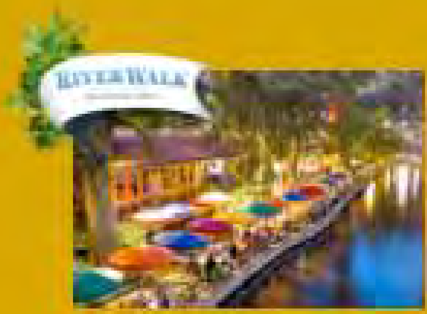
PROCEEDINGS

11 ELEVENTH INTERNATIONAL CONFERENCE ON CONCRETE PAVEMENTS

San Antonio, Texas USA

AUG 28-SEPT 1 2016



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ISBN-13: 978-0-9860291-2-7

ISBN-10: 0-9860291-2-2

Curing performance indicators of exposed aggregate layer in two-lift concrete pavement

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Abstract

The use of exposed aggregate concrete (EAC) in the upper layer of two-lift pavements is spread over many European countries including Poland. However, the EAC technology is considered difficult to apply because of inevitable dependence on operator's experience to control the whole process properly. The proper timing of technological operations is critical. The investigation on the performance of EAC was performed to gain a better understanding of material and environmental factors involved. EAC slabs were manufactured in the laboratory following the procedure applied at the construction site. Air entrained concrete mix design included a variable water to cement ratio and cement type while the type and the content of aggregate was constant. The effects of curing intensity were studied. The strength properties, air void characteristics of hardened concrete, the freeze-thaw resistance and the salt-scaling resistance were tested of specimens cored from the slabs, using the European standard methods. EAC permeability was also evaluated using the methods covered by ASTM C1585 and NT Build 492. Such permeability indicators and frost durability were applied to evaluate the differences in EAC layers performance. The environmental vulnerability of EAC mixes used in the upper layer of two-lift pavements is discussed.

Introduction

Many European countries have recognized the benefits of EAC pavements and have been constructing such composite pavements on a frequent basis. In Germany, the standard concrete pavement is constructed according to their technical specification, ZTV (2007). The technical specification on EAC pavement construction in Austria is included in RVS (2011). The specifications used in Poland are similar to these of Austria and Germany and the current plans for road infrastructure development include construction of new concrete highways of total length of 850 km. Exposed aggregate concrete, when properly executed, is considered as an efficient technique to provide desired friction for skid resistance without compromising the noise limitations.

Material selection for the upper layer of two-lift EAC pavements in Poland is based mainly on prescriptive specifications and on some performance indicators. The cement content of 430 kg/m^3 and w/c ratio < 0.45 is used with high quality crushed aggregates of 8 mm maximum aggregate size. The quality of aggregates is mainly

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determined by the following indicators: LA_{20}, PSV_{53}, f_1, $C_{100/0}$, FI_{15} or SI_{15}, frost resistance in 1% NaCl solution ≤6%, as determined using European standard methods referenced in PN-EN 12620 (2010). Accepted cement types include both Portland cement CEM I and slag-Portland cements CEM II/A-S and CEM II/B-S (as defined by PN-EN 197-1 (2012)) of limited content of Na_2O_{eq}. Concrete mix design is heavily influenced by the designed flexural strength of concrete (5.5 MPa) and the designed concrete durability in XF4 environment as defined by PN-EN 206 (2014).

Nonetheless, the exposed aggregate surface of the upper concrete layer is considered rather difficult to accomplish correctly, Akkari (2012), Hu (2014). Critical elements include not only the materials selection but also the technological factors of high importance. The application rate of the retarder and the curing compound has to be established experimentally in regard to the cement setting and hardening rate in particular weather conditions. The optimal time to brush with a mechanical broom is usually determined by a hand broom. The proper skills of the operator are definitely required. In several countries (UK, Belgium, Poland), instead of curing compound the use of polyethylene sheet is recommended. This is an issue for less skilled contractors who prefer to spray the mixed retarding/curing compound. The control of uniformity of such cover during a windy day might be questionable. Uneven cover may lead to uneven exposure of aggregates. Early-age moisture loss from the surface of a concrete pavement may induce undesirable effects that play a factor in long-term performance, Jeong and Zollinger (2003). Early-age detrimental behavior may include a weakened bond of exposed aggregate grains to cement matrix, plastic shrinkage cracking or microcracking due to autogenous or drying shrinkage. The investigation on the performance of EAC was performed to gain a better understanding of material and environmental factors involved, and eventually to contribute to a performance-based materials selection.

Experimental program

Materials

The specimens were manufactured in the laboratory in a way to mimic the EAC technique for texturing the surface of concrete pavements. The mortar fraction at the surface should be intentionally removed to leave the larger aggregates exposed, and thus to serve as the contact surface for traffic. To achieve that the top layer is covered with retarding compound that slows the cement hydration process in mortar near the surface and prevents it from adequately bonding with the aggregates. This allows for the mortar to be dry-brushed easily without removing aggregates from concrete.

Concrete mix design was chosen as typically used for upper layer of two-lift EAC pavements in Poland (Table 1). The reference concrete was prepared with CEM I type of cement (Table 2) and w/c =0.34. Two other concrete mixtures were designed by changing the type of cement or w/c ratio. The use of CEM III/A cement instead of CEM I could be a good alternative for summer construction provided that a required frost-salt scaling resistance is obtained. A change of w/c ratio up to 0.37 is expected not to bring significant detrimental effects while allowing for larger slump retention.

Specimens

Plate specimens of 800x500x80mm, beams of 150x150x700mm, 150mm and 100mm cube specimens were manufactured. After casting of plate specimens the surface of concrete was processed manually by a trowel. A retarding admixture Chryso Deco Lav P02 was sprayed over the surface (about 0.1 kg/m^2). After sufficient hardening of cement paste the thin surface layer was removed by using of water pressure washer. Results of such surface treatment are shown in Figure 1 – the aggregates are exposed to the depth of about 1mm.

Table 1. Concrete mix design [kg/m^3]

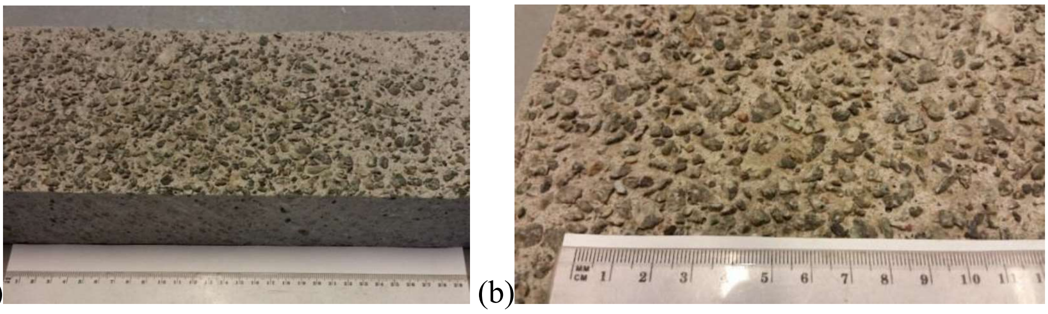
Concrete series	Cement type	Cement	Water	Aggregate		SP [3)]	AEA [4)]
				Fine [1)]	Coarse [2)]		
P-I-34	CEM I 42,5N -SR3/NA	430	145	553	1326	3.0	0.9
P-III-34	CEM III/A 42,5N LH/HSR/NA	430	145	553	1326	3.0	0.9
P-I-37	CEM I 42,5N-SR3/NA	430	160	542	1298	1.7	0.7

[1)] natural sand 0-2mm; [2)] crushed gabbro rocks 2-5 mm and 4-8 mm;
[3)] superplasticizer Chryso Plast Omega 132; [4)] air entraining admixture Chryso Air A.

Table 2. Properties of cements used (Warta[1)] and Małogoszcz[2)] cement plants)

Type of cement	Composition [%]					Compressive strength [MPa]			
	CaO	SiO_2	Al_2O_3	Fe_2O_3	LOI	2 days	7 days	28 days	90 days
CEM I 42,5N -SR3/NA [1)]	65.7	21.6	3.7	3.5	1.56	24.2	37.2	56.0	60.2
CEM III/A 42,5N LH/HSR/NA [2)]	52.0	27.9	5.55	1.63	1.95	14.2	-	50.3	-

The moulds were placed in a dry laboratory room at temperature of 20±2°C and relative humidity between 40% to 50%. One out of two identical plates was covered by curing agent Chryso Cure HPE, whereas the second one was left without curing. After 2 days the plates were removed from moulds and kept in dry laboratory conditions up to the age of 90 days. The specimens for microstructure, permeability and mechanical testing were drilled from plates using a 100mm diamond drill. The cubes used for the determination of compressive strength and splitting strength as well as beams used for flexural testing were not surface-processed and water cured at standard conditions.



(a) (b)

Fig. 1. Plate specimens with exposed aggregate surface prepared at laboratory conditions: (a) overview (b) exposed aggregate surface.

Test methods

The compressive strength, flexural strength and splitting strength was measured according to PN-EN 12390-3, PN-EN 12390-5, PN-EN 12390-6, respectively, using Controls Automax 5/50-C5652 testing machine. The strength tests were performed on three specimens for each concrete mix.

The air void characteristic in hardened concrete was determined using a computer-driven system of automatic image analysis, Glinicki and Zieliński (2008). Tests were performed using polished concrete specimens 100x100x25 mm cut from 150mm cube specimens. The measurement procedure complied with standard requirements imposed by PN-EN 480-11:2008.

The rate of water absorption was tested in accordance with ASTM C1585. Concrete discs 50 mm thick and 100 mm diameter were cut from cored specimens and placed in an environmental chamber at temperature of 50°C and RH of 80% for 3 days. Then, each specimen was stored in an individually sealed container for 15 days to attain an equilibrium of internal humidity. The specimens were placed in a pan containing water filled up to 3±1 mm above the top of the supporting device. The mass of the specimens was measured at regular intervals. The initial sorptivity (S_i) was calculated based on mass intake during the first 6 h. Rate of water absorption were obtained as average of three measurements.

Rapid chloride migration test was applied to determine the non-steady state migration coefficient according to Nordtest Method NT Build 492:1999. The non-steady-state migration coefficient (D_{nssm}), is calculated from the Fick's second law. The test was conducted on three specimens for each concrete mix. Specimens were placed into measuring rig with exposed aggregate face towards chloride ion solution.

Accelerated carbonation tests were performed in environmental chamber at 22°C, 50% RH and the concentration of CO_2 of 1%. The depth of carbonation front was measured on freshly split surface of concrete prisms. The indicator used in the testing was 1% phenolphthalein solution diluted in 70% ethyl alcohol. The depth of the uncolored zone is measured in several locations obtain an average depth of carbonation according to the procedure described in PN-EN 1329.

The resistance to cyclic freezing and thawing was tested on 100mm cubes according to Polish standard PN-B-06250:1988. Concrete specimens were subjected to cyclic freezing and thawing in specific program (freezing in air – 4 hours at -20°C; thawing in water – 2 hours at +20°C). The compressive strength and mass loss after 200 cycles of freezing and thawing was compared with that of control specimens stored in water.

The frost-salt surface scaling resistance test was carried out with an automatic chamber for freezing and thawing of samples, using Slab test, according to European technical specification CEN/TS 12390-9:2007. The slab specimens 150×150×80 mm were subjected to 56 freeze-thaw cycles while the exposed aggregate surface was exposed to 3% NaCl solution. To assess the resistance of concrete to scaling the criteria of the Swedish standard SS 137244:2005 were used.

Test results and discussion

Basic concrete properties

Fresh mixes properties are shown in Table 3. The target slump of 50mm in 10 minutes after mixing was almost achieved. Slump decrease after 70 minutes was significant and rather typical for such mixes. Advantageous slump retention in time was clearly observer at increased w/c ratio. Quite similar air content and density of fresh mixes confirm the proper air-entraining and consolidation processes.

Air void characteristics of hardened concrete is presented in Table 3. The results are evaluated in terms of specified parameters for the upper layer of pavements: the spacing factor ≤ 0.18 mm, the microvoids content A_{300} ≥1.8%. Such air void distribution is considered adequate for freeze-thaw and salt-scaling durability. The target air void characteristics was achieved; no detrimental effects of CEM III/A were observed.

Table 3. Properties of fresh concrete mix and the air void characteristics of hardened concrete

Concrete series	Slump [mm]		Air content [%]	Density [kg/m^3]	Air void characteristics of hardened concrete			
	10 min	70min			A [%]	α [mm^{-1}]	L [mm]	A_{300} [%]
P-I-34	40	20	5.3	2440	6.06	32.61	0.14	3.63
P-III-34	40	15	6.0	2435	6.31	33.02	0.13	3.90
P-I-37	45	30	5.7	2435	6.27	33.78	0.13	3.66

Compressive strength measurements show differences between each series of specimens after initial curing time (7 days) and similar values approximately 60-65 MPa after 28 days of water curing (Fig. 2a.). Use of slag cement CEM III/A caused a decrease of 7 day compressive strength by 30% in comparison to Portland cement concrete of the same w/c. An increase of w/c ratio caused a relative decrease of compressive strength of about 15%.

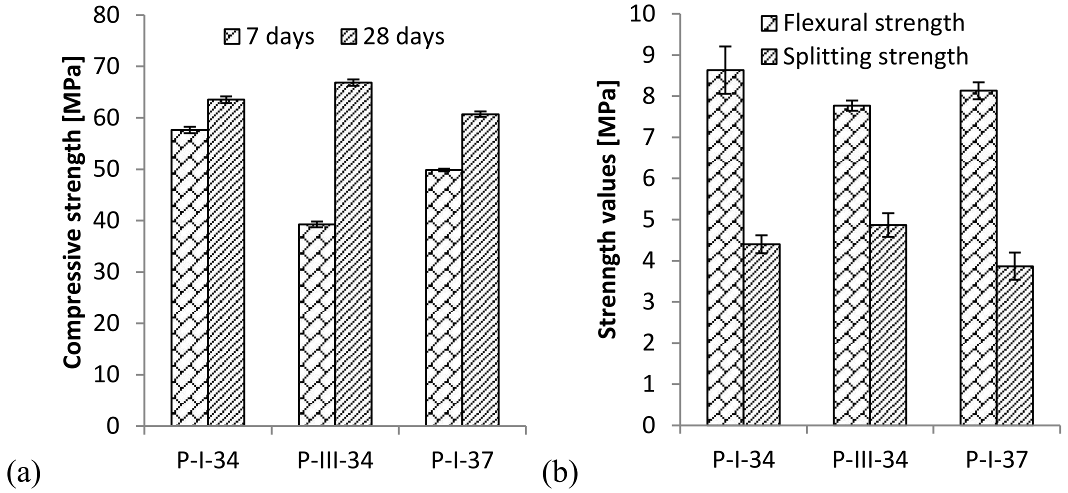


Fig. 2. Concrete strength data: (a) the compressive strength after 7 and 28 days of water curing; (b) flexural and splitting strength after 28 days of water curing.

Flexural and splitting strength was quite similar for all concrete specimens tested after 28 days of standard water curing (Fig. 2b). The highest average flexural strength of 8.6 MPa was achieved for the reference concrete P-I-34. The average flexural strength of two other concrete types was about 8 MPa. The splitting tensile strength revealed benefits of using slag cement. The average values of the splitting tensile strength were within the range from 3.9 MPa to 4.9 MPa. As expected the dispersion of tensile strength results is higher than in the case of the compressive strength.

Two hundreds of freezing and thawing cycles after 56 days of water curing of concrete specimens did not induce any measurable mass changes (Fig. 3). The influence of increased w/c ratio was more significant than a change of cement type on the compressive strength losses. In spite of an observed threefold increase of strength loss the differences in freezing-thawing performance of tested concrete specimens were not important. That is because the limit of 20% strength decrease is considered to indicate the adequate frost resistance of concrete.

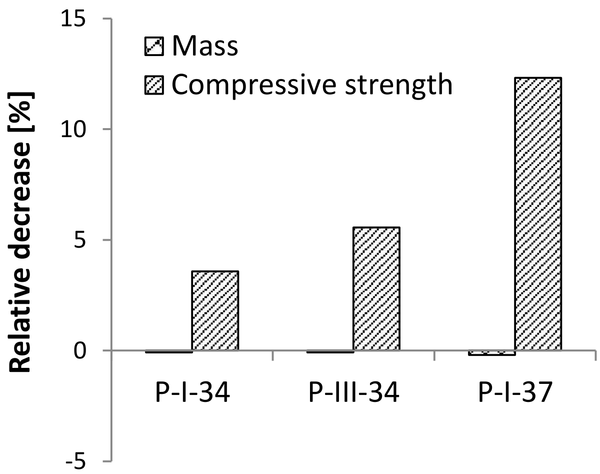


Fig. 3. Relative decrease of compressive strength and mass of concrete specimens subjected to 200 freezing-thawing cycles

Durability indicators for exposed aggregate concrete

Tests on concrete specimens with exposed aggregate surface were designed to measure differences induced by improper curing after surface mortar removal. The set of illustrations in Fig.4 shows such differences. Measurements of rate of water absorption revealed small changes induced by cement type change for well cured concrete surfaces (Fig. 4a) Highly increased initial water absorption rates were observed for not cured concrete specimens: twice higher (P-III-34) up to 3.5 times higher (P-I-37). An interesting observation can be made in regard to the role of slag cement in concrete: the obtained initial rate of water absorption was the smallest, $4\cdot10^{-4}$ mm/s$^{1/2}$, and by 40% lower than for reference concrete. Improper curing conditions were more important for concrete with higher w/c ratio. Without curing the rate of water absorption was $25\cdot10^{-4}$ mm/s$^{1/2}$, which was 5 times higher than for well cured reference concrete.

The chloride migration coefficient (D_{nssm}) showed a strong effect of slag cement to impede chloride ingress into concrete specimens (Fig. 4b). The following evaluation of the concrete resistance to chloride ions penetration was applied: from "very good" (D_{nssm} < $2\cdot10^{-12}$ m^2/s) to "unacceptable" (D_{nssm} > $16\cdot10^{-12}$ m^2/s). The chloride penetration resistance of concrete containing CEM I cement was classified as "acceptable" irrespective of w/c ratio. Differences of D_{nssm} for well cured and uncured concrete specimens were small, especially for P-III-34 and P-I-37 series, quite close to dispersion of data. The curing conditions were found more important for reference concrete, which exhibited a double increase of D_{nssm} without curing agent.

Carbonation depth measurements showed very good resistance of well cured Portland cement concrete (Fig. 4c). conditioning under curing agent were not found carbonation under aggregate exposed surface. Improper curing caused an increase of carbonation layer up to 3-4 mm for both series of Portland cement concrete. Use of slag cement in well cured concrete resulted in the same carbonation depth as uncured Portland cement concrete. The lack of proper curing caused an increase of carbonation depth to 12 mm at 90 days of exposure to atmosphere of 1% of CO_2.

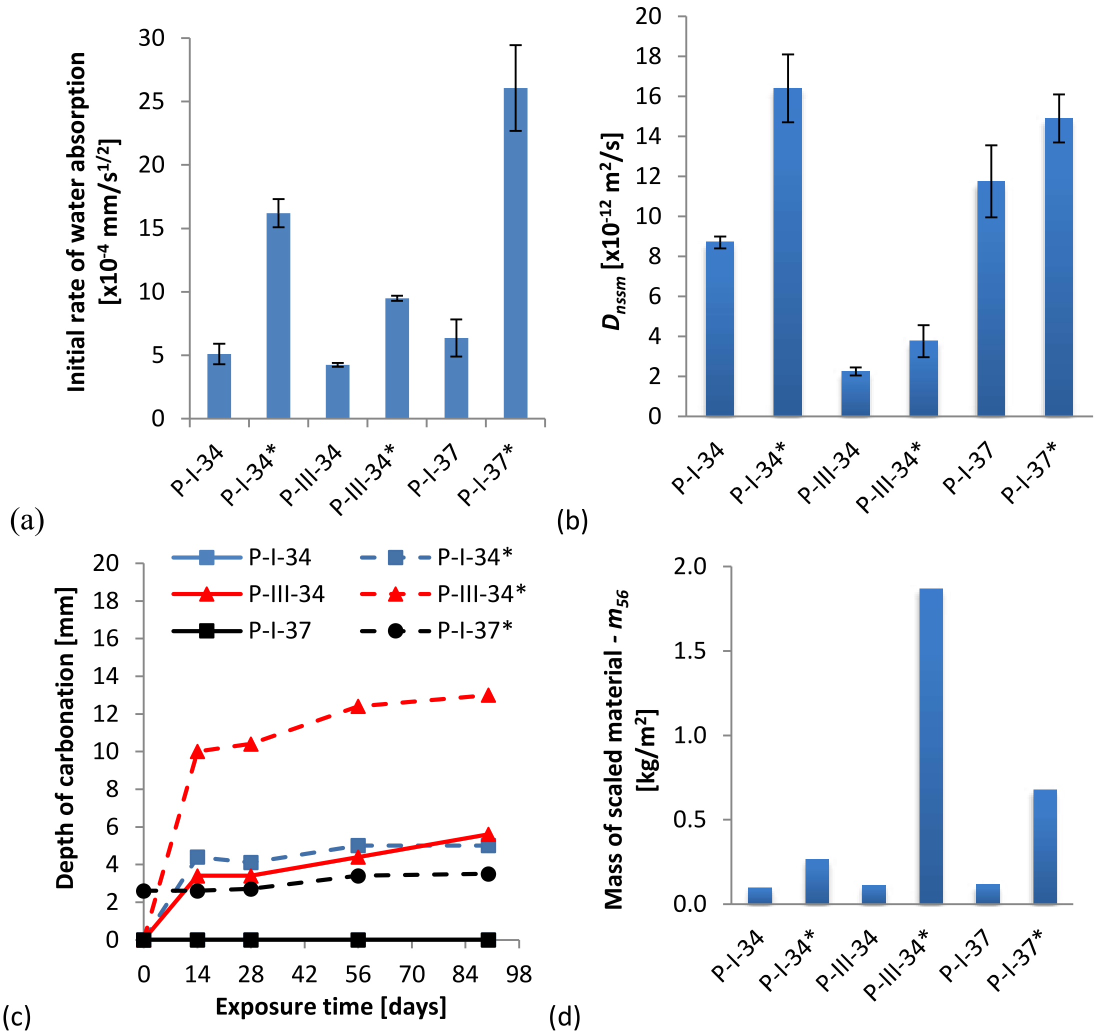


Fig. 4. Influence of curing condition on durability indicators for exposed aggregate concrete specimens: (a) rate of water absorption; (b) chloride migration coefficient D_{nssm}; (c) carbonation resistance; (d) surface scaling resistance; (* denotes specimens without curing agent)

The suitability of the air void system to ensure high concrete resistance to frost-salt surface scaling was demonstrated by data in Table 3, Breitenbucher (2013). The actual scaling test results (Fig. 4d) confirm such expectations for well cured concrete specimens. The total mass of scaled material after 56 standard cycles of freezing and thawing was below 0.1 kg/m^2. Using the evaluation scale of SS 137244:2005 this corresponds to the class of "very good" scaling resistance. However the improper curing had a major influence on scaling increase. In the case of slag cement such mass increase was up to 1.8 kg/m^2 ("unacceptable" scaling resistance). For the increased w/c ratio the improper curing of concrete resulted in the increase of scaling up to 0.7 kg/m^2 ("acceptable" scaling resistance). The huge increase of scaling of slag cement concrete can be associated with increased carbonation, as suggested by Giergiczny (2009).

To evaluate the significance of increased scaling one should recall the target texture characteristics of well constructed exposed aggregate pavements. The texture depth is expected to fall within the narrow range between 0.8mm and 1.1mm. The scaling mass of 1.8 kg/m^2 for mortar density of about 2100 kg/m^3 can be simply expressed as the volume of material of 0.9 mm thick evenly distributed over 1 square meter. So a decreased scaling resistance of concrete would roughly result in a double increase of the texture depth. The low-noise performance and riding quality expressed by IRI would be compromised. Such consequences could be associated with improper curing (e.g. uneven coverage of exposed pavement surface with curing agent) even in a case of concrete proportioned of high quality materials.

Conclusions

A set of performance indicators was proposed for exposed aggregate concrete surfaces and the significance of such indicators was revealed on EAC specimens manufactured at laboratory conditions. The relevant indicators include: the rate of water absorption, the chloride penetration resistance, the carbonation resistance and the frost-salt scaling resistance. On the basis of test results the following conclusions can be drawn.

- Tests on fresh concrete mixes revealed an adequate air void content 5.3 to 6.0% and adequate slump 40-45mm. However the slump retention after extra 1 hour was low, except for the mix of w/c ratio increased to 0.37.
- The performed materials selection and concrete proportioning resulted in high flexural strength and splitting tensile strength, within the range 7.9-8.6 MPa and 3.9-4.9 MPa (average values), respectively. The relative decrease of compressive strength after 200 F-T cycles was low, from 4 to 12%. The entrained air void system in hardened concrete was characterized by the spacing factor of 0.13-0.14mm and the specific surface of 32-34 mm^{-1}, representing a stable system of mostly small air voids desired for high frost-salt scaling durability.
- Proper concrete curing with curing agent of high surface closing efficiency resulted in very good surface properties of exposed aggregate concrete. That was demonstrated by relevant concrete durability indicators irrespective of the w/c ratio (0.34 or 0.37) or cement type (CEM I or CEM III/A).
- Improper surface curing of EAC specimens was found to increase significantly the rate of water absorption, the chloride ion permeability, the depth of carbonation and the mass of scaled material. It was possibly due to microcracking and lower hydration degree of cement paste at the skin layer. The lack of curing was particularly demonstrated by a huge decrease of frost-salt scaling resistance that was pronounced for slag cement concrete.
- The use of slag cement CEM III/A in EAC for the upper layer of road pavements is risky due to the overwhelming negative effects of potential curing deficiencies. Except the chloride migration coefficient the other performance indicators were drastically worsened by improper curing in slag cement concrete.

It is recommended that the set of curing performance indicators should be supplemented by a developed abrasion resistance test method, relevant to EAC to sense possible deficiency of aggregate paste bond.

Acknowledgment

A close cooperation with Chryso Poland is gratefully acknowledged.

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