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Heat Resistance and Heat-and-Mass Transfer in Road Pavements

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Abstract. The paper presents a fragment of on-going investigations directed on creation of optimal information environment that ensures an access to the R&D publications from the known scientific journals and other scientific serials which are necessary for qualitative execution of scientific and technological activities on priority areas in highway engineering. A citation analysis has been applied while using data of Journal Citation Reports for selection of world scientific publications which are necessary for execution of investigations on heat and mass transfer in road dressings. Their deformations occur under various climatic conditions due to heat- and mass transfer processes, interaction of transport flows and road surface that leads to crack formation in depth and on the surface of road dressings. Structure of constructive layers especially which are created with the help of technogenic wastes (asphalt-, reinforced concrete, concrete, brick scrap and products of their recycling, various wastes of production etc.) exerts an influence on heat and mass transfer. The paper presents results of investigations on heat flows, boundary layers according to viscosity, air velocity, geometric characteristics, permeability, capillary pressures in materials. It has been shown that calculations based on principles of complex number usage have specific features in engineering practice: it is required to observe their accuracy in approaches, calculation reduction due to some accuracy degradation as a consequence of transition from complex numbers to their modules with exclusion of phase shift account and related with propagation of thermal waves. In this respect calculations of heat resistance without phase shifts are considered as rather important if they are in agreement with principles based on the fact that a complexity is characterized by thermal absorptivity of the material in a great number of calculations. The investigations have been supported by Henan Center for Outstanding Overseas Scientists, Grant Number GZS 2018006 (People's Republic of China, Henan Province).

Keywords: object, calculation, temperature, cement concrete, asphalt concrete, technology, heat resistance, model, flow, problem, coefficient, module, road dressing, heat- and mass transfer, structure, stress, surface, deformation, crack formation, boundary layer

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Теплоустойчивость и тепломассообмен дорожных покрытий

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Реферат. Материалы статьи являются фрагментом продолжающихся исследований, направленных на создание оптимальной информационной среды, обеспечивающей доступ к научным публикациям из известных научных журналов и других изданий, необходимым для качественного выполнения научно-технической деятельности по приоритетным направлениям в области дорожно-строительной отрасли. Использовался цитат-анализ с применением данных Journal Citation Reports отбора мировых научных серийных изданий, необходимых для выполнения исследований тепло- и массопереноса в дорожных одеждах. В различных климатических условиях имеют место их деформации вследствие тепло- и массообменных процессов, взаимодействия транспортных потоков с поверхностью дороги, при которых происходит трещинообразование по глубине и на поверхностях дорожных одежд. На тепло- и массоперенос влияют структура материалов конструктивных слоев, особенно выполненных из техногенных отходов (асфальто-, железобетонный, бетонный, кирпичный лом и продукты их переработки, различные отходы производств и т. д.). Представлены результаты исследований тепловых потоков пограничных слоев в зависимости от вязкости, скорости воздуха, геометрических характеристик, проницаемости, капиллярных давлений в материалах. Показано, что расчеты, основанные на принципах использования комплексных чисел, имеют особенности в инженерной практике: требуется точность в подходах, сокращение объема вычислений, обусловленных некоторым снижением точности вследствие перехода от комплексных чисел к их модулям, с устранением учета сдвига фаз и связанных с распространением тепловых волн. При этом актуальны расчеты теплоустойчивости без сдвигов фаз, согласуемые с принципами, основанными на том, что во многих расчетах комплексность характеризуется коэффициентом теплоусвоения материала. Работа выполнялась при поддержке со стороны Хенаньского бюро выдающихся иностранных специалистов, номер гранта GZS 2018006 (КНР, провинция Хэнань).

Ключевые слова: объект, расчет, температура, цементобетон, асфальтобетон, технология, теплоустойчивость, модель, поток, задача, коэффициент, модуль, дорожная одежда, тепло- и массоперенос, структура, напряжение, поверхность, деформация, трещинообразование, пограничный слой

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Introduction

Automotive highways at various climatic conditions are considered as open non-linear heterogeneous thermodynamic systems because cracking, road deformation must be studied while using synergetics principles as result of collective behavior, self-organization of structural pavement elements in case of reaching critical temperatures. Formations occurring due to these processes represent in themselves dissipative structures adapted to external conditions and in this case road dressings change their mass [1–6] as a result of heat and mass transfer with air, external flows, sources.

An example of dissipative structure formation is a road dressing with due account of the Bénard effect: a convection with hexagonal cells in the layer of viscous fluid and critical difference of temperatures between down- and upstreams occurs at various distances, for this reason there is an intensity jump of heat transfer. In case of long temperature drop a road pavement dissipates a part of the accumulated heat to the horizon and various object. When there is a balance in stress of limit dressing material strength then jump-like removal of pavement heat portion takes place (for example, a reduction in air temperature by 10 °C leads to change of temperature field through road thickness up to 0.45–0.50 m).

At the same time longevity, economical efficiency, optimal operational conditions of road pavements depend not only on physical and chemical characteristics of roads and environmental systems ("road surface – horizon"; "road surface – thermal flows – atmospheric air", afforestation, number (density, load capacity) of transport facilities"), thermodynamic, heat and mass transfer potentials of road dressing materials and others. The most important role is played by a complex of issues pertaining to external and internal matters which are attributed to actual processes of heat and mass transfer in single- and multi-layer systems of road dressings. While having known coefficients of heat-conduction, vapor- and mass permeability, diffusion, filtration, thermometric conductivity, layer material density, initial and boundary conditions it is possible to carry out optimization of problems concerning heat and mass transfer from road surface to its base (bulk materials, borrow soil). Density of heat flows in road pavements, their degradation are characterized by geometric roadbed dimensions (width), radiation characteristics (emissivity factor, albedo), etc. Deformation characteristics, longevity, crack resistance of road pavements depend on decay in external air temperature variations [6–9].

An analysis of calculations has shown that coefficients of heat absorption and heat resistance of road materials depend on coefficients of heat- and temperature conductivity, pavement components, heat capacity, density, periods of regular variations, indices of temperature variation decays calculated according to a formula

$$\nu_s = \exp^{\frac{\sum RS}{\sqrt{2}}} \psi = \exp^{\frac{\sum RS}{\sqrt{2}}} \frac{S_1 + S_{0,11}}{S_1 + S_{0,1}} \frac{S_2 + S_{0,1}}{S_2 + S_{0,2}} \frac{S_{0,k-1}}{S_k} \frac{S_n + S_{n-1}}{S_n + S_{0,n}} \frac{S_{0,n} + \alpha_n}{\alpha_n}, \qquad (1)$$

where ψ – heat conduction coefficient of road layers; S_1, S_2, S_n – heat absorption coefficient of the 1st, 2nd, …, n-layers, W/(m^2·K).

The calculation presupposes a presence of temperature waves in one direction (absence of temperature variations at surface), in this respect a decay in temperature waves can be calculated at an infinite large distance from the surface with the help of nomograms.

Processes of heat transfer in cement concrete pavements

Cement concrete road pavements are usually constructed under the following conditions: absence of atmospheric precipitations and temperature 5–25 °C, mean daily temperature from 5 to 10 °C, minimum daily temperature more than 0 °C. Maximum transportation time period of tempered heavy concrete mixes with workability grade П-1 must be equal to 60 minutes; air temperature 20–30 °C and mix temperature 18–20 °C with its average transportation speed 30 km/h.

An analysis of temperature gradients has been carried out in calculations; duration of temperature equalization has been determined in the massive with due account of the given initial boundary conditions while presenting the road dressing as a semi-closed body. A relative non-dimensional temperature has been calculated in accordance with the expression:

$$\Theta = \frac{\mathrm{Bi}(1-\eta)}{2(\mathrm{Bi}+1)} - \sum_{n-1}^{\infty} A_n \sin\left[\nu_n (1-n)\exp(-\nu_n^2 \mathrm{F_O})\right], \tag{2}$$

where A_n – initial thermal amplitude of road n-layer.

Calculation results are presented in Tab. 1.

Table 1

Temperature of cement-concrete pavement surface in dependence to time-period

Duration of heat transfer τ, h	Fourier number (F_0)	Biot number (Bi)	Θ (relative non-dimensional temperature)	Surface temperature t_0, °C
1	0.05	3.55	0.50	10.0
3	0.15	3.55	0.63	7.4
5	0.25	3.55	0.70	6.0
10	0.50	3.55	0.75	5.0
20	0.10	3.55	0.77	4.6

While calculating heat transfer for plane road dressing it is accepted that its surface temperature is equal to t_0 that is temperature of air flow with constant velocity. If we take into account the fact that a portion of horizontal surface with length x_0 is not heated and a temperature is not equal to the flow temperature (Fig. 1, 2) then a dynamic layer appears at a frontal edge and a thermal one appears at a heated area boundary of horizontal surface.

Thicknesses of boundary layers are increased in direction of flow motion. Calculations of a thermal and dynamic boundary layer thickness and heat transfer have been made in conformity with classical expressions [10–12]. For that purpose it is logical to accept assumptions in respect of a temperature distribution profile which are the more correct the closer they coincide with actual ones. An expression with some arbitrary functions can be applied and the functions are determined in such a way that the expression fulfills real conditions: at $y = 0$, $t = t_0$; if $y = \infty$, $t = t_\infty$, $\frac{\partial t}{\partial y} = 0$. The following equation for stationary flow with small velocity if $y = 0$ is recommended $\frac{\partial^2 t}{\partial y^2} = 0$. Then it is acceptable to use a polynomial with four functions and numerical values of Prandtl number are rather significant in this case.

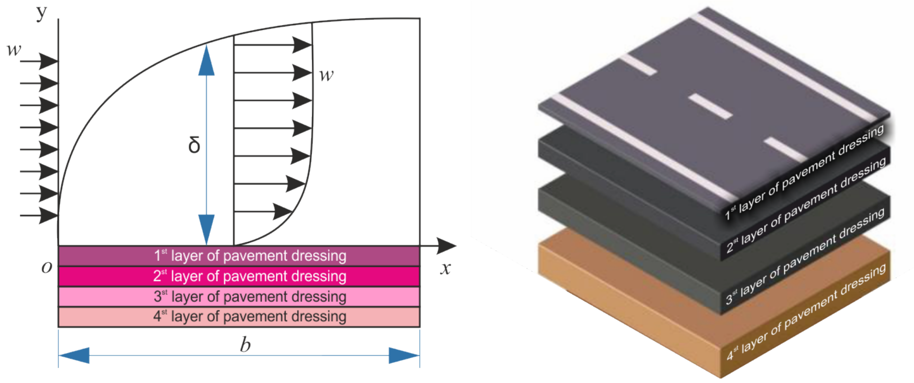

Fig. 1. Influence of dynamic flow velocity on multi-layer road pavement

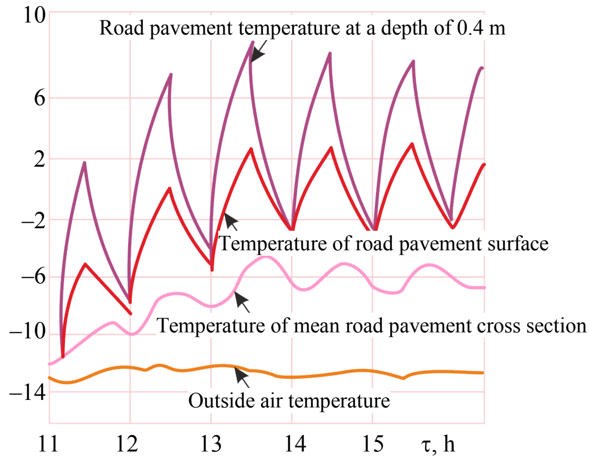

Fig. 2. Temperature fields of road pavements and outside air according to time

An analysis of non-isothermal temperature fields in road dressings has been made similar to mathematical models while calculating of temperatures (multi-layer structures) at boundary conditions of III and IV type on interface of pavement layers. Moreover, at autumn–winter–spring periods processes of heat- and mass-transfer are the most complicated so a complex of conditions with calculated optimum transport speeds is necessary attributed to them. Amount of precipitation, a specific feature of temperature regime being peculiar for an object, constructive thermal- and mass-physical characteristics of materials must be taken into account while developing technologies under such conditions. Equations of non-stationary thermal- and mass-conductivity considering thermodynamic air parameters, thermal and physical characteristics of road materials are considered as more correct for calculation of temperature fields.

It is necessary to note that road dressings, soil foundations (multi-layer system), its every layer is characterized by heat- and temperature conductivity factors, density, etc. which are functionally connected with coordinates $x, y, z,$ time τ.

Temperature field in depth of road dressing, road bed can be presented in the form of ratio $t(x, y, z)$ at some specific (characteristic) time moment $\tau = 0$. Temperature regime of design changes due to meteorological conditions; phase transitions occur in boundaries of layer separation at negative temperatures; heat emission arises during crystallization; absorption happens during defrosting. Thermal- and mass-physical characteristics of materials change intermittently in going from a crystalline zone to a drop one. Temperature difference in layers of road design leads to molecular heat transfer by heat conductivity.

Thermal and physical characteristics of road dressing materials, temperature regimes characterize thermal and inertial properties of pavement layers and surfaces and temperature field of pavement surface is determined by character of surface heat-transfer, aggregate coefficient of heat exchange: $\alpha = \alpha_1 + \alpha_2$, where α_1 – a convection component, which is subjected to an influence of specific features of transport flow, roadside situation, topography, and α_2 characterizes conditions of heat inflow, losses depending on radiation, determined by absorptive surface ability (colour, roughness), its orientation with regard to solar rays.

Correct mathematical setting of the problem must take into account: introduction of differential heat conductivity equations, describing the process of heat transfer through road design layers; initial conditions, temperature field near surface at the initial moment of time; boundary conditions.

It is known that a temperature regime of road dressing near its surface is described by the equation

$$c\rho \frac{dt(x,y)}{d\tau} = \frac{d}{dy}\left[\lambda \frac{dt(y,\tau)}{dy}\right] + q, \tag{3}$$

where q – internal heat liberations.

Experimental and analytical investigations of some researchers have shown that longevity, economical efficiency, optimal interaction conditions of transport elements and road objects depend on physical and chemical, technical characteristics of road surfaces and environmental systems ("road surface – horizon"; "road surface – atmospheric air, afforestation"), density of transport flows, thermodynamic, heat- and mass transfer potentials of road materials, air, air flow velocity, etc. – a complex of problems pertaining to exterior problems.

Effect of dynamic forces on concrete, bitumen-concrete pavements being in moistened state for a long period of time reduces their strength, longevity, and these phenomena cause processes of structure destruction which are developing at static, dynamic exposure to water. When moisture is rather long in concrete material pores water diffuses and facilitates to partial structure deformations.

In this case heat- and mass transfer processes in asphalt concrete are mainly determined by material micro-structure, so their analysis is considered as an actual task of investigations.

In accordance with the Young-Laplace equation, Washburn principle external pressure is a function of pore dimensions and it is determined from the expression

$$p = \frac{2\sigma\cos\theta}{r}, \tag{4}$$

where p – absolute external pressure, MPa; σ – surface tension coefficient, dine/cm; θ – angle of boundary wetting, deg; r – capillary radius, cm.

Considering the fact that mercury σ = 480 dine/cm, and θ = 141.3°, according to (4), a pore radius is calculated with the help of a formula

$$r = \frac{7500}{p}. \tag{5}$$

Volume of efficient porous space within specific pressure interval can be calculated while using

$$V = \frac{F(h_1 - h_2)}{m}, \tag{6}$$

where F – cross section of a dilatometer (7.065 mm^2, type SMHB); h_1 – general mercury level drop at pressure 100 MPa; h_2 – mercury level drop due to its compression at pressure 100 MPa; m – weight of a specimen, g.

It is known that the less the specimen dimension the easier mercury penetrates into material pores. So it is considered that specimens with diameter of 8–10 mm are the most preferable for investigations.

Fig. 1 shows an increase of integral porosity in the specimens with fine-grained structure in comparison with road materials with medium grained structure types. The experimental investigations have made it possible to reveal that porosity extremes of medium- and fine-grained asphalt-concrete are located in the zones 700–800, 70–80 and 30–40 Å, respectively.

While taking into account the accepted classification of pores and capillaries according to dimensions the obtained results can be interpreted in the following way: micro-pores and micro-capillaries are present in materials of the investigated specimens and their volume from the total efficient porous space constitutes up to 29 % in fine-grained and up to 50 % in medium-grained asphalt-concrete (Tab. 2). Micro-pore volume these are pores with a radius of less 10^3 Å constitutes 71 % in fine-grained and within 42–55 % – in medium-grained asphalt-concrete.

Table 2

Distribution of pore volume according to radius

Type of asphalt concrete	Integral porosity, cm^3/g	%								
		Pore volume with radius, Å								
		50	50–100	100–200	200–300	300–400	400–600	600–1000	10^3–10^4	10^4
Medium-grained B	0.0065	8	12	6	3	2	5	14	28	22
Medium-grained C	0.0041	8	13	7	4	2	3	15	23	25
Fine-grained A	0.0156	20	27	10	4	3	3	4	16	13

Experimental investigations on distribution of pores in the studied material according to size have been carried out with the help of a mercury steam meter (model H-70 of Carlo Erba Company). Interaction of non-wetting fluids with capillary-porous body is the main operational principle of this measuring device.

The investigations of porous space in asphalt-concrete specimens make it possible to presuppose that similar heterogeneous systems having micro- and macro-capillaries will have molar and molecular processes of dropping vapor phase transfer due to diffusion filtration flows.

Calculations of boundary layer at surface of road pavement

Solution of a problem on flow-around of road pavements plays a great role in theory of heat- and mass transfer, construction mechanics.

Road pavement located along a longitudinal flow of transport elements is considered as a stream-lined body and its resistance firstly depends on tangential stresses. Dependence of frictional resistance coefficient used for calculation of a boundary layer in an air flow resolves itself into determination of change character in layer thickness these are functions $\delta = \delta(y)$ and degree of friction resistance on the condition that we know a velocity of incoming flow and coefficient of kinematic air viscosity. An integral relation of steady-state flow has the following type [10]:

$$w_\infty^2 \frac{d}{dx} \delta_2 w_\infty^2 + \frac{dw_\infty}{dx} \delta_1 = \frac{t_0}{\rho}. \tag{7}$$

As in the analyzed case $w_\infty = 0,$ $\frac{\partial \rho}{\partial x} = 0,$ that is $w_\infty = \text{const},$ a road pavement can be considered as a body with a zero pressure gradient along a link then an integral relation has the following type:

$$w_\infty^2 \frac{d\delta_2}{dx} = \frac{\tau_0}{\rho}. \tag{8}$$

In order to calculate a boundary layer thickness and resistance force exerted to a surface it is necessary to take into account a law of velocity distribution according to thickness layer; an equation, binding shear stresses on road surface, and in this case $w_\infty = w_y$ [4, 10]

$$\frac{d}{dx}\delta_2 w_\infty^2 + \frac{dw_\infty}{dx}\delta_1 = \frac{\tau_0}{\rho}, \tag{9}$$

where ρ – air density; τ_0 – shear stress on roadbed surface (measure function of internal forces due to application of external actions, temperature, velocity, stress tensors to it).

Boundary conditions can be kinematics which are imposed on velocity at the edge of a boundary layer and they can be also dynamic which are imposed on forces of internal friction.

The executed investigations have studied main technological principles pertaining to usage of preliminary heated components (fillers) while making road concrete pavements.

Calculations have been made in respect of duration time for equalization of temperature fields of multi- and single-layer pavements, influence of initial temperatures at stationary, non-stationary thermal regimes [7, 8, 11]. Duration of heat-transfer has been determined for geometric dimensions of bodies having a classical shape at boundary conditions of first kind. For example, a correlation dependence of medium temperature on time has a parabolic shape for fractions having medium diameter of 35 mm. For this purpose a physical model of cement-concrete pavement has been presented and it has been observed that medium inter-spherical space is equal to 7 mm.

An equation of non-stationary temperature field which is changed according to parabolic dependence on depth (x) in time (τ) has the following type:

$$t = 0.6574x^2 - 6.0039\tau + 36.194; \tag{10}$$

according to linear dependence

$$t = -1.603x + 39.846; \tag{11}$$

according hyperbolic dependence

$$t = -0.4435x^2 + 4.5768 - 37.003. \tag{12}$$

Temperature fields of asphalt concrete have been calculated at initial temperature 10 °C, air temperature 20–30 °C, time interval 0.00837 h, specific flows of heat from air to pavement surface q_{air}, W/m^2, accumulated by layers q_a, W/m^2.

An analysis and calculations for layers with jumping temperature variations have been made for cement concrete, concrete, asphalt concrete pavements. It has been supposed that it is a layer located at some distance from road surface and heat wave is coming to the depth ΣRS through it. Heat flows and temperatures are decreasing in infinite thickness-wise pavement limited by air and material layers depending on thermal and physical characteristics of layers, their geometric dimensions, heat resistance, heat absorption in accordance with various laws and they can be determined while using complex analytical calculations and graphical methods.

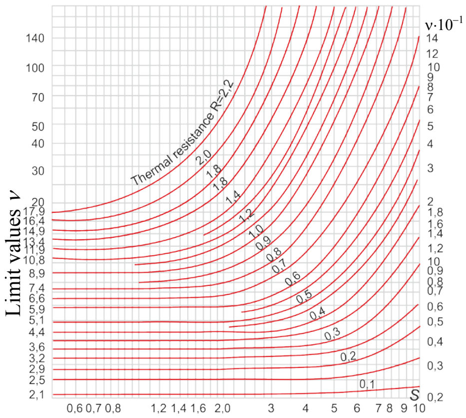

Fig. 3. Dependences of decay coefficients on thermal resistance of road pavement

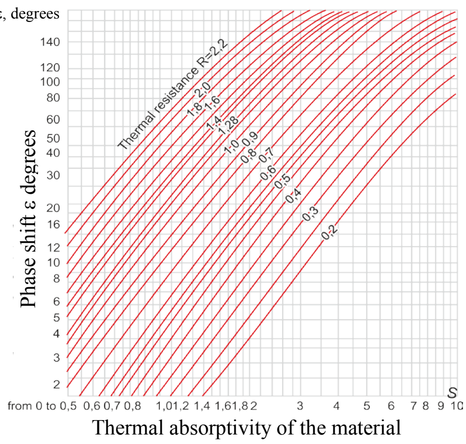

Fig. 4. Dependences of phase shifts on thermal absorptivity of road pavement materials

CONCLUSIONS

1. Analytical and experimental investigations on study of optimal operational conditions for road dressings have been carried out within the framework of international project and they have been supported by Henan Center for Outstanding Overseas Scientists, Grant Number GZS 2018006 (People's Republic of China, Henan Province).

2. An analysis of national and foreign investigations has shown that up to the present moment only problems related to objects from capillary porous materials have been studied and at the same time road pavements have not been fundamentally considered from the point of view of heat- and mass resistance. There is no qualitative analysis of heat- and mass transfer in road pavements of not only multi-layer but also single-layer asphalt concrete, concrete road objects.

3. Temperature fields of single- and multi-layer road pavements have been considered while using equivalent characteristic dimensions at boundary conditions of I–III kind and methodologies for setting and solution of problems in road pavements have been proposed with usage of complex numbers and nomograms.

4. The required investigations have been carried out, graphic dependences have been plotted between decay coefficients, thermal resistances, heat absorption coefficients, phase shifts, heat-transfer coefficients neat road dressing surfaces which are presented in Fig. 3, 4.

5. In order to increase reliability and longevity of road pavement operation in various climatic conditions it is necessary to continue fundamental experimental investigations with the purpose to study heat engineering and physical and mathematical properties of all composite materials being in structure of road dressing mixes.

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