Quality Assurance Methods Applied For Exposed-Aggregate Concrete Pavement Construction

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The exposed aggregate pavement technology for construction of concrete highways is used in European countries, including Poland, mostly for heavy trafficked roads. It is mainly a two-lift slip-form technology with a special treatment of the top surface after the final smoothing operation. This is a demanding technology that leaves a little margin for mistakes. When properly done the pavement layer with exposed aggregates ensures designed skid resistance for vehicle wheels even in adverse weather conditions without excessive traffic noise. The challenge is to provide its cost-effective long term performance including both the adequate roughness and the desired smoothness of the pavement. The paper presents tools and methods for construction quality assurance specific for exposed aggregate concrete pavements. Required monitoring of the stability of concrete mix properties is discussed. The importance of concrete curing is analyzed in respect to the long term durability in wet-freeze regions with heavy use of deicing salts. Macrotexture assessment at the early stage of pavement construction is seen as the key factor for assurance of the proper skidding resistance. Local evaluation of smoothness is also a useful approach to assure the target IRI. Examples of quality assurance efforts applied on concrete highways recently constructed in Poland are presented.

air entrainment | exposed aggregate | evenness | jointed plain concrete pavement | quality assurance | macrotexture depth

1. INTRODUCTION

The construction of two-layer exposed aggregate concrete pavement is a demanding task that is justified by the target high performance characteristics of such a highway pavement. It is largely considered the most adequate for highly-trafficked highways, such as for example “high quality roads” defined for European transnational transport network. When considering the whole life costs of highway pavement the benefits of such a solution are clearly demonstrated [1-2].

The technology of constructing concrete road pavements with exposed aggregate is successfully used in a number of European countries, however in the USA it has not been frequently used [3]. It is a two-layer pavement technology - the layers are laid and compacted within a short time period to maintain a monolithic interlayer connection. The upper layer concrete contributes to meeting the load capacity requirements of the entire pavement cross-section, but also meets the requirements of resistance to environmental and operational factors. A properly made surface with an upper layer of exposed aggregate ensures the target skid resistance at wet conditions without excessive increase in noise caused by vehicle traffic [4], [5], [6]. However, production of two-layer pavement with exposed aggregate at the upper surface requires extensive experience of the contractor and appropriate selection of materials [7]. The mistakes made can negatively affect the grip of the vehicle wheels, longitudinal evenness, i.e. driving comfort, or cause premature deterioration of these functional properties.

The intrinsic feature of Portland cement pavement construction technology is the extended waiting period (related to advancement of cement hydration) for achieving the designed mechanical properties and durability of concrete as well as for checking the anti-slip properties and longitudinal evenness of the finished surface. The properties of concrete in the pavement are obviously affected by the natural variability of properties of the components, but a significant impact of weather conditions and concreting/finishing procedures is also observed. It is rational to supervise the construction of concrete pavement not only using the acceptance tests of final properties, but also by ongoing checks of these material features and technological processes that will determine the final functionality of the pavement [8], [9]. The idea is to detect any material or technological deficiencies during the construction of the pavement, bearing in mind a potentially high speed of pavement slip-forming, up to 0.8 km per day. This paper presents the appropriate actions related to the quality assurance of pavement construction when using exposed aggregate cement concrete technology. The discussion is illustrated by examples of activities carried out during pavement construction of the expressway located in the north-east part of Poland. The pavement was designed as a double-layer doweled and anchored concrete slab with exposed aggregate at the surface, placed over a geotextile separation layer laid over a cement treated base layer. Wet-on-wet concrete pouring results in a monolithic two-layered structure. The surface of the upper layer is subjected to technological treatments to give the target texture to provide the target skid resistance.

2. RESEARCH SIGNIFICANCE

The two-layer exposed aggregate pavement technology for construction of concrete highways is a demanding technology that leaves a little margin for mistakes. It requires the proper contractor skills, particularly at the surface finishing stage. To support the construction process the adequate quality assurance tools are needed to address specific issues. The set of tools was developed and implemented during the construction of heavily trafficked pavement in the wet-freeze zone of Central Europe. Such tools are mostly focused on monitoring the macrotexture and evenness of pavement. At the same time

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Table 1. Design criteria for two-layer pavement concrete (for both layers unless stated otherwise).

Properties of concrete	Criteria	Test method
Apparent density – deviation from the accepted mix design value	± 3.0 %	PN-EN 12390-7
Compressive strength class as per PN-EN 206, not lower than	C35/45	PN-EN 12390-3
Flexural strength at 28 days (1) of curing (the average of 3 beams), not lower than	5.5 MPa	PN-EN 12390-5
Splitting strength at 28 days (1) of curing (the average of 3 cube specimens), not lower than	3.5 MPa	PN-EN 12390-6
For the upper layer: Frost-salt scaling resistance: S_{56} – the average mass of scaled material after 56 F-T cycles, S_{28} – the average mass of scaled material after 28 F-T cycles, not higher than	S_{56} < 0.50 kg/m^2 and S_{56} / S_{28} < 2	PKN-CEN/TS 12390-9 (slab test)
Air void characteristics in concrete: - micropores content (A_{300}), not less than - spacing factor $\bar{L}$, not more than	1.8 % 0.18 mm	PN-EN 480-11
For the upper layer Penetration resistance for gasoline, oil 2), not more than	30 mm	PN-EN 13877-2 App. B
For the lower layer Freeze-thaw resistance after 200 F-T cycles 1), 3) mass reduction, not more than compressive strength reduction, not more than	5 % 20 %	PN-B-06250
Explanation: 1) or at equivalent curing age corresponding to cement hardening advancement related to cement composition; the equivalent curing age is: 28 days for CEM I R, CEM II/A-S R; 56 days for CEM I N, CEM II/A-S N, CEM II/B-S N,R 2) only for areas exposed to potential oil or gasoline spill, e.g. toll plaza, parking places, 3) for the lower layer – the test is considered equivalent to test no.6.		

proper monitoring of basic concrete properties is performed that mostly consists of frequent testing of water content and air content/void distribution in fresh concrete. The emerging technique of sequential pressure method was found feasible to be applied to dense concrete mixtures adequate for slip-form paving technology.

3. TOOLS AND METHODS OF QUALITY ASSURANCE DURING CONSTRUCTION

According to AASHTO, the quality assurance is defined as "all planned and systematic actions necessary to ensure an adequate level of confidence that a product or service will meet certain quality requirements". The quality assurance during the construction of a concrete pavement is a set of tests and activities carried out by the contractor and supervision to monitor the quality of material supplies and the processes of mixing, placing and finishing concrete. Their purpose is to ensure that the surface meets the minimum quality criteria.

For typical catalogue pavement structures in Poland the general requirements for concrete are given in [10]. The required properties for the designed concrete for double-layer jointed concrete pavement slabs with exposed aggregate at the surface are given in Table 1. In the freeze-wet region in the north-east winter climate zone [11] of intense use of deicing salts the admissible mass of scaling is reduced [12]. The frost-salt scaling resistance of concrete is known to be largely dependent on the air void characteristics and w/c ratio [13], [14], that is reflected in the requirements. Functional requirements for the concrete pavement given in Table 2 specify the properties of concrete in the pavement layer, which guarantee the compliance with the requirements specified for the designed pavement concrete. The frequency of testing on fresh and hardened concrete and the frequency of acceptance testing on cores is given in Table 3 and 4.

Documentation of quality assurance procedures during the construction of cement concrete pavement should be detailed so that the construction processes can be tracked and even problem situations can be anticipated. The most frequently conducted qualitative tests concern such properties that are easily verified, such as the air content in the mix, the concrete

Table 2. Functional requirements for a cement concrete pavement.

Properties	Criteria	Test methods
Concrete strength in pavement		
The lower layer Compressive strength class as per PN-EN 13877-2 p. 4.2.2, not lower than	CC 40	PN-EN 12390-3
Concrete pavement thickness		
Tolerance category for layer thickness acc. to PN-EN 13877-2 p. 4.3 :	T5	PN-EN 13877-2 p. 4.3
Apparent density of concrete in pavement		
For the lower layer Concrete density in relation to reference specimens acc. to PN-EN 13877-2 p.4.4, not less than	95 %	PN-EN 12390-7
Frost-salt scaling resistance of concrete in pavement		
For the upper layer: Scaling resistance: S_{56} – the average mass of scaled material after 56 F-T cycles, S_{28} – the average mass of scaled material after 28 F-T cycles, not higher than	S_{56} < 0,50 kg/m^2 and S_{56} / S_{28} < 2	PKN-CEN/TS 12390-9 („slab test")
Air void characteristics in concrete: - micropores content (A_{300}), not less than - spacing factor $\bar{L}$, not more than	1.5 % 0.20 mm	PN-EN 480-11
Penetration resistance for gasoline, oil (if required)		
For the upper layer Penetration resistance for gasoline, oil, not more than	30 mm	PN-EN 13877-2 App. B
Location of dowels and tie bars	following the design documents	ASTM E3013/E3013M-15

Table 3. Frequency of testing on fresh and hardened concrete.

Fresh mix testing – mix for lower and upper layer	
Consistence	3 per day
Density, water content	3 per day
Air content	each 1 hour
Temperature	each 1 hour
Hardened concrete testing on specimens – mix for lower and upper layer	
Compressive strength	6 specimens per day
Flexural strength	6 specimens per day for 30 000 m^2
Splitting strength	3 specimens per day
Density	6 specimens per day
Scaling resistance (the upper layer concrete only)	4 specimens per day for 30 000 m^2
Freeze-thaw resistance (the lower layer concrete only)	12 specimens per day for 30 000 m^2
Air void characteristics	2 specimens per day for 30 000 m^2

Table 4. Frequency of acceptance testing on cores Ø150 mm.

Frequency	Tests on cored specimens	Test method
1 core per 5000 m^2	layer thickness	PN-EN 13863-3
	upper layer: disk specimen 50 mm thick– scaling resistance testing	PKN-CEN/TS 12390-9
	lower layer: cylinder 150 mm thick – density and compressive strength testing	PN-EN 12390-3 PN-EN 12390-7
1 core per 20000 m^2	layer thickness	PN-EN 13863-3
	upper layer: flat specimen– air void characteristics in the cross section	PN-EN 480-11
	lower layer: flat disk specimen– air void characteristics in the cross section	PN-EN 480-11

Table 5. List of methods for monitoring concrete mix properties affecting the paving and finishing process.

Technological feature	Test method
Variability of mix workability	Aggregate particle size, fines content Water to cement ratio in the mix Mixture density and consistency
Water evaporation rate from the surface	Weather monitoring, surface temperature Temperature of components and concrete mix
Air entrainment stability	Air content – regularly in fresh mix by the pressure method and occasionally in hardened concrete by PN-EN 480-11 Air-void distribution – the sequential pressure method (trial implementation)

Table 6. Non-destructive methods for quick check of the correctness of paving construction process.

Pavement feature	Test method
Pavement layer thickness	Magnetic induction method: MIT Scan-T2 (trial implementation)
Dowel placement	Magnetic induction method: MIT-Scan2-BT
Longitudinal evenness	Measurement of longitudinal evenness during construction - Dipstick manual prolifograph (trial implementation)
Macrotexture depth	Stationary laser profilograph: ELAtextur

strength, the pavement thickness and evenness of the surface. Tables 5 and 6 present the methods used to monitor the properties and early check the correctness of the concrete pavement process (the frequency of testing – as needed).

4. MONITORING OF WEATHER CONDITIONS

Placing the pavement layer takes place in stages after proper preparation of base layers, placing and fixing of geotextile along the length of the working plot. Using a set of modern machines in slip formwork during one extended working day a roadway is built at a width of about 10 m along the length of about 800 m. An extended shift may last longer, unless weather or organizational obstacles occur. The obstacle is, among others, a heavy rain preventing the achievement of appropriate concrete properties at the road surface, possibly strong wind causing rapid drying of fresh concrete surface. Rapid temperature changes can also be a reason for stopping the placing process. To respond appropriately to weather changes, monitoring of both air temperature and relative humidity, wind speed and precipitation at the construction site is recommended. The rate of water evaporation from the concrete surface depending on weather conditions can be determined using the well known nomogram according to the recommendations of ACI 308 R-16 [15].

5. MONITORING THE STABILITY OF CONCRETE MIX PROPERTIES

A. Water content in concrete mix. The variability of the grain size of natural rocks used for the concrete mix, especially fine aggregate (sand) constituting about 20-25% of the weight of concrete components, affects the properties of concrete mix. Regular checking of aggregate grain size, and in particular the content of fines in coarse aggregate, is a required procedure to ensure the quality of the pavement construction process. Small changes in aggregate grain size and humidity are taken into account during mix production by correcting the water content and observing the mixture consistency. In the long process of placing concrete over a pavement section, approximately 3 cubic meters of mixture per 1 meter long roadway is produced. That is equivalent to about 2400 m^3 per daily section of 800 meters (with a thickness and width of 29 cm and 10.5 m respectively). This volume of concrete holds over 4,000 tons of aggregate, and in such a large mass one can expect a natural variability in grain size, shape and fines content. The effective water content in the mixture depends, among others, on aggregate moisture and absorbability. Monitoring of water content in the mixture delivered to the construction site allows checking the recipe limits in relation to water-to-cement (w/c) ratio [16]. Using the test method described in AASHTO T318-15-UL, using a microwave oven of sufficiently high power, such a determination is made at the construction site (Fig. 14.3) in a short time.

Fig. 1. Field test stand for measuring the water content of the concrete mix by the microwave oven

B. Air entrainment of fresh mix. The measurement of air content by the pressure method in accordance with PN-EN 12350-7 is performed as a routine check of the stability of air entrained concrete mix production. As shown in Fig. 2, measurements carried out often, e.g. every hour, allow for accurate monitoring of the air entrainment stability. The use of smartphones allows for immediate data communication between the involved partners and support quick decision on possible need to modify the composition of the mixture. Both the air content and the SAM number characterizing the air void size distribution in concrete mix can be determined using a modified pressure apparatus, called SAM [17]. The sequential pressure method can be practically used at the road construction site close to the paver, as shown in Fig. 3, with no influence of paver vibration. The preliminary SAM measurements performed at the construction site of slip-form concrete pavement were discussed in [18]. The obtained results demonstrated a fair correlation between the SAM number and the air void spacing factor in hardened concrete: the SAM number below 0.30 corresponded to the spacing factor <0.25 mm. The correlation between the SAM number and the content of microvoids in hardened concrete was even more pronounced. The method of determining the air void characteristics in hardened concrete according to PN-EN 480-11 is not suitable for ongoing monitoring of air entrainment, but allows the calibration of the methods discussed above.

Fig. 2. Results of air content monitoring in fresh concrete for the lower (a) and upper (b) layer of highway pavement, using the pressure method, ready for immediate communication via smartphones

Fig. 3. Field measurements of air content and air void size distribution using SAM apparatus

6. ASSESSMENT OF THE SURFACE MACROTEXTURE

Although the calibrated sand method based on PN-EN 13036-1 is considered a reference method for determining the depth of macrotexture, a laser profile measurement method was used to assess it immediately after the aggregate was exposed, in accordance with PN-EN ISO 13473-1. The stationary ELAtextur device was used to measure the macrotexture depth of the pavement surface layer with exposed aggregate, as shown in Fig. 4. The macrotexture of the pavement along the direction of travel marked on slabs shown in Fig. 5 was measured along a section of the highway pavement made in 2017. A good compliance of the measurements was found ELAtextur on individual plates with laser profilograph measurement.

The macrotexture of pavement with exposed aggregate is assumed to be an indicator of the predicted coefficient of friction between the tire and the pavement. Fig. 6 shows examples of measurement results of the macrotexture depth, determined in cross-sections of the road every 10 m along the line passing through the center of each plate on the part of the section shown in Fig. 5, i.e. on 6 plates from km 12 + 300 to km 12 + 355. The macrotexture depth was within the limits from 0.9 mm to 1.4 mm, which indicates good repeatability of the pavement macrotexture profile.

Table 7 summarizes the measurements of macrotexture depth, friction coefficient and longitudinal evenness (IRI) on six panels at the selected section from km 12 + 300 to km 12 + 355. The homogeneity of the surface profile is evidenced by the average values of the macrotexture depth within the narrow range from 0.9 to 1.3 mm (Fig. 7). Measurements of the coefficient of friction at the speed of 60 and 90 km/h confirm a favorable assessment of the friction between the vehicle tire and the road surface. In this case, a high friction coefficient and an appropriate macro texture of the pavement should be associated with a sufficiently high content of aggregate fraction 4/8 mm in concrete mix for the upper pavement layer (approx. 70%) and a favorable cubic shape of aggregate grains. Macrotexture depth mapping with ELAtextur device (measurements along the lines in the transverse and longitudinal directions) can be treated as an alternative to macrotexture evaluation by counting the heads of grains over a defined surface on the pavement with exposed aggregate. Such a procedure may be useful for assessing the macrotexture depth in a pavement test section, when due to its insufficient length it is impossible to perform a laser profilograph measurement or use a device for measuring the friction coefficient.

7. ASSESSMENT OF THICKNESS AND EVENNESS OF PAVEMENT

At the acceptance stage, the pavement thickness is verified using specimens drilled from the pavement in accordance with PN-EN 13877-2. Non-destructive measurement of pavement thickness allows you to monitor the placing process and allows you to take early corrective actions. For non-destructive thickness measurement, the MIT Scan-T2 device was used according to the methodology described in the AASHTO standard T359-18-UL.

The longitudinal evenness is usually expressed by International Toughness Index (IRI). The results of measurements of IRI along the selected section of pavement are given in Table 7. For exposed aggregate concrete pavement the longitudi-

(a) (b)

Fig. 4. Macrotexture depth measurements using ELAtextur device

Table 7. Results of measurements of macrotexture depth, friction coefficient and longitudinal evenness on 6 pavement slabs along the section from km 12 + 300 to km 12 + 350.

Location	Fast lane	Slow lane	Shoulder
Macrotexture depth (average of 11 measurements along transverse direction. ELAtextur)			
km 12+302.5	1.2 mm	1.0 mm	1.1 mm
km 12+312.5	1.2 mm	0.9 mm	1.0 mm
km 12+322.5	1.1 mm	1.0 mm	1.1 mm
km 12+332.5	1.0 mm	1.1 mm	1.2 mm
km 12+342.5	1.2 mm	1.1 mm	1.1 mm
km 12+352.5	1.3 mm	1.3 mm	1.2 mm
Coefficient of friction at 60 km per hour by SRT-3 test device			
1 month after pavement construction date			
km 12+300	0.67	0.58	--
km 12+350	0.59	0.52	--
3 months after pavement construction date			
km 12+300	--	0.61	--
km 12+350	0.63	0.56	--
15 months after pavement construction date			
km 12+300	0.60	0.59	--
km 12+350	0.61	0.57	--
Coefficient of friction at 90 km per hour by SRT-3 test device			
15 months after pavement construction date			
km 12+300	0.52	0.50	--
km 12+350	0.55	0.53	--
Longitudinal evenness (IRI) at 60-70 km per hour by laser profilograph			
from km 12+300 to km 12+350	0.72 mm/m	0.70 mm/m	0.73 mm/m

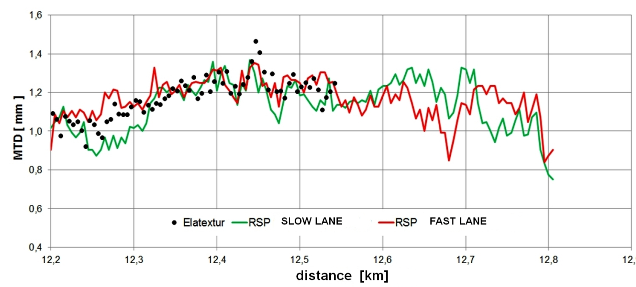


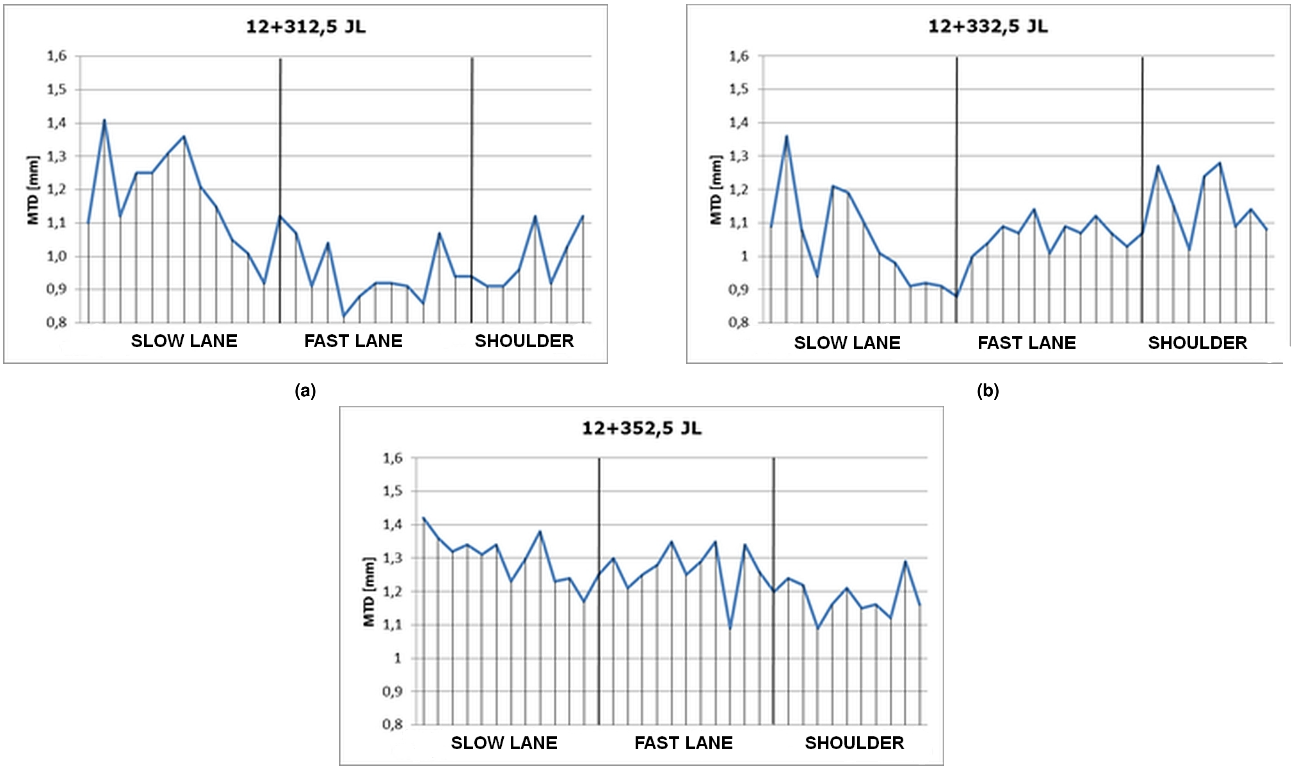
Fig. 5. The mean texture depth (MTD) of the pavement along the direction of travel, determined locally by ELAtetxtur and a laser profilograph (RSP) on slow and fast lane

nal evenness, determined by IRI of 0.70-0.73 mm/m can be assessed as excellent.

Continuous monitoring of the longitudinal evenness of the pavement [19] is recommended in order to optimize the process of placing and smoothing the pavement. The process consists of several repetitive operations. This can lead to repetitive patterns / bumps / surfaces that need to be eliminated. For early checking of longitudinal evenness on completed working plots, a prototype Dipstick was used (Fig. 8) based on the AASHTO R041-05-UL standard. The possibilities of using this device for ongoing monitoring of longitudinal evenness shortly after placing the pavement on a given section is currently being analyzed.

8. AIR ENTRAINMENT MONITORING

Presented tools for quality assurance specific for exposed aggregate concrete pavements are mostly focused on monitoring the macrotexture and evenness of pavement. At the same time proper monitoring of basic concrete properties is per-



(a)

(b)

(c)

Fig. 6. The depth of macrotexture of the pavement along the lines transverse to the direction of travel, determined by ELAtextur method on a part of the section from Fig. 5.

Fig. 7. The macrotexture view of exposed aggregate two-layer concrete pavement constructed in wet-freeze region for heavy trafficked transnational highway [6]

Fig. 8. Longitudinal evenness measurement with a Dipstick.

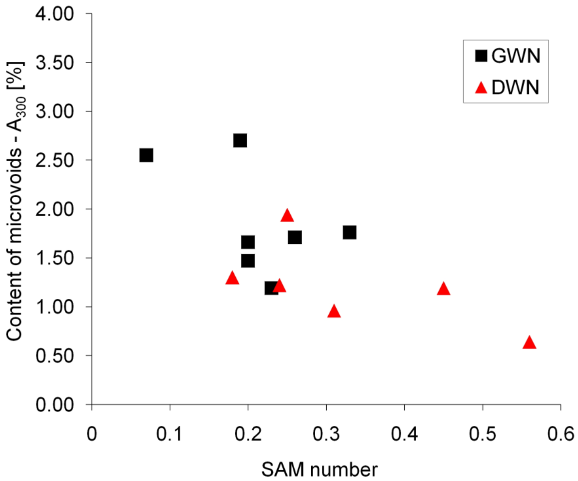


Fig. 9. The field relationship between SAM number of fresh concrete delivered for highway construction and the content of microvoids A300 in hardened concrete [18].

formed. Mostly it consists of frequent testing of water content and air content/void distribution. The emerging technique of sequential pressure method was found feasible to be applied to dense concrete mixtures adequate for slip-form paving technology. An established correlation [18] between the fresh mix SAM number and the air vid distribution in hardened concrete seems to provide a necessary tool for prediction of freeze-thaw resistance of pavement concrete [20]. Also the frost-salt scaling can be roughly evaluated on the basis of air-void characteristics and w/c measurements. In Fig.9 the relationship content of microvoids A_{300} and SAM number is presented both for the lower and the upper layer concrete, DWN and GWN respectively [18].

The frost-salt scaling resistance was evaluated according to PKN-CEN/TS 12390-12 on cores from few pavement sections only for the upper layer concrete. The mass of scaled material after 56 freeze-thaw standard cycles was small, from 0.04 to 0.28 kg/m^2, demonstrating a high scaling resistance, corresponding to SAM number in the range from 0.19 to 0.33 and the content of microvoids in the range from 1.19 to 2.70%. A comparison with criteria given in Table 2 shows that the monitoring of SAM number in the mix might be helpful to ensure the frost-salt scaling resistance of concrete in pavement.

9. DISSCUSION AND CONCLUDING REMARKS

Maintaining the air content in concrete mix and subsequently in placed concrete layers is important both to maintain the evenness of the surface and to ensure the designed durability of hardened concrete. However, a prediction of frost-salt scaling resistance of concrete using air void characteristics can be valid only when the curing of fresh concrete surface was effective to ensure proper cement hydration without microcracking [21], [22]. Curing issues are even more pronounced in the case of exposed aggregate concrete. It was shown that [5], [23] lack of curing of concrete layer with exposed aggregate resulted in an increase in the water absorption rate and an increase in the chloride ion migration rate by 100-300% and 30-50%, respectively, presumably due to micro-cracks and a lower degree of cement hydration. The properly air-entrained concrete layer with exposed aggregate, which was cured with a curing agent with closure capacity $> 85\%$, was characterized by a very good resistance to surface scaling - the mass of scaled material m_{56} was equal to 0.10-0.12 kg/m^2, irrespective of the type of cement and w/c ratio. Due to a lack of proper curing an increase in the mass scaled material m_{56}, by a factor from 2 to 15 was observed.

Laboratory-scale observations do not include the important factors that occur on an industrial scale [21]. Due to the high surface modulus (surface to volume ratio), the surface concrete is exposed to accelerated drying, especially in dry weather conditions. This results in the risk of cracks occurring due to plastic shrinkage. In literature there are opinions that a surface concrete layer of about 2 to 3 cm in thickness is the most vulnerable to curing errors. Cracks in the exposed aggregate concrete layer may initiate the development of damage that results in a premature loss of service life - especially, reduced abrasion resistance.

The presented methods for construction quality assurance are considered adequate for exposed aggregate concrete pavements – they cover most of specific issues. However the significance of concrete curing is not addressed adequately and there is a need to develop such procedures that are crucial for the long term performance of pavements in wet-freeze regions with heavy use of deicing salts.

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