Synergetic Properties of Asphalt Concrete

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Abstract—**The synergetic period in road asphalt concrete life cycle at a stage of construction completion and initial exploitation is allocated. The approach which is based on the use of the catastrophe theory which allows calculating duration of the post-construction period of life cycle of road asphalt concrete pavement is offered. The post-construction period, despite comparative short duration, in many respects defines future consumer properties of a transport construction.**

Keywords–synergetic properties of material, post-construction period, asphalt pavement, dissipative structures, bifurcation point

I. Introduction

In this paper the road asphalt concrete pavement is considered as thermodynamic, engineering-geological system. At thermodynamic approach in relation to processes of construction and exploitation of road asphalt concrete pavement it is conditionally convenient to divide a set of engineering-geological objects material of different ranks, making the engineering-geological environment into the specifically studied thermodynamic system and the environment surrounding it [1]. Thus, from the thermodynamic point of view within the engineering-geological environment it is always possible to allocate thermodynamic engineering-geological systems, i.e. the macroscopic objects of different ranks of the organization capable to exchange among themselves or with surrounding environment by substance and (or) energy. Interaction of any engineering-geological system with environment is carried out through so-called boundary, or control surface. It can coincide or not coincide with borders of engineering-geological objects and is carried out so that to capture only those objects which are included into the considered system or are defined by a research objective. The objects which are not entering into this thermodynamic system, being outside a control surface, belong to environment.

In thermodynamics, depending on condition, systems are subdivided into some types. In their turn, some types can be distinguished from engineering-geological thermodynamic systems. If due to any properties of boundary surface the engineering-geological thermodynamic system cannot exchange substance ($dm = 0$), and energy ($dU = 0$) with environment, such system is called isolated; if $dm \neq 0$ and (or) $dU \neq 0$, system – uninsulated. The uninsulated system in a case when it cannot exchange substance, but can exchange energy ($dm = 0$, $dU \neq 0$), is called closed; otherwise – open thermodynamic system (for which $dm \neq 0$, $dU = 0$).

If inside the system there are no interfaces, separating parts of system with different properties from each other, such system is called homogeneous, otherwise – heterogeneous. The homogeneous part of heterogeneous thermodynamic system is called a phase. The majority of engineering-geological thermodynamic systems represent multiphase heterogeneous uninsulated systems. The entering parts of engineering-geological thermodynamic system are called components. Within one component subcomponents can be separated.

According to the possible conditions of isolation or not isolation of system stated above from environment, the existing systems of different ranks of the organization can be subdivided into two classes: isolated and uninsulated. Depending on conditions of constancy or inconstancy of properties of engineering-geological system in time, the further division of systems is made on stationary in which all properties eventually remain constants during observation, and non-stationary in which at least one of properties changes in time. The majority of engineering-geological systems belongs to the class of non-stationary systems, their various properties change in time with a different speed and intensity. Stationarity of properties also depends on duration of the observation.

The following important splitting of set of system possible conditions is formed by classes of equilibrium and non-equilibrium states. The equilibrium state is characterized under constant external conditions by an invariance of parameters in time and absence of streams of substance, energy and impulse in a system. If these conditions are not met, the system is in a non-equilibrium state. Equilibrium states are possible only at stationary systems. Paired crossing of classes of stationary and non-stationary states with classes of equilibrium and non-equilibrium states gives one more division of possible states.

For the isolated systems only two types of states are possible: the non-stationary non-equilibrium and stationary equilibrium; for uninsulated systems four types of states are distinguished: the non-stationary non-equilibrium, non-stationary quasi-equilibrium, stationary non-equilibrium, and stationary equilibrium ones. We consider a road asphalt concrete pavement in the course of construction as the closed uninsulated system, i.e. a system which can exchange energy with environment, but not by substance. During the exploitation process of asphalt pavement we consider it as the uninsulated system.

Along with other methods in classical thermodynamics the method of thermodynamic potentials offered by J. W. Gibbs [2] is applied to research of energy increment in various systems. Its main idea is that such state functions, which change when the variation of system condition is equal to the sum of its separate parameters changes, increased by some constants, are selected for thermodynamic system. For these purposes we are able to use three characteristic functions, or thermodynamic potentials: G – isobaric-isothermal potential (Gibbs's energy); F – isochoric-isothermal potential (Helmholtz's energy) or free energy; H – enthalpy.

The road pavement is a thermodynamic, engineering-geological system which state is characterized by temperature T, pressure p, volume V, internal energy U and entropy S. We can consider the following ratios [1]:

$$G = F + pV, \tag{1}$$

$$F = U - TS, \tag{2}$$

$$H = U + pV. \tag{3}$$

Internal energy, as well as the listed above thermodynamic potentials, is also a characteristic function. It is stated that for various options of thermodynamic conditions of the process in engineering-geological system only those processes can proceed spontaneously which are followed by reduction of the corresponding thermodynamic potential [1]. Besides, the change of thermodynamic potentials is equal to the sum of all types of work made in this system. Methodological application value of thermodynamic potential method in transportation branch, for the purpose of forecasting of intensity of processes and nature of change of construction properties, follows from these important provisions. One of advantages of a method of potentials is that at an assessment of change of one value – thermodynamic potential there is an opportunity to estimate the total change of energy of the considered thermodynamic system, resulting from several physical and chemical processes which proceeded at the same time and are difficult to divide.

II. Statement of the Problem

Duration of the technogenic processes, defining life-cycle of a road asphalt concrete pavement in time, can be divided into three main stages: the first – pavement construction; the second – completion of construction and initial exploitation; the last one – exploitation process.

We analyze power condition of the considered technogenic systems by means of thermodynamic functions apparatus. We consider that at construction stage of asphalt pavement the following kinetics of Gibbs potentials changing takes place. Internal energy of asphalt concrete pavement at this stage does not change; it keeps the potential of workable asphalt concrete mix. The size TS decreases: temperature – due to cooling, entropy – because of mechanical work on laying and compaction. The size of free energy, for the reasons stated above, according to (2), grows. The multiplication pV does not change if considering that change of pressure at pavement construction is in inverse proportion to change of its volume. Respectively, the size of an enthalpy does not change (3). But Gibbs's energy surges, because free energy increases (1).

At a stage of construction completion and an initial stage of operation due to synergetic and inertial properties material of a road asphalt concrete pavement keeps the same kinetic tendencies, like at a construction stage: entropy continues to decrease, causing growth of free energy and Gibbs's energy.

At the last stage – exploitation process – free energy decreases, despite continuous pumping by dissipative energy as a result of pavement contact with vehicle wheels. The size TS grows, due to entropy increase grows, work pV size decreases, owing to covering material ablation, the size of an enthalpy, free energy and Gibbs's energy (2.1)–(2.3) respectively decreases.

Within the first stage – process of construction the irreversible processes, leading to artificial decrease of entropy, take place. During the construction the material of asphalt pavement needs to be considered as object far from balance because of irreversible non-equilibrium processes.

Proceeding from the second law of thermodynamics, change of extensive size of entropy in the creating asphalt pavement and its subsequent aging can be presented as the sum

$$dS/dt = dS_e/dt + dS_i/dt, \tag{4}$$

where dS_e/dt – the entropy stream caused by interaction with environment (external); dS_i/dt – production of entropy, owing to the processes proceeding in system (internal); t – time. That is change of entropy results from processes in system (production of entropy) and from border with environment (an entropy stream). Production of entropy according to the second beginning of thermodynamics is not negative. I. Prigogine claims [60] that "the second beginning does not impose any conditions on an entropy stream". If an entropy stream is negative, separate developments of system can take place at the general decrease of entropy. According to traditional treatments, it means that in process of system disorder will decrease due to outflow of entropy [3]. As the entropy increment caused by changes in system never has negative value, reduction of system entropy in the course of construction happens because the stream of entropy has a negative sign. The negative stream of entropy is created forcibly due to the made work and is explained by reduction of volume of asphalt concrete mix in compaction, ordering of the formed texture, mix cooling. Production of entropy at a stage of laying and compaction of asphalt concrete mix, because of relatively short duration of processes (in comparison with pavement exploitation and service life), is quite reasonable to consider equal to zero:

$$dS_i = 0. \tag{5}$$

Then construction process of asphalt concrete pavement is described by the following system of the equations:

$$\begin{cases} d\,S_e < 0; \\ d\,S_i = 0. \end{cases} \tag{6}$$

Probability of the event that asphalt concrete mix will spontaneously become a pavement, with the set technological parameters, is almost equal to zero, and to reach necessary value of entropy size, it is necessary to reduce its level forcibly. From the point of view of statistical approach (the law of increase of entropy – the law of increase of disorder [4]) it is possible to draw a conclusion that actually the process of construction is the movement of a system from more probable state to less probable, and process of further existence of pavement, on the contrary, is the movement from less probable to more probable condition of system.

III. Results

The post-construction period within whole life cycle of road asphalt concrete pavement (completion of construction – the beginning of exploitation) is not long. However, possibilities of the analysis of process of this period and calculation of its duration, depending on properties of pavement material, technology of construction and service conditions, in many respects define consumer qualities of transportation constructions during life cycle.

Dependences of thermodynamic functions of asphalt pavement on the value of a thermal capacity of its material were received [5]:

$$\delta F = -\mu T\left[C_m \ln T + C_m^0\left(\frac{T_0}{T} - 1 - \ln T_0\right)\right]; \tag{7}$$

$$\delta U = \mu\left(C_m T - C_m^0 T_0\right); \tag{8}$$

$$\delta S = \mu\left[C_m\left(1 + \ln T\right) - C_m^0\left(1 + \ln T_0\right)\right], \tag{9}$$

where F – free energy; U – internal energy; S – entropy; T_0, T – initial and current values of temperature; C_m – specific heat capacity; C^0_m – initial value of C_m, at $T=T_0$; μ – magnitude in number equal to density of material (dimension of weight).

For various options of thermodynamic conditions of this or that process in engineering-geological system only those processes which are followed by reduction of the corresponding thermodynamic potential spontaneously can proceed. Besides, the change of thermodynamic potentials is equal to the sum of all types of the work made in this system. Application expediency of thermodynamic potentials method in road branch for forecasting the intensity of processes and the nature of thermo asphalt concrete pavement material physical properties change follows from these important provisions. One of advantages of Gibbs' method of potentials is that, after estimating change of one size – thermodynamic potential, there is an opportunity to estimate the total change of energy of the considered thermodynamic system, resulting from several physical and chemical processes which usually proceed at the same time and which are difficult to be divided.

The consistent patterns of asphalt concrete material specific heat value change depending on exploitation time, brand of asphalt concrete and category of the road were also determined [6]. The analysis of nature of the received regularities and their comparison to experimental data and visual supervision, allowed us making the following conclusion: time of the beginning performance of a road asphalt concrete pavement repair work is defined by the quasilinearity loss moment function graphs of specific heat from time of pavement exploitation.

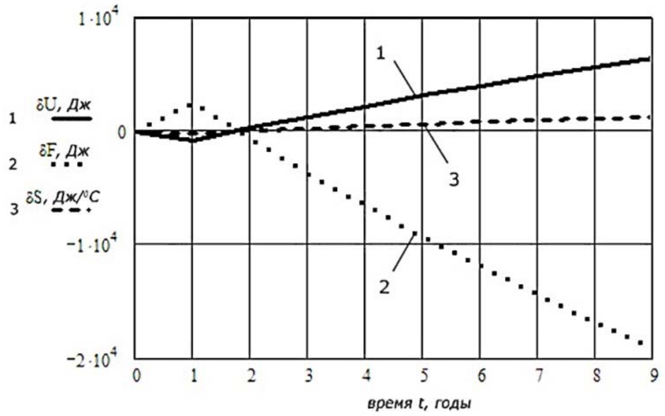

Fig. 1. Dependences of change of internal U (1), free energy F (2) and entropy S (3) on time of pavement exploitation (fine-grained dense asphalt concrete of type B, brand I, category of the road I-A, calculations are given in work [1], page 224)

The calculations have shown that the specified timepoint (the beginning of repair work performance) is characterized, according to schedules in fig. 1, by deficiency of free energy, its negative increment. Similar dependences, proceeding from experimental data, were received for various types and brands of asphalt concrete [5].

IV. Discussion

During the operation period of road asphalt pavement internal energy and entropy of its material increases, in particular, the size of internal energy constantly increases, owing to accumulation of dissipative energy from pavement contact with vehicle wheels. At the same time, the free energy playing a compensation role in various deformation processes at pavement exploitation decreases. As criterion of pavement functional condition was entered the deficiency coefficient of free energy as the relation of the module of free energy increment at present time to the maximum value of this increment for the entire period of exploitation. The accepted deficiency coefficient of free energy is considered as the standard criterion, determining the term of production of repair work. In other words, it is a timepoint in which the current value of deficiency coefficient of free energy becomes more than its standard value. Standard value of deficiency coefficient of free energy corresponds, in its turn, to the violation moment of quasilinearity of specific heat dependences, from this point dependences become nonlinear, and defines the beginning of repair work.

Measure of rational application of technological operations during construction of asphalt concrete pavement, and also at a stage of completion of construction, is the achievement condition of asphalt material of non-equilibrium steady state. Thus the morphogenesis proceeds with formation in pavement material new qualities: density increases [7], free energy increases, the level of entropy decreases [5]. The irreversible processes playing here a constructive role provide reduction of entropy by self-organization of dissipative structures [8].

The post-construction period of the road asphalt concrete pavement life cycle considered as open thermodynamic, engineering-geological system is characterized by rather sharp transitions of energy to a new state happening at continuous evolution of parameters. These sudden changes were called by Rene Thom accidents to emphasize fast cardinal reorganization of the studied object [9]. To a steady state in our case, there corresponds the minimum of free energy, and to a non-equilibrium steady state – a maximum. Besides, by changing of this system condition, in particular, an increment of free energy (fig. 1, line 2), it is possible to interpret the scheme presented in fig. 2.

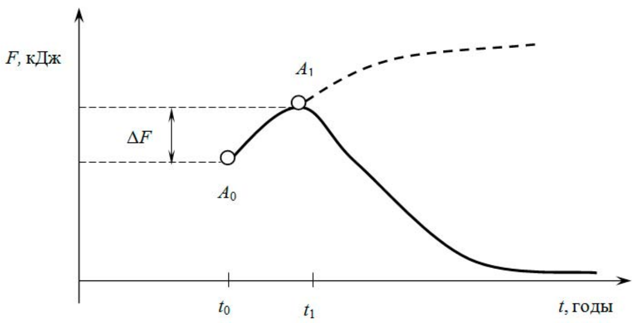

Fig. 2. The scheme of system energy condition change in time: o – a symbol of the ball interpreting the level of free energy (F); t_0, t_1 – time of construction completion and the post-construction period, respectively; points of A_0 and A_1 characterize values of free energy in timepoints of t_0 and t_1; the continuous line from A_1 corresponds to a steady state, dotted – to unstable state.

The scheme of a system power condition change can be considered as some bifurcation chart where the point $A_1(t_1, F(t_1))$ is a point of bifurcation (branching). The matter is that at the end of the post-construction period the nonlinear power condition of system is defined not only and not so much by inertial processes of self-organization, but considerably by the stream of dissipative energy which arrives from the contact with vehicles during asphalt concrete pavement exploitation. Therefore power development of system can go according to the dotted scenario, depending on the entry conditions determined by technology of construction and the mode of exploitation. Though, in usual exploitation conditions probability of such event is rather low. The analysis and comparison of power changes and surfaces types nature in response to Catastrophe theory allows, proceeding from the principle of "soft modeling" [5], establishing accident type. In this case, it is an accident like cusp catastrophe which corresponds, in particular, to potential [3]

$$W(t) = \frac{t^4}{2} + \frac{(1-2b)\,t^2}{2} + a\,t\,, \tag{10}$$

here a and b – the operating parameters which value and ratio depend on technological level of construction, quality of its realization, and also on type and brand of asphalt concrete.

Having differentiated expression (10) and having equated a derivative to zero, we receive a potential extremum condition

$$U(t) = W'(t) = 2t^3 + (1-2b)\,t + a = 0\,. \tag{11}$$

Therefore, an equilibrium state of thermodynamic system is defined by roots (critical points) of the equation (11). As any polynomial of odd degree, *U(t)* has, at least, one valid root. We will enter a condition of frequency rate of roots

$$U'(t) = 0 \quad \Rightarrow \quad 6t^2 + (1-2b) = 0\,. \tag{12}$$

Having excluded (11) and (12) variable t from the equations, we will receive a ratio of the operating parameters:

$$27a^2 = 2\,(2b-1)^3\,. \tag{13}$$

Under a condition, for example $b=a^2$, the equation (11) will assume

$$2t^3 - 3t + \sqrt{2} = 0\,, \tag{14}$$

The numerical solution of the equation (14) allows to establish that fact that its multiple valid root will be $t \approx 0{,}8$, that is $t_1 - t_0 = 0{,}8$ (fig. 2).

In other words, the synergetic period during which there is a self-organization of dissipative structures of material, its morphogenesis which is characterized by increase of free energy and decrease in level of entropy of system is equal to 0,8. If as time scale is accepted one year, the received duration of post-construction period is equal 9 – 10 months, so it will be coordinated quite well with previous results [1].

V. CONCLUSION

Thus, bifurcation approach, consideration of synergetic tendencies of material properties from positions of Catastrophe theory, gives us the opportunity, depending on values and a ratio of the operating parameters which in turn are a subject of separate research, to calculate duration of the post-construction period considerably defining, in its turn, the duration of the entire period of life cycle of a road asphalt concrete pavement.

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