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# Equipment desing automation at asphalt-concrete production modernization

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**Abstract.** The relevant task in the field of road construction and maintenance is gradual transition to the production of asphalt-concrete mixtures on polymer-bitumen binders. Most asphalt-concrete plants of small and medium capacity consider this transition as challenging due to a relatively high cost of the specialized equipment for polymer-bitumen binders production. Most proposed techniques involve the utilization of colloid mills. The practice of such mills operation shows that production lines experience long downtime periods due to the necessity of preventive maintenance and repair. A promising direction in polymer-bitumen binders manufacture is to use polymer waste materials for the bitumen modification. This provides the reduction of the modified binder costs and the solution of environmental problems. The paper deals with the problem of asphalt-concrete plants modernization to obtain polymer-bitumen binders in its own production using agitated mixers common in the chemical industry. Optimization problem is formulated for design and operating parameters of such equipment to provide required quality indicators for the resulting polymer-bitumen binders. Algorithmic and software assistance is developed to solve the set problem. The proposed technical solutions were tested when solving the modernization problems regarding the process diagram of the asphalt-concrete plant to release products on polymer-bitumen binder of its own production.

**Keywords:** design and operating parameters of the equipment, modification algorithm, machinery calculation method, polymer-bitumen binder, optimization.

## 1. Introduction

To improve the quality and the durability of the road surface in modern conditions of constantly increasing weight of the transported goods and traffic intensity, better-quality bitumen-concrete mixture based on polymer-bitumen binders (PBB) should be used [1]. To obtain modern commercially viable road construction materials, asphalt-concrete plants (ACP) can choose alternative options: either to purchase ready-made PBB from specialized enterprises, or to modernize own production and to produce PBB themselves by modifying oil bitumen with polymeric materials. In the former case, the increase in the asphalt-concrete costs can deprive enterprises of competitive advantages. Moreover, the remoteness of existing PBB-producing enterprises may hinder the solution of the problem from the logistics point of view. In Russia, there is quite a large number of regional asphalt-concrete plants, which need to be upgraded and reoriented to the use of advanced polymer-bitumen binders in road materials. Often such enterprises store petroleum bitumen in winter, when its price falls significantly,



to use it during the periods of intensive construction and maintenance of the roads. It is advisable to modify such bitumen directly at the enterprise. At present, the supply of turnkey equipment for PBB production significantly exceeds the demand due to the relatively high cost. In addition, the vast majority of technologies for obtaining PBB on an industrial scale is based on colloid mills, an expensive equipment often requiring repair. At the same time, as studies have shown the source oil bitumen can be modified to obtain PBB on a simpler and more reliable equipment, commercially available in industry, i.e. agitated devices [2]. This provides significant reduction of the capital costs for the production modernization. Moreover, additional competitive advantages are ensured by the use of research results on replacing the bitumen of expensive thermoplastic elastomers, most commonly used for the modification, by polymer wastes [3].

To solve the re-equipment problem of asphalt-concrete plants with medium and low capacity, it is necessary to develop a methodology for the equipment selection and engineering calculation of design parameters and operating variables of the bitumen modification process on the proposed equipment that provides the required performance and quality indicators of the resulting PBB.

## 2. Problem statement

The objective of developing the algorithms for computer-aided design of the equipment for bitumen modification with polymeric materials to modernize asphalt-concrete plants of average and small capacity is formulated.

To achieve the objective, it is necessary to solve the following tasks:

1. To develop a method of selection and calculation for devices providing a given performance of PBB.
2. To formulate the optimization problem for the design parameters and operating variables of the machinery to obtain PBB and to develop an algorithm for its solution.
3. To test the developed algorithm and the corresponding software when solving the modernization problem for the process diagram of the asphalt-concrete plant.

## 3. Theory

The theoretical basis of this work is laid in previous researches on the interaction of petroleum bitumen with complex modifiers based on thermoplastic elastomers, polymer waste materials and adhesive additives. The results of studies suggest rubber-bitumen binders [4] and polymer-bitumen binders [5] can be obtained with practically acceptable quality indicators under the combined effect of thermoplastic elastomers and rubber crumb regenerates from worn tires or polymer packaging waste. This opens up prospects for a real reduction in the modified binders costs compared to the traditionally used technology of modifying bitumen with expensive thermoplastic elastomers. This also solves an important problem of long-decomposed polymer waste disposal. Publication [6] considers the issues of constructing a mathematical model for the dependence of the main quality indicators of polymer-bitumen binder obtained by modifying petroleum bitumen with developed compositions of polymeric materials. The obtained dependences allow the formulation and solution of optimization problems for the polymer-bitumen binder composition.

To ensure the possibility of computer-aided design of the equipment providing the modification of petroleum bitumen with developed compositions of polymer materials, it is necessary to have a mathematical description of the components mixing in the proposed equipment. Article [7] presents a mathematical model of polymer-bitumen binder production by dispersing the developed complex modifier in the medium of bitumen. This model allows one to calculate industrial agitated devices designed for bitumen modification.

The engineering calculation method for obtaining PBB based on a complex modifier with minimal power consumption for mixing includes several stages. The aim of the first stage is to determine the required performance of the designed equipment to modify bitumen due to maximum plant performance of producing asphalt-concrete based on the resulting PBB.

Our studies have shown that to obtain polymer-bitumen binder with required parameters of penetration, melting point, ductility and elasticity, turbulent mixing conditions should be provided at circulatory Reynolds number  $Re_c > 1000$ . The mean size of the polyethylene drops with low density should be no larger than  $1.7 \times 10^{-4}$  m and Peclet number  $Pe < 0.3$  in modification process [7]. Necessary machinery performance  $G_2$  for bitumen modification is determined as follows:

where  $G_1$  is the maximum performance of the technological line on the ACP producing bitumen-concrete mixtures, focused on the use of polymer-bitumen binders;  $\varphi$  is the maximum permissible content of the binder in the ACM. Consequently, effective volume of the machinery for PBB production is:

$$V_{\Sigma} = G_1 \varphi t,$$

where  $t$  is the duration of modification process cycle.

To ensure the flexibility of production and reduced losses caused by forced downtime of the equipment, it is proposed to use two devices of the same performance working alternately. While one unit is in the process of unloading the ready-to-use PBB into an intermediate container, the second unit is in the process of modifying the bitumen. It also allows the equipment downtime to be reduced during periods of unloading the product and preparing the equipment for a new cycle of works. Our studies have shown that to obtain a polymer-bitumen binder with the required quality indicators, it is sufficient to have a process duration of about 45 minutes [8]. Considering the above stated, the device volume can be found following the expression:

$$V = 0.75 G_1 \varphi, \quad (1)$$

To use the mathematical description of the mixing process, it is necessary to provide a geometric similarity of the designed devices with the laboratory installations of diverse productivity values, which were used to construct a mathematical model and verify its adequacy [7]. Therefore, the choice of an agitated device calculated according to (1) with volume  $V$  is carried out due to the principle of hydrodynamic similarity at  $H/D \approx 1.2$ , where  $H$  and  $D$  are, respectively, the height and diameter of the designed device [9]. The task of designing a device for obtaining PBB is set as follows:

For the selected device with the specified geometric parameters of the casing: height  $H$  and diameter  $D$ , type and number of the agitators on the shaft  $z_m$ , parameters of the continuous and disperse phases ( $\rho_{sp}, \rho_{dp}, \mu_{sp}, \mu_{dp}, \phi$ ), one should find design parameters (agitator dimensions) and mode variable (agitator rotation speed) that provide minimum supplied power  $N$  at:

relations determined due to the equations of the mathematical model [7]:

$$M_t = M_b + M_{in} \quad (2)$$

$$M_b = \frac{\pi}{2.2} \cdot \frac{\lambda}{Re_c^{0.25}} \cdot \gamma \cdot G_d^{2.75} \cdot v_{av}^{1.75} \quad (3)$$

$$M_{in} = G_d \cdot z_{bp} \cdot \left[ \zeta_{bp} \cdot f_{bp} \cdot \frac{v_{av}^2 \cdot r_{bp}}{(0.5 \cdot D)^3} \right] \quad (4)$$

$$M_t = z_m \cdot \zeta_m \cdot k_N \quad (5)$$

$$k_N = 0.25 - 0.67 \cdot v_{av} + 0.5 \cdot v_{av} \quad (6)$$

$$\rho = \rho_{dp} \cdot \phi + \rho_{sp} \cdot (1 - \phi) \quad (7)$$

$$N = 3.87 \cdot \zeta_m \cdot z_m \cdot k_N \cdot \rho \cdot n^3 \cdot d_m^5 \quad (8)$$

$$d_K \approx 0.13 \cdot \left( \frac{\sigma}{\rho_{sp}} \right)^{0.6} \cdot \left( \frac{N}{\rho_{sp} \cdot V} \right)^{-0.4} \quad (9)$$

$$Pe = \frac{\omega_{dr} \cdot H}{D_T} \leq 0.3 \quad (10)$$

$$D_T = 0.435 \cdot n \cdot d_m \cdot D \cdot \sqrt[3]{\frac{z_m \cdot \zeta_m}{G_d \cdot \gamma}} \quad (11)$$

$$\omega_{dr} = \left( \frac{d_k^2 \cdot |\rho_{dp} - \rho_{sp}| \cdot g}{18 \cdot \mu_{sp}} \right) \cdot \left( \frac{3 \cdot (\mu_{sp} + \mu_{dp})}{2 \cdot \mu_{dp} + 3 \cdot \mu_{sp}} \right)$$

$$\mu = \frac{\mu_{sp}}{1 - \phi} \cdot \left( 1 + 1.5 \cdot \phi \cdot \frac{\mu_{sp}}{\mu_{sp} + \mu_{dp}} \right) \quad (13)$$

and permissible limits:

$$Re_c = \frac{n \cdot d_m^2 \cdot \rho}{\mu} \geq 1000 \quad (14)$$

$$9 \cdot 10^{-5} \leq d_k \leq 1.5 \cdot 10^{-4}, \quad n \leq 1.5 \quad (15)$$

$$G_d = \frac{D}{d_m} \geq 1.5 \quad (16)$$

$$0.01 \leq \phi \leq 0.07 \quad (17)$$

where  $M_t$  is the torque, N m;  $M_b = M_w + M_{bot}$  is the moment of resistance for the device casing, N m;  $M_w$  and  $M_{bot}$  are moments of resistance on the walls and bottom of the device, N m;  $Re_c$  is circulatory Reynolds number;  $\lambda$  is the resistance coefficient of the device casing;  $\gamma$  is the parameter of the device filling;  $G_d$  is the diameters ratio for the device  $D$  and the agitator  $d_m$ ;  $v_{av}$  is the mean value of the circumferential speed, rad/s;  $z_{bp}$  is the number of internal partition walls;  $\zeta_{bp}$  is the hydraulic resistance coefficient of the deflecting baffle wall;  $f_{bp} = h_{bp} \cdot b_{bp}$  is the area of the wall projection on the meridian plane, m<sup>2</sup>;  $h_{bp}$  is the sinkage height of the deflecting baffle walls in the medium, m;  $b_{bp}$  is the width of the deflecting baffle walls, m;  $r_{bp} = 0.5 \cdot (D - b_{bp})$  is the walls arrangement radius, m;  $z_m$  is the number of the agitators on the shaft;  $\zeta_m$  is the resistance coefficient of the agitator;  $k_N$  is the coefficient linking the power with the characteristics of the circular fluid flow in the device;  $\rho$ ,  $\rho_{sp}$ ,  $\rho_{dp}$  are the density values of the mixture, disperse phase and the continuous phase, kg/m<sup>3</sup>;  $\phi$  is the concentration of the disperse phase, vol. fraction;  $d_k$  is the mean diameter of the disperse phase drops, m;  $\sigma$  is interfacial tension, N m;  $V$  is the volume of the medium being mixed, m<sup>3</sup>;  $Pe$  is Peclet number;  $\omega_{dr}$  is the setting (rise) rate of the particles or drops, m/s;  $D_T$  is the coefficient of macro-scaled turbulent transfer (turbulent diffusion), m<sup>2</sup>/s;  $g$  is the gravitational acceleration, m/s<sup>2</sup>;  $\mu$ ,  $\mu_{sp}$ ,  $\mu_{dp}$  are dynamic viscosity values of the mixture, continuous phase and disperse phase, respectively, Pa·s;  $n$  is the rotation rate of the agitator, rev/s. To solve the optimization problems (2) - (17), the following algorithm and software have been developed [10].

#### 4. Results of optimization problem solution and discussion

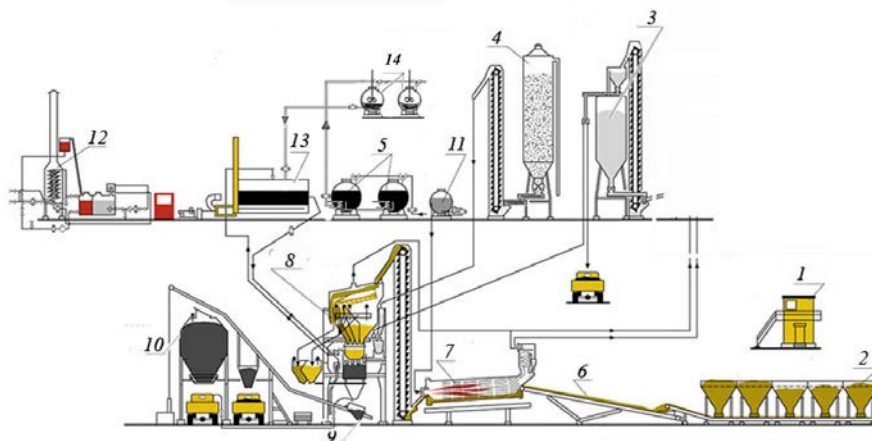
The developed technical solutions were tested when solving the modernization problems regarding the process diagram of the asphalt-concrete plant OOO "Agropromdorstroi" (Tambov) to release products on polymer-bitumen binder of its own production.

Fig. 1 shows a modernized process diagram for ACM production equipped with developed mixers 14 and providing asphalt-concrete mixtures based on a proposed polymer-bitumen binder.

Bitumen from storage tanks 5 enters one of the mixers 14 to produce PBB, a developed complex modifier is also fed there, and a modification process proceeds for 45 minutes. After the completion of the road binder modification process in the first mixer, the finished mixture is fed into the input device 13 in the mixing unit. At this time, bitumen and a complex modifier are supplied into the second mixer and the modification process begins. Working alternately units 13 provide a predetermined performance for PBB.

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At the mentioned enterprise asphalt concrete was prepared at the modular asphalt mixing unit AMOMATIC-160 (Finland). The calculated demand of the enterprise for PBB was 6 tons / hour.



**Figure 1.** Process diagram of ABM production: 1 - computer control panel; measuring bins of mineral materials; 3, 4 – silos of own and imported fillers; 5 – tanks for bitumen; 6 – band conveyers; 7, 8 - dryer and mixing units; 9 – bucket; 10 - silo storage; 11 - diesel fuel tank; 12 – oil heating station; 13 – input device; 14 - mixers for the PBB production

Considering the dispersion process duration of 45 min, 2 mixers with the mixed medium volume  $V = 6.3 \text{ m}^3$  were proposed for use, built into the process diagram of the ABM production and working alternately. The proposed vertical industrial batch apparatus with blade agitators and a working volume  $V = 6.3 \text{ m}^3$  was selected by the geometric similarity method of [11] with a medium filling height of 1.6 m, with two deflecting baffle walls completely immersed in the mixed medium, to reduce the circumferential velocity component with a corresponding increase in the axial and radial components. The solution of the supplied power minimization for the mixing allowed one to determine the rotation frequency of the agitator  $n=1/5 \text{ rev/s}$  and its diameter  $d_m=1.4 \text{ m}$ . These values result in mean LDPE drops diameter of the resulting PBB equal to  $d_k = 1.37 \cdot 10^{-4} \text{ m}$ , i.e. it lies in the necessary range of  $d_k = 9 \cdot 10^{-5} \div 1.5 \cdot 10^{-4} \text{ m}$  [11]. The calculated mixing power values are 16 kW. It is recommended to equip the mixer with a gear motor of Mr-1-315U-14-100 brand, whose electric motor power is 18.5 kW. In this case, the calculated Reynolds number in the selected apparatus is  $Re_c = 2.95 \cdot 10^4$  that satisfies the mathematical model requirements of the present turbulent mixing mode, as  $Re_c \geq 1000$  [7].

## 5. Conclusion

The task of developing the algorithms for computer-aided design of the equipment for bitumen modification with polymeric materials to modernize asphalt-concrete plants of average and small capacity is considered.

The method of selecting and calculating the devices ensuring the specified performance and the PBB quality is developed, when modifying the petroleum bitumen with complex modifiers in the composition of thermoplastic and plastic waste materials. The algorithm was is devised for solving the optimization problem of design parameters and operating variables for the machinery to obtain PBB. The algorithm and the corresponding software were tested when solving the modernization problem for the process diagram of the asphalt-concrete plant.

The choice of equipment is determined by the geometric similarity of the devices with laboratory units used to build a mathematical model of the modification process for petroleum bitumen complex modifiers included in thermoplastic elastomers and polymeric waste materials. The obtained results can be used to modernize asphalt concrete-plants of medium and low capacity for using polymer-bitumen binders produced on the plant itself, with minimal changes in the process diagram. The utilized equipment in the form of agitated devices is characterized by simplicity and reliability. The

Use of the proposed device eliminates the need for cold-chamber usage, whose operation is associated with forced downtime periods of production lines.

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