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Mathematical model-building of reological and thermodynamical processes in modified concrete mix at vibro impact compact method of comression

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S u m m a r y. In the article is examined the modified cementing system at vibro impact compact method of compression. It is solving the task of system's movement taking into consideration relax processes. It has been considered the interaction of the system components with each other, there have been received the formulas of movement and internal parameters characterizing movements of relaxing system.

K e y w o r d s . Modified concrete mix, vibro impact compact method of compression, relax processes, phenomenological formulas of movement.

ACTUALITY OF RESEARCH AND PROBLEM DEFINITION

In comparison with the flow of Newtonian liquids the flow of modified concrete mix at compressing by vibro impact compact method has the series of peculiarities [Okorokov 1956, Polak 1986, Pilipenko 2011]. Thus, at a simple move the normal stresses appear in the modified concrete mix which is not observed in Newtonian liquids. The viscosity of modified cement systems depends not only on the applied stresses (or the velocity gradients), but also on the flow pattern. At a simple move the viscosity, as a rule, decreases, and it increases at a simple extension [Rudenko 2010, Bazhenov 2005]. At a non-stationary system movement it is also observed the series of "non classical" effects [Tomosawa 1997].

In the general case the cause of abnormal behavior can be immediately indicated and does not cause any doubt – the presence of the processes with the relax times comparable with characteristic times of system movement or exceeding them [Sawaide, Iketani 1992]. At deformation such system turns to be derived more considerably from the state of thermodynamical equilibrium the more the gradients of rate of flow are.

At very small (in comparison with the characteristic times en route) relaxation times the thermodynamical equilibrium is not locally broken during the movement by a marked way [Shayan, Quick 1992]. The presumption of a local equilibrium of a system together with the conservation laws leads to the equations of motion of Newtonian liquid. Thus, the description of the impulse movement of modified concrete mix brings to the task of the system movement taking into account the relax processes.

On the one hand, considering the modified concrete mix as the continuous medium, we can formulate phenomenological equations of the movement in the form fit for the description of relatively slow movements on the basis of the view of non-equilibrium thermodynamics and the most common concepts [Mchedlov-Petrosyan, Babushkin 1992]. And at this the view of equations of motion and, accordingly, the properties of concrete mix as the system are defined by tensorial dimension of internal parameters [Moranville-Regourd 1999, Pashchenko 1991].

On the other side, the modified concrete mix represents itself the ensemble of interactive one to each other components. At a sequent review of the components in a moving system it is possible to get the equations of motion which are the particular case of common phenomenological equations of motion. While this relax processes are clearly considered and it becomes obvious the sense of phenomenological parameters of an equation. Whereas the cement system defines viscous ductile properties of modified concrete mix, let's consider the cement system as the continuous medium [Batrakov 1998, Punagin 2010]. Let the elements of the volume of the medium be so huge that it can be applicable macroscopic description for them.

PURPOSE AND OBJECT, MATERIALS AND RESULTS OF INVESTIGATIONS

Let's stop on the kinematics of deformed system. Let's denote by xk the point of deformed system at the moment t xk = xk(t). The tensor of the gradients of movements at the moment t against the moment t' we define by the following way

$$\lambda_{ik}(t,t') = \frac{\partial x_i(t)}{\partial x_k(t')}. \quad (1)$$

That is $\lim\limits_{t'\to t} \lambda_{ik}(t,t') = \delta_{ik}$,

where: δ_{ik} – Kronecker symbol.

It follows from the definition of the tensor of the gradients of movements that it is true the ratio

$$\frac{\partial}{\partial t}\left[\lambda_{ik}(t,t')\lambda_{s\ell}(t',t)\right] = = \frac{\partial}{\partial t}\left[\lambda_{ik}(t,t')\right]\cdot\lambda_{s\ell}(t',t) + \lambda_{ik}(t,t')\cdot\frac{\partial}{\partial t}\left[\lambda_{s\ell}(t',t)\right]. \quad (2)$$

Let's further define the local velocity $v_i = \frac{\partial x_i(t)}{\partial t}$ and the tensor of gradients of the velocity

$$v_{ik}(t) = \frac{\partial v_i}{\partial x_k} = \frac{\partial}{\partial x_k}\left(\frac{\partial x_i}{\partial t}\right) = = \lim_{t'\to t} \lambda_{ik}\frac{\partial}{\partial t}\lambda_{ik}(t,t') = \lim_{t'\to t} v_{ik}(t,t'). \quad (3)$$

It can be analogically defined the other tensor of the angular velocity:

$$\omega_{ik}(t) = \lim_{t'\to t} \lambda_{ik}\frac{\partial}{\partial t}\lambda_{ik}(t,t') = \lim_{t'\to t}\omega_{ik}(t,t'). \quad (4)$$

Differentiating (2) to t, we find the ratio between the tensors of the gradients of the velocity

$$\lambda_{ik}(t,t')\,\omega_{s\ell}(t',t) = -v_{ik}\lambda_{s\ell}(t',t). \quad (5)$$

Considering the moments of time t' < t, let's insymbol t – t' = s. In this case at small s the tensor of the gradients of movements and the tensor of deformations can expanded into series near the moment of time t

$$\lambda_{si}\lambda_{jk} = \delta_{si}\delta_{jk} + \left(\delta_{si}v_{jk} + \delta_{jk}v_{si}\right)s - -\left(2v_{si}v_{jk} + \delta_{si}\zeta_{jk} + \delta_{jk}\zeta_{si}\right)s^2 + \ldots \quad (6)$$

$$\lambda_{[si]}\lambda_{[sk]} = \delta_{[ik]} + 2v_{(ik)}\,s - -2\left(v_{[si]}v_{[sk]} + \zeta_{(ik)}\right)s^2 + \ldots, \quad (7)$$

where: $\zeta_{ik}(t) = \lim\limits_{t'\to t}\frac{\partial v_{ik}(t,t')}{\partial t}$.

In the formula (7) and the round brackets are further used for the definition of symmetrical index and square brackets are used for antisymmetric index.

The local thermodynamical state of the system at the equilibrium can be characterized by different parameters, for example, by the density ρ and the pressure p, including the temperature T. Whereas as in principal there always exists the equation of the state connecting all these values f (T, ρ, p) = 0 then for the full characteristics of the cement system in the equilibrium is enough two values out of the three indicated ones. It is acceptable at this that the system is one-component, i.e. all the process of diffusion have been excluded beforehand.

A small change of internal energy is written by the following way

$$d\,E = \rho T\,ds + \omega\,d\rho\,, \quad (8)$$

where:s – entropy density of a system;

ω – enthalpy of a mass unit.

At a uniform and rectilinear movement of a system the thermodynamical equilibrium isn't obviously broken. But if there are the gradients of the velocity and the gradients of movements then the deformed system, generally speaking, is not already in equilibrium even locally. At small external changes the inner process can be on time to follow the change of the system state [Kaprielov, Travush, Karpenko 2006]. By other words, all relax times of the system turn to be small in comparison with the character times of system motion. This is true for small viscous liquids the equilibrium for which is able to come stable in the process of the movement. It is used (8) for the description of the change of the energy of the element of the volume.

In the process of the movement the system is defined besides the velocity only by pressure and density (except for the temperature which is constant at isothermal flows). At the flow the system remains isotropic. The consistent building of phenomenological theory of motion of such systems leads to the system of Navier-Stokes equations which describes the motion of law-viscous liquids.

In the process of faster motions some inner processes are not on time to follow external changes [Bratchun, Zolotarev, Pakter, Bespalov 2011, Pilipenko 2010]. Deforming takes place by non-equilibrium mode and the state of the system is described additionally by some inner independent variables $\xi\alpha$. We consider that the set $\xi\alpha$ fully characterizes the deviation of the system from the equilibrium. At the equilibrium $\xi\alpha = \xi\alpha 0$.

Thermodynamical functions of the system now depend additionally on the inner parameters. For example, the inner energy of the volume unit

$E = E(s, \rho, \xi\alpha)$ and, thus, the change of the density of the inner energy in the moving frame

$$dE = \rho T\, ds + \omega\, d\rho + A_\alpha d\xi^\alpha , \tag{9}$$

where: $A_\alpha = \left(\frac{\partial E}{\partial \xi^\alpha}\right)_{s,\rho}$ – affinity of relax process;

T, ω, $A\alpha$ – functions of variables s, ρ, $\xi\alpha$.

The introduced system itself aims at the equilibrium state: $\xi\alpha \to \xi\alpha 0$. Moreover, if the deviation from the equilibrium is small, the rate of change of parameters is proportional to the deviation of the parameters from the equilibrium [Ziegler 1976]

$$\frac{d\,\xi^\alpha}{d\,t} = -\frac{1}{\tau_\alpha}\left(\xi^\alpha - \xi_0^\alpha\right). \tag{10}$$

We consider that selected variables are the normal coordinates. The equation (10) defines the relax time corresponding to this normal coordinate. Solution of the equation (10) is given by

$$\xi^\alpha - \xi_0^\alpha \approx e^{-\frac{t}{\tau_\alpha}} . \tag{11}$$

This function describes the system's approaching to the equilibrium.

Let stationary liquid be in the state of thermodynamical equilibrium which is broken at motion. It would appear reasonable that the rate of change of inner parameters at motion also depends on kinetic performances. In the process of deforming stoppage the inner parameters relax according to the law (11). The relaxation process also takes place at deforming and, thus, the rate of change of inner parameters is defined simultaneously by two effects [Mchedlov-Petrosyan, Babushkin 1992, Gusev, Kondrashchenko, Maslov, Faivusovich 2006]. The phenomenological theory of irreversible processes doesn't allow defining this dependence without additional concepts. It is usually limited to the first expansion terms in small gradients of the rate and small inner parameters [Ziegler 1976]. In the general case it's possible to consider that

$$\frac{d\xi^\alpha}{d\,t} = D_\alpha[\xi^\alpha, \lambda_{js}(t, t-s)\lambda_{pq}(t, t-s)]. \tag{12}$$

The functional (12) can be introduced in the integrated form. It is necessary to account for tensor dimension of inner parameters which can be scalars, vectors or top ranks tensors. According to the tensor of deforming in linear approaching for the scalar parameter

$$\frac{d\,\xi}{d\,t} = B(\xi) + \int_0^\infty C(\xi, s)\lambda_{ii}(t, t-s)\, ds \tag{13}$$

(in this case the rate of change of parameters is only defined by the rate and accelerations of volume change) and for the parameter – second rank tensor

$$\frac{d\xi_{ik}}{dt} = B_{ik}\left(\xi_{js}\right) + \\ + \int_0^\infty C_{ikjspq}\left(\xi I_n, s\right)\lambda_{js}(t, t-s)\gamma_{pq}(t, t-s)\, ds . \tag{14}$$

Formulas (13) and (14) are written in the supposition that integral kernels C and Cikjspq are decreasing, positive, stated at $s > 0$ functions of their variables. Besides at $s \to \infty$ the functions aim for the zero faster than any other degree s.

Let integrand functions in (13) and (14) fade very quickly i.e. there's a considerable influence of the deformations close in time. We use expansions (6) and (7) and get in the first approximant

$$\frac{d\xi}{dt} = b(\xi) + c(\xi) v_{ii}, \tag{15}$$

$$\frac{d\xi_{ik}}{dt} = b_{ik}(\xi_{js}) + c_{ikjspq}(\xi_{ln})(v_{js}\delta_{pq} + v_{pq}\delta_{js}). \tag{16}$$

It can be supposed further that the changes of inner parameters are small values in which can be expanded the functions in the equations (15) and (16) depending on them. As the result of expansion we get for the scalar parameter

$$\frac{d\xi}{dt} = -\frac{1}{\tau}(\xi - \xi_0) + (\alpha_1 + \alpha_2\xi)\, v_{ii} \tag{17}$$

And for the tensor parameter symmetric in indexes

$$\begin{aligned} \frac{d\,\xi_{ik}}{d\,t} = &-\frac{1}{\tau}\left(\xi_{ik} - \xi_{ik}^{0}\right) + \\ &+ \beta_1\delta_{ik}v_{ss} + \beta_2 v_{(ik)} + \\ &+ \beta_3\xi_{ss}v_{(ik)} + \beta_4\delta_{ik}\xi_{js}v_{js} + \\ &+ \beta_5\xi_{jj}\delta_{ik}v_{ss} + \beta_6\xi_{ik}v_{ss} + \\ &+ \beta_7(\xi_{is}v_{sk} + \xi_{ks}v_{si}) + \\ &+ \beta_8(\xi_{is}v_{ks} + \xi_{ks}v_{is}). \end{aligned} \tag{18}$$

The equations (17) and (18) in linear as per the tensors of the gradients of the rate and inner parameters approaching define the law of change of inner parameters at deforming.

The system of the equations of motion of continuous medium can be obtained as the consequence of the laws of conservation of mass, energy, impulse and the moment of impulse in their differential form [Loitsiansky 2003]. For the isothermal motion of one-component medium these equations after the introduction of the tensor of the stresses σik are reduced to the form

$$\frac{\partial\,\rho}{\partial\,t} + \mathrm{div}(\rho v) = 0, \tag{19}$$

$$\rho\frac{d\,v_i}{d\,t} = \frac{\partial\,\sigma_{ik}}{\partial\,x_k}. \tag{20}$$

Equations (19) and (20) have absolutely common character and are applicable to any moving medium.

At an equilibrium motion four equations – (19) and (20) modified with the equation of the state $f(T, \rho, p) = 0$ and rheological equation of the state or constitutive equation $\sigma ik = \sigma ik(vjl, \xi sq,\ldots)$ are enough for the description of isothermal movement of the system the state of which at a constant temperature is described by four variables: pressure p or density ρ and three components of the rate vi.

In the elementary case we suppose that the tensor of the stresses depends only on the gradients of the rate. At this the equation of the first order for the incompressible system

$$\sigma_{ik} = -p\delta_{ik} + 2\eta v_{(ik)} \tag{21}$$

defines Newtonian liquid and the second rank equation – Reiner-Rivlin fluid [Cherny 1988]:

$$\sigma_{ik} = -p\delta_{ik} + 2\eta v_{(ik)} + 4\eta_c v_{(ik)}v_{(kj)}. \tag{22}$$

We are not limited only by the account of the gradients of the rate for the description of the expression of cement system of modified concrete mix, but we admit that the accelerations of highest orders can also enter the constitutive equation. The account of the acceleration of the first order leads to the constitutive equation of Reiner-Ericksen [Wollis 1982]

$$\begin{aligned} \sigma_{ik} = &-p\delta_{ik} + 2\eta v_{(ik)} + \\ &+ 4\eta_c v_{(ij)}v_{(kj)} + 2\eta_a\left(\zeta_{(ik)} + v_{si}v_{sk}\right). \end{aligned} \tag{23}$$

It is obvious that can be written also the constitutive equations of the highest orders with the accelerations of higher orders, but it is a common supposition of the local equilibrium of cement system in the process of fluid for all above mentioned equations. As the consequence of this the cement system remains isotropic at the fluid.

The situation changes if the deforming takes place by equilibrium way: to the enumerated independent variables is added m of inner variables $\xi\alpha$. The equations (19) and (20) should be modified by m equations of inner variables chosen in the way (17) or (18) by the equation of the system state $f(T, \rho, p, \xi\alpha) = 0$ and constitutive equation which should be considered in more details.

In the general way the tensor of the stresses is defined by the tensor of the gradients of movements at some moment of the time in relation to earlier moments of time and values of inner parameters at this moment of time

$$\sigma_{ik}\left(\xi^{\alpha},t\right)=\sigma\left[\xi\gamma,\lambda_{js}\left(t,t-s\right)\lambda_{pq}\left(t,t-s\right)\right]. \qquad (24)$$

We suppose that the tensor of the stresses is also defined by independent variables except for the tensor of deformation – by inner parameters which are changed at the deforming of the concrete mix. The functional (24) can be introduced by integral way (in linear) as per the tensor of deformation in approach for the scalar parameter

$$\sigma_{ik}\left(\xi,t\right)=N\left(\xi\right)\delta_{ik}+\int_0^{\infty}\Gamma\left(\xi,s\right)\Lambda_{ik}\left(t,t-s\right)ds \qquad (25)$$

And for the parameter – the tensor of the second rank

$$\sigma_{ik}\left(\xi_{j,s},t\right)=N_{ik}\left(\xi_{mn}\right)+ \\ +\int_0^{\infty}\Gamma_{ikjspq}\left(\xi_{mn},s\right)\lambda_{js}\left(t,t-s\right)\lambda_{pq}\left(t,t-s\right)ds. \qquad (26)$$

We suppose at this that integral kernels Γ and Γ_{ikjspq} are decreasing, positive, stated at $s>0$ by the functions of their variables of times aiming for the zero at $s\to\infty$. As the functions of the inner parameters, the integral kernels can be expanded into series about their equilibrium value. The character of the dependence of integral kernels on the time is defined by the relax properties of the system. The less the time of relaxation, the quicker the functions are decreasing. If the times of relaxation are small in comparison with characteristic times of motion than the deformations close to the moment of t turn to be considerable. In the consequence of this it can be used the expansion of the tensor of the deformation in the variable s near the moment of time t. Putting expansions (7) and (6), accordingly, in (25) and (26), we got the expressions for the tensor of stresses at scalar and tensor parameters

$$\sigma_{ik}\left(\xi,t\right)=n\left(\xi\right)\delta_{ik}+\gamma\left(\xi\right)v_{(ik)}, \qquad (27)$$

$$\sigma_{ik}\left(\xi_{js},t\right)=n_{ik}\left(\xi_{ls}\right)+ \\ +\gamma_{ikjspq}\left(\xi_{nm}\right)\left(v_{js}\delta_{pq}+v_{pq}\delta_{js}\right). \qquad (28)$$

Depending on the inner parameters the coefficients in the equations (27) and (28) are changing at the motion of system that is are not material constants. If according to the inner parameters can be made the expansion, we come to the formulas

$$\sigma_{ik}\left(\xi,t\right)=-p\delta_{ik}+\varepsilon_0\xi\delta_{ik}+2\left(\varepsilon_1+\varepsilon_2\xi\right)v_{(ik)}, \qquad (29)$$

$$\begin{aligned}\sigma_{ik}\left(\xi_{js},t\right)=&-p\delta_{ik}+q\xi_{jj}\delta_{ik}+\mu\left(\xi_{ik}-\xi_{ik}^{0}\right)+\\&+\zeta_1\delta_{ik}v_{ss}+\zeta_2 v_{(ik)}+\zeta_3\xi_{ss}v_{(ik)}+\\&+\zeta_4\delta_{ik}\xi_{js}v_{js}+\zeta_5\xi_{jj}\delta_{ik}v_{ss}+\zeta_6\xi_{ik}v_{ss}+\\&+\zeta_7\left(\xi_{is}v_{sk}+\xi_{ks}v_{si}\right)+\zeta_8\left(\xi_{is}v_{ks}+\xi_{ks}v_{is}\right)+\\&+\zeta_9\left(\xi_{is}v_{sk}-\xi_{ks}v_{si}\right)+\zeta_{10}\left(\xi_{is}v_{ks}-\xi_{ks}v_{is}\right)-\\&-\left(2/3\right)\left(\zeta_9+\zeta_{10}\right)\xi_{ss}v_{[ik]}.\end{aligned} \qquad (30)$$

The coefficient at the last term in the equation (30) has been chosen so that at the deformation of the system as the whole the tensor of stresses would not change. The constant coefficients which are in the equations (29) and (30) are material constants characterizing the system.

The tensor of stresses with tensor inner variables can be asymmetric. At the absence of the external moments of forces the dissymmetry of the tensor of stresses is connected with rotator Brownian motion [Nigmatulin 1987].

Thus if the inner parameters characterizing the system have been known, the constitutive equation can be established with desired precision. But in the general case we cannot establish the universal connection between the tensor of stresses and the tensor of the gradients of the rate ignoring the inner parameters.

Isothermical deformation of visco elastic cement system with m inner parameters is described by the system of the equations m+4 into which number logs on the continuity equation (19), three equations of motion (20) with constitutive equation (29) or (30) and m equations describing the law of change of inner variables. Inner parameters can be excluded from the system of the equations which leads in this case to the system of a small number of the equations of a higher order. Thus, the constitutive equation written in the form of the correlation between the tensor of stresses, tensor of the gradients of the rate and their derivatives also can lead in the principle to the correct description of the motion of relax system.

The material constants of the system are defined by the correlations (18) and (30). Their number, the view of the equations of motion consistently, the properties of the system are defined by the tensor dimension of inner variables. This allows classifying the visco elastic cement systems according to the largest tensor rank of their inner parameters assigning the rank equal to the largest tensor rank of inner variables. The theory can be built at any approach.

CONCLUSIONS

On the ground of the results of the experimental theoretical investigations:

1. There has been established that whereas it is studied the modified concrete mix at vibro impact compact compression, then the study of concrete mix as the Newtonian liquid does not give full analysis of this system in the consequence of which it is necessary to consider thermodynamical non-equilibrium processes for the account of relax processes which allows to formulate the phenomenological equations of motion.

2. There have been obtained the equations of motion on the ground of the consideration of the behavior of the components in a concrete mix which are particular case for the common phenomenological equations of motion.

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МАТЕМАТИЧЕСКОЕ МОДЕЛИРОВАНИЕ РЕОЛОГИЧЕСКИХ И ТЕРМОДИНАМИЧЕСКИХ ПРОЦЕССОВ В МОДИФИЦИРУЕМОЙ БЕТОННОЙ СМЕСИ ПРИ ВИБРО-УДАРНОИМПУЛЬСНОМ СПОСОБЕ УПЛОТНЕНИЯ

Владимир Пилипенко

Аннотация. В статье рассматривается модифицированная цементная система при вибро-ударноимпульсном способе уплотнения. Решается задача движения системы с учётом релаксационных процессов. Рассмотрено взаимодействие компонентов системы друг с другом, получены уравнения движения, и внутренние параметры, характеризующие движения релаксирующей системы.

Ключевые слова. Модифицированная бетонная смесь, вибро-ударноимпульсный способ уплотнения, релаксационные процессы, феноменологические уравнения движения.