concrete porous medium.

Mathematical modeling of implications of dynamic loads for cement concrete pavements allows one to predict and improve its performance.

Fig. 1—4 show dependencies of the velocities of propagation of a longitudinal acoustic elastic wave on different characteristics of a pavement material.

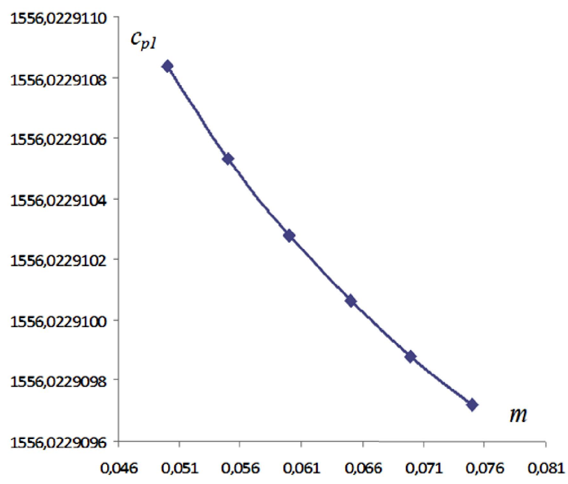

Fig. 1. Dependence of the velocity of propagation of a longitudinal acoustic wave on the porosity of cement concrete

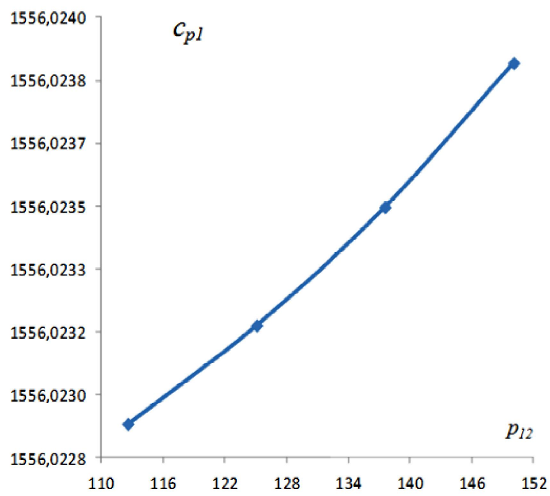

Fig. 2. Dependence of the velocity of propagation of a longitudinal acoustic wave on the porosity of cement concrete

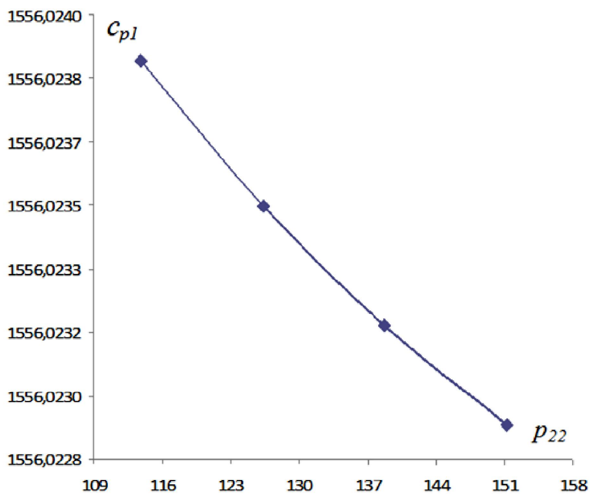

Fig. 3. Dependence of the velocity of propagation of a longitudinal acoustic elastic wave on the density of a gaseous phase of a pavement material

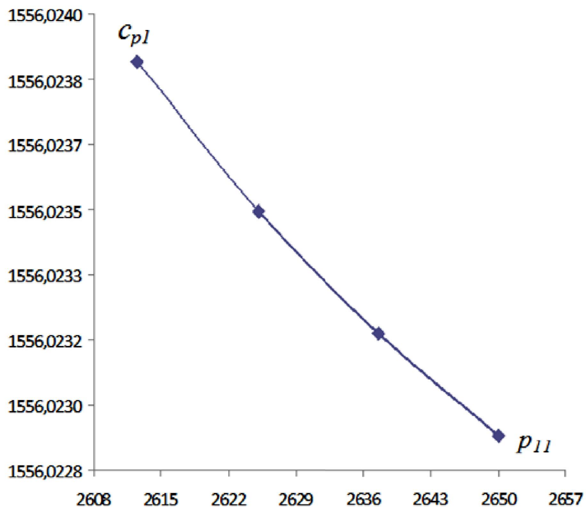

Fig. 4. Dependence of the velocity of propagation of a longitudinal acoustic elastic wave on the density of a gaseous phase of a pavement material

The analysis of the obtained results of modeling is expressed via a dependency captured in Fig. 1 and shows that a 20 % increase in porosity causes smaller velocities due to changes in porous properties of a wave propagation medium. Nevertheless using differential methods of measurement, we can see this happening with a great degree of certainty, which allows fundamental insight into a dynamic nature of a medium presented in Fig. 2 and indicating influences of micropores on propagation of an elastic wave. This is not just a change in the velocity of its propagation but also of its absorption. Energy dissipation is expressed through component transformation of waves at the boundary between an elastic and gaseous medium of pores. Fig. 3 and 4 show dependencies of changes in the velocity of propagation of a longitudinal elastic wave in materials (both for solid cement and materials saturated with gas). Graphs have a linear dependence which shows elastic energy of waves is redistributed on concentrations of stresses and cracks. A dynamic modulus changes in the identical fashion except its sign which is also indicative of residual resources of a cement concrete pavement.

Conclusions

1. The authors suggest the use of the method of acoustic emission based on reading elastic wave signals arising as microdefects occur in the structure of a material under the impact of mechanical loads and allowing detection of defects as they emerge.

2. The designed graphs show that the velocity of propagation of an elastic acoustic wave decreases as a material becomes more porous and dynamic connections between the components of a medium increase. There is a dependency of the velocity of waves on the density за materials: an increase in the latter causes a decrease in the former.

3. The developed physical and mathematical model of the formation of elastic waves of acoustic emission as the microstructure of a cement concrete material fails, it allows one to address further performance and residual resource of an airfield pavement. The connection identified between the characteristics of propagation of elastic waves and physical and mechanical properties of a medium contributes to the accuracy of predicting possible failures.

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