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Thermodynamic Approaches in Assessing Quality, Efficiency and Environmental Friendliness of Asphalt Concrete

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Abstract. The experience of developed countries shows that the development of the road network and transport infrastructure determines the intensity of economic ties and is one of the most important conditions for the development of the state's economy. Optimization of the composition and production technology of asphalt concrete mixture – the basis of paved roads, is of great importance, both from an economic and environmental point of view. The production of asphalt concrete mixture directly (during the production process at asphalt concrete plants) and indirectly (during delivery from the plant to the place of installation) determines the energy costs for the production of asphalt concrete. At asphalt-concrete plants the specific energy consumption per ton of hot asphalt concrete mixture varies from 0.3 to 0.7 GJ. The range in energy costs is large. This situation indicates the presence of a significant energy-saving potential of asphalt concrete mixture thermal technology. The exergy analysis of technical systems proposed in this paper, which are operated in the asphalt concrete mixture production processes, makes it possible to judge the efficiency of energy use in their thermal units. This approach is expedient not only in the primary production of asphalt concrete mixture, but also for more environmentally friendly, energy- and resource-saving production processes for the operation of equipment during the regeneration of road asphalt concrete.

Keywords: asphalt concrete mixture, bitumen, sand-gravel mixture, mineral powder, intensive energy saving, thermodynamic analysis, exergy method, concentration component of flow exergy

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Термодинамические подходы при оценке качества, эффективности и экологичности асфальтобетона

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Аннотация. Опыт передовых стран показывает, что состояние дорожной сети и транспортной инфраструктуры определяет интенсивность экономических связей и является одним из важнейших условий развития экономики государства. Оптимизация состава и технологии производства асфальтобетонной смеси – основы дорог с твердым покрытием имеет большое значение как с экономической, так и с экологической точки зрения. Затраты энергии на создание асфальтобетона включают непосредственные (получение смеси на асфальтобетонных заводах) и косвенные (доставка с завода на место укладки) затраты. На асфальтобетонных заводах удельные затраты энергии на тонну горячей асфальтобетонной смеси изменяются от 0,3 до 0,7 ГДж, т. е. в широком диапазоне. Данная ситуация указывает на наличие значительного энергосберегающего потенциала теплотехнологии производства асфальтобетонной смеси. В статье предложен эксергетический анализ технических систем, эксплуатируемых в процессах производства асфальтобетонной смеси,

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который позволяет судить об эффективности использования энергии в их тепловых агрегатах. Данный подход целесообразен не только в первичном производстве асфальтобетонной смеси, но и в экологически более чистых, энерго- и ресурсосберегающих производственных процессах, например в работе оборудования при регенерации дорожных асфальтобетонных покрытий.

Ключевые слова: асфальтобетонная смесь, битум, песчано-щебеночная смесь, минеральный порошок, интенсивное энергосбережение, термодинамический анализ, эксергетический метод, концентрационная составляющая эксергии потока

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Introduction

One of the factors in the growth of the economy in the People's Republic of China is the colossal development of its transport infrastructure. The length of the road network in 2021 exceeded 5 million kilometers [1]. The road network in the Republic of Belarus is 87 thousand kilometers, including 75.6 thousand kilometers of paved roads [2]. Most of these roads are roads with asphalt concrete pavement. The main energy costs for creating an asphalt concrete pavement are determined by the energy spent on the production of asphalt concrete mixture (ACM) at the plant and the energy costs associated with its transportation and installation. The specific energy consumption per tonne of hot asphalt concrete mixture at asphalt mixing plants (AMP) is about 0.4 GJ. In China and the Commonwealth of Independent States (CIS) at asphalt-concrete plants (ACP), the specific energy consumption per ton of hot ACM, depending on the moisture content of the feedstock, ranges from 0.3 GJ to 0.7 GJ [3, 4]. In a comparative assessment of the specific energy intensity of various materials and processes, the ACM production can not be classified as energy-intensive. At the same time, the ACM production is a large-scale production at the plants. Consumers and producers of the asphalt concrete mixture are increasingly aware of the fact that the cost of energy resources is rising. This leads to a change in the ACM cost structure, to an increase in its energy component, which has already exceeded 35 % in the creation of the road surface.

The ACM composition is different, first of all, on the granulometric composition of mineral materials (MM). In research, we focus on the ACM of the generalized mass composition. The resulting error of this approach is comparable to the error in determining some of the initial data and most of the calculation methods. In this regard, in the context of this work, the ACM is used, while its mass composition is calculated on the total mass (Fig. 1).

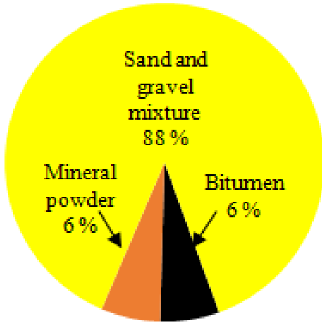

Fig. 1. Structure of generalized composition of asphalt concrete mixture

The theoretical energy costs for obtaining ACM can be determined by the difference between the sum of the enthalpies of the finished ACM and the removed moisture, on the one hand, and the total initial enthalpies of the ACM components, on the other hand. The moisture content of the sand-gravel mixture (SGM) in the initial state, ideally, should not exceed the equilibrium moisture content of 4 %. Energy costs caused by SGM over 4 % and bitumen water cut are unjustified additional costs [5]. At the same time, their value is such that it eliminates all measures to improve the operation of heat-technological units (Fig. 2, 3).

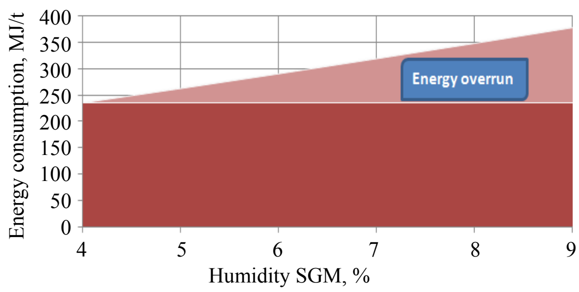

Fig. 2. Energy consumption for heating sand-gravel mixture depending on humidity

For further analysis, it is convenient to assume that the initial temperature of the ACM components is 0 °C. This is close enough to the average ambient temperature during the asphalt paving season and will not greatly affect the result and conclusions. In this case, the theoretical energy costs for preparation of ACM and their structure are determined by the value and structure of the ACM enthalpy for a specific temperature of the mixture, taking into account the costs of heating and evaporation of the equilibrium SGM moisture.

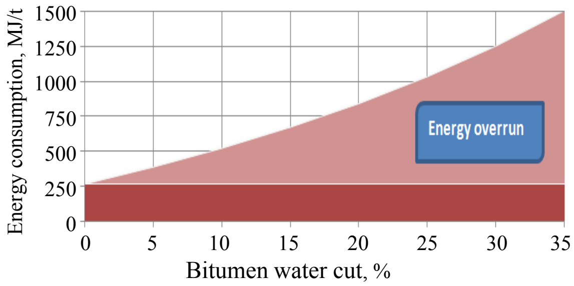

Fig. 3. Energy consumption for removing water from bitumen depending on its water content

For further analysis, it is convenient to assume that the initial temperature of the ACM components is 0 °C. This is close enough to the average ambient temperature during the asphalt paving season and will not greatly affect the result and conclusions. In this case, the theoretical energy costs for preparation of ACM and their structure are determined by the value and structure of the ACM enthalpy for a specific temperature of the mixture, taking into account the costs of heating and evaporation of the equilibrium SGM moisture.

According to technological requirements ACM temperature should be such that at the time of laying and compaction it is in the range of 80–120 °C [6]. Taking into account the delivery time and weather conditions, the ACM temperature should be within 140–180 °C after the mixing unit. In this case, the value equal to 160 °C can be taken as a characteristic value of the ACM temperature when making a general description. At this temperature, the ACM enthalpy is 0.15 GJ/t, and its structure is shown in Fig. 4.

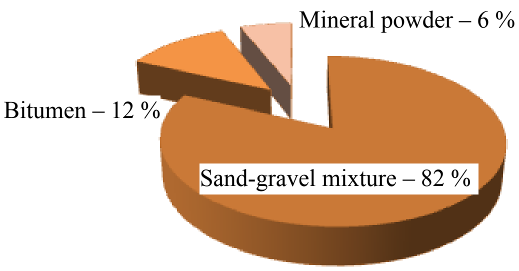

Fig. 4. Structure of asphalt concrete mixture enthalpy

Theoretical energy costs for ACM with a temperature of 160 °C, taking into account the cost of heating bitumen to 100 °C and evaporation of equilibrium moisture from SMG (≈4 %), will be 0.24 GJ/t (Fig. 5).

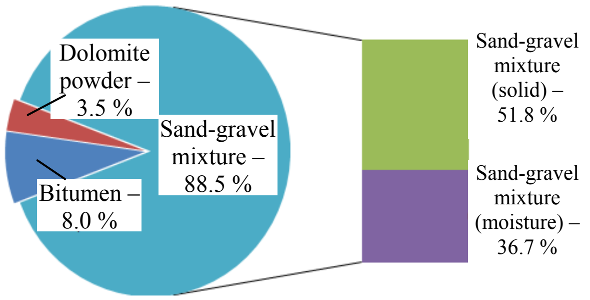

Fig. 5. Structure of theoretical energy costs for preparation of asphalt concrete mixture

The structure of real costs at asphalt-concrete plants is shown in Fig. 6.

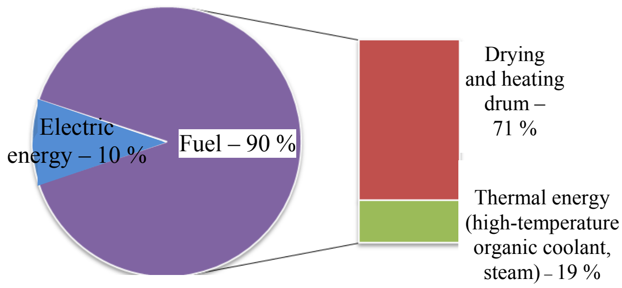

Fig. 6. Structure of incoming part of asphalt-concrete plant energy balance

An analysis of ACP energy consumption reveals a discrepancy in the technical level of heat treatment of each of the heat-technological stages of production: heating of MM requires 92 % of fuel costs, and 79 % is spent [7]. This means that there is a disproportionate over-expenditure of energy in comparison with theoretical costs in the technological stages of ACM production. There is a certain discrepancy between the levels of energy supply of subsystems: a vehicle – an asphalt-concrete mixing plant. The energy efficiency of the process of obtaining ACM against the background of the production of other materials is low. Naturally, this situation requires analysis and correction.

Another distinguishing feature of the organization of energy supply of the ACM heat technology is that heat treatment at each stage is carried out autonomously and leads to excessive consumption of energy resources. Such a decision is a common practice for enterprises built in the past period of energy abundance. Its introduction was connected:

with the ease of implementation of the technological chain; with simple operation of the equipment; with its service by low-skilled personnel. The internal organization of each of the selected sections of the ACM is considered below when analyzing the energy supply for heat technology at the ACP. Taking into account high requirements for ecology, reducing environmental pollution from thermal and harmful emissions into the atmosphere when working with ACM, this work on optimizing its production technologies is particularly relevant [8–10].

Energy components of asphalt concrete mixture

The exergy of the ACM flow contains all components of the exergy of the substance flow and is determined by the relation, MJ/t:

$$e_{ACM} = e_{pT,\,ACM} + e_{r,\,ACM} + e_{k,\,ACM}, \tag{1}$$

where $e_{k,\,ACM}$ – concentration component of the exergy of the ACM flux, MJ/t; $e_{pT,\,ACM}$ – thermomechanical component of the ACM exergy, MJ/t:

$$e_{pT,\,ACM} = \sum\left(g_j\,\overline{c}_{p,j}\Big|_0^{t_{abc}}\right)\times \times\left(\left(t_{ACM} - t_0\right) - T_0 \ln\left(T_{ACM}/T_0\right)\right), \tag{2}$$

where g_j – mass fraction ACM composition per total weight; $\overline{c}_{p,j}\Big|_0^{t_{abc}}$ – heat capacities of ACM components – specific mass, isobaric, average in the temperature range $t_0 - t_{abc}$, MJ/(tK); T_0, t_0 – ambient temperature, K; T_{ACM}, t_{ACM} – temperature ACM, °C; $e_{r,\,ACM}$ – the reaction component of the exergy of the ACM flux, MJ/t:

$$e_{r,\,ACM} = \sum g_j e_{\mu,\,j}, \tag{3}$$

where $e_{\mu,\,j}$ – specific mass chemical components of exergy of ACM components, MJ/t.

In general, ACM consists of: mineral aggregate SGM, mineral filler (mineral powder (MP)) and bitumen (B). The chemical component of the exergy of the mineral aggregate is zero ($e_{\mu,\,SGM} = 0$), since SGM is represented primarily by silicon SiO_2, whose chemical exergy is zero [11]. From the same sources, the specific mass exergy of the mineral filler $e_{\mu,\,MP} = 1045$ MJ/t is found, which is most often represented by dolomite $CaCO_3$. The value of the specific mass chemical component of the bitumen exergy $e_{\mu,\,B}$ cannot be calculated using methods intended for pure chemical compounds. The main difficulty in the calculation is that the exact molecular structure of bitumen is unknown. By its structure, bitumen is a colloidal system in which asphaltenes are dispersed, and resins and oils are the dispersion medium – a mixture of hydrocarbons and their nitrogenous, oxygenated, sulfurous and their derivatives. The chemical composition of bitumen is very complex. So, they contain saturated hydrocarbons from C_9H_{20} to $C_{30}H_{62}$. The elemental composition of bitumen varies within the limits: carbon 70–80 %, hydrogen 10–15, sulfur 2–9, oxygen 1–5, nitrogen 0–2 %.

The calculation of the chemical component of bitumen exergy is complicated by the fact that, until recently, CIS refineries produced bitumen not as a target product, for example, with light oil products, but as a residual, by-product. According to the known group composition of bitumen, the method recommended for calculating the chemical component of crude oil exergy is suitable for determining the chemical component of exergy, MJ/t [12]:

$$e_\mu = e_c\left(1066 + 67{,}4\omega + + 1875\nu + 3784\sigma + 177{,}8\xi\right), \tag{4}$$

where $e_c = 7{,}817C$ – minimum specific mass exergy of liquid hydrocarbon substances, MJ/t; ω = 6H/C; ν = 3/7·(N/C); σ = 1 + 3(H – (O – S)/8)/C; ξ = 3/8·(S/C) – dimensionless coefficients depending on bitumen composition; C, H, O, N – mass fractions of components, C + H + O + N = 1.

The composition of bitumen in this case can be averaged: C ≈ 0,70–0,85 – mass fraction of carbon; H ≈ 0,08–0,12 – the same of hydrogen; O ≈ 0,002–0,05 – the same of oxygen; S ≈ ≈ 0,005–0,7 – the same of sulfur; N ≈ 0,002–0,01 – the same of nitrogen.

Calculations of the value of the specific mass chemical component of bitumen exergy give e_μ = 38–44 GJ/t. Taking into account the errors of the calculation chain, we can write e_μ = 41 GJ/t, which is consistent with the values of chemical exergy e_μ of other petroleum products: unrefined gasoline e_μ = 46 GJ/t, fuel oil e_μ = 42 GJ/t. Taking into consideration the step of change in e_μ during the transition to a heavier fraction of oil products, the given value should be considered acceptable.

The quantity $e_{k,\,ACM}$ included in relation (1), represents the exergy component of the ACM flux, which is commonly called the concentration component. Its value is determined by the minimum thermodynamic work required to separate the components [12]. The indicated work in this case is required to overcome the adhesive interaction of bitumen with MM [6, 13]. The value of this component affects the quality of the finished ACM. It is necessary to consider the exergy transformations that occur during the process of creating ACM. Let us turn to a graphical representation of the balance of exergy of the mixing unit, in which the process of creating ACM takes place (Fig. 7).

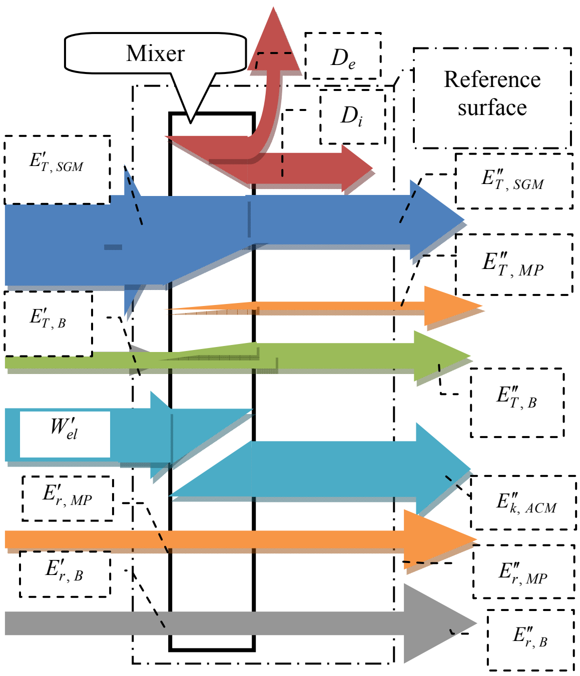

Fig. 7. Exergy transformations of asphalt concrete mixture formation process

At the Fig. 7 $E_{T,\,SGM}$, $E_{T,\,MP}$, $E_{T,\,B}$ – thermal components of exergy of sand-gravel mixture, mineral powder, bitumen flow, respectively, MJ; $E_{r,\,MP}$, $E_{r,\,B}$ – reaction components of exergy of mineral powder, bitumen flow, respectively, MJ; W_{el} – energy spent on mixing, MJ; $E_{k,\,ACM}$ – concentration component of exergy of asphalt concrete mix flow, MJ; D_e, D_i – external and internal exergy losses, respectively, MJ; upper indices (′), (″) – to denote input and output streams, respectively.

The block diagram of the mixer is shown in Fig. 8.

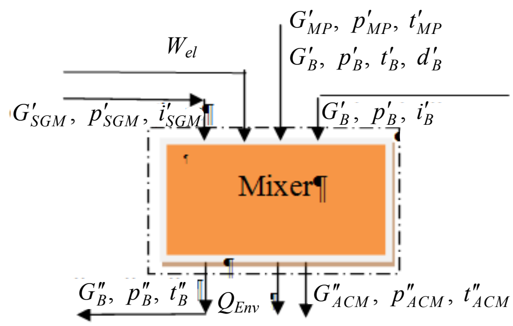

Fig. 8. Mixer flow diagram: G_B, p_B, t_B, i_B, d_B – flow rate, pressure, temperature, specific enthalpy of flow and bitumen density, respectively); G_{SGM}, p_{SGM}, i_{SGM} – flow rate, pressure, specific enthalpy of flow of sand-gravel mixture, respectively; G_{MP}, p_{MP}, t_{MP} – flow rate, pressure, temperature of mineral powder, respectively; G_{ACM}, p_{ACM}, t_{ACM} – flow rate, pressure, temperature of asphalt concrete mixture; Q_{Env} – heat flow to the environment

From the analysis of the Grassmann diagram, it follows that during the ongoing mixing process, the ACM components do not change and, therefore, are the terms of the transit exergy: $E''_{T,\,SGM}$ – thermal component of the exergy of the SGM outlet stream, MJ; $E'_{T,\,B}$ – the same of the bitumen input stream, MJ; $E'_{r,\,MP} = E''_{r,\,MP}$ – reaction component of the exergy of the MP flow, MJ; $E''_{r,\,B} = E'_{r,\,B}$ – reaction component of the exergy of the bitumen flow, MJ.

Part of the beneficial effect of the transformations in the mixer are:

• change in the thermal component of the exergy of the MP flow, in this case equal to the value of the thermal component of the exergy of the output MP flow – $E''_{T,\,MP}$, MJ. This fact follows from the fact that at the input the value of the thermal component of the MP flow exergy is equal to zero (thermal MP parameters are equal to the parameters of the environment – *Env*) and the output value determines the corresponding beneficial effect;

- change in the thermal component of the exergy of the bitumen flow, determined by the difference $E''_{T,\,B} - E'_{T,\,B}$, MJ;
- determining component of the beneficial effect – $E''_{k,\,ACM}$, MJ, – the concentration component of the ACM exergy, the appearance of which is associated with the preparation of a mixture from the initial ingredients [12].

Thus, the concentration component of ACM exergy acquires a completely new aspect – technological, reflecting the minimum required energy consumption to ensure the required product quality. Determination of $E_{k,\,ACM}$ – the concentration component of the exergy of the ACM flow gives a quantitative estimate of the minimum required energy impact in the mixer on the initial ACM components [6]. Thermodynamic approaches in assessing the quality of asphalt concrete are becoming more widespread [14]. The proposed quantitative assessment of the energy impact in the mixing unit based on the concentration component of exergy is proposed for the first time.

Physically, the possibility and legitimacy of its use follows from the following. No chemical relations occur during the creation process in the mixer, nor during laying, nor during compaction of the ACM. This allows us to speak about the invariance of the reactive component of ACM and asphalt concrete in relation to the reactive components of the elements included in their composition. It is obvious that the minimum energy of separation into the initial ACM components is determined by the energy of the adhesive interaction between MM and the bituminous binder. On the other hand, it determines the concentration component of ACM and asphalt concrete [12]. For the onset of complete adhesive interaction, one of the necessary conditions is to ensure contact of the bituminous binder with all particles of SGM and MP, including aggregated into complexes, which is achieved, first of all, in the mixer. To ensure the required contact of the entire surface of the MM and the binder, it is necessary to expend energy in the mixer. The minimum value of which, as follows from the presented Grassmann diagram (Fig. 7), is determined by the concentration component of exergy ACM – $E_{k,\,ACM}$. External D_e and internal D_i exergy losses are determined by the excess of the mechanical energy expended in the mixer over its minimum value, equal to the exergy change in the ongoing process. The exergy required for the occurrence of the concentration component of ACM is contributed by input streams and nothing else (Fig. 7). As a result of the redistribution of exergy in the course of transformations with ACM stirring, its required value is provided. As follows from the analysis of the Grassmann diagram, it can only be associated with the flow of mechanical work (Fig. 7). The work of mechanical mixing $L = W'$ can not be less $E_{k,\,ACM}$, since only in this case the key condition of exergy balance is fulfilled in the form of the relation $\sum E' > \sum E''$. This is the determining factor that makes it possible to relate the concentration of ACM exergy to the energy consumption for mixing. Thus, the adhesive interaction of the ACM components is provided through the introduction of the necessary mechanical energy for mixing in the mixer. In the ideal case, the minimum energy consumption for the formation of a mixture is determined by the adhesive interaction energy and heat treatment.

To confirm the connection between the adhesive interaction and the concentration component of ACM exergy, it is necessary to consider the process of ACM compaction and subsequent cooling of the resulting asphalt concrete sheet to ambient temperature [15]. A thermodynamic theory has been developed to estimate the duration of the overhaul period of an asphalt concrete pavement with traffic intensity which is to be established at the design stage [14, 16]. During the laying of the roadway, the quasi-dispersed material, which is ACM, is transformed into a monolithic material, which is asphalt concrete. The exergy balance of the processes for producing asphalt concrete is presented in the form of a Grassmann diagram in Fig. 9, where $E_{T,\,ACM}$ – thermal component of the asphalt concrete mixture exergy, MJ; $E_{r,\,MP}$, $E_{r,\,B}$ – reaction components of the exergy of the flow of mineral powder and bitumen included in the asphalt mix, respectively, MJ; L'_{ME} – mechanical energy for sealing, MJ; $E''_{m,\,ACM}$ – mechanical component of asphalt concrete exergy, MJ.

We restrict ourselves to a qualitative image of flows without a quantitative analysis of the energy transformations of ACM into asphalt concrete. The mechanical energy expended on compaction of the ACM layer ensures a reduction in the porosity of the dispersed material to values at which the cohesive interaction is switched on. In combination with adhesive interaction, the required strength of the resulting asphalt concrete monolith is formed.

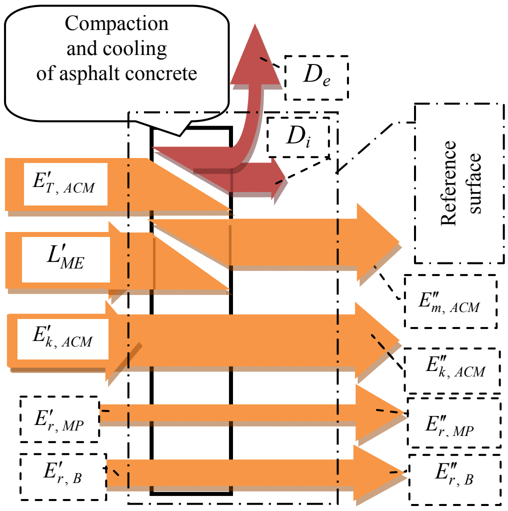

Fig. 9. Exergy transformations of the process of formation of asphalt concrete during compaction of the asphalt concrete mixture and cooling of the road bed

The cohesive bond depends on the temperature and pressure of the material. This indicates the need to attribute the energy of cohesive interaction of bitumen volumes in asphalt concrete to the thermomechanical component of the asphalt concrete exergy. The adhesive interaction in this case can be considered as the factor that determines the concentration component of the exergy which is not related to the temperature and pressure at which the substance is located. The above picture of the interactions of the components of ACM and asphalt concrete is in good agreement with the physical model of these materials (Fig. 10, 11) [17, 18]. Free bitumen fills the intergranular ACM space, defining a cohesive bond. Structured bitumen forms a film on the surface of MM, defining an adhesive bond.

In order to obtain a qualitative physical model, an energy consideration of the transformations of the transition process from ACM to asphalt concrete has been carried out in the paper. The model allows us to separate the role of cohesion and adhesion in the asphalt concrete exergy, to associate the first with the thermomechanical component, to confirm the relationship between the adhesive interaction of mineral materials with bituminous binder and the concentration component of the ACM exergy.

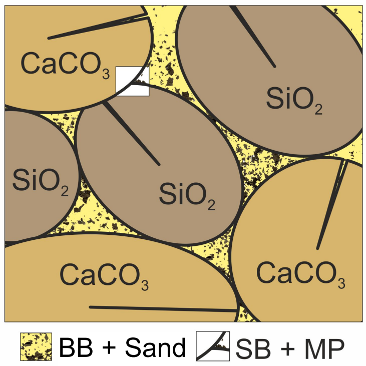

Fig. 10. Physical model of volume of asphalt concrete mixture [17, 18]: BB – bulk bitumen; SB – structured bitumen; MP – mineral powder

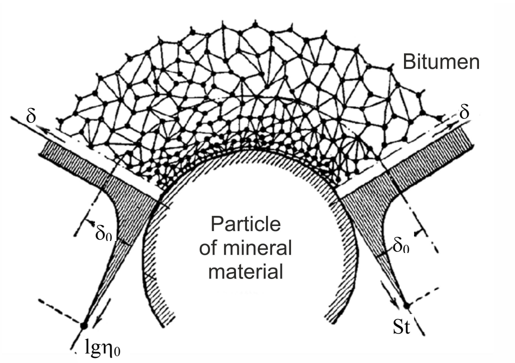

Fig. 11. Interaction of mineral materials and bitumen [17, 18]: δ – normal distance from mineral materials surface; δ_0 – thickness of structured bitumen layer; St – strength; η – viscosity

An important aspect that needs to be emphasized is the independence of the concentration component of ACM exergy from the amount of bitumen in the mixture, if it does not exceed a certain threshold value. In ACM, bitumen is divided into two types: structured or filmy and loose or bulk. The threshold minimum amount of bitumen in ACM is determined by the required amount of structured bitumen, which ensures that the entire

MM surface is covered with a film. There is a transition zone between structured bitumen (SB) and bulk bitumen (BB). In the transitional or diffuse zone, bitumen has a partially ordered structure. Its thickness varies from one to several microns. In the diffuse zone, there is a smooth transition from the properties of the bitumen of the structured film to the properties of the bitumen of the bulk zone. The structured layer of bitumen both in composition and thickness depends on the mineral substrate, which affects the composition of the bitumen film. The most active components of bitumen in relation to MM are asphaltenes containing active functional groups, due to which asphaltenes are accumulated in the structured zone. In it, high-molecular-weight bitumen compounds are ordered and form a solid-like layer, extremely saturated with asphaltenes, adjoining the mineral substrate. Asphaltenes are oriented among themselves by polar groups in chains. The film thickness depends on the size of the mineral particles and the material of the particles and, most often, does not exceed one micron. The relationship between the amount of SB and BB in ACM is considered in sufficient detail in a number of works, from which one can single out [19]. The data given in it allows you to calculate the threshold value of the bitumen content in ACM. The threshold value depends on a number of factors, primarily on the composition and size of the MM particles included in the ACM. The optimal technological thickness of the bitumen film in a mixture with optimized granulometry is the one at which the material with the highest strength is formed. The ratios between SB and BB in ACM, corresponding to the optimal technological thickness of the bitumen film, determined in [19], are shown in Fig. 12. From the analysis of the given data, it follows that in real ACM, the amount of bitumen always exceeds the threshold value determined by the amount of SB, and the reliability of determining the concentration component of exergy does not depend on it [20]. For this reason, further the question of the relationship between the value of the concentration component and the bitumen content in ACM in the context of the problem posed should be considered resolved.

The results of the evaluation according to the proposed method in finding the concentration component of the ACM exergy indicate a slight influence of the error on the results of the thermodynamic efficiency of the ACM production process and is sufficient to solve the problems of resource saving and improve the environmental situation at the ACP [21, 22].

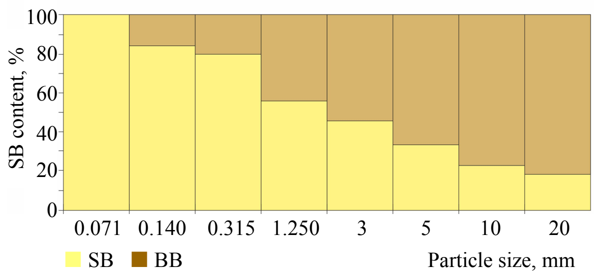

Fig. 12. Content of oriented layer of bitumen in total technological bitumen film on mineral grains in asphalt systems with increasing particle size:
BB – bulk bitumen; SB – structured bitumen

CONCLUSION

According to the results of the proposed exergy method of thermodynamic analysis, it is possible to determine the concentration component of the asphalt concrete mixture flow exergy $E_{k,\,ACM}$ and provide an objective assessment of the operation of the mixer in terms of its energy consumption ($E_{k,\,ACM}$ determines the energy minimum cost of an ideal mixer); obtain a quantitative assessment of the asphalt concrete mixture quality for technological purposes; calculate exergy flows of asphalt concrete mixture heat technology; determine absolute and relative exergy characteristics of asphalt concrete mixture production required for energy efficiency assessment.

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