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Evaluation methods of asphalt pavement service life

Методы оценки срока службы асфальтобетонного покрытия

M.A. Zavyalov,
Lomonosov Moscow State University, Moscow, Russia
A.M. Kirillov,
Moscow Automobile and Road Construction State Technical University (MADI), Sochi, Russia

Д-р техн. наук, доцент М.А. Завьялов,
Московский государственный университет им. М.В. Ломоносова, г.Москва, Россия
канд. физ.-мат. наук, доцент А.М. Кириллов,
Сочинский филиал Московского автомобильно-дорожного государственного технического университета, г. Сочи, Россия

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Ключевые слова: дорожное покрытие; асфальтобетон; межремонтный срок службы; мониторинг функционального состояния; термодинамические характеристики

Abstract. A functional relationship of the dynamics of asphalt concrete pavement condition and its thermodynamic and thermophysical functions and parameters (Helmholtz's energy, internal energy, entropy, specific heat, etc.) is described. Based on this functional relationship, novel approaches to the estimation of asphalt pavement lifetime are proposed. The dependence of pavement lifetime from the basic thermodynamic parameter – specific heat (for the determination of which expensive and complicated equipment is not required) is derived. The statistical approach to determination of pavement lifetime, based on the analysis of the temporal changes in the spatial distribution of the basic parameter (specific heat) is proposed. Overall, three alternative but complementary approaches are described to determine pavement service interval using either a molar weight, a change of free energy, or the uniformity of the basic parameter – specific heat based the index of thermophysical uniformity (a dimensionless coefficient). Numerical pavement lifetime values suitable for exploitation under the Russian service conditions (transportation and construction terms) are calculated analytically. Regardless of the approach used of the calculated pavement lifetimes are of the same order of magnitude. These initial results are quite promising and offer a new thermodynamic approach to the estimation of pavement condition and its useful lifetime. This practical new approach can be utilized to replace or complement the traditional "mechanical" and geo-radar methods.

Аннотация. В предыдущих исследованиях была показана возможность учета энергетических изменений, происходящих в системе дорожное покрытие – транспортное средство, и их вклад в формирование научно обоснованной системы назначения сроков ремонтных работ. В связи с этим также перспективным является развитие результатов работ, в которых приводится анализ зависимостей термодинамических функций дорожного покрытия от времени эксплуатации. Несмотря на то, что ранее был сформулирован термодинамический подход, удобные расчетные формулы для определения межремонтного срока службы покрытия отсутствуют. На основании анализа полученных соотношений, описывающих динамику состояния асфальтобетонного дорожного покрытия с помощью его термодинамических и теплофизических функций и параметров (энергия Гельмгольца, внутренняя энергия, энтропия, теплоемкость), предложены подходы к назначению межремонтного срока службы дорожного покрытия. Выведены зависимости межремонтного срока службы покрытия от базисного параметра – удельной теплоемкости. Обоснован статистический подход определения межремонтного срока службы покрытия, основанный на анализе временных изменений в пространственном распределении базисного параметра. В результате исследования получены три альтернативные по отношению друг к другу и, в то же время, взаимодополняющие подхода к нахождению времени жизни покрытия: через молярную массу; через изменение свободной энергии; через однородность базового параметра – удельной теплоемкости путем ввода безразмерного коэффициента теплофизической однородности. Аналитически получены числовые значения межремонтного срока службы покрытия адекватные российским условиям эксплуатации (транспортным и строительным условиям). Несмотря на различные подходы, полученные значения межремонтного срока службы

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покрытия имеют один порядок величины. Полученные результаты развивают сравнительно новый термодинамический подход к решению задач мониторинга покрытий и их эксплуатационных режимов и нацелены на замену или дополнение традиционных «механических» методов мониторинга состояния дорожного покрытия.

Introduction

Currently, the asphalt paved road infrastructure of the Russian Federation is undergoing an extensive expansion. There has also been a significant increase in the exploitation of the existing roads in recent years. These factors necessitate the development of a practical, inexpensive, and fast method to evaluate the functional condition of a pavement. It would be highly desirable if such a method is capable of predicting future changes in pavement characteristics and determining the optimum modes of road usage. Optimization of pavement management is expected to have a positive effect on pavement longevity which in turn should lead to an increase in its service life.

In our previous article [1] we described the numerical assessment of such characteristics as vehicle dynamic forces, work of a single wheel on pavement; analytical dependences of increments of internal energy, energy of elastic deformation, and dissipative energy. The main purpose was to establish the functional relationships between mechanical and thermal parameters in the system pavement – vehicle, and also to consider the processes of vehicle energy dissipation by pavement. We envisioned that a deeper understanding of energy dissipation between pavement and vehicle should make it possible to devise a method of defining pavement functional condition at any time. This in turn should lead to better monitoring and forecasting of asphalt pavement functional condition and its remaining service life.

In our previous publications [2] we described the dependences of asphalt concrete thermodynamic functions from specific heat: change of internal energy, entropy and free energy. The main focus of our paper was to apply the thermodynamic framework to the description of changes of physical, mechanical and thermophysical parameters of a material during the lifetime of an asphalt concrete layer. Dependences of specific heat versus time for different asphalt brand, type and road category were obtained. The analysis of a nature of the obtained dependences, their comparison to the experimental data and visual evaluation allowed us to conclude that the starting time of required asphalt pavement repair is directly linked to quasilinearity loss in the function graphs of asphalt specific heat versus time. Calculations showed that this specified time point is characterized by free energy deficiency, i.e., its negative increment. Based on experimental data similar dependences were derived for various types and brands of asphalt concrete [2]. We can conclude that during the normal exploitation of asphalt pavement, internal energy and entropy of its constituent materials increase. In particular, the amount of internal energy constantly increases because of accumulation of dissipative energy from the contact with vehicle wheels. At the same time, the amount of free energy decreases (it plays a compensation role in various deformation processes).

The available scientific publications that study the relationship of physical, mechanical and thermophysical parameters in the system "pavement – vehicle" can be divided into three large groups. The first and, most representative group contains research of tire-pavement interaction with the goal of providing the optimum vehicle speed [3, 4], safety [5], motion comfort [6], and fuel economy [7]. The second group encompasses research on the thermophysical properties of asphalt concrete. Optimization of these properties has shown to help reduce thermal absorption and high temperatures of pavement surface [8, 9] to prevent rutting [10], and cracks [11]. The third group includes approaches using surface radiation properties: albedo and emissivity, surface temperature gradient [12, 13], taking into consideration hydrogeological and climatic conditions of the region [14], and urban heat island effect [15]. The main goal of these approaches is to develop a network of smart roads with possibility of energy cumulation [16, 17]. There are also a number of papers [18–24] where the results of laboratory studies demonstrated conclusively the influence of thermophysical properties on mechanical characteristics. However, to date the authors are not aware of any publications related to development of an approach of asphalt pavement condition monitoring using the thermodynamic framework.

In previous research analytical dependences of thermodynamic functions versus specific heat of asphalt concrete have been obtained [2]:

$$\delta F = -\mu T\left[C\ln T + C_0\left(\frac{T_0}{T} - 1 - \ln T_0\right)\right]; \tag{1}$$

$$\delta U = \mu(CT - C_0 T_0); \tag{2}$$

$$\delta S = \mu[C(1 + \ln T) - C_0(1 + \ln T_0)], \quad (3)$$

where F – free energy (Helmholtz's energy); U – internal energy; S – entropy; T_0, T – initial and current values of temperature; C – specific heat; C_0 – initial value of C, at $T=T_0$; μ – value in number equal to density of material, dimension of mass.

Proceeding from experimental data, dependences of change of free energy, internal energy and entropy versus time for the different types of pavements and road types have been constructed (Fig. 1) [2].

As it is possible to see from expressions (1)–(3), changes (variations) of thermodynamic functions are more sensitive to changes of temperature (seasonal and daily fluctuations). However, these changes are reversible. On the contrary, variations of thermodynamic functions caused by changes of specific heat are irreversible. The use of "average" dependences (Fig. 1) allows us to observe the evolution of changes of thermodynamic functions depending only on specific heat.

The main result obtained by physical and mathematical models is the ability to predict the pavement lifetime. A thermodynamic simulation model of changes the material of asphalt pavement during its life cycle has been constructed. The simulation model allows us to determine pavement degradation at any time. Since the heat capacity varies over time under the certain law, then this option can be selected as the base, thereby linking the variation of the thermodynamic functions with pavement lifetime.

The coefficient of free energy deficiency was input to determine the numerical values of pavement lifetimes as the relation of the module of an increment of free energy at present time to the maximum positive value of this increment for the entire period of pavement life. Determination of pavement lifetimes is obtained by an analysis of graphs, constructed using the Eq. (1).

Despite the fact that the basis of the thermodynamic approach is formulated in previous studies, a convenient formula for calculating pavement lifetime is absent.

In order to develop an approach associated with the variation of the free energy and its deficit, consider the processes of energy exchange in the system of pavement – vehicle.

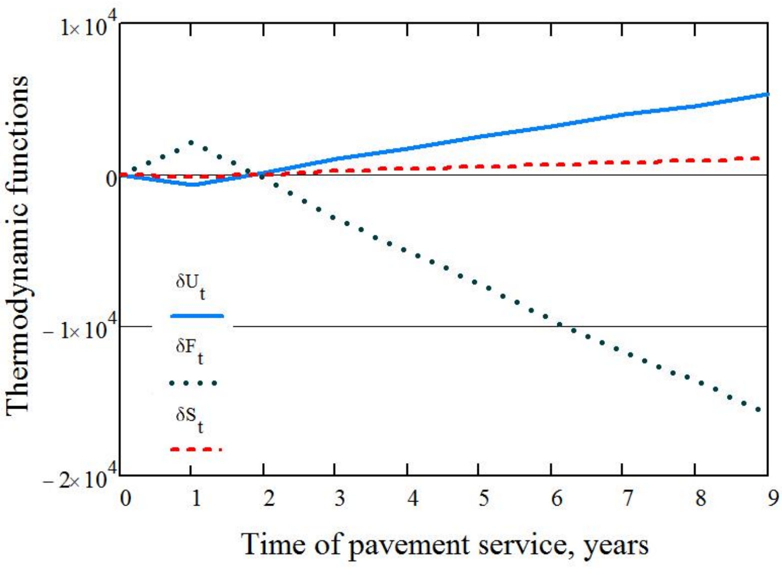

Figure 1. Dependences of change of internal energy δU, free energy δF and entropy δS versus time (fine-grained asphalt concrete of type A)

Free energy decrease is equal to the maximum full work A_{max} made by system over external solids in quasistatic thermodynamic process:

$$A_{\max} = -\Delta F. \quad (4)$$

In other words F – that part of internal energy U of system which is capable of turning into mechanical work:

$$F = U - TS \quad (5)$$

where T – the absolute (thermodynamic) temperature, S – entropy. We can define the rest of internal energy TS as the connected energy. The degradation of system (increase in its entropy ΔS) connected with internal and external processes can be slowed down by free energy reserve. The reserve of free energy is available for system at an initial stage of its usage (after the end of construction), further we can expect the replenishment of free energy level because of external forces (during service, maintenance and rehabilitation).

Since work of external forces A_{ex} over system is equal to work of system A made over external solids ($A_{ex} = -A$), from Eqs. (4) and (5) it follows that

$$\Delta S = (\Delta U - A_{\mathrm{ex}})/T. \tag{6}$$

Thus, from Eq. (6) it is possible to assume that degradation of system is connected with increase in its internal energy and can be slowed down due to work of external forces. Eq. (6) also shows influence of temperature on degradation processes.

Opening Eq. (6), it is possible to deduce the expression for entropy increment as follows:

$$\Delta S = 3\nu R \ln\frac{T_2}{T_1} - \int_{T_1}^{T_2}\frac{\mathrm{d}A_{\mathrm{ex}}}{T}, \tag{7}$$

where ν – amount of substance, R – gas constant, and T_1 and T_2 can be interpreted as boundary values of temperature at the time of pavement service (seasonal or daily fluctuations).

Eq. (7) allows us to draw a valid conclusion: the less the fluctuation of temperature, the less the value of the first summand in Eq. (7) and, therefore, the less entropy increment (degradation) of asphalt pavement. Eq. (7) is derived in approach of ν = const. However physical and chemical processes that go in pavement in conjunction with “destructive”, “negative” influence of vehicle lead to increase in amount of substance. And it, in turn, leads to increase in pavement entropy.

Vehicle positive influence on asphalt pavement condition is reflected in the second summand of Eq. (7). This summand plays a role in the recovery processes. Thus, the transport traffic has both positive and negative effects. Domination of negative effects, obviously, will lead to pavement degradation, and, on the contrary, domination of positive effects – to increase in pavement service life. It is possible to conclude that optimum transport traffic should exist (where pavement service life has the maximum value). Existence of such extreme dependence was shown in the seventies of the last century [25].

If to present Eq. (7) as a function of time, we get

$$\Delta S(t) = 3\cdot\nu(t)\cdot R\cdot\ \ln\frac{T_2}{T_1} - \int_0^t\frac{\mathrm{d}A_{\mathrm{ex}}}{T}, \tag{8}$$

where t – time passed from the initial moment of road startup.

There are two approaches will be applied to determine pavement lifetimes:

1) The analysis of changes in molar mass associated with the change in entropy and free energy;

2) A comparison of the free energy change to the amount of the internal energy.

A principal goal of this study is to develop a system of monitoring of asphalt pavement condition using the thermodynamic framework. The mechanism of the effect of specific heat on the pavement lifetime will be investigated by applying the thermodynamic approach and using the dependences of thermodynamic parameters from specific heat of asphalt concrete, in this paper. Thus, the specific objectives of this study are as follows:

- To derive the functional relationship of pavement lifetime on the basic parameter – specific heat;
- To determine the numerical values of pavement lifetimes suitable for exploitation under the Russian conditions (transportation and construction terms);
- To develop an approach that takes into account the variation of the free energy and its deficit;
- To substantiate the application of the statistical approach to pavement lifetime description of the dynamics properties of the pavement.

Methods

1) Molar mass application

We assume that asphalt concrete consists of two main substances: mineral aggregate and bitumen; with own molar masses M_1 and M_2 subsequently. Hence the molar mass of the asphalt concrete has the form

$$M = \frac{(1+k)M_1M_2}{kM_1+M_2}, \tag{9}$$

where $k=m_2/m_1$ – the relation of corresponding components of masses.

We also assume that the rate of decay of molecular links in the bitumen is proportional to their number; the molar mass of bitumen decreases under the exponential law:

$$M_2 = M_{20}e^{-\frac{t}{t^*}}, \tag{10}$$

where M_{20} – the initial molar mass of "young" bitumen; t^* – time constant (period of time when molar weight decreases by a factor of e times).

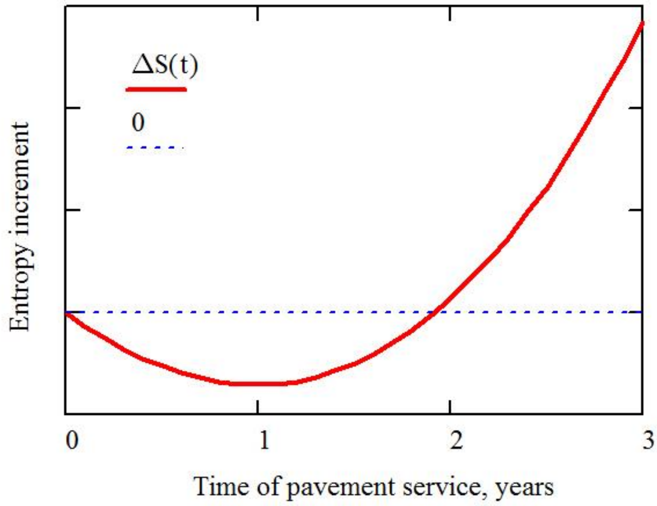

Figure 2. Qualitative entropy increment of asphalt pavement

Taking into account the reduction of molar mass of an asphalt concrete and constancy of daily work of external forces on pavement we get the following form for entropy increment:

$$\Delta S(t) = 3 \cdot \frac{m_1}{M_1} \cdot R \cdot \ln\frac{T_2}{T_1} \cdot \left(\frac{M_{20}e^{-\frac{t}{t^*}}+kM_1}{M_{20}e^{-\frac{t}{t^*}}} - \frac{M_{20}+kM_1}{M_{20}} \right) - \frac{b}{T} \cdot a \cdot t, \tag{11}$$

where a – the speed of work made by external forces; b – dimensionless coefficient considering material characteristics of asphalt concrete and technological aspects of pavement construction. Figure 2 shows the qualitative type of Eq. (11).

Material parameters of asphalt concrete, technological and climatic factors are integrally considered in time constant t^* and coefficient b.

We rewrite Eq. (9) as

$$M = \frac{(1+k)M_1M_{20}e^{-\frac{t}{t^*}}}{kM_1+M_{20}e^{-\frac{t}{t^*}}}, \tag{12}$$

The molar mass M is connected with specific heat of the asphalt concrete: $C = 3R/M$, thus Eq. (11) takes the form,

$$C(t) = 3R\frac{kM_1+M_{20}e^{-\frac{t}{t^*}}}{(1+k)M_1M_{20}e^{-\frac{t}{t^*}}}. \tag{13}$$

It is enough to make one measurement of specific heat of the asphalt concrete in some time point for calculation of time constant t^* and, according to Eq. (13), to calculate value of this constant.

Using Eq. (13), we obtain

$$t^* = t \cdot \ln\left(\frac{C(t)\cdot(1+k)M_1 M_{20} + 3RM_{20}}{3RkM_1}\right). \quad (14)$$

For example, for $M_1 = 100$ g/mol, $M_{20} = 500$ g/mol, $k = 0.1$ and value of specific heat for fine-grained asphalt concrete of *A* type (traffic – 15–20 thousand vehicles per day) $C = 1065$ J/(kg·K), one year later after the initial road startup the value of time constant calculated by Eq. (14) is equal to 5.2 years.

It is possible to determine α with help of the equations derived in [26]. We can also calculate the coefficient *b*, using Eq. (8). If to take a small period of time during which the change of entropy can be neglected, Eq. (8) allows us to obtain system of two equations with two unknowns (ΔS and *b*). The solution of that system defines constant *b* as

$$b = 3 \cdot \frac{T}{a(t_2 - t_1)} \cdot \frac{m_1}{M_1} R \cdot \ln\left(\frac{T_2}{T_1}\right) \cdot \left(\frac{M_{20}e^{-\frac{t_2}{t^*}} + kM_1}{M_{20}e^{-\frac{t_2}{t^*}}} - \frac{M_{20}e^{-\frac{t_1}{t^*}} + kM_1}{M_{20}e^{-\frac{t_1}{t^*}}}\right). \quad (15)$$

We are able to calculate constant *b* for the current values: $t^* = 5.2$ years, $T_1 = 280$ K, $T_2 = 300$ K, $T = 290$ K, $m_1 = 20$ kg. Using method from paper [25], we get $\alpha = 8.6\cdot10^7$ J/year. Calculation at the specified above values and $(t_2 - t_1) \to 0$ showed that $b \to 5.4\cdot10^{-6}$. Figure 2 models the entropy increment for asphalt concrete for above parameters. For example, Figure 3 shows the relationship of specific heat versus time (for stated above asphalt concrete and road category), this graph is constructed using the dependence: $C(t) = 7.82 \cdot (t - 0.9)^2 + 1065$. This dependence was proposed as a result of data approximation in paper [26].

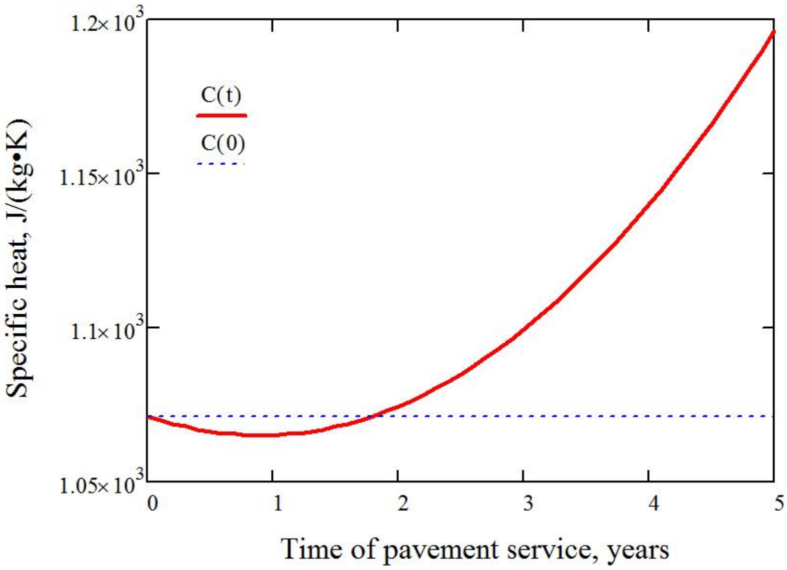

Figure 3. Dependence of the asphalt concrete specific heat versus time

Comparing Figure 2 to Figure 3, it is possible to conclude that the behavior of entropy and specific heat increments coincide qualitatively in time, it can be shown on Figure 4 by dependences of time derivatives of the above values.

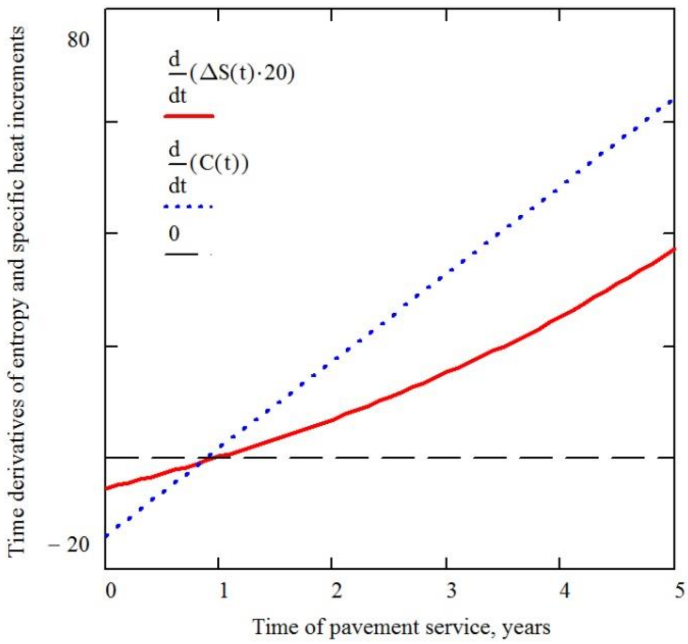

Figure 4. Time derivatives of entropy and specific heat increments

Figure 4 also shows that entropy and specific heat increments reach the minimum value approximately at the same time. Such "good" correlation between increment of entropy and specific heat serves as argument that specific heat, this thermophysical parameter, is possible to choose as basic parameter in the thermodynamic method of monitoring and predicting of a service life of asphalt pavements.

2) Free energy criteria

Using Eq. (5) and equation for internal energy of a solid state, and also considering correlation between entropy and specific heat of pavement material, it is possible to deduce the increment of free energy as follows:

$$\Delta F(t) = 3\nu RT\left(1 - \frac{C(t)}{C(0)}\right), \tag{16}$$

where $C(0)$ – value of specific heat in the initial time point.

Figure 5 models free energy increment versus time, it is constructed with use of experimental dependence of specific heat of the asphalt concrete.

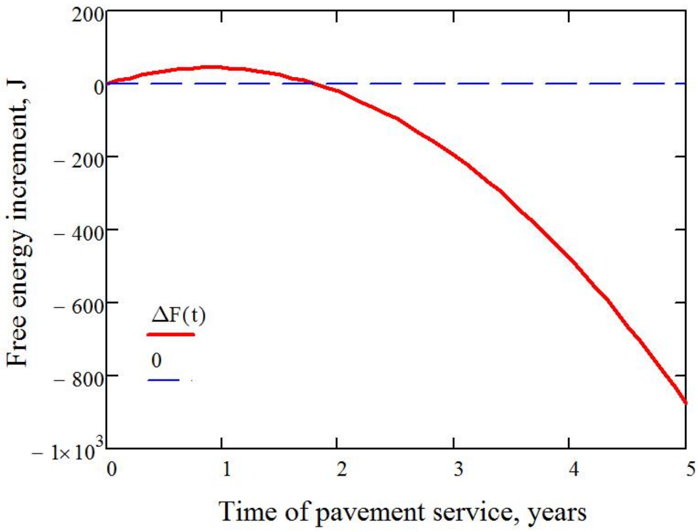

Figure 5. Free energy increment of asphalt pavement
(for 1 mole of a substance and temperature 300 K)

The analysis of Eq. (16) shows that at $C(t) = 2 \cdot C(0)$ decrease of free energy becomes equal to value of internal energy $U = 3\nu RT$. This time point can be considered critical for asphalt pavement. Figure 3 shows result of specific heat versus time that is constructed using the approximating dependence: $C(t) = 7.82 \cdot (t - 0.9)^2 + 1065$ $\left(\frac{\text{J}}{\text{kg}\cdot\text{K}}\right)$. The critical time calculated for this case $t_{\text{cr}} = \sqrt{\frac{1065}{7.82}} + 0.9 = 12.6$ years. If we define this time period as pavement lifetime before reconstruction, then it is possible to offer time interval t_r equal to some part of critical time, i.e., $t_r = 0.5 \cdot t_{cr}$, as pavement lifetime before rehabilitation, $t_r = 6.3$ years.

We can suggest another option to estimate t_r, it can be accepted as boundary value of free energy decrease, for example, 70 percent of the level of internal energy. Then from Eq. (16) it follows that $t_{\text{r}} = \sqrt{\frac{0.7\cdot 1065}{7.82}} + 0.9 = 10.7$ years.

Previous researches [26] show that specific heat for various asphalt pavements is approximated by dependences in the following form:

$$C(t) = k(t - t_0)^2 + C_0, \tag{17}$$

where k – the proportionality coefficient that defines speed of specific heat change, t_0 – time point of the beginning of specific heat increase, C_0 – value of specific heat in time point $t = t_0$ (the minimum value of specific heat).

Thus, the particular case considered above can be generalized as:

$$t_{\text{cr}} = \sqrt{\frac{C_0}{k}} + t_0 \tag{18}$$

and, respectively,

$$t_{\text{r}} = 0.5\left(\sqrt{\frac{C_0}{k}} + t_0\right) \tag{19.1}$$

or

$$t_{\text{r}} = \sqrt{\frac{0.7\cdot C_0}{k}} + t_0. \tag{19.2}$$

Though Figure 5 was obtained by different method from paper [23] it shows coincidence with previous graphs. Figure 6 models coefficient of free energy deficiency as the relation of the module of an increment of free energy at present time to the maximum positive value of this increment for the entire period of pavement life.

$$K_{\text{def}} = \frac{|\delta F|}{\delta F_{\max}}. \tag{20}$$

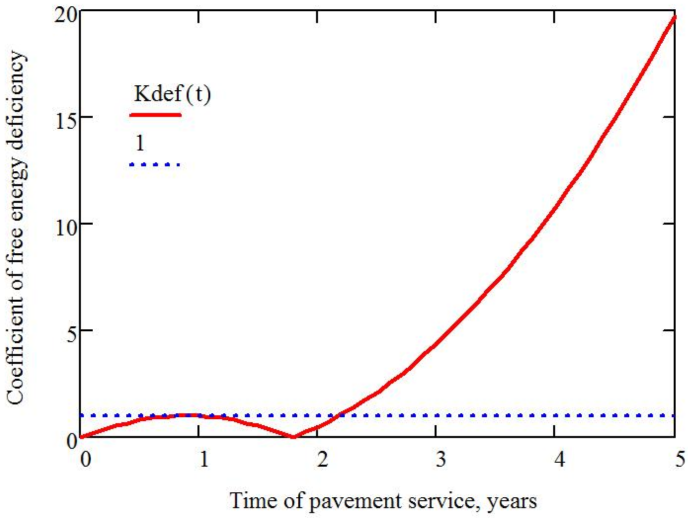

Figure 6. Coefficient of free energy deficiency

Schedule of dependence on the Figure 6 qualitatively and quantitatively identical to the same schedule in the paper [2], which is another argument in favor of the adequacy of the model.

The accepted value of coefficient of free energy deficiency can be considered as the standard criterion, determining the time of repair. In other words, a time point in which the current value of coefficient of free energy deficiency becomes more than its standard value. The question how to define the standard value of coefficient of free energy deficiency appears. Standard value of coefficient of free energy deficiency may be corresponded to the end of quasilinearity of specific heat dependences, from the point where dependences become nonlinear. Using this statement in paper [23] the standard value of coefficient of free energy deficiency was obtained within numerical values from 3 to 6, depending on pavement service conditions and type of asphalt concrete; for example, the coefficient of free energy deficiency for asphalt concrete of *A* type and the first category of road accepts value close to the left border, for porous asphalt concrete and the second category of road – to the right border. It is also necessary to note that after each repair we need to define the standard value of coefficient of free energy deficiency, because it tends to be reduced (in comparison with the previous one). Thus if we evaluate the standard value of coefficient of free energy deficiency, using Figure 6 we can define the service life of asphalt pavement.

3) Thermophysical uniformity as a condition criterion

Spatial uniformity of property of construction material can serve as an additional condition criterion. Using specific heat as the basic parameter in the thermodynamic approach, it is possible to input such criteria parameter as the index of thermophysical uniformity (ITU), that takes the form,

$$ITU = \frac{\Delta C_{\mathrm{in}}}{\Delta C_{\mathrm{pr}}}, \tag{21}$$

where ΔC_{in}, ΔC_{pr} – initial and present distribution of a specific heat, respectively.

We assume that the distribution of specific heat of asphalt concrete has normal character. This dependence reflects the specific heat deviation character of asphalt concrete of rather standard value that corresponds to the center of a curve. Figure 7 shows the distribution of specific heat during pavement lifetime. We can see that at initial stage of pavement service (curve 1) deviations from standard value are small, but then variation becomes more significant (curve 2). Values of ΔC_{in} and ΔC_{pr} also determine distribution width at the identical level concerning a maximum (in Fig. 7 it is level 0.7). From properties of normal distribution it follows that ITU has identical value on any level (i.e. it is not obligatory to consider a certain level), and also $\frac{\Delta C_{\mathrm{in}}}{\Delta C_{\mathrm{pr}}} = \frac{f_{\mathrm{pr}}^{max}}{f_{\mathrm{in}}^{max}}$.

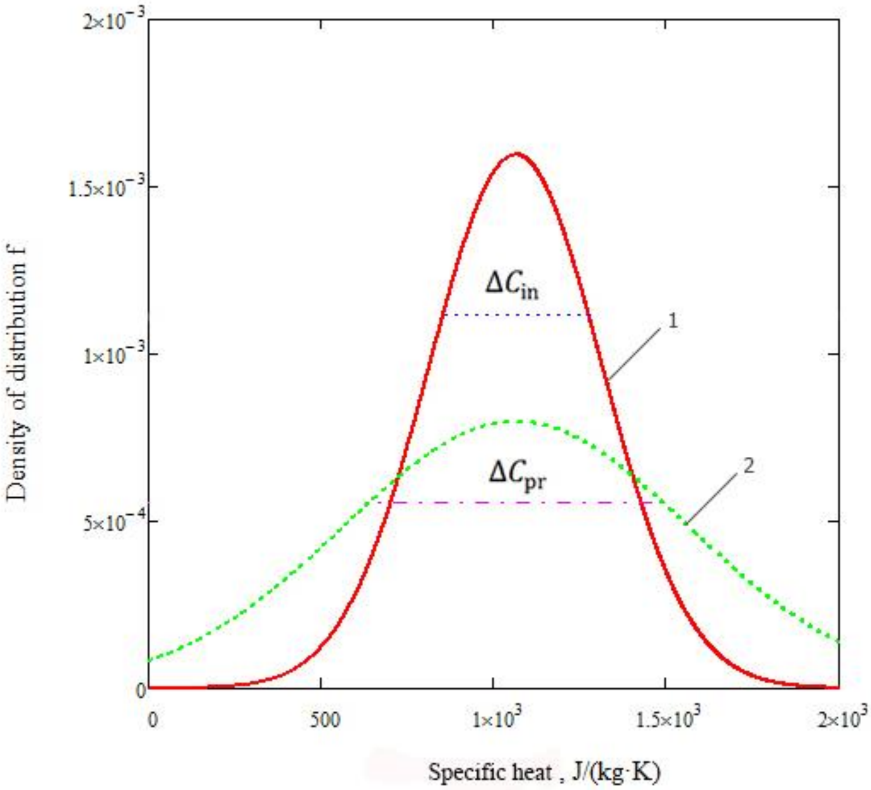

Figure 7. Normal distribution of specific heat C (density of distribution f):
1 – in initial stage of service;
2 – at present time of service of asphalt pavement

Properties of normal distribution allow us to derive more convenient equation for practical application:

$$ITU = \sqrt{\frac{\sum_{i=1}^{n}(\langle C_{\text{in}}\rangle - (C_{\text{in}})_i)^2}{\sum_{i=1}^{n}\left(\langle C_{\text{pr}}\rangle - (C_{\text{pr}})_i\right)^2}}. \qquad (22)$$

The value of *ITU* is positive and does not surpass unit. In initial time point (t = 0) $\Delta C_{\text{in}} = \Delta C_{\text{pr}}$ and, therefore *ITU* = 1.

Practice shows that the higher the quality of asphalt pavement construction is, the higher and thermophysical uniformity is, that is *ITU* → 1. In process of aging and degradation the *ITU* index decreases. The analysis of experimental data allows us to conclude that change of *ITU* during pavement service can be described adequately as follows:

$$ITU = e^{-at^2}, \qquad (23)$$

where a – the parameter depending on type and brand of asphalt concrete and service conditions, 0< a <1; t – time, years. The analysis of Eq. (23) shows that *ITU* sharply decreases before inflection point of function graph. Figure 8 shows that after the inflection point the speed of *ITU* reduction decreases. It is advisable to take this time point for time of the beginning of repair. This time point, from condition of equality of the second derivative of *ITU* to zero, is defined as

$$t_{\text{r}} = \sqrt{\frac{1}{2a}}. \qquad (24)$$

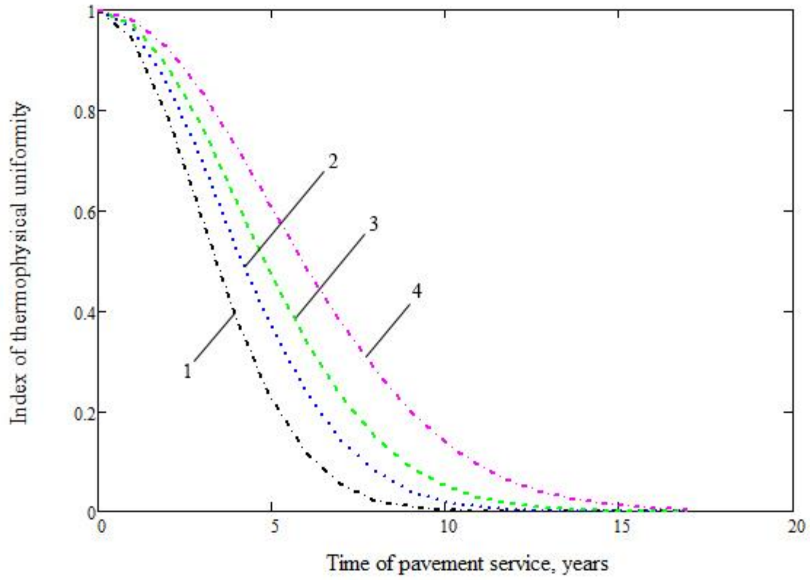

Figure 8. The character of the thermophysical uniformity index change in time: 1,2,3,4 lines are built for *a* = 0.06; 0.04; 0.03; 0.02 respectively

It is necessary to know a value of a, it can be defined at each pavement service interval, to define t_r, using equality of the right parts of Eqs. (21) and (23). Besides, ln(*ITU*) = – at^2 and using Figure 9, it is possible to calculate a as the relation of value increments of ln(*ITU*) and t^2.

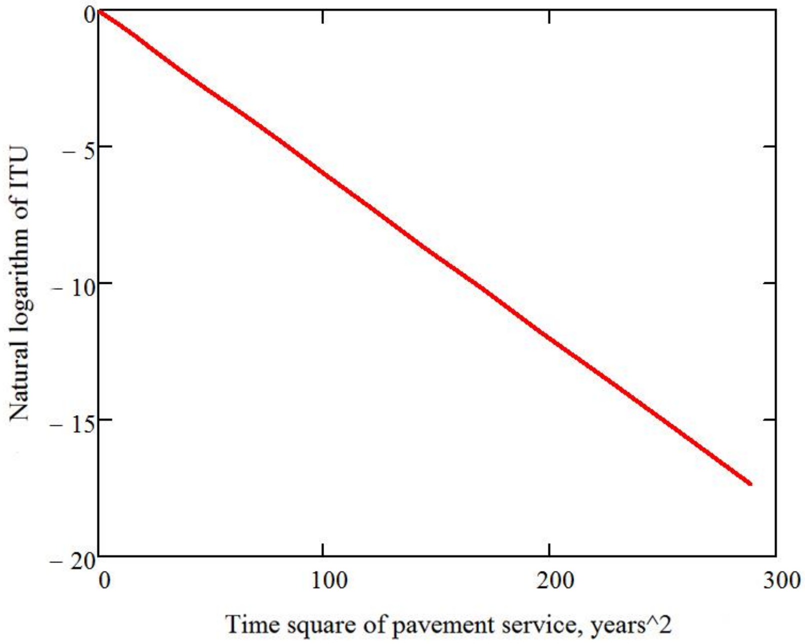

Figure 9. Linearized dependence of ITU on time square

Figure 9 also allows us to show visually the theses sounded above 1) the higher the quality of construction is, the closer the *ITU* to unit is, *ITU* → 1 (dependence in this case will be “sharper”); 2) *ITU* during service of asphalt pavement eventually aspires to zero, *ITU* → 0.

One more option of definition of repair time can be set by boundary value of *ITU*, for example, if *ITU*=0.5, then from Eq. (23) we get

$$t_r = \sqrt{\frac{\ln 2}{a}}. \qquad (25)$$

Or it is possible to find the time at which *ITU* is reduced to *e* times its initial value as follows:

$$t_r = \sqrt{\frac{1}{a}}. \tag{26}$$

At α = 0.04 year^{-2} using Eq. (24) we get $t_r = 3{,}5$ years; using Eq. (25) – $t_r = 4{,}2$ years; and finally using Eq. (26) – $t_r = 5$ years.

Results and Discussions

We used the experimental data of the previous study to calculate the values of pavement lifetime ([t] = 1 year). The results of calculation of pavement lifetime values and dependences of the specific heat are given in Table 1.

Table 1. Calculation of pavement lifetimes (years)

	1	**2**	**3**	**4**
Type of asphalt concrete / road category	Coarse porous asphalt, II grade / I-B	Fine dense asphalt, A type, I grade / I-B	Fine dense asphalt, B type, I grade / I-A	Fine dense asphalt, B type, I grade / II
Specific heat, J/(kg·K)	$C_1 = $ $= 7.82(t-0.9)^2 +$ $+1065$	$C_2 = $ $= 7.91(t-1.35)^2 +$ $+1033$	$C_3 = $ $= 9.8(t-1.25)^2 +$ $+965$	$C_4 =$ $= 7.02(t-1.2)^2 +$ $+1000$
Molar mass application, Eq. (14)				
*t**	4.7	7.0	6.4	6.2
Free energy criteria, Eq. (16) – (19)				
t_{cr} (Eq.18)	12.6	12.8	11.2	13.1
t_r (Eq.19.1)	6.3	6.4	5.6	6.5
t_r (Eq.19.2)	10.7	10.9	9.6	11.2

Despite the different approaches, pavement lifetime values calculated by Eqs. (14) and (19.1) are equivalent to results calculated previously by Eqs. (1)–(3).

Analyzing graphical representation of deterioration curves predicted by the different pavement deterioration models [27], we can conclude that if a boundary PCI (pavement condition index) value is chosen between “fair” and “poor” (= 55) as per ASTM D 6433-07, we obtain the age of the pavement equal to 6.5 - 7 years. These values are identical to the pavement lifetime values calculated by Eqs. (14) and (19.1).

According to the typical Maintenance and Rehabilitation (M&R) strategy the asphalt pavement with PCI value from 55 and below is in need of rehabilitation. Comparison of the calculated pavement lifetimes to the level of serviceability and determination of the required treatment values is a promising direction of future research.

Considering the correlation between the PCI value and the remaining service life of asphalt pavements [28], we calculate approximately 4.5 years of remaining useful lifetime for pavement with the PCI of about 90. Thus, for new pavements with age of 1–1.5 years, we also obtain rather close values of total age to the values calculated by Eqs. (14) and (19.1).

The analysis of change of PSI values (present serviceability index) as a function of time also allows us to define approximately 6–7 year cycles for application of the M&R operation [29].

Currently, experiments on the *ITU* are not available, so we cannot calculate the pavement lifetime using this method. However, we can solve the inverse problem – to determine the order of magnitude of the parameter a, Eq. (23).

Table 2 shows the results of calculations using the pavement lifetime, obtained by the Eqs. (14) and (18).

The values of parameter a calculated by Eqs. (14) and (18) differ by an order of magnitude. Since the Russian service conditions correspond to the pavement lifetimes calculated by Eq. (14), the most appropriate order of values a is the order of the values listed at the top of the Table 2. Figure 8 also models dependencies, using the value of a of the same order.

Table 2. Parameter α

The calculation formula of the parameter *α*	for C_1	for C_2	for C_3	for C_4
Parameter *α* calculated according to t^* Eq. (14)				
(24) $a = \frac{1}{2t_r^2}$	0.023	0.010	0.012	0.013
(25) $a = \frac{ln2}{t_r^2}$	0.031	0.014	0.017	0.018
(26) $a = \frac{1}{t_r^2}$	0.045	0.020	0.024	0.026
Parameter *α* calculated according to t_{cr} Eq. (18)				
(24) $a = \frac{1}{2t_r^2}$	0.0031	0.0031	0.0040	0.0029
(25) $a = \frac{ln2}{t_r^2}$	0.0044	0.0042	0.0055	0.0040
(26) $a = \frac{1}{t_r^2}$	0.0063	0.0061	0.0080	0.0058

Conclusion

Three alternative but complementary approaches are described to determine pavement service interval using either a molar weight, a change of free energy, or the uniformity of the basic parameter – specific heat based the index of thermophysical uniformity (a dimensionless coefficient).

The following conclusions can be drawn from this research:

- Pavement lifetime dependence is derived from the basic parameter – specific heat;
- Pavement lifetime values suitable for exploitation under the Russian service conditions (transportation and construction terms) are calculated analytically. Regardless of the approach used of the calculated pavement lifetimes are of the same order of magnitude.
- An approach of a variation of the free energy and its deficit has got a further development;
- The statistical approach (*ITU*) to determination of pavement lifetime, based on the analysis of the temporal changes in the spatial distribution of the basic parameter (specific heat) is proposed.

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Mikhail Zavyalov,
+7(964)7744042; zavyalov.m.a@gmail.com

Andrey Kirillov,
+7(918)1302257; kirill806@gmail.com

Михаил Александрович Завьялов,
+7(964)7744042;
эл. почта: zavyalov.m.a@gmail.com

Андрей Михайлович Кириллов,
+7(918)1302257; эл. почта: kirill806@gmail.com

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