Magazine of Civil Engineering. 2024. 17(1). Article No. 12505

Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 625.852

DOI: 10.34910/MCE.125.5

Calculation of the influence of various compaction on the wear resistance of asphalt concrete using material loss calculation approach

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Keywords: air voids, asphalt, abrasive wear, asphalt compaction, wear model, asphalt pavements, experimental investigations, wear resistance

Abstract. Rutting is the most common and most dangerous defect of asphalt pavements. One of the problems of northern countries such as the Russian Federation is abrasive rut due to studded tire loading. Precise prediction of the asphalt concrete abrasion and wear resistance allows improving the durability and reliability of asphalt pavements. Several laboratory tests are used for the prediction of asphalt concrete abrasion resistance. An abrasive wear model of asphalt concrete is needed to predict wear resistance changes under different conditions. The aim of this article is to evaluate compaction quality effect and air voids value on the abrasion resistance of asphalt concrete. To estimate the influence of the percentage of connected voids on abrasive wear of asphalt concrete, an asphalt wear model was presented. This model is based on G.Y. Lee's approach. This approach divides the abrasive processes into normal abrasion and particle loss. Air voids lead to the aggregate loss and affect the abrasion resistance of the asphalt pavements. Calculation of these effects is possible using G.Y. Lee's approach. Calculations of the lost particles include the empirical coefficient X (1/mm) characterizing the influence of the pores on the lack of adhesion to the aggregate particle surface and the influence of the lack of adhesion on the fraction of lost particles. The Prall test was used for the abrasion resistance estimation. The saturation degree method was used for the estimation of compaction quality and air voids content. For the coefficient estimation, 63 samples of different mixes were tested. The mixes were used for the construction of the Republic of Tatarstan road network. The used asphalt concretes correspond to requirements of Russian standards GOST 9128-2013 and GOST 31015-2002. The experiments show good reliability of the presented model. This model predicts abrasion resistance of asphalt concretes under uncompaction and provides insight into the abrasive wear processes in the asphalt concretes. Furthermore, the study results allow us to improve the laboratory tests precision by 2.3 % by excluding the uncompaction effect during the comparison of the results.

Citation: Baimukhametov, G., Gayfutdinov, R., Khafizov, E. Calculation of the influence of various compaction on the wear resistance of asphalt concrete using material loss calculation approach. Magazine of Civil Engineering. 2024. 17(1). Article no. 12505. DOI: 10.34910/MCE.125.5

1. *Introduction*

Fast and safe roads between cities and regions is the most vital component of every country. The Russian Federation has more than 1.4 million km of roadways including 1 million km of roads with concrete pavement. Rutting is one of the most dangerous defects of pavements; it can result from permanent deformation or abrasion. Most roads of the Russian Federation are located in regions with cold climates, which leads to damages to roads during the winter season. Abrasive ruts have become a commonplace with the increasing traffic and the emergence of studded tires. Many researches aimed to confirm the abrasion genesis of the ruts on heavy traffic roads [1]. Abrasion rutting is a common problem for the Nordic countries, the northern states of USA, et.al. [2].

This problem has been under study in different countries. In 1980s, the government of Japan began investigating complaints about increasing dust pollution and rut propagation in different cities. After public litigations pursued by civil society organizations it was decided to reduce the use and distribution of studded tires in Japan. These government limitations were accompanied by studless tire use education programs carried out in different cities. Studless tires have better performance than the studded tires in the case of dry and wet surface without snow. Tests in the ice crust conditions showed that accurate and effective using of studless tire can have the same performance as a studded tire [3]. As a result, the rut propagation and dust pollution reduction was achieved in Sapporo within the three years of the requirements enactment. Despite a small increase of the vehicle accident rate these measures were admitted as an expedient by the Japanese government and society [4]. In the Nordic countries this problem has become sever in the second half of the last century. Many researches were performed to estimate the effect of studded tires on the pavement. In Sweden, regular and lightweight studs damage on the pavement was compared by Swedish National Road and Transport Research Institute. Based on the above statistical data, it was calculated that the studded tire damage causes above 1.5–2 times more road maintenance costs, including the road wear and the environmental damage [5]. In the Baltic countries, similar calculations were performed by Vilnius Gediminas Technical University. It was concluded that the use of studded tires brings more than 38 million EUR losses. Despite the road accidents, it was concluded, that the Baltic countries have to prohibit studded tires use [6]. The researches performed in the United States show that the annual cost to repair the damage caused by studded tires in Alaska is approximately $13.7 million and it has significant effect for the other northern states [7]. Thus, the performed researches emphasize the significance of abrasive wear resistance. Therefore, it is important to research the abrasive wear properties of asphalt concretes.

a) b)

Figure 1. Wear rut investigation in Kazan: (a) rut propagation monitoring by Glavtatdortrans; (b) transverse profile of rut by the KGASU [8].

SOI “Glavtatdortrans” supervises all of the region roads of the Republic of Tatarstan and controls the quality of roads. Abrasive wear investigation was carried out in SOI “Glavtatdortrans” due to rut propagation on the new roads (Fig. 1. a). Before it, in 2016 the Kazan State University of Architecture and Engineering did a research to confirm the wear nature of the ruts on the main streets of Kazan city (Fig. 1. b). The rutting became a common problem for the Russian Federation and the Republic of Tatarstan particularly. It affects both asphalt and rigid pavements. The investigations of these types of defects were performed in the Russian Federation by many researchers [9]. The relevance of the investigation in this direction is emphasized by the increasing number of cement concrete pavement roads. The president of the Republic of Tatarstan ordered to construct such pavements using local road construction materials. Abrasion resistance is a critical parameter for the cement concrete roads in contrast to the asphalt pavements with the bitumen binders, which have the ability to remove a fraction of microcracks in the asphalt concrete structure. The understanding of the processes between the pavement and studded tires is necessary for the safe and reliable road network construction in the future.

Several researches were performed to evaluate the properties of asphalt concrete, which affects the abrasion resistance. Field measurements collected in Alaska and analyzed by the National Academy of Sciences show that the best abrasion resistance of asphalt concrete can be achieved using a polymer modified binder with a hard aggregate in the asphalt pavement. Good binder quality can lead to higher toughness of material and abrasion resistance of asphalt concrete, while hard aggregate improves the abrasion resistance of asphalt concrete [10]. Different properties of asphalt concrete were estimated several times in the Nordic countries. It was concluded that aggregate properties and a type of mix grading have the most influence on the asphalt pavement abrasion resistance. Increasing the maximum aggregate size and the amount of a coarse aggregate improve the abrasion resistance of asphalt concrete. However, it is impossible to unlimitedly increase the coarse aggregate size due to the huge noise pollution of such pavements [11, 12]. Increased abrasion resistance of aggregate can be used for the high abrasion resistance asphalt concrete production. Several researches were performed to estimate the effect of various types of an aggregate for the asphalt pavements abrasion resistance [2, 13]. The previous researches of the SOI "Glavtatdortrans" show the influence of the aforementioned properties of asphalt concrete on the asphalt concrete abrasion resistance and note the air voids content effect [8].

The effect of air voids on the abrasion resistance of asphalt concrete was explored in several studies [14–17]. Air voids can reduce the asphalt concrete abrasion resistance due to different causes. One paper [15] studying the raveling resistance of the porous asphalt pavements affected by hydrocarbon spills noticed the air voids effect on the raveling resistance. The influence occurs both from the side of the decrease of asphalt concrete strength and the susceptibility to the erosion of the asphalt concrete by water and the other conditions. A few air voids can lead to severe rutting, similar to the case of low compaction [14]. However, the increasing of air voids leads to the reduction of asphalt strength. It leads to freeze damage of asphalt concrete and low fatigue life [18]. The importance of this parameter stipulates the requirements for pavements.

Asphalt concrete can be classified as a composite material. Nowadays several models for the different abrasion types exist. Existing models of composite wear are mostly related to the pin-on-disc type of abrasive wear due to the typical exploitation conditions of such composites. Existing models are based on the tribological properties of several particle and fiber reinforced composites [19, 20]. The G.Y. Lee's composites abrasion model includes the reinforcement particle removal (Fig. 2); this process is similar to the wear processes in asphalt concretes. G.Y. Lee's approach is based on the inverse rule of mixtures, and includes the composite microstructure. It can be used for the simplified modeling of the abrasive wear of asphalt concrete including the air voids and uncompacting effect [21].

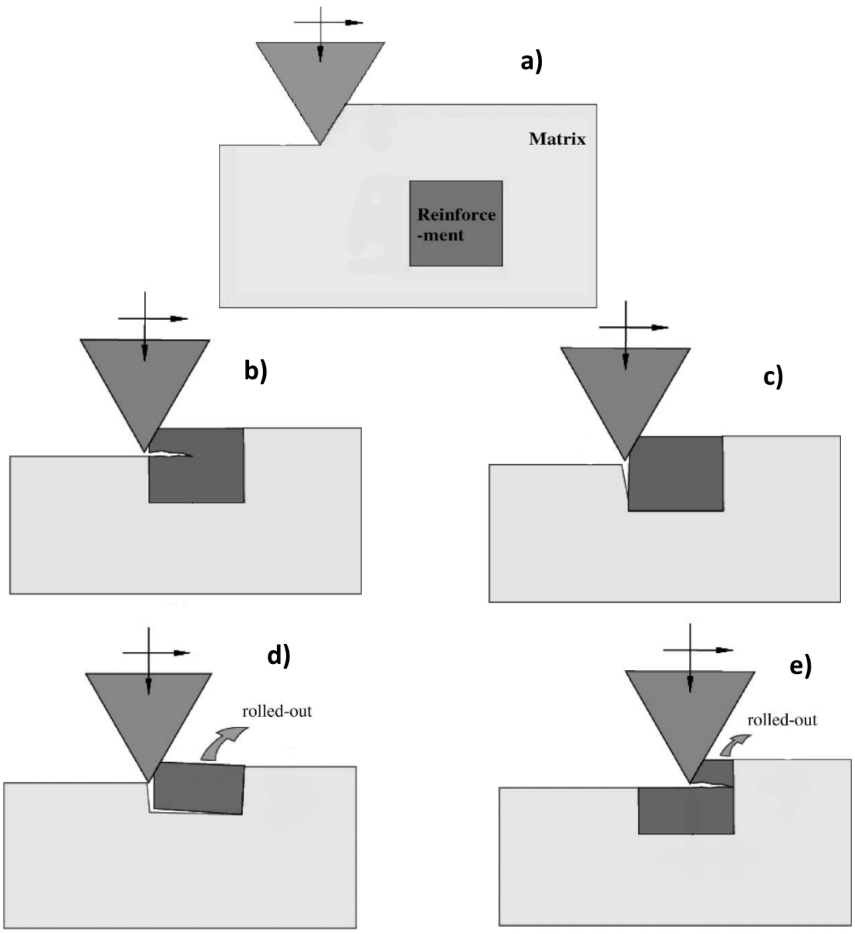

Figure 2. General schematic drawing of two-phase composite in abrasion with simplified sliding wear geometry: plowing mechanism (a); cracking at the matrix (b)/reinforcement (c); particle removal at the matrix (d)/reinforcement (e) [21].

Calculation of the air voids effects in asphalt concretes is important due to various compaction requirements for the asphalt concrete pavements. The existing testing methods and abrasion resistance requirements do not include uncompacting and air voids effect on the asphalt material. It can lead to the misunderstanding of pavement properties and reduction in durability of pavement in the northern countries with severe winter exploitation conditions. The existing models of composite abrasion resistance use and the empirical data can reduce the mix design errors and increase the reliability of abrasion resistance evaluation.

The aim of this study is to determine the compaction quality effect on abrasion resistance of asphalt pavement. This is necessary for accurate prediction of the development of pavement wear on highways and accurate selection of materials in the design of asphalt concrete mixes. The study includes the existing model of composite materials wear modification for the case of studded tire wear of asphalt concrete. For the empirical determination of the equation coefficient, various mixes were tested. The analysis of obtained data is needed for the coefficient determination.

2. Materials and Methods

2.1. Applied materials

The research includes testing of various grades of stone mastic asphalt and dense graded asphalt with different types of aggregate and binder. Tests and materials were made according to the Russian series of standards (GOST). GOST include dense graded and stone mastic hot mix asphalt with nominal maximum sizes of 5/10/15/20 mm regulation. The difference between the nominal dimensions of the aggregate from European and American ones is that the shape of the sieve hole is round according to Russian standards [22].

For this study, sixty-three asphalt samples of mixes were tested during 2018–2020. The mixes included different mix types: stone mastic asphalt concretes and dense graded asphalt concrete type A. In the Russian Federation, specifications on stone mastic asphalt concrete (SMA) are given in GOST 31015-2002 “Bituminous stone mastic mixtures and stone mastic asphalt. Specifications” and specifications on dense graded mix type “A” in GOST 9128-2013 “Asphaltic concrete and polimer asphaltic concrete mixtures, asphaltic concrete and polimer asphaltic concrete for roads and aerodromes. Specifications”. Grading of the tested mixes is shown in Fig. 3. Nominal sizes 2.5; 5; 10; 15; 20 mm in Russian standards corresponds to 2; 4; 8; 11,2; 16 mm in European and US standards due to round sieve opening shapes. Comparing of Russian mixes with international ones by the EN and other protocols is not necessary for this study.

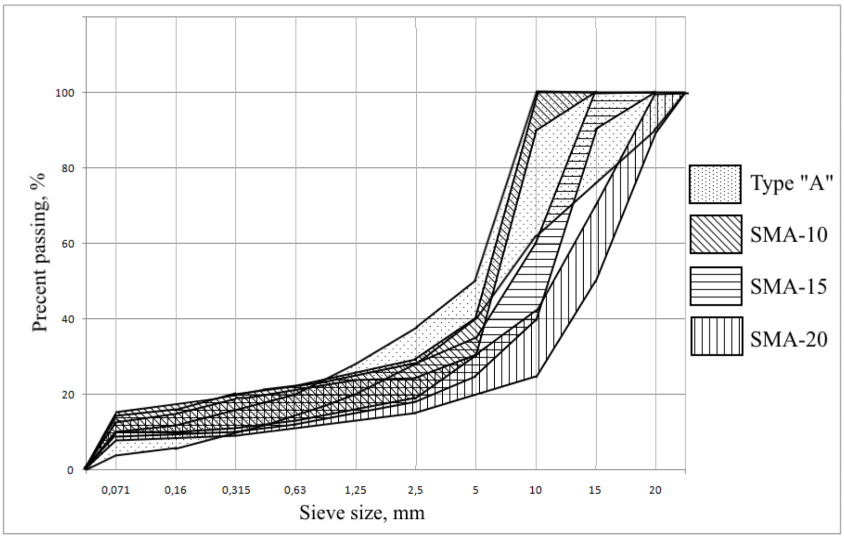

Figure 3. Tested mixes grading limits according to GOST 9128-2013 and GOST 31015-2002 [8].

Testing mixes fell into nineteen groups according to the mix type, type of binder and type of aggregate. Mix samples are shown in Table 2. Each mix was used in the real construction of the road network of the Republic of Tatarstan. Aggregates include stone from the different carriers of the Russian Federation as a “Sangalyck”, “Pervouralskiy”,”Sheleyka” et al. Binders include the polymer modified binders (styrene-butadiene-styrene) and non-modified binders.

2.2. Numerical methods

Asphalt concrete is defined as a particle composite material containing three parts: mastic or binder as a matrix, coarse and fine aggregate as a reinforcement and pores inclusion. Besides, the abrasive wear of asphalt concrete can be shown as a two-dimensional process with a wear surface, which can be represented as a line. In this case, wear surface is defined as a surface of asphalt concrete in contact with an abrasive medium such as a studded tire or a steel ball in laboratory experiment and loses the material due to abrasion (Fig. 4,a).

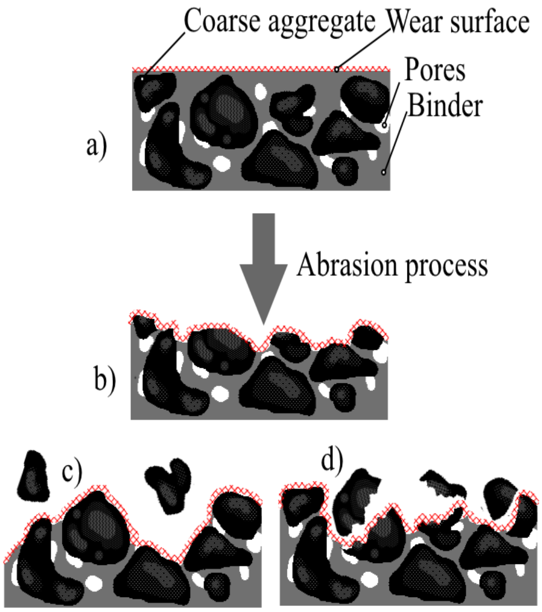

Figure 4. Asphalt concrete abrasive wear process: a) Original asphalt concrete before abrasion, b) regular abrasion process is plowing, c) particle removal, d) cracking [8].

G.Y. Lee reports that the mechanism of composites abrasive wear can occur in three general scenarios: plowing, cracking and particle removal [21]. In terms of asphalt concrete, it means the abrasion of aggregate with binder (Fig. 4 (b)), aggregate fragmentation due to removal (Fig. 4(c)) and cracking (Fig. 4(d)). Plowing is a simple process which can be modeled by several models [23]. Thus, the abrasion resistance of asphalt concrete depends on abrasion resistance of aggregate, binder and pores. However, the abrasion resistance of pores and binder is much less than the abrasion resistance of aggregate. The mutual influence of the various content can be described using two main approaches. The first is an inverse rule of mixtures introduced by Khrushchev and Babichev:

$$1/W_c = V_1/W_1 + V_2/W_2, \tag{1}$$

where W_c is the wear rate of the composite; W_i is the wear rate of the material, meaning wear of each material separately under an equal abrasion loading, the subscript means the number of components; V_i is the volume part of the materials, the subscript means the number of components.

In Eq. (1) $1/W_i$ means wear resistance of the component. Eq. (1) is based on the assumption that each component of the composite wears at the equal rate. The equal wear rate means straight wear surface and uniform wear of each component due to its fraction. For example, the wear rate of aggregate is less than the wear rate of binder and pores in the case of asphalt concrete and wear resistance primarily depends on the wear resistance of asphalt aggregate, which is perfectly observed in practice [10, 24].

The second approach is given by K.-H. Zum Gahr and is aimed to explain the experimental data. The governing assumption is an independent wear of each component of the composite, summary wear is an algebraic sum of each component wear multiplied to its volume fraction.

$$W_c = V_1 \cdot W_1 + V_2 \cdot W_2. \tag{2}$$

The geometrical representation of this approach is the lack of continuous wear surface and nonlinear process of wear. Despite the nonlinear wear process representation, according to practice, this approach is disadvantageous for the pores problem due to complexity of pores representation in equations and the nature of abrasive wear in case of flat pavements (Fig. 4 (b)). For our problem, both of these approaches are required for different parts of abrasive wear evolution. The first approach in Eq. (1) needs to be modified due to the curved form of the wear surface (Fig. 5). However, the second approach in Eq. (2) can be used as is because of the continuous wear surface.

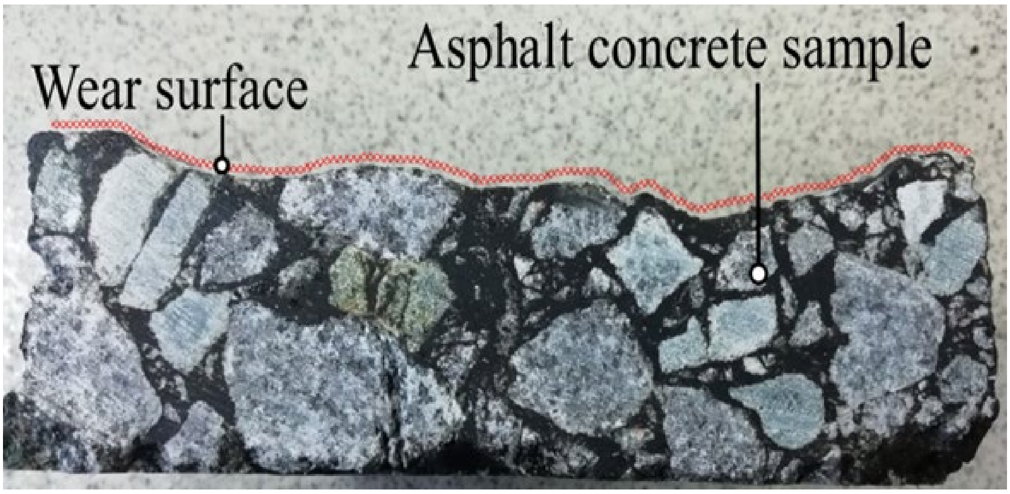

Figure 5. Asphalt concrete wear surface.

In any case, using both assumptions is complicated due to the impossibility of wear surface control during the test and modified Khrushchev and Babichev method is comprehensive with required for the test precision.

G. Y. Lee suggested a modified approach for the problem solving. This approach is based on the modified Eq. (1) with a coefficient of non-contributing portion (NCP). The governing equation based on the G.Y. Lee's approach is shown below [21].

$$1/W_c = C \cdot V_1/W_1 + V_2/W_2\,, \tag{3}$$

where C is the contribution coefficient of the reinforcement;

$$C = 1 - C', \tag{4}$$

where C' is the non-contributing portion.

The physical meaning of NCP is a fraction of material particles that are removed during the abrasion (Fig. 4 (c)). Because of the similar processes of cracking (Fig. 4 (d)) and removal (Fig. 4 (c)) of material during testing and the impact of pores on these processes, we assume that cracking particles in this problem can be replaced as removed particles. For the determination of the NCP removal model is needed. For the aggregate particles modeling we represent them in a form of spheres. Potential volume of pores can be represented as a space around the sphere thickness of dl. The dl variable does not characterize actual space thickness around the particle, it is a representation for the determination of the contact area between pores and particles. This space can be filled with the binder or other particles and in these cases this space represents a filled space. Pores can open the space on the fraction of L'. The opening of the space on the proportion of L' is a condition to lose the NCP with volume of X' fraction (Fig. 6).

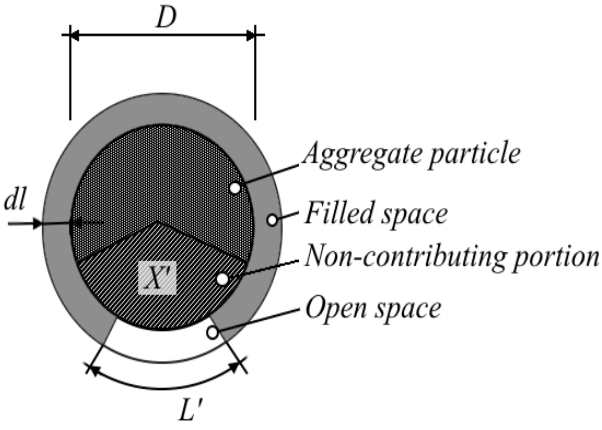

Figure 6. Non-contributing portion loss condition.

With the proportional increase of particle size, proportional increase of surface area occurs, which makes these conditions independent of the particle size. The volume of the space around the particle can be shown with the equation below.

$$CV_v = \pi \cdot D \cdot dl, \tag{5}$$

where CV_v is the volume of space around the particle; D is the size of a particle.

The volume of a single non-contributing portion can be represented as:

$$V' = X' \cdot \pi \cdot D^2 / 4, \tag{6}$$

where X' is the fraction of a single particle supposed to be a non-contributing portion.

The non-contributing portion can be represented as:

$$C' = V' \cdot CV / \left(L' \cdot CV_v\right), \tag{7}$$

where $CV / \left(L' \cdot CV_v\right)$ is the conventional number of non-contributing portions.

This assumption is conventional due to the lack of tangible representation of L'. In the practice this value is not a fraction of open space around the particle but characterizes the total number of deficiencies of adhesion. The tangible sense of equations above is a coefficient area of the particle in the contact of pore and lack of adhesion on the surface. Due to equations above, the final expression of C' is:

$$C' = D \cdot CV \cdot X' / \left(4 \cdot dl \cdot L'\right) = D \cdot CV \cdot X / 4, \tag{8}$$

where X is the conventional empirical value characterizing the area of contact between pores and particles and the amount of lost material due to the lack of adhesion. This value includes all of the unknown constants of the Eq. (8). This coefficient is unique for every material and depends on the adhesion, quality of aggregate, roughness and the binder type. The aim of this study is finding average X coefficient for the group of materials conventionally used in the construction in the Russian Federation. The problem of this equation is determining the diameter of the particles D. Calculation of the fraction of NCP for each size of material is complicated. Therefore, the average diameter of particles can be represented as:

$$D = 4 \cdot \sum pV_i / \sum pS_i, \tag{9}$$

where pV_i is the volume of the particles of i size; pS_i is the surface area of the particles of i size.

The particles less than 1 mm are determined as a part of binder. The volume of particles of every size and mass is a proportional value due to the conventional constant of specific gravity of every size of particles. Thus, the volume of particles can be founded through the grading curve of mixes. The surface area of particles can be found by Eq. (10).

$$pS_i = 4 \cdot pV_i / D_i. \tag{10}$$

V_1 and V_2 variables of the Eq. (3) mean asphalt concrete without connected voids fraction and connected voids fraction respectively. It is obvious that wear resistance of the open voids V_2 / W_2 is equal to zero. So, the summary equation for this study is presented below:

$$W_1^{ab} = \frac{W_2^{ab} \cdot \left(1 - D \cdot CV_2 \cdot X/4\right) \cdot \left(1 - CV_2\right)}{\left(1 - D \cdot CV_1 \cdot X/4\right) \cdot \left(1 - CV_1\right)}, \tag{11}$$

where W_1^{ab} is the wear value or the Prall test value of an asphalt concrete with CV_1 connected void value or the degree of saturation; W_2^{ab} is the wear value or the Prall test value of an asphalt concrete with CV_2 connected void value or the degree of saturation.

2.3. Experimental methods

As a measure of the compaction quality, the saturation degree method can be used. This method is trivial for quality control of the asphalt concrete pavement in the Russian Federation. Moreover, it had been the most common method of compaction quality control before the new asphalt concrete designing systems were introduced in 2020. The degree of saturation value is equivalent to the connected void under the vacuum conditions for the asphalt concrete saturation in the laboratory (2000 Pa/15 mm Hg, 1 hour). Usually this parameter shows more than 80 % of the total air voids in the asphalt concrete [25]. It depends on the quality of compaction, mix grade, percentage of binder and type of aggregate. The value of saturation test method according to GOST 12801-98 “Materials on the basis of organic binders for road and airfield construction. Test methods.” was used to determine the compaction quality. The value of saturated water depends on a percentage of air voids [16]. This method is fast and acceptable for the case when the evaluation of maximum specific gravity is impossible. This method is acceptable for the determination of connected void value as a compaction quality.

For the evaluation of percentage of saturated water according to GOST 12801-98, clean and dry weighted samples of asphalt were saturated under (20±2) °C water for the specific bulk volume evaluation for 30 min. After saturation, the samples were weighed in water and in the air. After the weighing, the samples were placed under water and saturated under 2000 Pa vacuum for 1 hour and with atmospheric pressure for 30 minutes. The degree of saturation was determined by the following formula:

$$CV = \frac{m_3 - m}{m_2 - m_1}, \quad (12)$$

where m is the mass of the dry sample in the air (g); m_1 is the mass of the sample under water (g); m_2 is the mass of the sample saturated for 30 minutes, in the air (g); m_3 is the mass of the vacuum-saturated sample in the air (g).

It is impossible to make evaluation for this research based on the field measurement of the rut propagation. Constant abrasion loading requires laboratory test equipment. The Glavtatdortrans, SPI laboratory is equipped with a Prall testing machine to imitate the damage from the studded tires. The Prall test is commonly used in Northern Europe for the testing of asphalt specimens and has good precision to determine the abrasion resistance of asphalt concrete [26]. As an alternative, the following methods are most commonly used in the world practice: Cantabro test, VTI road simulator and various tests for the abrasion resistance of stone testing [27]. The Cantabro test was invented for the similar type of the asphalt concrete damage: raveling and adhesion loss. But it cannot be used for the abrasion modeling. At the same time, different testing methods for the abrasion resistance of stone cannot be used due to the polishing nature of abrasion loading (for example, EN14157 or ASTM C241 tests) [28]. One of the main drawbacks of these methods is temperature and moisture conditions. In the case of asphalt concrete it is obvious that the typical abrasion conditions are spring and fall weather with wet and cold surface of the road. Due to the prevalence of Prall test in Europe, it is more often applied for the researching and testing in the Russian Federation as well.

The Prall test method was used to determine the abrasion resistance. It is described in EN 12697-16 “Bituminous mixtures – Test methods – Part 16: Abrasion by studded tyres” in Europe and in GOST 58406.5 “Automobile roads of general use. Hot asphalt mixtures and asphalt. Method for determination of abrasion.” in the Russian Federation. The Russian test method corresponds to the European one [8].

The test requires asphalt specimens with a height of 30 mm and diameter of 100 mm. The specimens can be prepared on Marshall or gyratory compactor or can be sampled from the pavement. Compacted specimens must be cut to the required size. Preparing for the test includes saturation with water at a temperature of 5 °C for 5 hours. Sample weight after saturation is m_4. Prall apparatus included specimen holder (Fig. 7), abrasive loading, including 40 steel balls 12 mm in diameter, engine and cooler. During the test, the specimens were subjected to a loading impact with frequency of 950 strikes per minute with water cooled for 5 °C for 15 minutes. After the test, the samples were weighted (m_5).

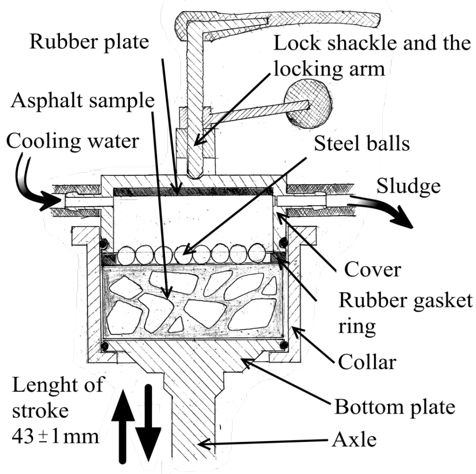

Figure 7. Prall test equipment.

Prall test wear value is determined by the following formula:

$$W^{ab} = \frac{m_4 - m_5}{G_{mb}}, \quad (13)$$

where W^{ab} is the Prall test abrasion value (cm^3); m_4 is the mass of the specimen before testing (g); m_5 is the mass of the specimen after testing (g) (Fig. 8); G_{mb} is the bulk gravity of the specimen (g/cm^3).

Figure 8. Asphalt sample with steel balls after testing.

The classification of the abrasion resistance of asphalt concrete in the Russian Federation is carried out in accordance with GOST R 58406.1 "Automobile roads of general use. Stone-mastic asphalt mixtures and asphalt concrete. Specifications" recommendations. The classification is shown in Table 1.

Table 1. Abrasion resistance classification of asphalt concrete according to the Russian Federation GOST R 58406.1 "Automobile roads of general use. Stone-mastic asphalt mixtures and asphalt concrete. Specifications".

The abrasion resistance class	The Prall Test value, cm^3
1	Less than 25
2	From 26 to 35
3	From 36 to 45

For example, for the stone mastic asphalt it is recommended to use mixes with the 1st class of abrasion resistance. The contractor can decide on abrasion resistance for each road depending on the loading if necessary.

Considering all of the above, using these laboratory tests, it is possible to obtain all the necessary terms of Eq. (11).

3. Results and Discussion

To provide experimental verification of the proposed model abrasive wear test, we prepared and analyzed 63 samples. For the abrasive wear test, VTI Prall test machine was used (Fig. 7). The test results are presented below (Table 2).

Table 2. Mixes abrasion testing result with calculated average size (Eq. 9) of aggregate and estimated degree of saturation.

The sample number	The mix number	Average size of aggregate, D (mm)	Mix type	The degree of saturation, CV (%)	Prall test value, W^{ab} (cm^3)
1	1	11.04	SMA 20	4.19	18.00
2	1	11.04	SMA 20	1.14	13.23
3	2	7.98	SMA 15	2.18	20.26
4	2	7.98	SMA 15	1.73	18.29
5	3	11.04	SMA 20	3.38	22.40
6	3	11.04	SMA 20	0.91	20.20
7	3	11.04	SMA 20	0.96	20.80
8	4	7.98	SMA 15	2.59	23.58
9	4	7.98	SMA 15	2.26	23.95
10	5	11.04	SMA 20	1.94	24.67
11	5	11.04	SMA 20	1.86	25.05
12	6	11.04	SMA 20	3.35	27.33
13	6	11.04	SMA 20	3.77	20.68
14	6	11.04	SMA 20	3.60	25.29
15	6	11.04	SMA 20	2.29	23.32
16	6	11.04	SMA 20	3.18	22.64
17	6	11.04	SMA 20	3.80	25.64
18	6	11.04	SMA 20	3.34	21.46
19	6	11.04	SMA 20	2.73	20.94
20	6	11.04	SMA 20	3.55	25.04
21	7	11.04	SMA 20	3.68	17.45
22	7	11.04	SMA 20	1.51	16.08
23	7	11.04	SMA 20	2.16	18.38
24	7	11.04	SMA 20	4.83	20.90
25	7	11.04	SMA 20	3.31	18.58
26	7	11.04	SMA 20	1.92	17.95
27	7	11.04	SMA 20	2.69	22.33
28	7	11.04	SMA 20	3.14	17.77
29	7	11.04	SMA 20	3.94	29.60
30	8	4.70	Type "A"	3.87	28.54
31	8	4.70	Type "A"	4.03	25.22
32	8	4.70	Type "A"	3.07	21.60
33	8	4.70	Type "A"	3.67	23.58
34	8	4.70	Type "A"	3.67	22.74
35	9	6.10	SMA 10	3.92	26.80
36	9	6.10	SMA 10	0.61	22.92
37	9	6.10	SMA 10	4.42	28.29
38	9	6.10	SMA 10	3.12	28.67
39	10	7.98	SMA 15	2.17	18.68
40	10	7.98	SMA 15	1.08	19.71
41	11	11.04	SMA 20	1.34	27.54
42	11	11.04	SMA 20	0.59	26.34
43	12	7.98	SMA 15	1.40	21.40

The sample number	The mix number	Average size of aggregate, D (mm)	Mix type	The degree of saturation, CV (%)	Prall test value, W^{ab} (cm^3)
44	12	7.98	SMA 15	2.60	23.37
45	12	7.98	SMA 15	2.02	18.40
46	13	11.04	SMA 20	1.97	21.31
47	13	11.04	SMA 20	3.20	26.58
48	13	11.04	SMA 20	3.03	23.35
49	13	11.04	SMA 20	3.50	26.84
50	14	7.98	SMA 15	3.65	29.53
51	14	7.98	SMA 15	2.12	27.53
52	15	6.10	SMA 10	3.04	33.70
53	15	6.10	SMA 10	0.51	28.30
54	16	7.98	SMA 15	2.63	28.40
55	16	7.98	SMA 15	3.85	28.90
56	16	7.98	SMA 15	0.67	26.30
57	16	7.98	SMA 15	2.44	30.70
58	17	7.98	SMA 15	0.70	23.47
59	17	7.98	SMA 15	2.41	25.20
60	18	11.04	SMA 20	0.83	19.59
61	18	11.04	SMA 20	0.53	20.01
62	19	6.10	SMA 10	3.28	22.98
63	19	6.10	SMA 10	3.62	26.67

Statistical values of the tested mixes are shown in Table 3.

Table 3. Mean abrasion value, standard deviation and coefficient of variation of every mixes test with the average of the values.

The mix number	Mean abrasion value (cm^3)	Standard deviation (cm^3)	Coefficient of variation
1	15.615	3.373	0.216
2	19.275	1.393	0.072
3	21.133	1.137	0.054
4	23.765	0.262	0.011
5	24.860	0.269	0.011
6	23.593	2.350	0.100
7	19.893	4.092	0.206
8	24.336	2.695	0.111
9	26.670	2.627	0.099
10	19.195	0.728	0.038
11	26.940	0.849	0.031
12	21.057	2.503	0.119
13	24.520	2.665	0.109
14	28.530	1.414	0.050
15	31.000	3.818	0.123
16	28.575	1.810	0.063
17	24.335	1.223	0.050
18	19.800	0.297	0.015
19	24.825	2.609	0.105
Average	23.575	1.901	0.083

The data obtained were analyzed using Eq. (11). To verify the approach, for each of the 19 groups of materials, the Prall test value for the asphalt concrete with zero connected void was calculated. The minimum of the average coefficient of variation was found by changing the X coefficient value. The empirical X coefficient was found equal to 1.974 (Fig. 9).

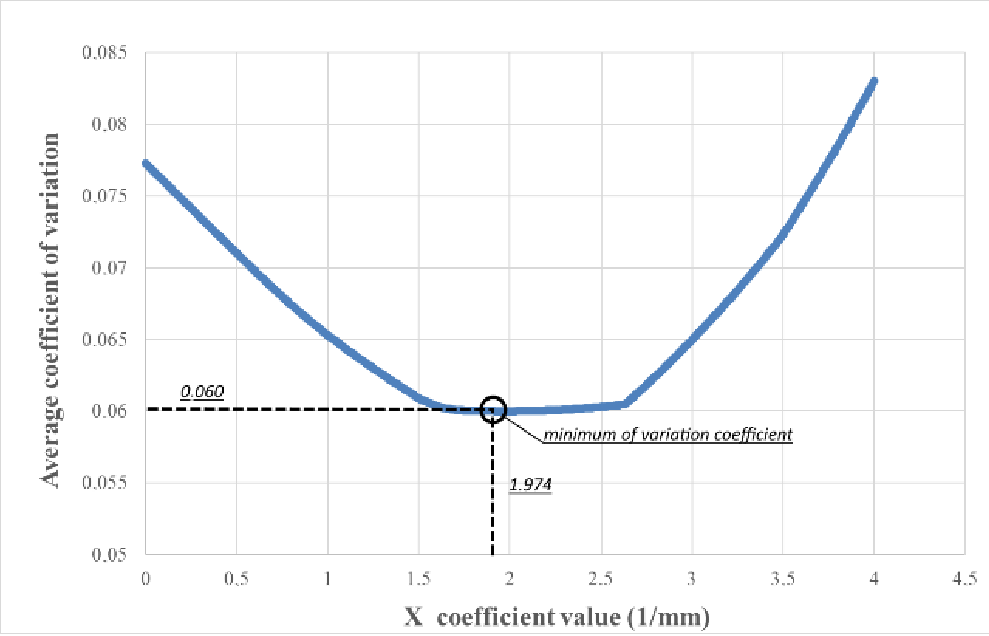

Figure 9. Average coefficient of variation depending on the X value.

The large minimum range of the graph and the presence of an obvious minimum indicates a good reliability of the approach and the obtained value of the coefficient X. The final value of abrasion loss for the asphalt concretes with zero value of connected voids is given in the table below (Table 4).

Table 4. Mean abrasion value, standard deviation and coefficient of variation of every mix obtained by Eq. 11 abrasion value.

The mix number	Mean abrasion value (cm^3)	Standard deviation (cm^3)	Coefficient of variation
1	12.787	0.736	0.058
2	17.433	0.967	0.055
3	18.734	0.966	0.052
4	20.975	0.494	0.024
5	21.863	0.324	0.015
6	18.712	1.788	0.096
7	16.013	2.778	0.174
8	21.436	2.185	0.102
9	23.420	1.248	0.053
10	17.690	1.382	0.078
11	25.265	0.110	0.004
12	18.987	2.087	0.110
13	19.939	1.352	0.068
14	24.529	0.237	0.010
15	28.704	1.387	0.048
16	25.217	1.458	0.058
17	22.461	0.286	0.013
18	18.939	0.552	0.029
19	21.467	2.031	0.095
Average	20.767	1.177	0.060

Using the particle loss model (Eq.11) reduces the variation coefficient of the test results from 0.083 to 0.060 and points to good reliability of the approach. In addition, the approach to evaluation of the connected voids influence of asphalt concretes allows improving the laboratory abrasion tests precision due to ignoring the voids fraction influence in the comparison of the asphalt specimen's abrasion values.

Summary expression for the asphalt concretes with obtained X coefficient is shown below:

$$W_1^{ab} = \frac{W_2^{ab} \cdot \left(1 - D \cdot CV_2 \cdot 1.974/4\right) \cdot \left(1 - CV_2\right)}{\left(1 - D \cdot CV_1 \cdot 1.974/4\right) \cdot \left(1 - CV_1\right)}. \quad (14)$$

Note that connected voids value in the expression is in fractions of a unit.

The obtained model and the expression does not contradict the existing model of the abrasive wear of composites, but complements it. A fast and reliable way to include the pores effect on the abrasive wear can effectively improve the precision of the abrasion resistance assessment.

This expression Eq. (14) allows us to calculate the degree of the connected voids influence on the abrasion resistance of the asphalt concrete. For the demonstration of the connected voids effect on the asphalt concrete, abrasion resistance evaluation of the relative abrasion resistance of asphalt concrete for the different connected voids values is presented in Fig. 10.

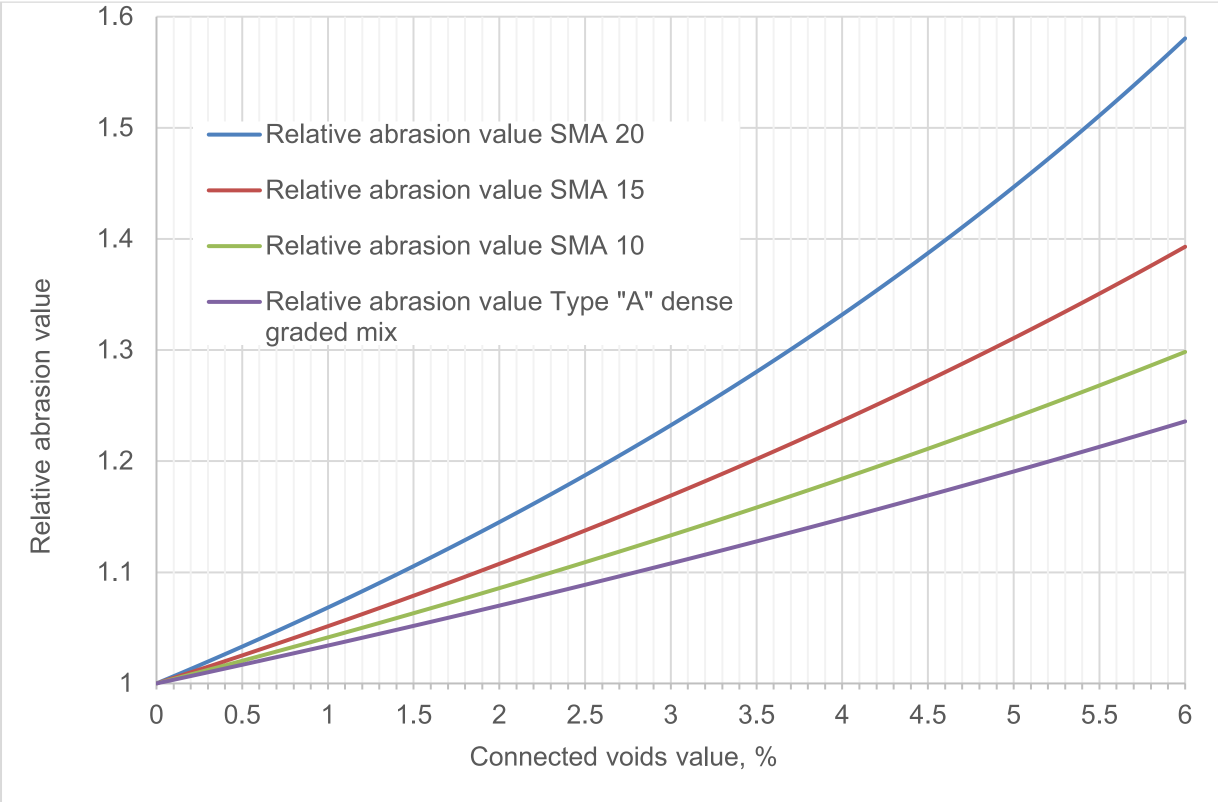

Figure 10. Calculated relative abrasion value for different mix types with different connected voids values.

The obtained dependence confirms the other studies results [8]. These results allow us to assess the abrasive wear resistance of asphalt concretes. For example, for SMA mixes to be reliable asphalt pavements, the Prall test value has to be less than 20 cm^3 to have the 1st class of the abrasion resistance in the case of uncompaction in the permissible limits by specifications (1 to 3.5 % of saturating water or the connected voids value). On the contrary, abrasion resistance can be reduced for the pavements with the stable compaction quality. This approach shows the vital role of compaction quality for the pavement life.

4. Conclusions

1. The existing models of composite abrasion have good accuracy for various types of composite and single materials but the asphalt concrete. Asphalt concrete is a unique composite structure, which consists of a hard reinforcement coarse aggregate, fine aggregate and binder presented by bitumen, mineral powder and various additives. Asphalt concrete in pavement as a material can contain pores and other inclusions which affect asphalt concrete. Various models obtaining asphalt properties were investigated, but the conventional model of asphalt concrete abrasive wear needs to be evaluated for the accurate prediction of the asphalt pavement behavior under loads.

2. The proposed model of asphalt concrete fragmentation under abrasive wear is based on two basic processes: normal abrasive wear of each component and particles loss (Fig. 4). Due to a large aggregate influence on the abrasive wear resistance, the latter has a big impact on abrasive wear. Normal abrasive wear of each component is a common task for the existing models of composites wear (Eq. (1–2)). However aggregate particles evaluation is a difficult problem. Based on the G.Y. Lee's approach, th presented model uses Khrushchev-Babichev wear model to estimate particles loss. The particles loss condition is based on the case when a part of particle surface lacks adhesion due to pores. The lack of adhesion and fraction loss calculations are a practical problem. It was solved with finding an empirical coefficient X (Eq.11). G.Y. Lee's approach can not be applied to the wear of asphalt concrete due to the complex loading conditions and difference of the aggregate size. The empirical coefficient calculation presented in this study allows us to modify the method for particle loss calculation.
3. The proposed model allows us to assess the abrasion resistance of the asphalt concrete and changes under various compaction conditions. An understanding of the particle loss process is necessary for the following research. The approach allows obtaining all the coefficients by laboratory tests for every type of material or an average coefficient for all types of the materials used.
4. The Prall test was used to verify the model. We tested 63 samples in 19 groups (Table 2). The mixes were sampled at the road construction works of the Republic of Tatarstan in 2018–2020. The saturation method was used to estimate pores volume fraction. In accordance with the mix grading (Fig. 3), the average particle size (Eq. (9)) was calculated. The standard deviation and the coefficient of variation were calculated for each mix (Table 3).
5. The experimental data show good reliability of the model. The average coefficient of variation was reduced from 8.3 % to a 6.00 % significantly improving the test accuracy. The empirical coefficient X was found equal to 1.974 (1/mm) for the mixes presented.
6. The obtained coefficient for materials used in the Russian Federation road construction and the modified G.Y. Lee's approach (Eq. (14)) allows assessing the connected voids and compaction effect on the abrasion resistance of materials and provides insight into the processes in asphalt concrete under hard winter loads.

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Received 10.09.2021. Approved after reviewing 12.01.2024. Accepted 12.01.2024.