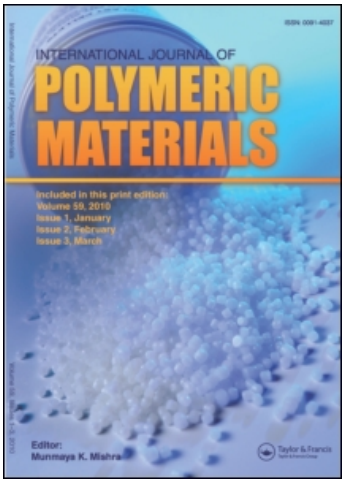

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Complex System Analysis of Asphalt Pavement

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System analysis is a point departure for the solution of modeling, optimization, control and optimum of asphalt pavement. Essentially, the system approach in this case acumulates all a-priori information, as well as obtained in laboratory experiments, test devices, and industrial installations, and enriches this information in the process of developing a complete mathematical model of the asphalt pavement. System analysis provides a scientific foundation for a consideration of the complex process at three levels: the micro-level, meso-level and the macro-level. Under these conditions the determination of the optimum composition of the feed mixture is possible only simultaneously with solving the problems of the macro-level of their subsequent treatment in order to obtain a final product with a specifed spectrum of properties (strength, stability, resistance of shock, etc.). Thus, it is possible to find an actual optimum solution only by solving a complex problem of a unifed model of the whole "life cycle" of the material being produced.

Keywords: System analysis; asphalt; pavement; mathematical morphology

Creation of optimum asphalt pavement is a complex problem because these pavements are often supposed to have contradictory and sometimes even incompatible properties. Examples of incompatible requirements of asphalt pavements may be strict specifications for strength, stability, elasticity, resistance of shock, resistance to destruction, heat resistance, resistance to water, adhesions characteristics, etc.

Development and maintenance of asphalt pavements involve long-term empirical research of asphalts (bitumens) optimal for a concrete local

feedstock. In most cases statistical regression models are employed, and sometimes simple phenomenological models of certain processes and phenomena are used. Much less commonly, a systemic approach embraces the entire problem of the pavements property formation at different stages of its "life cycle" and relates microstructural changes to macroscopic processes and useful features of the final pavement.

System analysis is a broad strategy for scientific research and for the analysis of complex system [1,2], including, in particular, asphalt pavements [3]. As a mathematical research method, the strategy of systems analysis employs the method of mathematical modeling (mathematical models).

System analysis is a point of departure for the solution of modeling, optimization, identification, and optimum design of asphalt pavement. Essentially the systems approach in this case accumulates all a-priori information, as well as information obtained in laboratory experiments, test devices, and industrial installations, and enriches this information in the process of developing a complete mathematical model of the asphalt pavement. After the mathematical model has been constructed and found to correspond to the object under study (adequacy), it is used to optimize and manage of the asphalt pavement, with registration of transport and climates loads.

With its accent on sequential consideration of phenomena at various hierarchy levels, on testing hypotheses by experiment, and on strict selection procedures, system analysis as a scientific approach creates powerful instruments for understanding the physical world and combines such instruments into a flexible system, but one that can rigorously investigate complex phenomena of creation of asphalt pavement.

The use of system analysis strategy enables us to employ the hierarchy principle for the design of complex process at three levels: the micro-level, meso-level and the macro-level.

Microkinetic effects are the set of the physico-chemical effects that govern the rate at which physical or chemical phenomena take place at the molecular or atomic level [4]: chemical composition of asphalts and different chemically active admixture to the asphalts; chemical composition of gravel and its physico-chemical characteristics.

This effects makes itself felt through the history of the formation of the phase and chemical compositions of the non-equilibrium systems, i.e., through the sequence of occurence of the chemical, and physico-mechanical processes and the structural changes connected with them.

On the meso-level characteristic of the asphalt pavement being produced exist which arise directly as a result of the granulometry of the initial

components; this refers particularly to the dimensions of the structural non-homogenities which have one functional significance or another. These may be pores, grains of inert filler-components, partly reacted and intergrown particles of active components forming secondary skeletons, reinforcing fibers, etc.

Under these conditions the determination of the optimum composition of the feed mixture is possible only simultaneously with solving the problems of the macro-level of their subsequent treatment in order to obtain a final product with a specified spectrum of properties (strength, stability, elasticity, resistance of shock, resistance to destruction, heat resistance, resistance to water, adhesions characteristics, etc.). It is precisely these problems which come into play in the models of the corresponding processes occurring within the structures of the materials during their production, creation of optimum base layer, asphalt paving, compressing and also during their subsequent utilization.

The structure of a asphalt pavement is formed in constricted conditions (compressing) under the action of numerous physico-chemical, structural, and physico-mechanical processes. The result is that a polydispersed, polyorganic, polymineral feed asphalt mixture is transformed into a system with polymutually distributed phases: a rigid solid framework and networks of "liquid" and "gas" pores. The final structure of the material lacks equilibrium and is therefore sensitive to the initial conditions and the processes of its formation: chemical composition of asphalts [5], different chemically active admixture to the asphalts; granulometric, mineralogical, and chemical compositions of the feedstock (stone, gravel); conditions of formation and temperature of mixing; initial moisture.

The "life cycle" of Asphalt Pavement

Producing of asphalt pavements with the required set of technical characteristics and reconciling incompatible properties are facilitated under a molde of multicomponent hierarchically organized system with many mutually distributed phases. These problems also require a proper account of the interaction among the hierarchic levels at all stages of the pavement's life cycle. This life cycle consists of the following stages:

- 1. Preparation of the feed (treatment of the feed materials);
- 2. The formation itself of the asphalt pavement with a specified set of properties (formation of the multifunctional structure of the asphalt pavement) and possible time of "life cycle";

• 3. The usage of the asphalt pavement, i.e., aging and breakdown under the influence of a previously specified set of destructive factors;
• 4. The timely utilization of the asphalt pavement, taking into account the problems of environmental protection, during the process of recycling (especially for the cities).

Hardening Physicochemical System (HPCS)

A hardening physicochemical system (HPCS) is an astringent mixture with several distinctive features. The first feature is the strong chemical nonequilibrium that causes the nonlinearity of processes at all stages of hardening. "Structural memory" effects come into play in nonequilibrium structures in the course of their evolution: a fine-crystalline phase takes the place of one of the coarse-crystalline phases; a dissolved phase with dissolving particles is replaced by pores, which close up for longer periods when the effective coefficient of volumetric expansion of the astringent mixture hydration products is smaller.

For this reason [3,6] they participate in the formation of the material's properties over a long period of time. The second feature is the formation and fixation of metastable nonstereochemical compounds. Nonequilibrium intermediate crystalline phases, which originate during hardening, remain intact for many years, as if frozen. The third feature of an HPCS is that the solid, liquid, and gaseous phases are multiphase and multicomponent, condensed and mutually distributed, with a specific kind of transfer processes (threshold effects and transition to cooperative behavior).

An HPCS has one more peculiar feature: feedforward and feedback take place between the material's structure and the processes occurring in it. The structure governs transfer of heat, mass, momentum, and charge, whereas these processes, in turn, change the structure. Thus, hardening is a form of cooperative phenomenon in a nonequilibrium system and a kind of self-organization process of natural nonequilibrium systems. Thereshold effects, or abrupt changes in the properties (such as a loss of the mixture fluidity), are common to self-organizing system upon transition to cooperative behavior. The start of astringent mixture hardening may be a topological transition from the local cohesion of the solid phase to its global cohesion (rigid framework).

To include these features of HPCS in simulation of the production of asphalt pavements, it is necessary to work out a formal mathematical technique adequate to the problem field in question. We propose to construct such a formal technique on the basis of the following methods:

- The methods of topological feedback;
- The methods of mathematical morphology for analysis of complementary phases;
- The method of percolation analysis for describing topological phase transitions (transitions like "permeable-impermeable" or "plastic-elastic" in structured systems);
- The method of discrete phase mappings for predicting the phase composition of the reaction mixture (predicting the phase composition of the system upon change-over to new feedstock or introduction of different chemically active admixture to the asphalts).

The Methods of Topological Feedback

The methods of topological feedback is introduced to reflect the evolution of structurally inhomogeneous media where quantitative changes results in qualitative transformations of the structures. An appropriate model incorporates two blocks; one accounts for quantitative changes in the system, and the other is periodically used for analysis of qualitative changes–topological phase transitions which "turn on and off" particular processes. Transformations of the material's structure are formalized as a directed evolution of a topological operator S_{tr} (material's structure) from a state S_{tr}^0 (at the beginning of the stage) into a state S_{tr}^N (at the end of the stage).

The evolution of the system's topological operator is directed so that the final structure of the operator conforms to the criterion of R_{str} optimization or a complex of M criteria that characterize the pavement's properties at the end of the stage [2]:

$$R_{str} = \bigcap_{i=1}^{M} R_1\{S_{tr}^e\}$$

The Methods of Mathematical Morphology for Analysis of Complementary Phases

The methods of mathematical morphology for analysis of complementary phases is employed to correlate different topological characteristics of structurally inhomogeneous medium with the methods of their formalization. Two complementary approaches are singled out in mathematical morphology: combinatorial topology and integral geometry, which together provide

a powerful formal technique for quantitatively describing the topology of the combinatorial topology method [7], the evolution of the solid phase topology can be represented in terms of Betti's groups [8], whose number in the material is related to the phase surface curvature. Such a relation allows simulation of simultaneous changes of the phase topology (cohesion, the number and sizes of clusters [5] and the quantitative characteristics of the phase (the distribution of particle sizes, the rates of particle growth and dissolution, modification of their shape, values of the thermodynamic potentials at the interface, and the like [9].

The Method of Percolation Analysis for Describing Topological Phase Transitions (TPT)

The term "percolation" is used here in the classical sense, as a structural phase transition in a statistically organized system (transitions like "permeable-impermeable" or "plastic-elastic" in structured systems) [10,11].

It is clear that percolation is the principal mechanism of cooperative behavior (self-organization) of heterogeneous HPCS and a key concept for quantitative characterization of the relation between the pavement's structural properties and the macroscopic properties of finished products [12]. We proposed to develop the percolation approach to embrace the specific nature of hardening multiphase systems.

The percolation theory, like mathematical morphology, offers two main approaches to solving such problems: combinatory-topological and probabilistic. The drawbacks of the first approach are common for both of them: there are a number of moldes for processes in ordened d-dimensional lattices with randomly removed ribs, but they are for approximations to the physical problems. However, if we adopt the hypothesis of the statistical isotropy of the stochastic composite space, as we see for the method of mathematical morphology, we can apply the probalistic approach to finding the desired percolation dependence between the process probability and the phase characteristics.

The Method of Discrete Phase Mappings (PM) for Predicting the Phase Composition of the Reaction Mixture

Predicting the phase composition of the system upon change-over to a new feedstock or introduction of different chemically active admixtures to the feedstock in hand is crucial [13–15].

We have an attempt to create a predicting algorithm for prognostication of phase states of chemical systems on the basis of the method of discrete mappings advances in nonlinear physics.

In order to solve concrete problems in the production of asphalt pavements, we made an attempt to construct a discrete mapping that differs from the traditional ones in the following:

(1) this mapping does not have a prototype and is to be constructed specifically to solve "phase" problems for multicomponent materials;
(2) it is multidimensional, as distinct from one-dimensional mappings considered in most applied and theoretical studies in nonlinear dynamics;
(3) it describes a timeless (t = cons.) state of a chemical systems with distributed parameters in the absence of long-range correlations between its volume elements, whereas most existing models use a "classical" interpretations of a logistic mapping (system with lumped parameters and implicit discrete time).

With these relations taken into consideration, we have worked out an algorithm [1] for calculating an evolving system with pseudochemical kinetics in several steps.

1. Determination of the initial Gibbs energy $G(t_0)$ of the asphalt system as a sum of the Gibbs energies of the respective components (or individual components, or minerals, if they are constituents of the feed mixture) with due account of their concentrations in the system [16].
2. Activation of mapping for the whole chemical system (a mixture which is ideal, on the molecular level, is adopted, for which the relative activities of the components are calculated and then recalculated for the mass and charge balances). The mapping yields a final equilibrium phase composition of the hardening system under given conditions, which represents the global tendency of the system's evolution. For this composition the Gibbs energy is calculated [16].
3. Determination of the chemical potentials or activities of the components in the system for the initial phase composition. Activation of the mapping, starting from the real activities of the components in the aqueous solution. The mapping gives the phase composition for these activities as the current tendency of the system's evolution. Now we can write the first system of equations of pseudochemical kinetics.
4. Integration of the system equations of pseudochemical kinetics with respect to t_r. During integration over the "constant set of phases", the behavior of the K-entropy of the phase mapping attractor is analyzed at

each step and depends on the current overall activities of the components in the current set of phases. At the same time, the driving forces are corrected according to the changes of the current mean component activities and, respectively, the chemical potentials of the components in the phases. The fact that the second derivative of the attractor's K-entropy with respect to the integration time phases through zero is indicative of the nonequilibrium chemical phase transition, which results in a loss of stability of the previous system of phases and necessitates introduction of a new system of pseudokinetic equations.

5. Analysis of the new phase composition generated by the mapping for the current mean activities $a_{ij}^0(t_r)$ of the components in the systems, gives a new system of chemical outlets (of the phases). For this system, The components of the previous system are either sources or outlets depending on the direction of the force, which is determined by the component activity $a_{ij}^k(t_r)$ in the phase and the current mean activity $a_{ij}^0(t_r)$ of the same component in the system. The phase space of the system is clustered so that the existing and the emerging compounds, having close values of the phase coordinates and the K-entropy of the phase mapping attractor, are considered as one phase. The primary classification is conducted according to the K-entropy of the phase, and then, after passing this test, according to the composition similitude. At this point the integration cycle begins on the new start of pseudochemical equations with new kinetic coefficients.

As it is apparent from this algorithm, the system of formal equations of pseudochemical kinetics has maximal dynamism. The number of components and equations in it changes continuously (increases or decreases).

CONCLUSION

On the basis of these methods worked out integrated package (based on the FORTRAN-77 and RAFTOR programming languages) for calculating and evolving system with pseudochemical kinetics. The result of optimization is a significant increase of the pavement's strength and the cost of feedstock for its production was appreciably reduced. Moreover technological flowsheets were approved for optimal production control. These flowsheets were designed for original feedstock as well with chemical admixtures which meet the demands of technological feasibility of the optimal control regimes. And finally, a tangible economical effect was yielded by increase the strength of

asphalt pavement's and simultaneous reduction of feedstock costs, energy expenditures, and actual production costs.

Thus the application of the methods of mathematical modelling opens up the possibility of realizing systems analysis wherever, in the investigations or design of a asphalt pavement as a system, all information obtained first from laboratory research on test installations and in the design of the asphalt pavement is successively accumulated, enriched, and realized in the form of algorithms on a computer. The enriched and systematized informations is retrieved for use in planning in the last step, after all asphalt pavement have been modeled mathematically. Systems analysis serves as a scientific basis for sharply cutting down the time required to complete laboratory work in creation of the asphalt pavements.

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