SIMULATION OF THE INFLUENCE OF MINERAL MATERIALS' HOMOGENEITY ON THE STABILITY OF ASPHALT CONCRETE MIXES GRADING

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1. INTRODUCTION

Road pavement asphalt concrete has some features of heterogeneity due to which its separate sections have worse characteristics than adjacent sections, and they deteriorate faster. Such type and range of asphalt concrete characteristics' variation is often impacted by the instability of the used asphalt concrete mixture (ACM) composition: separate lots of the produced ACM have different quantity of the same components (crushed stone, sand, cold imported fillers, bitumen). Even if portions (batches) of highly stable mass mineral materials (3-5 hot fractions, reclaimed dust, cold imported fillers) are dosed accurately, the ACM produced in an asphalt concrete mixing plant is not homogeneous due to their segregation ([1]).

Asphalt concrete mixing plants controlled by modern computers enable to achieve sufficiently stable dosing of materials; however, ACM produced in them is not homogeneous ([2]). It shows that the homogeneity of the ACM is influenced by the variation of mineral materials' grading used for its production.

The mathematical models constructed by us ([3,4]) enabled to reveal the impact of technological factors on the size of dispersion of each mineral component's (crushed stone, sand, cold imported fillers) quantity. Average values of experimental investigation data obtained from the study of the composition and technological parameters of the ACM produced in seven non-computerized asphalt concrete mixing plants during one working day were used. It was found out that in the produced ACM the standard deviation value of crushed stone quantity (particles larger than 5 mm) depends by 42 % on the grading variation of the used mineral materials and by 58 % on the dosing errors; of sand (particles of 5-0,71 mm) by 70 % and 30 % respectively, cold imported fillers (particles smaller than 0,71 mm) by 60 % and 40 % respectively. These data show that the actual variation of mineral materials' grading reduces the stability of the ACM composition at almost the same rate as their dosing errors. When very strict permissible limits of dosing materials are used in the asphalt concrete mixing plant controlled by the computer, their dosing errors may be minimized, and the stability of ACM components' quantity may be increased. The variation of ACM components' quantity, occurring due to the heterogeneity of the used finally dosed mineral materials, may be reduced in the asphalt concrete mixing plant hot bin by setting up anti-segregation equipment; by screening the mixture of mineral materials into a greater number of hot fractions (5, 6 or 7); by reducing their contamination with by-particles and by maintaining the constant amount of hot fractions in the sections of the bin ([3,5]).

Average values of mineral materials' grading, obtained by taking and studying a certain number of separate samples of each material, are applied in the methodologies of designing asphalt concrete mixture of optimal composition. In fact, each mineral material is heterogeneous, and its grading varies around the mean within the interval of a certain width. When mineral materials of unstable grading are used, ACM with the different quantity of its components in separate lots is produced as well.

The mixture of mineral materials dried and heated in modern asphalt concrete mixing plants is screened into four or five hot fractions, the grading of which varies as well. The variation range depends on a majority of factors, and it can vary not only between separate mixing plants but in the same plant as well. According to our information, the impact of the used mineral materials' homogeneity on the scattering of the produced ACM grading has not been studied yet. It is supposed that due to the heterogeneity of mineral materials, the designed ACM of optimal grading according to the values of screenings passing through all control sieves, complying with the requirements of standard R35-01 ([7]) will be produced so that some of its lots will not conform to these requirements: they will not be within the lower and upper permissible limits. Denying or confirming its correctness shall verify this hypothesis. Therefore, the methods of mathematical simulation are applied.

The aim of the research is to show through mathematical simulation the variation of asphalt concrete mixture grading, when per cent values of the used mineral materials' particles' full screenings passing through control sieves vary within the interval of different width.

The aims of the research are to obtain the curves of asphalt concrete mixture grading and to calculate statistical indices (arithmetic mean, standard deviation, dispersion, etc.) for each sieve by changing the composition of mineral materials so that the full screenings passing through control sieves complied with the normal distribution (the values of their statistical indices are known) and equal ratio materials' mass was maintained (specified for the mixture of the designed mark).

2. SIMULATION ALGORITHM

The algorithm is illustrated by one sample of ACM grading simulation: hot ACM of 0/16-A mark is produced from seven mineral materials. The initial data of mineral materials used to produce the mixture, i.e. means $\overline{X}$ and standard deviations σ of full screenings passing through control sieves, are presented in table 1. When applying the data from the carried out experimental investigations, the following values of standard deviations are presented: minimum – $\sigma_{\min}$, medium – σ_{m} and maximum – $\sigma_{\max}$.

Stage one – design of the pilot asphalt concrete mixture

First of all, the pilot asphalt concrete mixture was designed, i.e. the quantity in per cent of asphalt concrete mixture mineral materials in the mixture was estimated. To solve the problem, the mathematical analogue presented in [9, 10, 11] was used:

$$\left.\begin{aligned}
&\sum_{j=1}^{m} c_j \cdot y_j \to min, && (a)\\
b_{min,i} \le &\sum_{j=1}^{m} a_{ij} \cdot y_j \le b_{max,i}, \quad i = 1, 2, \ldots, n, && (b)\\
&\sum_{j=1}^{m} d_{vj} \cdot y_j \le h_v, \quad v = 1, 2, \ldots, s, && (c)\\
&\sum_{j=1}^{m} y_j = 1, && (d)\\
&y_j \ge 0, && (e)
\end{aligned}\right\} \qquad (1)$$

where c_j is the weight multiplier of mineral material j, y_j is the quantity of mineral material j of an asphalt concrete mixture in parts of the unit, m is the number of mineral materials, a_{ij} is the quantity of mineral material j in percent that pass through sieve i; $b_{\min,i}$, $b_{\max,i}$ are limited quantities of a mineral part of asphalt concrete mixture in percent that can be passed through sieve i; n is the number of sieves; d_{vj} is the coefficient of additional inequality v corresponding to mineral material j; h_v is the limit value of additional inequality v; s is the number of additional inequalities.

Table 1. Statistical data of mineral materials' grading used to produce asphalt concrete mixture

Serial number	Mineral material	Statistical index	Size of control sieves' mesh, mm							
			0,09	0,25	0,71	2	5	8	11,2	16
1	Cold imported fillers	$\overline{X}$	83,6	99,4	100	100	100	100	100	100
		σ_{min}	0,60	0,02	0	0	0	0	0	0
		σ_{m}	1,15	0,11	0	0	0	0	0	0
		σ_{max}	2,20	0,24	0	0	0	0	0	0
2	Reclaimed dust	$\overline{X}$	79,5	98,1	99,8	100	100	100	100	100
		σ_{min}	0,78	0,12	0,04	0	0	0	0	0
		σ_{m}	1,32	0,25	0,14	0	0	0	0	0
		σ_{max}	2,71	0,32	0,24	0	0	0	0	0
3	Hot fraction 0-2	$\overline{X}$	18,3	41,7	58,0	69,9	100	100	100	100
		σ_{min}	1,58	3,39	4,12	2,49	0	0	0	0
		σ_{m}	2,81	5,71	6,88	4,50	0	0	0	0
		σ_{max}	4,04	8,03	9,64	6,48	0	0	0	0
4	Hot fraction 2-5	$\overline{X}$	2,6	9,1	9,6	11,5	96,8	100	100	100
		σ_{min}	1,03	1,26	1,44	2,37	0,90	0	0	0
		σ_{m}	1,39	1,71	2,09	3,24	1,35	0	0	0
		σ_{max}	1,75	2,16	2,73	4,12	1,80	0	0	0
5	Hot fraction 5-8	$\overline{X}$	0,3	0,4	0,5	0,6	1,9	91,6	100	100
		σ_{min}	0,11	0,21	0,24	0,30	0,71	1,70	0	0
		σ_{m}	0,17	0,27	0,31	0,38	1,14	2,19	0	0
		σ_{max}	0,22	0,33	0,39	0,46	1,58	2,69	0	0
6	Hot fraction 8-11	$\overline{X}$	0,2	0,3	0,4	0,6	0,8	10,6	86,7	100
		σ_{min}	0,04	0,11	0,13	0,18	0,21	1,89	2,46	0
		σ_{m}	0,08	0,24	0,31	0,35	0,42	2,53	3,64	0
		σ_{max}	0,12	0,37	0,49	0,51	0,62	3,16	4,82	0
7	Hot fraction 11-16	$\overline{X}$	0,1	0,2	0,4	0,7	1,0	2,9	20,0	70,4
		σ_{min}	0,03	0,13	0,16	0,23	0,48	0,61	1,77	1,98
		σ_{m}	0,06	0,21	0,27	0,36	0,55	0,90	2,82	3,33
		σ_{max}	0,09	0,29	0,37	0,49	0,62	1,19	3,87	4,69

Table 2. Quantities of mineral materials in the pilot ACM of 0/16-A mark

Mineral material	Quantity, %
Cold imported fillers	0,5
Reclaimed dust	1,3
Hot fraction 0-2	33,6
Hot fraction 2-5	17,7
Hot fraction 5-8	11,8
Hot fraction 8-11	6,8
Hot fraction 11-16	28,3

Table 3. Values of particular points of the grading curves

Sieve size, mm	Limit curves of ACM of 0/16-A mark, %		Pilot ACM curve, %
	min	max	
0,09	3	9	8,1
0,25	7	25	17,5
0,71	15	33	23,2
2	25	40	27,6
5	36	55	53,1
8	46	68	65,5
11,2	57	80	76,5
16	90	100	91,6

The object function (1*a*) is a numerical value of optimal criterion of the designed ACM mineral part. For example, if c_j is the price of one mass unit of *j* mineral material, the numerical value of the object function equals to the price of one mass unit of ACM mineral part. Such task is usually called the task of minimal price. Inequalities (1*b*) limit the quantities of ACM mineral part passing through respective sieves, i. e. they express the field of solutions mathematically. The inequalities (1*c*) mathematically express technological limitations (there may be none of them). For example, these inequalities can be used for limitation of a maximum or minimum quantity of certain mineral material in a mixture. The equation (1*c*) shows that variables are expressed as parts of a unit, and the inequality (1*d*) guarantees the validity of solution.

The aim of identifying ACM mineral materials' quantity in per cent in the mixture was not to obtain the optimal solution according to one or another optimal criterion. The main task was to ensure that all mineral materials were used in the designed mixture since all finally dosed materials, making up the section of its largest and smallest particles, are used when producing ACM. In exceptional cases, cold imported fillers or reclaimed dust may not be used. When reclaimed dust is not used, it is stored in air purification equipment, and later is used when producing ACM of lower mark or is eliminated from the production process, for example, dumped. Since cold imported fillers and reclaimed dust are of similar grading, partial optimization task with the ratio between cold imported fillers and reclaimed dust set in advance is frequently used when selecting the optimal ratio of all mineral materials' mass ([8]).

When considering the possibility of using all mineral materials in the pilot mixture, inequalities of the mathematical model were of great use (1*c*). Versatility of this mathematical model was confirmed again. The findings of calculations are presented in table 2. Table 3 presents values of particular points of 0/16-A mark hot ACM limiting curves and the designed mixture grading curve. They show that the ACM designed according to full screenings passing through control sieves comply with all permissible limit requirements.

Stage two – simulation of full screenings passing through control sieves

The research carried out by us showed that the per cent of mineral materials' full screenings mass passing through control sieves distributes according to the normal distribution. It is only full screening which deviates from the normal distribution passing through the sieve with the largest mesh, where they make up ca 100 %.

In the second stage of simulation, when mean $\overline{X}$ and standard deviation σ of mineral material's full screening passing through control sieve are known, the theoretical function ordinate of the normal distribution (normal distribution density) is calculated and the curve is drawn:

$$p(x) = \frac{1}{\sigma\sqrt{2\pi}} \cdot e^{-\frac{(x-\overline{X})^2}{2\sigma^2}} . \qquad (2)$$

Only part of the section below the theoretical curve of normal distribution, covering 0.9973 of the normal distribution diagram area, is investigated. This part is obtained by taking away sections equal to 3σ on both sides of the mean of full screenings. Let us call part of this section the calculated section of the theoretical curve of normal distribution. Its beginning and end are the smallest and the largest values of mineral material's full screenings passing through control sieves:

$$B_{\min} = \overline{X} - 3\sigma , \qquad (3)$$

$$B_{\max} = \overline{X} + 3\sigma . \qquad (4)$$

The simulation of full screenings passing through control sieves is illustrated by the example of 0-2 mm hot fraction's screenings passing through 0,71 mm control sieve ($\overline{X} = 58{,}0\%$, $\sigma_m = 6{,}88\%$). The theoretical curve of normal distribution and its calculated section of the sieve under investigation are presented in fig. 1.

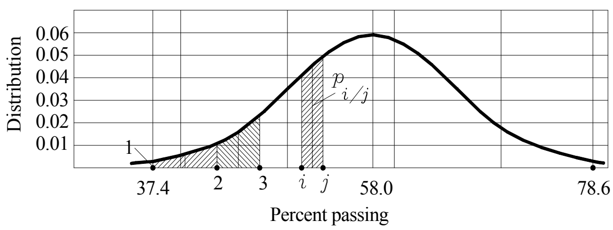

Fig. 1. *Theoretical curve of normal distribution and calculated section of screenings passing through 0,71 mm control sieve*

When the calculated section of the theoretical curve of normal distribution is identified, values of mineral material's full screenings passing through control sieve, complying with the theoretical curve of normal distribution, are calculated. The following algorithm is used.

1. The area of the theoretical curve of normal distribution per one value is calculated:

$$a = \frac{A}{n}, \tag{5}$$

where A is the area of the theoretical curve diagram of normal distribution above the calculated section, n is the number of mineral material's full screenings passing through control sieve separate values set during simulation (in the example under investigation it equals to 64).

2. The following step of simulation is identified:

$$\Delta x = \frac{B_{max} - B_{min}}{r}, \tag{6}$$

where r is any number at least 100 times bigger than n (the bigger this number is the more precise the calculation is).

3. One step (Δx) is added to the smallest value of the calculated section; thus the calculated interval is obtained.

4. The central point of the calculated interval is identified.

5. The ordinate (density) of the theoretical function of normal distribution is calculated for the central point.

6. The obtained density is multiplied by the calculated interval; thus, the calculated area is obtained.

7. The difference between the calculated area and area a is verified. If the difference is larger than the assumed criterion of accuracy, one-step and parts 4, 5, enlarge the calculated interval 6 of algorithm are repeated. This cycle is continued until the difference between the calculated area, compared with area a, becomes smaller than the assumed criterion of accuracy (it is accepted that the criterion of accuracy is equal to the half of the last change of the calculated area). If at the end of the cycle the value of the mineral material's full screenings passing through control sieve is less than zero, it is considered equal to zero; if it is more than 100, it is considered equal to 100.

8. When the difference between the calculated area and area a is less than the assumed criterion of accuracy, the last point becomes the initial point of the new calculated interval. The simulation step (Δx) is added and algorithm stages 4, 5, 6, 7 are repeated. For example (fig. 1), the calculated area of the interval, the initial point of which is i, and the final point of which is (at the moment of investigation) j, is $a_{i/j} = p_{i/j}(\frac{x_j - x_i}{2})$, here $p_{i/j}$ – density of normal distribution, calculated for central point ($\frac{x_j - x_i}{2}$) of interval ij using the formula (2).

Table 4. Hot fraction 0-2 of sieve 0,71 mm full screenings simulated values

No	Value (%)	No	Value (%)	No	Value (%)	No	Value (%)	No	Value (%)	No	Value (%)	No	Value (%)	No	Value (%)
1	40,6	9	50,5	17	53,6	25	56,0	33	58,2	41	60,4	49	62,9	57	66,3
2	44,7	10	50,9	18	54,2	26	56,3	34	58,5	42	60,7	50	63,2	58	66,8
3	46,2	11	51,4	19	54,6	27	56,6	35	58,7	43	61,0	51	63,6	59	67,5
4	47,2	12	51,8	20	54,9	28	56,8	36	59,0	44	61,3	52	64,0	60	68,3
5	48,1	13	52,2	21	55,2	29	57,1	37	59,3	45	61,6	53	64,4	61	69,2
6	48,8	14	52,6	22	55,4	30	57,4	38	59,6	46	61,9	54	64,8	62	70,3
7	49,4	15	52,9	23	55,7	31	57,7	39	59,8	47	62,2	55	65,2	63	72,1
8	50,0	16	53,3	24	56,0	32	57,9	40	60,1	48	62,5	56	65,7	64	75,9

The calculations are completed when the required number of full screenings passing through control sieve values (n) is obtained. It is recommended to verify the obtained results by calculating the standard deviation of the obtained normal distribution. If the accuracy is not achieved, the larger number r is accepted and the algorithm is repeated. The values of full screenings of the sieve under investigation are presented in table 4.

Calculations are carried out for all mineral materials and all sieves by using the proposed algorithm. Therefore, before starting to simulate asphalt concrete mixtures, we have to obtain values of seven materials after 64 full screenings of each sieve. The graphs of possible grading curves' scattering fields of all mineral materials are presented in fig. 2.

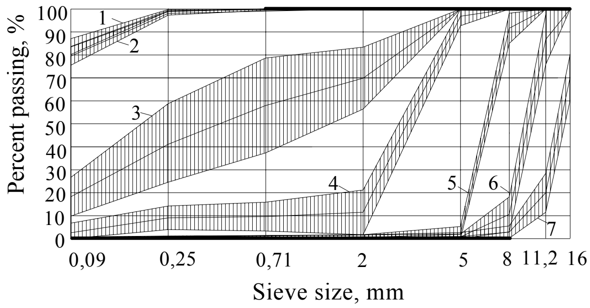

Fig. 2. *Grading curves' scattering fields of all mineral materials*

Stage three – simulation of asphalt concrete mixtures

Using the generator of random numbers, the grading curve is selected for each mineral material. The condition that larger (or the same amount) of mineral material passes through sieves with larger mesh size if compared to the amount of the material passing through an adjacent sieve of smaller size, is verified. On the basis of the simulated grading curves of all mineral materials, ACM grading curve is calculated (the applied solution of the task under investigation is presented in table 2). This stage of algorithm is carried out the necessary number of times. In this work the number of such grading curves was 2000.

Table 5. Results of the calculated experiment (after 2000 iterations)

Sieve size, mm	Values of special points of the simulated mixtures' grading curves, %											
	σ_{min}				σ_m				σ_{max}			
	medium	standard deviations	limited min	limited max	medium	Standard deviations	limited min	limited max	medium	standard deviations	limited min	limited max
0,09	8,1	0,54	6,47	**9,72**	8,1	0,93	5,29	**10,9**	8,0	1,31	4,05	**11,9**
0,25	17,2	1,09	13,9	20,5	16,9	1,84	11,4	22,4	16,4	2,46	8,97	23,8
0,71	23,0	1,31	19,1	27,0	22,6	2,14	16,2	29,1	21,9	2,72	**13,7**	30,0
2	27,6	0,88	**24,9**	30,2	27,5	1,54	**22,9**	32,2	27,5	2,15	**21,1**	34,0
5	53,1	0,20	52,5	53,7	53,1	0,30	52,2	54,0	53,1	0,37	52,0	54,2
8	65,5	0,28	64,6	66,3	65,4	0,38	64,3	66,6	65,4	0,48	64,0	66,9
11,2	76,4	0,50	74,9	77,9	76,4	0,81	74,0	78,9	76,4	1,08	73,2	79,7
16	91,6	0,53	90,0	93,2	91,6	0,88	**89,0**	94,3	91,6	1,28	**87,8**	95,4

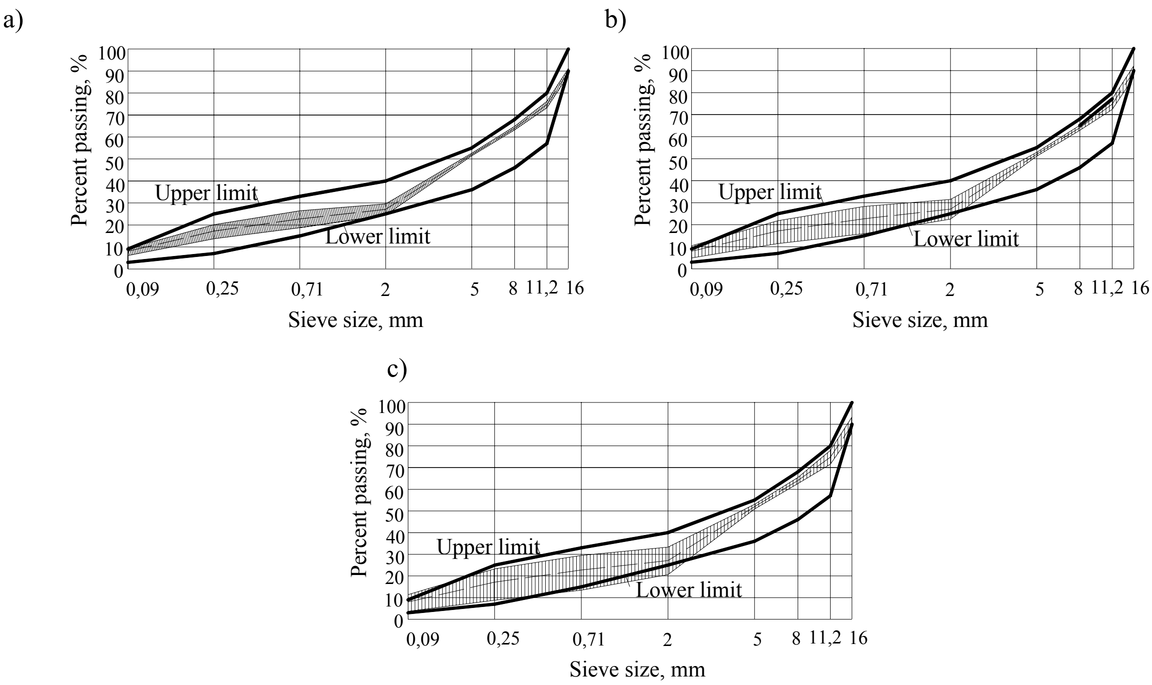

Fig. 3. *Grading curves' scattering fields of pilot ACM: a) standard deviation σ_{min} is used, b) standard deviation σ_m is used, c) standard deviation σ_{max} is used*

Finally, arithmetic means $\overline{X}$ and standard deviations σ of full screenings are calculated for each sieve. The results of the numerical experiment are presented in table 5. Beside the values of particular points of the simulated average grading curve of the mixture, a possible distribution of such curves is presented. The table shows that standard requirements are not met on certain sieves (values of full screenings passing through control sieves which do not comply with the standard requirements are presented in bold in the table). It is obvious that the greatest number of infringements (four) is found when maximal values of standard deviations are applied during simulation. The graphs of the calculated experiment are presented in fig. 3. ACM full screenings passing through 0,71 mm control sieve are scattered within the widest range. The screening makes up 22 % and is less than 50 %. Theoretically and practically the standard deviation of screenings of particles making up 50 % of the mixture is the largest ([3,4]). Having added material dosing errors, which are bigger for larger hot fractions, the widest scattering section of the produced ACM would be similar to those particles (sieves) that make up 50 % of the mixture.

3. CONCLUSIONS

1. Due to the change of production technological parameters and raw materials' characteristics, poor quality of transportation, storage and delivery, mineral materials used to produce asphalt concrete mixture are heterogeneous. On a certain section their grading fluctuates around the arithmetic means of full screenings passing through control sieves. Even extremely precise dosing of stable mass heterogeneous mineral materials' doses, the composition of separate ACM lots is not the same and varies within a certain range depending on the homogeneity of the used mineral materials.

2. Having carried out the calculated experiment with seven mineral materials of different homogeneity, complying with the real values of minimum, medium and maximum standard deviations of their full screenings passing through control sieves, it was found out that the grading of the designed ACM varies within the widest range on that section (sieve) which is made of mineral materials' particles of the greatest variation. Particles ($\overline{X} \approx 22\%$) passing through 0,71 mm sieve ($\sigma_{\text{min}} = 1{,}29\%$, $\sigma_{\text{m}} = 2{,}06\%$, $\sigma_{\text{max}} = 2{,}66\%$) have the greatest ACM standard deviation, influenced by the heterogeneity of the used materials (without dosing errors) since the major part of it is made up of hot fraction 0-2 mm of the highest variation range.

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