

Effect of aggregate graining compositions on skid resistance of Exposed Aggregate Concrete pavement

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Abstract The paper presents the evaluation of skid resistance of EAC (Exposed Aggregate Concrete) pavements which differ in aggregate graining compositions. The tests were carried out on concrete mixes with a maximum aggregate size of 8 mm. Three types of coarse aggregates were selected depending on their resistance to polishing which was determined on the basis of the *PSV* (Polished Stone Value). Basalt (*PSV* 48), gabbro (*PSV* 50) and trachybasalt (*PSV* 52) aggregates were chosen. For each type of aggregate three graining compositions were designed, which differed in the content of coarse aggregate > 4mm. Their content for each series was as follows: A - 38%, B - 50% and C - 68%. Evaluation of the skid resistance has been performed using the FAP (Friction After Polishing) test equipment also known as the Wehner/Schulze machine. Laboratory method enables to compare the skid resistance of different types of wearing course under specified conditions simulating polishing processes. In addition, macrotexture measurements were made on the surface of each specimen using the Elatexure laser profile. Analysis of variance showed that at significance level $\alpha = 0.05$, aggregate graining compositions as well as the *PSV* have a significant influence on the obtained values of the friction coefficient μ_m of the tested EAC pavements. The highest values of the μ_m have been obtained for EAC with the lowest amount of coarse aggregates (compositions A). In these cases the resistance to polishing of the aggregate does not significantly affect the friction coefficients. This is related to the large areas of cement mortar between the exposed coarse grains. Based on the analysis of microscope images, it was observed that the coarse aggregates were not sufficiently exposed. It has been proved that *PSV* significantly affected the coefficient of friction in the case of compositions B and C. This is caused by large areas of exposed coarse aggregate. The best parameters were achieved for the EAC pavements with graining composition B and C and trachybasalt aggregate.

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1. Introduction

Skid resistance plays a special role in ensuring the safety of traffic on wet road pavements. It is related to the texture of road pavement, which is responsible for draining water from the plane of contact between a tire and a pavement surface. Pavement surface texture is specified in the three-level scale, each defined by the wavelength (λ) and peak – to peak amplitude (A) of its components. According to this division there are: megatexture ($\lambda = 50$ to 500 mm; $A = 0.1$ to 50 mm), macrotexture ($\lambda = 0.5$ to 50 mm; $A = 0.1$ to 20 mm), microtexture ($\lambda < 0.5$ mm; $A = 1$ to 500 μm) [1]. Especially macrotexture and microtexture influence skid resistance. Microtexture depends on polishing resistance of coarse aggregate and content of fine aggregate in a mixture. Macrotexture is related to the type of asphalt



mixture and the content of the individual fractions in a mineral mix. In the case of PCC pavement macrotexture depends on the technique of texturing of the upper layer.

The following texturing techniques are used on concrete pavements in Poland: burlap drag, transverse broom drag, transverse tine texturing and exposed aggregate concrete (EAC). The first three techniques do not ensure satisfactory durability on heavy traffic roads. Currently exposing of aggregate with the use of chemical agents is the only texturing method that is specified in Poland for the expressways pavements [2, 3]. This method is planned to be used on over 800 km of national roads to be built by the year 2023. The rationale for the choice of this method is the conviction that it provides both very good durability and skid resistance of road pavement.

The EAC was developed in the 1980s in Austria. In this method the process of cement hydration is retarded by applying appropriate retarding admixtures on the surface of fresh concrete. Then, after few hours, the not-hydrated cement mortar is removed with mechanical brushes or washed off with water jet [4]. Graining composition was designed on the basis of two aggregate fractions: 0/1 as fine aggregate (ca. 30%) and 4/8 as coarse aggregate (ca. 70%). This will ensure open grading of the mineral mix and optimum number of coarse particles on exposed surface. Currently, the Austrian guidelines allow the use of fractions: 0/2 and 5/8, as well as an EAC with a maximum aggregate size 11 mm. But recommendations are for the use of the maximum aggregate size of 8 mm so that the stone count or contact points should be at least 50 points per 25 cm² of surfacing [5]. Recommendations for maximum grain size aggregates are different in different countries. This has a direct impact on the diverse requirements of the texture depth, which are in the range from 0.90 to 1.80 mm depending on the country [6, 7, 8, 9]. EAC with the maximum aggregate grains 16 mm and 22 mm were made in Sweden and the Netherlands [7, 10, 11]. In contrast, the British requirements only allow the use of maximum grains 10 mm on highways and 8 mm on other pavements. Studies show that noise emission is much lower on pavements with such graining compositions compared to pavements with grains bigger than 11 mm [7, 10, 12]. In addition the impact of selection of aggregate graining on the proper execution of the texture of EAC pavement is indicated. It should be noted that the amount of coarse aggregate allows to achieve high macrotexture. Due to that fact pavement made of EAC has good skid resistance at high speeds [13, 14]. However skid resistance depends on both macrotexture and microtexture. Due to the low amount of fine aggregates used, microtexture of EAC is almost completely dependent on the resistance to polishing of coarse aggregates [107]. Therefore aggregates with PSV (Polished Stone Values) above 50 or 53 (depending on the country), should be used for EAC in order to meet the required level of skid resistance [5, 15, 16].

In Poland it is recommended to use aggregate with the maximum size of 8 mm and compose it from minimum three fractions. However, experiences of other countries show that in order to perform correct textures of concrete pavements it is required to compose aggregate from two fractions: fine aggregate 0/1 or 0/2 and coarse aggregate 4/8 or 5/8 [5]. The lack of such records may lead to insufficient or excessive exposure of coarse aggregates and their losses. As a consequence, it has a significant impact on the skid resistance of EAC pavement during its exploitation period.

The aim of this study was to determine the impact of aggregate graining as well as the PSV of coarse aggregate on skid resistance of EAC pavement. In actual conditions, skid resistance is associated with the characteristics of the wearing course, specially its surface texture, traffic intensity, the period of pavement life, climate, ect. Therefore, it was important that the tested EAC pavements could be subjected to the processes that simulate phenomena occurring in actual traffic conditions. Such studies in laboratory conditions are possible using FAP test equipment, popularly known as the Wehner/Schulze machine. It was developed in Germany over 30 years ago. In 2014 this method was adopted as a harmonized European Standard EN 12697-49 as the Friction after Polishing test. The device simulates the phenomenon of polishing on the wearing course. Studies show that determination of the friction coefficient before construction of wearing course allow to avoid the use of materials that could contribute to the slipperiness of the road pavement [17, 18].

This paper presents the comparison of skid resistance of EAC pavements which differ in aggregate grading compositions and the resistance to polishing of coarse aggregate measured using the FAP test equipment.

2. Research program

2.1. Materials and compositions

The tests were carried out on concretes with the maximum aggregate size of 8 mm. Three types of coarse aggregates were selected: basalt, granite and trachybasalt. Their choice depended on resistance to polishing which was determined on the basis of the *PSV*. Table 1 shows physical properties of the tested aggregates.

Table 1. Physical properties of coarse aggregate.

Properties	Test method	Basalt	Gabbro	Trachybasalt
Resistance to polishing, <i>PSV</i> [-]	EN 1097-8	48	50	52
Resistance to fragmentation, <i>LA</i> [%]	EN 1097-2	9	23	12
Resistance to freezing and thawing, F_{NaCl} [%]	EN 1367-6	1	1	1
Density, ρ_a [Mg/m ³]	EN 1097-6	3.09	2.90	2.70
Water Absorption, WA_{24} [%]	EN 1097-6	0.3	0.5	0.5

For each type of aggregate three grading compositions were designed, which differed in the content of coarse aggregate > 4 mm. The content of coarse aggregate for particular series was as follows: A – 38%, B – 50% and C – 68%. Three fractions of aggregates: 0/2, 2/5, 4/8 were used in composition A and B, whereas for composition C only two fractions 0/2 and 4/8 were used. Aggregate particle-size distribution of particular aggregate compositions are presented in Table 2.

Table 2. Aggregate particle size distribution.

Sieves [mm]	Passing fraction [%]								
	A			B			C		
	Basalt	Gabbro	Trachybasalt	Basalt	Gabbro	Trachybasalt	Basalt	Gabbro	Trachybasalt
11.2	100	100	100	100	100	100	100	100	100
8	98	97	99	95	94	98	93	92	97
5.6	82	81	86	66	67	68	44	47	46
4	63	62	62	48	49	48	32	33	32
2	38	36	39	28	34	33	28	29	28
0.125	3	4	3	2	3	3	2	3	3
0.063	1.0	1.0	1.0	0.0	1.0	1.0	1.0	1.0	1.0

Cement CEM I 42.5R was used in amount from 430 to 440 kg/m³, the water-cement ratio w/c was in the range 0.36 - 0.37. Air-entraining and water reducing admixtures were applied. The consistence of concrete mixes has been classified to V2 according to the Vebe method. Three slabs of size 35 × 35 × 5 cm were formed for each concrete composition. In order to expose the aggregate, surfaces of slabs were sprayed with retarding admixture. The aggregate was exposed after approx. 18 hours by removing the unhydrated layer of cement mortar with a steel brush. Then slabs were stored at 20 °C and RH 50%. Specimens with a diameter of 225 mm for testing in the FAP device were drilled from the slabs after 28 days. Exemplary specimens of EAC with particular aggregate graining compositions are shown in figure 1.

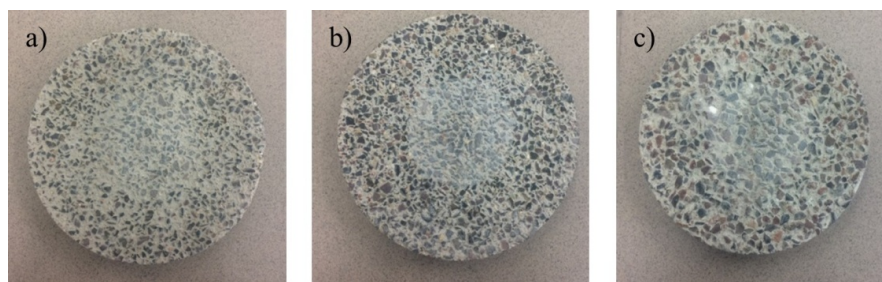


Figure 1. Exemplary specimens of EAC with trachybasalt aggregate a) composition A; b) composition B; c) composition C.

2.2. Test procedure

The FAP equipment (figure 2a) consists of two heads: for polishing and for measurement of friction coefficient μ_m . The polishing action is performed by means of three rubber cones mounted on rotary disc and rolling on the specimen surface (figure 2b). A water-quartz powder mix is projected during the polishing process. The second measuring head is composed of three small rubber sliders disposed at 120° on the rotary disc (figure 2c). The disk rotates at tangential velocities up to 100 kph. Water flows over the surface being tested. The rotating disk is then dropped onto the wet surface and the coefficient of friction μ_m is measured. Measuring of μ_m was conducted after 2000, 4000, 6000, 8000, 10 000, 20 000, 40 000, 60 000, 80 000, 100 000, 160 000, 180 0000 passes of polishing head. In this study μ_m at slip speed 60 kph was taken. Before starting the test the function of the measuring device was tested using the glass control plate (figure 2d). If the results of coefficient of friction μ_{ref} is not in the range from 0.095 to 0.125, the rubber sliders should be exchanged.

In addition, macrotexture measurements were made on the surface of each specimen using the Elatexure laser profile. This is the rotating laser sensor which scans the road pavement surface with high resolution: vertical - 0.01 mm and horizontal - 0.2 mm. When the measurement starts the laser sensor rotates on a circumference of the measurement circle 400 mm. The software calculates the Mean Profile Depth (MPD) parameter that characterizes the profile macrotexture.



Figure 2. a) The FAP test equipment b) polishing rotary head, c) friction measuring rotary head, d) glass control plate.

3. Results and analysis

The mean values of friction coefficient μ_m obtained on the tested EAC pavements during polishing process with standard deviation are presented in figure 3.

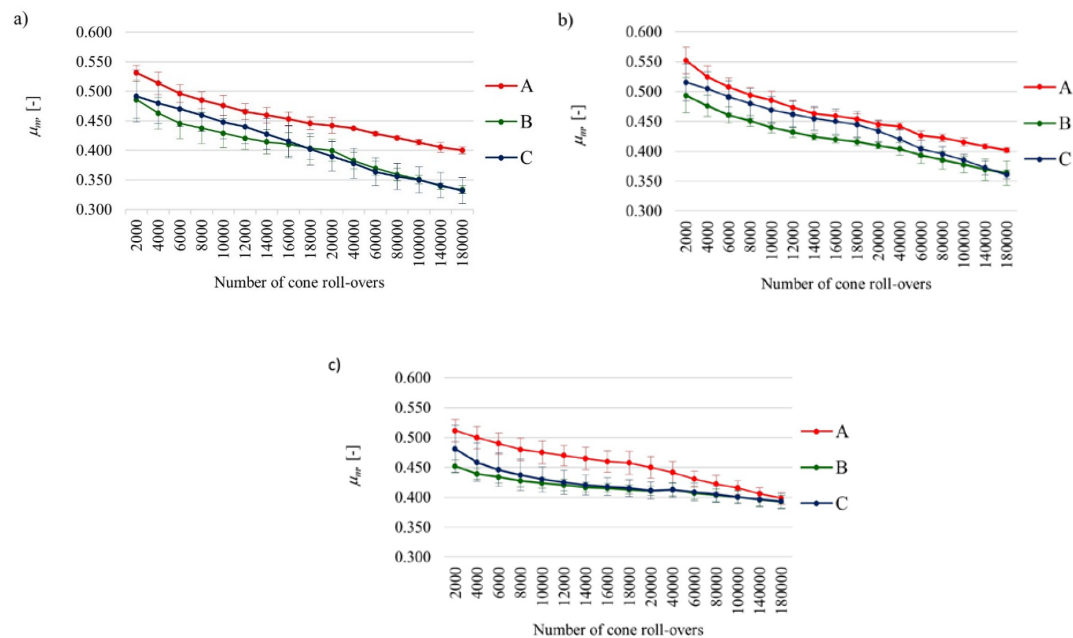


Figure 3. Changes of friction coefficients obtained on the tested EAC with individual graining composites with a) basalt; b) gabbro; c) trachybasalt aggregate.

Significant differences between changes of friction coefficients were noted for tested EAC pavements in polishing process. Specimens with graining composition C were affected by polishing more quickly than those with composition A. This is caused by large area of exposed coarse aggregate >4 mm. However, the most rapid surface changes occurred on EAC with basalt aggregate. In this case, the following decreases in friction coefficients were recorded: for composition A – 25%, B – 31% and C – 33%. In contrast, decreases of friction coefficients on EAC with trachybasalt aggregate ranged from 13 to 22% depending on the aggregate composition. Different susceptibility to polishing factors is related to the structure of rocks and properties of particular minerals. Both basalt and trachybasalt are volcanic rocks, but they differ in structure. Trachybasalt has an aphanitic structure. Therefore, small crystals contribute to better polishing resistance than aggregates from basalt rocks with a cryptocrystalline structure. Whereas gabbro is a igneous rock with crystalline structure. This is probably the reason of its better polishing resistance than basalt. But gabbro consists of minerals of similar hardness, which makes it more susceptible to polishing than trachybasalt.

The analysis of variance (ANOVA) was carried out in order to determine on the accepted significance level $\alpha = 0.05$ the significant effect of the aggregate graining composition and the PSV of coarse aggregate on the obtained coefficient of friction μ_m . The comprehensive evaluation of skid resistance should also include macrotexture measurements. The obtained results of the *MPD* parameter indicate the influence of the aggregate graining composition on macrotexture of surface EAC. Therefore, the ANOVA was used to determine on the accepted significance level $\alpha = 0.05$ the significant effect of aggregate graining compositions and the PSV of coarse aggregate on the obtained parameter *MPD*. The calculations were carried out using the Statistica 13.1 program. Tables 3 and 4 summarizes the main results of these analyses. It was found that at the level of significance 0.05, both graining the composition of tested EAC and the PSV of aggregate have the significant effect on the values of the μ_m . In the case of *MPD* results at the significance level of 0.05, the significant effect of graining composition was proved.

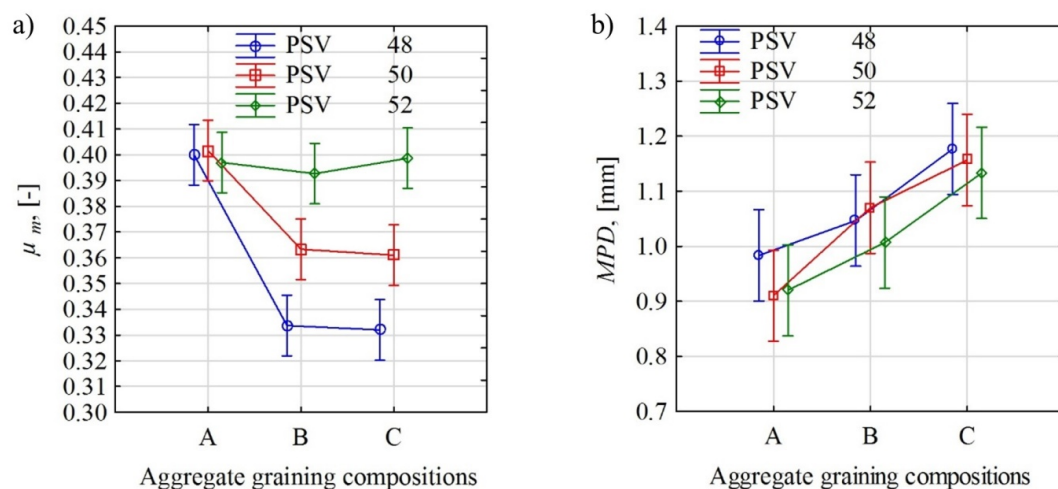
Table 3. ANOVA summary table (effect of aggregate graining composition and the PSV on the values of μ_m).

Source of variance	Sum of squares SS	Degrees of freedom	Mean squares MS	F ratio	p - value
Composition	0.0075	2	0.0038	40.18	0.00000
PSV	0.0078	2	0.0039	41.54	0.00000
Composition* PSV	0.0044	4	0.0011	11.84	0.00007
Error	0.0017	18	0.0001		
Total	0.0214	26			

Table 4. ANOVA summary table (effect of aggregate granining compositon and the *PSV* on the values of the *MPD*.

Source of variance	Sum od squares SS	Degrees of freedom	Mean squares MS	F ratio	p - value
Composition	0.21361	2	0.10680	22.83	0.00001
PSV	0.0108	2	0.0054	1.15	0.33870
Composition* PSV	0.0077	4	0.0019	0.41	0.79789
Error	0.0842	18	0.0047		
Total	0.3163	26			

The graphic interpretation of the results is shown in the figures 4 and 5. The highest values of the μ_m have been obtained for EAC with the lowest amount of coarse aggregates > 4mm (compositions A). In these cases the resistance to polishing of the aggregate does not significantly affect the friction coefficients. This is related to the large areas of cement mortar between the exposed coarse grains because of the low content of coarse aggregate in these compositions. It can be seen on the microscope images of the surfaces of specimens (Fig. 5a, 6a, 7a). Although they were characterized by the highest value of the coefficients of friction, this solution should not be used due to problems with obtaining the correct and homogeneity of the texture surface of the upper concrete layer.

**Figure 4.** Mean values of the μ_m (a) and the *MPD* parameter (b) obtained on the tested EAC pavements with 95% confidence interval.

It has been proved that PSV significantly affected the coefficient of friction in the case of compositions B and C. This is caused by large areas of exposed coarse aggregate. The spaces between the exposed grains on the surface of the EAC with the grading compositions B and C are definitely smaller than in the case of the compositions A (Fig. 5 – 7). Additionally, the significant changes due to polishing can be noticed on these images. It should be noted that due to the shape of the aggregate

grains, the polishing process occurs only on these parts of aggregate grains which have the direct contact with the rubber cones. A typical gloss is visible on these areas. However, the surface of coarse aggregate grains in specimens of EAC with composition C is more exposed than in specimens of EAC with composition B. The difference in content of coarse aggregate also affects the macrotexture of the tested EACs. The Mean values of MPD were obtained in the following ranges: compositions A 0.91 – 0.98; compositions B 1.00 – 1.07 and compositions C 1.13 – 1.17. Based on the evaluation of macrotexture it could be expected that compositions B and C ensure an optimal number of exposed aggregate grains so that the passing tire is mostly in contact with the aggregate tips, thereby allowing sufficient space between the tire and the mortar for drainage.

It should be noted that there were no significant differences between the results of the μm obtained for compositions B and C when the same type of aggregate was used. Differences in the coefficients of friction result only from the PSV of aggregates. The effect of aggregate resistance to polishing caused that the friction coefficients of EAC with trachybasalt were/are higher by about 0,08 unit than the coefficients of EAC with basalt.

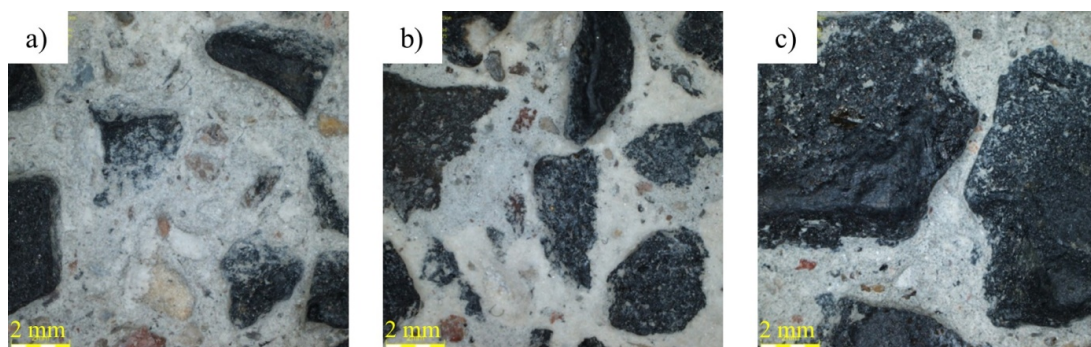


Figure 5. Comparison of EAC surfaces with basalt aggregate a) composition A; b) composition B; c) composition C;

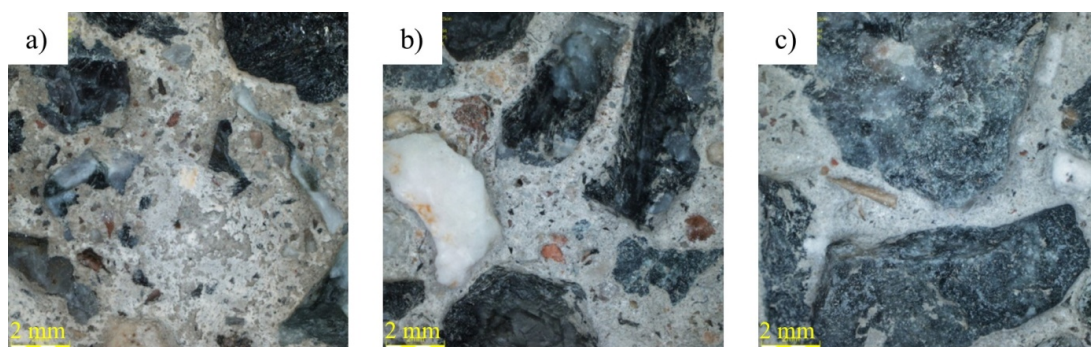


Figure 6. Comparison of EAC surfaces with gabbro aggregate a) composition A; b) composition B; c) composition C;

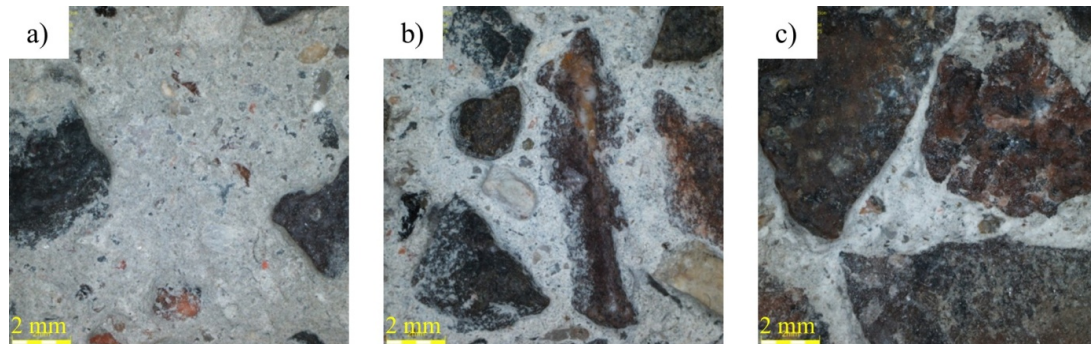


Figure 7. Comparison of EAC surfaces with trachybasalt aggregate a) compositions A; b) compositions B; c) compositions C.

Conclusions

The use of the FAP test equipment made it possible to compare EAC pavements differing in graining composition as well as the coarse aggregate resistance to polishing. The tests are valuable at the stage of designing the upper layers of the pavement, because they enable assessment of skid resistance at the design stage in laboratory conditions. However, the results obtained using the FAP test equipment should be complemented by macrotexture measurements on tested specimens. This will allow for comprehensive verification of materials for the wearing course, which can contribute to the slippery of road pavement.

It has been proven that the skid resistance is related to the aggregate graining composition as well as the resistance to polishing of the coarse aggregate used for EAC. The best parameters were achieved for the EAC pavements with about 50% content of aggregate > 4 mm (composition B and C) and coarse aggregate with the highest PSV. It should be noted that EAC is a very difficult technology for constructing upper layers of road pavements. To obtain the proper texture, it is very important to comply with the regimes during its construction, especially at the stage of its texturing and curing.

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