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SURFACE TEXTURE AND LAYER PERMEABILITY OF AQUAPLANING RESISTANT ASPHALT PAVEMENTS

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Abstract. Tire/pavement noise is one of the biggest environmental problems caused by the contact between the car tire and the pavement surface. It is known that porous asphalt (PA) pavements has good properties in noise absorption, however these mixtures could also solve another important problem which appear on roads – aquaplaning. This phenomenon reduces traffic safety and driving comfort. Aquaplaning appears when tires become separated from the pavement surface by thin water film and the ability to increase braking force or control the vehicle motion is almost entirely lost. Although, PA pavements have relatively low durability properties. This research aims analyse surface texture and permeability characteristics of aquaplaning resistant asphalt pavements. Four different mixtures with different largest particle size (AT 5, AT 8, AT 11 and AT 16) were tested. Large-scale laboratory testing was performed to evaluate their surface texture and permeability properties The research revealed, that mixtures with 8 % activated mineral limestone powder (AMLP) showed better mechanical and physical properties than comparing to other mixtures with 4 % AMLP and 4 % granite screenings or just 4 % AMLP.

Keywords: aquaplaning, porous asphalt, skid resistance, mean profile depth, splash & spray

Introduction

Road traffic noise is a widespread problem, especially in the densely populated cities of Europe. Different type of asphalt mixtures are used for noise-reducing asphalt pavements. Optimisation of asphalt mixtures for tyre/road noise reduction mainly depends on the potential application area of these mixtures (Vaitkus *et al.* 2019). If asphalt pavements are not adequately designed, they will require frequent repair because of premature failures of the asphalt wearing layer (Vaitkus *et al.* 2017a). Moreover, to ensure a lower tire/road noise level and proper friction, exposed aggregate concrete widely used for the construction of major highways in Europe (Šernas *et al*. 2020).

In case of rain or wet road surface, the main factor of traffic safety is the sufficient grip between the road surface and the car wheel, which can be lost due to the resulting aquaplaning phenomenon, when the water accumulating on the top of the road surface does not run to the curb. Various traffic safety studies from indicate that approximately 20% of all road traffic accidents occur in wet weather conditions (Ivan *et al*., 2012; Mayora and Pina, 2009; McGovern *et al*., 2011). The formation of aquaplaning phenomenon is influenced by three factors: road surface characteristics (water film thickness, wearing course material); tire condition (load, tread depth, pressure); driving speed. When driving on the road, the grooves (tread) in the tire collect water from the surface of the pavement and push it out, thus ensuring good grip between the tire and the pavement. The aquaplaning phenomenon occurs when the tread of a tire no longer manages to displace water that has entered the grooves and the tire rises from the surface of the tread on a thin layer of water. This creates dangerous driving conditions (especially when driving over 80 km/h (Herrmann, 2008)) and exponentially increases the risk of an accident. Two of the three factors that determine the formation of the aquaplaning phenomenon can be controlled by the road users themselves – the condition of the tires and the driving speed. However, the condition of the road surface and the type of surface are controlled by the relevant authorities. Meaning that when the road surface is wet, road users must take safety measures and avoid aquaplaning.

Concept of aquaplaning asphalt pavements

Elimination of water from the road surface is possible in two ways: by the geometrical parameters of the pavement or by a certain pavement mixture (wearing course material). Usually in Lithuania, water is eliminated from the surface of the pavement by designing roads with a longitudinal and / or transverse slope, by which the water flows to the predetermined water collection points. This method of drainage usually uses conventional asphalt pavements, the surface of which flows with water, and when the unevenness of the pavement occurs, the water remains standing on the surface of the pavement, which can lead to the phenomenon of aquaplaning. In order to solve the formation of the aquaplaning phenomenon, various pavement structures have been used in other countries for a long time (about 50 years ago (Jacobson *et al.* 2016)), which drain the water "through themselves". Such structures are called permeable pavements and are designed that the water on the surface of the pavement runs directly through part of the pavement structure, meaning that no water accumulates on the surface of the wearing layer. Due to their ability to allow water to quickly infiltrate through the surface, permeable pavements allow to reduce the runoff quantity and peak runoff rates

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(Bratteo and Booth, 2003; Bean *et al.* 2005). This type of construction solves the problem of aquaplaning and the formation of water splashes. Different countries use different designs and technologies, however most common permeable pavement applications are: porous concrete, porous asphalt or permeable interlocking concrete pavers (PICP). The construction design and permeability properties also varies depending on the type of surface. The typical structures are shown in Figures 1 - 2.

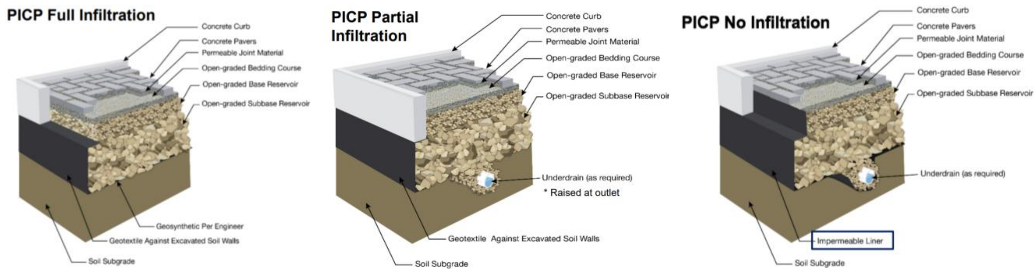

Figure 1. Principal permeable concrete pavers pavement structure (Biknel, 2016)

Figure 2. Principal permeable asphalt concrete pavement structure

Permeable structures vary in use. Often, in porous asphalt or concrete pavement structures, only the top (wearing) layer is porous. Additional waterproof layers are installed to prevent water from penetrating into the other layers of the structure below. In this way, the water entering through the surface layer of the pavement structure due to the transverse and longitudinal slopes in the pavement flows in the layer pores to the water collection point. This type of structure is the mostly used in roads. Fully permeable structures are the mostly used in parking lots or driveways to houses. Such structures are used in cases when it is difficult to transport water to the collection points with a transverse or longitudinal profile or a long water flow light is formed. These structures are unique in that the water on the surface penetrates through all layers of the structure all the way to the ground.

Permeable interlocking concrete pavers with a specific installation design can provide good water drainage, but such structures are most commonly used in parking lots. The top layer of such a structure is made of prefabricated concrete tiles, but the bottom layer is permeable to water. The gaps between the tiles make up 5–15% of the total surface area, so the water is drained throughout the pavement structure all the way to the subsoil. This type of structure can drain 10.2–15.2 mm/h of rainwater, depending on the environmental conditions and the composition of the structure (Haselbach *et al*. 2017).

Porous concrete is an uncommon alternative in Europe, but is widely used in the United States of America (USA). Porous concrete mixtures differs from conventional concrete mixtures in a similar way as conventional asphalt mixtures differ from porous asphalt mixtures. Porous concrete contains a higher fraction of aggregates, thus forming a concrete mixture with a voids content of 15 – 25%. Porous concrete can drain 7.6–50.8 mm/h of rainwater, depending on environmental conditions and the composition of the mixture (Haselbach *et al.* 2017). Porous concrete should theoretically absorb less heat from the environment due to the surface color, but no research has been done on this topic. In the USA, porous concrete pavements are most widely used on low volume roads, parking lots, and residential neighborhoods. Because this type concrete pavement has poor resistance to cracking, and it is not recommended to apply this type of pavement on primers with a low water conductivity. When choosing porous pavement, it is important to pay attention to two factors: bearing capacity and resistance to cold, depending on the climatic conditions of the area (Amirjani, 2010).

Porous asphalt (PA) is the most common and popular low noise as well as to reduce aquaplaning phenomenon pavement solution used across the world (Vaitkus *et. al.* 2017b) Porous asphalt is an asphalt mixture with a void content of more than 15%. This type of pavement is single-layer or double-layer. Porous asphalt has become most widespread as an alternative to reduce tire and asphalt pavement contact noise and to reduce the likelihood of aquaplaning. The large content of voids absorbs surface water, which also solves the problem of dripping and splashing, which results in better visibility for drivers and higher vehicle speeds in the rain. Porous asphalt, depending on environmental conditions and the composition of the mixture, can drain 4.3–12.7 mm/h of rainwater (Haselbach *et al.* 2017). Permeability, or otherwise, hydraulic conductivity, is the property of a material to pass fluids through its structure. Porous asphalt has this property and water permeability depends on the voids content and their relationship. The hydraulic properties of porous asphalt have been observed for a long time and the use of this type of pavement has been introduced precisely because of the water permeability to reduce the amount of water on the road surface. After some time, the acoustic properties of porous asphalt were also discovered. Also, the porous asphalt mixture acts as a filter to collect foreign particles that are in the water. This filtration function improves the quality of groundwater, but trapped foreign matter in the mixture impairs the properties of the

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binder, clogging the pores in the mixture (Ahmed, 2015). Clogged pores mean lower hydraulic conductivity of the mixture and poorer acoustic properties (Vaitkus *et al.* 2019). This type of pavement is not only clogged by surface water filtration, but is also affected by other external factors: dirt near the road or dirt spilled from car tires is compacted by vehicles and clogs the mixture pores, studded tires damage the microtexture of the pavement surface and the resulting dust is absorbed into open pores of the pavement. Due to the increased transport volume or increased traffic load, the aggregates in the mixture decompose inside the mixture, distorting the hydrological properties of the mixture.

Testing of prototypes in the laboratory

New asphalt mixtures (AT 5, AT 8, AT 11, and AT 16) have been designed under laboratory conditions in order to develop new pavement structures to drain water and eliminate the possibility of aquaplaning phenomenon. Asphalt mixtures that reduce aquaplaning differ from each other in the size of the largest particle, from the fine mixture of 5 mm maximum particle size to the course mixture of 16 mm maximum particle size. In each individually designed aggregate size distribution composition variant, three essential variables were used: the standard amount of activated mineral limestone powder (AMLP), the significantly increased amount of AMLP, and the granite fine aggregate fr. 0/2. The detailed compositions are presented in Table 1.

Table 1. Design compositions of porous asphalt mixtures

Asphalt mixture	Mix code	Binder content, %	AMLP content, %	Granite fine aggregate 0/2, %	Granite 2/5, %	Granite 5/8, %	Granite 8/11, %	Granite 11/16, %
AT 5	5-1	6.5	4.0	-	96.0	-	-	-
	5-2	6.5	8.0	-	92.0	-	-	-
	5-3	6.5%	4.0	4.0	92.0	-	-	-
AT 8	8-1	6.5%	4.0	-	-	96.0	-	-
	8-2	6.5%	8.0	-	-	92.0	-	-
	8-3	6.5%	4.0	4.0	-	92.0	-	-
AT 11	11-1	6.0%	4.0	-	-	-	96.0	-
	11-2	6.0%	8.0	-	-	-	92.0	-
	11-3	6.0%	4.0	4.0	-	-	92.0	-
AT 16	16-1	5.5%	4.0	-	-	-	-	96.0
	16-2	5.5%	8.0	-	-	-	-	92.0
	16-3	5.5%	4.0	4.0	-	-	-	92.0

Mixture codes in Table 1 denote different asphalt mixtures and their compositions. Codes 5-1, 8-1, 11-1 and 16-1 denote mixtures of normal composition. Codes 5-2, 8-2, 11-2 and 16-2 denote mixtures containing an increased amount of AMLP (0.063 mm) (8%). Codes 5-3, 8-3, 11-3 and 16-3 denote mixtures containing 4% of AMLP and additionally 4% of granite fine aggregates 0/2. The amount of mineral powder and the amount of fines were increased in order to increase the amount of mastic in the asphalt mixture and to evaluate the properties of the modified asphalt mixture composition.

The general trend in European countries shows that polymer modified binders (PMBs) are mostly used for porous asphalt mixtures in recent years. The additives contained in the binder prolong the durability of the coating by increasing the cohesive and adhesive properties of the mixture. It is also ensured that the rough aggregate particles are covered with a thicker layer of binder. Due to the properties of viscous additives, asphalt mixtures are more resistant to heat, but also provide sufficient flexibility in the cold season. For this reason polymer modified bitumen PMB 45/80-65 was selected for designing aquaplaning resistant asphalt mixtures (AT), since this binder have the most suitable physical and mechanical properties to design durable asphalt mixture for noise and aquaplaning reducing asphalt pavements. The properties of the selected aggregates and binder are presented in Tables 2–3.

The shape of granite course aggregates were determined in terms of the flakiness index and shape index. The flakiness index was determined by standard EN 933-3 and shape index – by standard EN 933-4.

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Table 2. Shape properties of the aggregates

Material	Flakiness index	Shape index
Granite 2/5	9	2
Granite 5/8	4	3
Granite 8/11	3	2

Table 3. Physical and mechanical properties of the binder

Material	Penetration at 25 °C, dmm	Softening point. °C	Elastic recovery. %	Critical temperature. °C	
				high	low
PMB 45/80-65	51.8	65.9	96.8	79.7	–20.5

The properties of PMB 45/80-65 evaluated according to the requirements of standard EN 14023. The penetration at 25 °C determined by standard EN 1426. The softening point determined by standard EN 1427:2015 and elastic recovery by standard EN 13398:2018.

The physical and mechanical characteristics that are given below were determined in the laboratory by testing 3 specimens for each asphalt mixture and for each test condition.

Air voids content

The air voids content determined by standard EN 12697-8. The air voids of the asphalt specimen calculated using the maximum density (standard EN 12697-5. Procedure A) of the mixture and the bulk density of the specimen (standard EN 12697-6. Procedure C: Bulk density - Sealed specimen)). The specimens for determining the bulk density were prepared by a Marshall compactor according to standard EN 12697-30 (2×50 blows).

Horizontal and vertical water permeability

Horizontal and vertical water permeability tests carried out according to standard EN 12697-19. The specimens for this test were prepared by a Marshall compactor according to standard EN 12697-30 (2×50 blows). For the determination of water permeability in the vertical direction, the sample placed in the device, and water allowed to flow through the sample at a distance of 300±1 mm (Figure 3). To prevent leakage of water along the wall of the tube, the tube covered in a rubber membrane, and a pressure of 50 kPa applied. At least 10 minutes of water flowing through the sample was required to saturate the specimen and to remove enclosed air. After that, an empty vessel placed, and water allowed to flow for 1 minute. After 1 minute, the water entering the vessel was determined, and the water permeability calculated in the vertical direction.

To determine the horizontal water permeability, the sample placed in the device, and water allowed to flow through the sample at a distance of 300±1 mm. To prevent leakage of water, the bottom of the sample insulated with paraffin, and an aluminium ring placed on the top of the sample and glued with silicone glue.

1. 2. 3. 4. 5.

Figure 3. Vertical water permeability method sequence of work (1 – beginning, 5 – end)

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Drainability

The drainability of asphalt mixtures is determined by a standardized method according to EN 12697-40 . For the method, 4 cm thick slabs were prepared according to the standard EN 12697-33 + A1. The device used to determine the drainability of the asphalt mix is shown in Figure 3. A device with a load and a leveling surface is placed on the plate. The tube was filled with 5 litres of water and waiedt until no air bubbles remain in the water. When the plunger is pulled out in the vertical direction, the time taken for 4 liters of water to flow is calculated. The test is performed 3 times and the time is averaged.

1. 2. 3. 4. 5. 6.

Figure 4. Drainability determination method sequence of work (1 – beginning, 6 – end)

Skid resistance

Determination of skid resistance of asphalt mixtures was performed according to standard EN 13036-4. Skid resistance was determined by pendulum on asphalt slabs which were made in the laboratory. Skid resistance was performed for each asphalt mixture - a total of 12 different specimens (Table 1). The measurement were performed with a pendulum and a type 57 slider. This type of slider was used for asphalt pavements intended for motor vehicle traffic. The asphalt samples were moistened before each test. The value of the slip resistance (PTV) was determined for each sample 5 times, from which the average value of the PTV coefficient was calculated.

Macrotexture

The macrotexture of each asphalt sample surfaces was evaluated based on the MPD (mean profile depth) parameter obtained by CTM (circular tester) measurements in accordance with standard EN ISO 13473-1. Measurement of MPD under laboratory conditions was performed on prepared asphalt slabs. Measurements were performed for each asphalt mixture and 5 times.

Texture and permeability characteristics of aquaplaning asphalt mixture prototypes

The test results for the void content, permeability and drainage properties of the four asphalt mixtures are presented in Table 4.

The analysis of tests results shows that void content varies from 16.3% to 29.5%, and the courser the mixture, the higher void content as expected. The lowest void content (16.3%) was determined for asphalt AT 5 mixture with increased amount of AMLP, while normal composition asphalt AT 16 mixture had the highest void content (29.5%). Comparing each type of asphalt mixture and their composition, it was found that the use of increased amount of AMLP reduces void content by about 12.3% (ratio) comparing to normal composition asphalt mixture AT, and the use of AMLP plus granite fine aggregates reduces void content by about 12.4% (ratio) comparing to normal composition asphalt mixture AT.

Horizontal and vertical water permeability test results shows that permeability values of normal composition asphalt mixtures AT are about 2 times higher than asphalt mixture AT with increased amount of filler aggregate (see Table 2). It was found that vertical water permeability of asphalt mixtures AT 5 and AT 8 varies from 0.101×10^{-3} m/s to 0.692×10^{-3} m/s, while values of asphalt mixtures AT 11 and AT 16 are from 1.130×10^{-3} m/s to 2.762×10^{-3} m/s. Or vertical water permeability of asphalt mixture AT 11 and AT 16 are from 4 to 11 times higher than those of AT 5 and AT 8. Such results are due to the increased amount of filler aggregate, which reduce voids content in the asphalt mixture. It was found that the higher content of voids, the higher the vertical and horizontal water permeability. Comparing the dependence of the vertical water permeability results on the maximum aggregate particle size of the asphalt mixture it was found that vertical

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water permeability values between asphalt mixtures AT 5 and AT 8, or AT 8 and AT 11 differ almost 3 times, and between AT 11 and AT 16 only 22%. The analysis of horizontal water permeability test results shows similar tendencies. The horizontal water permeability of asphalt mixtures AT 5 and AT 8 varies from 0.268×10^{-3} m/s to 1.173×10^{-3} m/s, while values of asphalt mixtures AT 11 and AT 16 are from 1.142×10^{-3} m/s to 2.730×10^{-3} m/s. The use of increased amount of AMLP reduces horizontal water permeability by twice comparing to normal composition asphalt mixture AT. The use of AMLP plus granite fine aggregates reduces horizontal water permeability by 2.4 times for asphalt mixtures AT 5 and AT 11, while for asphalt mixtures AT 8 and AT 16 by 1.2 times comparing to normal composition asphalt mixtures AT. It was found that horizontal water permeability values of asphalt mixtures AT 5 are 64% lower than that of AT 8, but values of AT 8 are 150% lower than that of AT 11, and the difference between values of AT 11 and AT 16 is insignificant. Thus, some values got in these water permeability tests appear to be sufficient ($1.130–2.762\times10^{-3}$ m/s), but lower than those found by Haselbach *et al.* (2017) (4.3-12.7×10^{-3} m/s) for porous asphalt.

Drainability test showed that water drainage values correlate similarly with water permeability in the horizontal and vertical directions (see Table 2). Drainage values varies from 0.083 s^{-1} to 0.500 s^{-1}, and the courser the mixture, the higher drainability. The lowest drainability (0.083 s^{-1}) was determined for asphalt AT 5 mixture with increased amount of AMLP, while asphalt AT 16 mixture with increased amount of AMLP showed the highest drainability (0.500 s^{-1}). The use of increased amount of AMLP reduces horizontal water permeability by 50% comparing to normal composition asphalt mixture AT, except asphalt mixture AT 16, where the use of increased amount of AMLP almost does not effected to reduction of drainability. The use of AMLP plus granite fine aggregates reduces drainability by 47% comparing to normal composition asphalt mixture AT, except asphalt mixture AT 5, where the use of AMLP plus granite fine aggregates increased drainability by 11%. There was not found the dependence of the drainability on the maximum aggregate particle size of the asphalt mixture.

The analysis of the average profile depth showed that the depth of the profile depends on the maximum aggregate particle size of the asphalt mixture. The larger aggregates are used for asphalt mixture, the greater the profile depth value. The analysis of profile depth results shows that mean profile depth increases by 33% using larger aggregates. The lowest mean profile depth (0.78–0.95 mm) was determined for asphalt AT 5 mixtures, and the highest (about 2.00 mm) for asphalt AT 16 mixtures.

Table 4. Results for the the air voids content and water conductivity

Asphalt mixture	Mix code	Maximum density (average). kg/m^3	Bulk density (average). kg/m^3	Air voids (average). %	Vertical water permeability. K_v(m/s) x10^{-3}	Horizontal water permeability. K_h (m/s) x10^{-3}	Drainage (HC). s^{-1}
AT 5	5-1	2.036	2.525	19.4	0.239	0.663	0.110
	5-2	2.100	2.509	16.3	0.103	0.344	0.083
	5-3	2.073	2.522	17.8	0.101	0.268	0.122
AT 8	8-1	1.974	2.575	23.3	0.692	1.173	0.326
	8-2	2.036	2.561	20.5	0.358	0.521	0.110
	8-3	2.054	2.567	20.0	0.407	1.006	0.149
AT 11	11-1	1.910	2.626	27.3	2.608	2.657	0.492
	11-2	1.967	2.618	24.9	1.130	1.434	0.197
	11-3	1.995	2.601	23.3	1.257	1.142	0.211
AT 16	16-1	1.844	2.616	29.5	2.762	2.730	0.484
	16-2	1.931	2.601	25.8	1.493	1.413	0.500
	16-3	1.940	2.616	25.8	1.620	2.231	0.337

The mean values from the measurements of the Pendulum test value (PTV) are presented in Figure 5. The PTV is used as a surrogate for microtexture. The slip speed of the British Pendulum Tester is very low and equals approximately 10 km/h. Therefore, the PTV is mainly dependent on microtexture (J.J. Henry, 2000). Microtexture is having direct influence to the friction between the tyre and pavement surface and with that to the traffic safety. Macrotexture is assuring waterless contact between tyre and pavement surface and decreasing aquaplaning danger but at the same time increasing tyre noise. The analysis of skid resistance measurement results shows that PTV varies from 68 to 83. These values are high as PTV for newly constructed asphalt pavement should be not less than 55.

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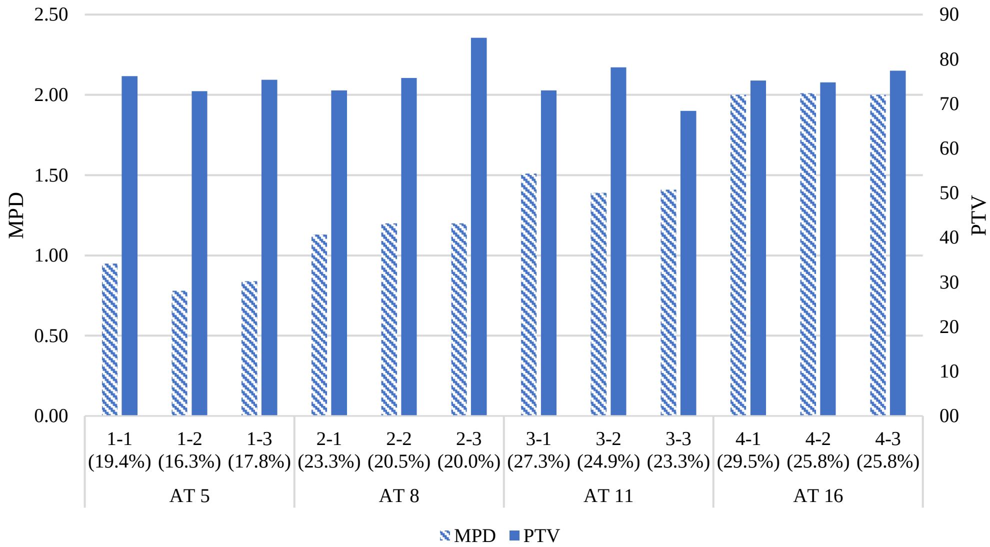

Figure 5.Dependency of MPD and skid resistance of AT asphalt mixtures

Conclusions

1. Vertical water permeability of asphalt mixtures AT 5 and AT 8 varies from 0.101×10^{-3} m/s to 0.692×10^{-3} m/s, while values of asphalt mixtures AT 11 and AT 16 varies from 1.130×10^{-3} m/s to 2.762×10^{-3} m/s. It means that vertical water permeability of asphalt mixture AT 11 and AT 16 are from 4 to 11 times higher than those of AT 5 and AT 8. However all tested asphalt mixtures meet the hydrological conditions of Lithuania, where it is recommended that the value of the vertical water permeability should be at least 0.08×10^{-3} m/s.
2. The analysis of vertical and horizontal water permeability results showed that permeability depends on aggregate particle size of asphalt mixture. Vertical water permeability values between asphalt mixtures AT 5 and AT 8, or AT 8 and AT 11 differ almost 3 times, and between AT 11 and AT 16 only 22%. It was found that horizontal water permeability values of asphalt mixtures AT 5 are 64% lower than that of AT 8, but values of AT 8 are 150% lower than that of AT 11, and the
3. The lowest drainability (0.083 s^{-1}) was determined for asphalt AT 5 mixture with increased amount of AMLP, while asphalt AT 16 mixture with increased amount of AMLP showed the highest drainability (0.500 s-1). The use of increased amount of filler aggregate reduces horizontal water permeability by about 48% comparing to normal composition asphalt mixture AT, except asphalt mixtures AT 5 and AT 16, where the use of increased amount of filler aggregate almost does not effected to reduction of drainability.
4. The analysis of profile depth results shows that mean profile depth increases by 33% using larger aggregates for asphalt mixture. The lowest profile depth was obtained for asphalt AT 5 mixtures (average MPD of three different composition asphalt mixtures is 0.86) and the highest results of profile depth were obtained for asphalt AT 16 mixtures (average MPD of three different composition asphalt mixtures is 2.00).
5. The analysis of skid resistance measurement results shows that surface of specimens prepared from tested asphalt mixtures is significant rough. Pendulum test values varies from 68 to 83. For newly constructed asphalt pavement PTV value should be not less than 55.
6. The purpose of porous asphalt mixtures is to drain the water on the surface of the pavement and to reduce the noise generated by the contact of vehicle tires with asphalt pavement surface. In addition, in order to investigate the applicability of these asphalt mixtures in cold climates, additional tests for the determination of frost resistance, stiffness, resistance to permanent deformations (ruts) and abrasion resistance should be performed.

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