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INFLUENCE OF ASPHALT ADDITION AND CONSOLIDATION METHOD ON THE DURABILITY OF CEMENT CONCRETE

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Abstract. At present the durability of engineering structures built of high performance cement concrete constitutes a very important issue especially when we consider the reliability of these structures under the impact of different classes of aggressive environment and dynamic loads acting on them. In the authors' opinion the above problem can be solved by applying chemical-mechanical methods to ensure proper material-structural protection of building structures in specific operating conditions. In order to chemically modify concrete microstructure, asphalt addition dissolved in high boiling organic solvent was applied. On the other hand, in order to form concrete structure, special consolidation methods of concrete mixture was used.

Keywords: concrete, asphalt addition, porosity, compressive strength, vibropressing, vibro-vibropressing.

1. Introduction

In our times there has been an ever growing and universal use of high performance concretes in building practice. C55/67 concrete classes and higher ones are frequently applied to erect structural frames of high-rise buildings, bridges and tunnels. Owing to concrete's high quality and strength, engineering structures can have longer spans, smaller cross sections and thinner concrete reinforcement covers. During their working life slender structures made of reinforced concrete are often exposed to extreme conditions such as aggressive environments and dynamic loads. Hence the problem of keeping the durability and stiffness of such structures often arises (Kamaitis 2007, 2008). Durability is one o the major components in the rational design of concrete structures (Elahi *et al*. 2010; RILEM 2008). Durability of concrete greatly depends on its ability to prevent the ingress of aggressive chemical species. The resistance to chloride, water and air penetration is some of the simplest measures to determine the durability of concrete. Therefore, permeability of concrete is a major index for this ability (Shi *et al.* 2008, 2009; Song, Kwon 2007; Pereira *et al.* 2009). Carbonation resistance has also been greatly concerned, especially in the case where concrete structures are reinforced (Song, Saraswathy 2006; Ismail *et al.* 2010). Due to corrosion the resistance of structures decreases much earlier than their expected service life and requires repairs of arising degradation (Wang, Lee 2009; Kim *et al.* 2009).

In December 2000 European concrete standard (EN 206-1 2000) was established and finally worded as: "specification, performance, production and conformity". During the development of the standard, CEN/TC 104 came to the conclusion that at that stage it was unable to propose suitable methods of concrete design and testing associated with the appropriate level of structural durability in the construction of certain environment classes. Thus, EN 206-1 has authorized the continuation of the specific practices adopted in a given country provided that they ensure adequate material and technological requirements, which in turn should guarantee working durability of structures for a minimum of 50 years.

The authors of the research and development grant titled "Material-structural protection of small-sized elements against the corrosion achieved through the modification of asphalt concrete" are currently working on the technology of concrete to ensure its high resistance to strong aggressiveness of the environment through chemical formation of concrete microstructure as well as through modification of its mechanical structures.

In the authors' opinion the attainment of such a high resistance and quality of high performance concrete may be effected exclusively by applying chemical-mechanical methods providing appropriate material-structural protection for constructions operating in specific conditions.

2. Laboratory experiment

For the chemical modification of concrete microstructure asphalt addition made according to the Polish Patent No. 136449 was used. In order to form concrete structures a special device for the consolidation of various concrete mixtures including vibro-vibropressing technique was employed (Fig. 1). The device has a possibility of adjusting the exciting force of the top vibrator and the pressing force acting on the piston during the compaction of the concrete mix.

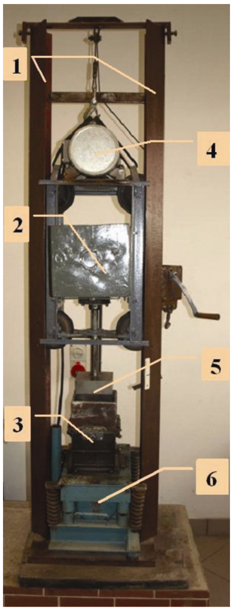

Fig. 1. Workstand for vibro-vibropressing of concrete mixture: 1 – runners, 2 – inert load, 3 – form with a top 4 – top vibrator with adjustable exciting force, 5 – pressing piston, 6 – bottom vibrator

Asphalt addition consists of appropriate proportions of industrial asphalt, paraffin oil, calcium stearate and Laureth 10 (a synthetic compound obtained by the extensive chemical modification of lauric acid, a natural fatty acid, and ethylene oxide). It can be applied to concretes as an additive or an addition. Its regular distribution in concrete mix volume is achieved through the use of cement as a carrier. Preliminary tests have shown that the best properties of the structure of cement concrete is obtained by using vibro-vibropressing of concrete mixes of V0 or V1 consistencies according to Vebe method and the addition to cement ratio (p/c) not greater than 0.07 (Wieczorek *et al.* 2004). Samples of cement pastes, mortars and concrete were prepared using two types of Portland cements. Their chemical and phase composition are presented in Table 1.

In the investigations the norm sand CEN (PN-EN 196-1 2005) of 0/2 mm size fraction was applied as fine aggregate and basalt of 2/16 mm size fraction was used as coarse aggregate. The amount of sand in aggregate grading equalled 41.95%. The content of cement in the concrete ranged from 450 to 500 kg/m^3. The w/c ratio of concrete mixes was varied from 0.22 to 0.40 and the content of asphalt addition ranged from 2 to 14% in proportion of cement mass. The following types of samples were formed:

- norm beams – 4×4×16 cm;
- cubes – 10×10×10 cm and 15×15×15 cm;
- cylinders – 102 mm in diameter.

Subsequently appropriate tests of physical, chemical and mechanical properties of cement pastes, mortars and concrete were performed. The tests aimed at determining the following parameters: compressive and flexural strength, specific gravity, skeleton density (PN-76/B-06714.02), absorbability, water permeability, shrinkage, adhesion of mortar and asphalt addition to the base, abrasion (PN-84/B-04111), frost resistance in the presence of de-icing salt solutions, corrosion resistance of mortars and concrete under the influence of such aggressive substances as 1.4% NH_4Cl, $MgSO_4$, $(NH_2)CO$, CH_3COOH, $CaCl_2$ solutions changed each week. Corrosion evaluation was performed after 6, 9 and 12 months.

Table 1. Chemical and phase composition of cements used

Chemical composition %	CEM I 42.5 N-HSR/NA (cement A)	CEM I 42.5 R	CEM I 42.5 R+ 5% SiO_2 (cement B)
CaO	64.00	64.39	61.17
SiO_2	21.63	21.91	20.81+5.00
Al_2O_3	4.12	4.88	4.64
Fe_2O_3	5.30	2.26	2.15
SO_3	2.32	3.04	2.89
MgO	1.33	2.43	2.31
Cl	0.004	–	–
$Na_2O_{eqv.}$	0.41	0.84	0.80
Parts insoluble in HCl	0.30	–	–
Loss of ignition	0.65	–	–
Phase composition			
C_3S	54.38	67.5	64.12
C_2S	20.98	11.89	11.30
C_3A	1.93	8.63	8.20
C_4AF	16.11	8.06	7.66
SiO_2	–	–	5

The resistance of concrete to chloride penetration was conducted using a rapid method according to AASHTO T 277-831 and ASTM C 1202-97 (1997). Furthermore, structural tests of mortars and concrete were conducted using scanning electron microscope and X-ray microanalysis at the Institute of High Pressures of the Polish Academy of Sciences. The test samples were analyzed after their exposition to corrosion environments such as 1.4% solution of $MgSO_4$ in order to identify the corrosion products. Measurements were performed using the Oxford system. Porosimetric investigations of mortars and concrete were also carried out at the Institute of High Pressures of PAS. To specify the content of the hydration products of Portland cement in pastes, mortars and concretes thermal analysis (DTG, DTA and TG) was applied, whereas the qualitative phase composition of concrete and the identification of crystalline phases were determined by means of X-ray diffraction analysis.

3. Tests results and discussion

Previous research (Kosior-Kazberuk, Jezierski 2004) has shown that the asphalt addition content of above 5% as regards cement mass results in a significant improvement, for instance, in concrete resistance to frost in combination with the resistance to the impact of de-icing salts, which has significant practical importance in the case of prefabricated elements such as road and bridge constructions. However, applying such quantities of asphalt addition proportionate to cement mass will result in a considerable decreases of concrete's compressive strength, often more than 20% in relation to the concrete without asphalt addition (Wieczorek *et al.* 2004). The influence of the consolidation method of concrete mixes with the coefficients w/c = 0.22, w/c = 0.24 w/c = 0.31 and w/c = 0.30 with using cement A is presented in Fig. 2.

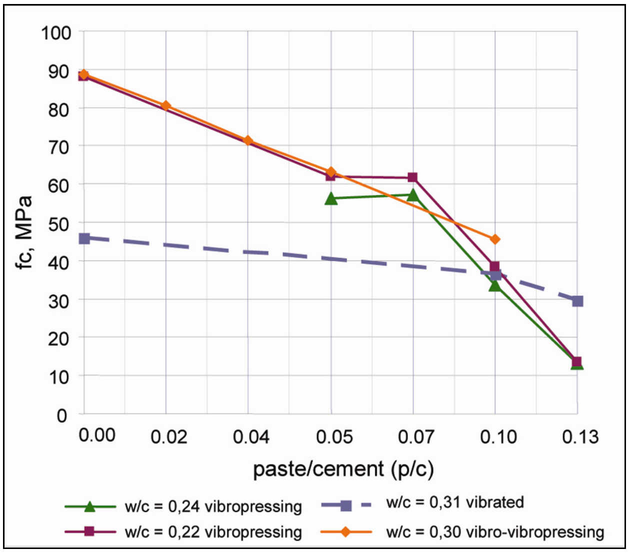

Fig. 2. Compressive strength of concrete depending on the addition/cement value at different w/c rates and different consolidation methods

The test results clearly show that the highest concrete compressive strength is obtained when applying the vibro-vibropressing method, which is characterized by high exciting force of the top vibrator. The investigations concerning the optimisation of vibro-vibropressing are still in progress, therefore in the next part of the paper only the results of the tests concerning vibrated concrete (n = 50 Hz; A = 0.5 mm) and vibropressed concrete obtained at constant pressing force of the piston upon the top surface of the formed sample are presented. In determining the composition of the concrete mix humid consistency was assumed as optimal for the application of special technologies of forming such as vibropressing and vibro-vibropressing. In order to obtain indispensable comparative parameters, consistency of concrete mixes with different addition content was examined. Classes of the consistency were determined by the Vebe method, in accordance with the standard (PN-EN 12350-3 2001). The results of the examinations are presented in Table 2.

Table 2. Consistency of concrete mixes depending on the content of asphalt addition

Asphalt addition, %	Vebe consistency, s
0	44
5	38
10	29

The results in Table 2 indicate that asphalt addition causes plasticization of concrete mix but, on the other hand, is characterised by high viscosity. Its conventional viscosity measured with the Ford viscosity cup should not exceed 3 minutes. For this purpose the main component of the addition, i.e. industrial asphalt PS-85/25 is additionally melted in high boiling organic solvent, typically paraffin oil.

Both the porosity characteristics (Table 3) as well as fractures of concrete samples with asphalt show that in the case of the typical vibratory consolidation large air pores are confined in the structure of concrete. As a result these pores significantly reduce the mechanical properties of hardened concrete, mainly its compressive strength.

On the other hand, by applying special methods of forming, e.g. vibropressing and particularly vibro-vibropressing large air pores do not appear in the concrete structure and the material density increases. As a result, a significant increase of compressive strength of concrete formed by means of the vibro-vibropressing method can be obtained (Fig. 2).

The influence of the amount of asphalt addition and the method of consolidation of concrete mixture are presented in Table 4. The tests were conducted using two types of cement: A and B. The concrete marked with symbols BA and BB were formed using the standard vibration method, whereas concretes formed with both cements A and B and asphalt addition were marked BAp and BBp respectively. Finally, vibropressed concretes with and without the asphalt addition were denoted respectively as BPAp, BPBp and BPA, BPB.

Table 3. Porosity structure of the examined mortars and concrete

Series	Total porosity	Pore size distribution, %					
		3÷30	30÷100	100÷300	300÷3000	3000÷30 000	30 000÷100 000
	cm^3/g	nm					
BPA_p	0.0225	38.23	20.44	11.11	18.66	5.78	3.56
BPA	0.0214	24.30	25.70	7.94	24.30	8.88	6.08
BA_p	0.0320	25.94	31.56	12.20	20.31	5.00	5.00
BA	0.0397	18.73	23.93	26.45	26.70	2.27	1.26
ZNA	0.0646	14.24	30.65	22.91	26.44	3.25	1.68
ZA_p	0.0708	19.49	30.51	11.44	27.83	5.22	2.97
BPB_p	0.0216	52.31	17.46	10.32	11.11	3.91	2.78
BPB	0.0230	23.48	23.04	11.31	24.34	8.70	6.56
BB_p	0.0262	46.95	25.57	8.01	9.16	5.73	3.05
BB	0.0310	22.90	33.23	13.55	14.51	10.47	3.23
ZNB	0.0562	18.33	40.03	13.35	16.55	8.00	2.32
ZB_p	0.0618	26.38	42.55	10.58	12.62	4.37	2.11

Table 4. Test results of concrete mixes and basic properties of concrete

Cement			CEM I 42.5 N HSR/NA (cement A)				CEM I 42.5 R + 5% SiO_2 (cement B)			
Series			BA	BA_p	BPA	BPA_p	BB	BB_p	BPB	BPB_p
w/c			0.40	0.31	0.27	0.23	0.40	0.31	0.30	0.28
p/c			0.00	0.07	0.00	0.07	0.00	0.07	0.00	0.07
Vebe consistency			V3	V2	V0/V1	V0/V1	V3	V2	V0/V1	V0/V1
f_c (28), MPa			55.7	49.8	62.7	48.5	52.9	44.2	54.6	43.4
f_c (90), MPa			69.7	55.8	74.5	55.9	61.2	46.3	65.2	45.2
$f_c (2) / f_c (28)$			0.39	0.50	0.58	0.59	0.67	0.74	0.84	0.81
$f_{ck.cube}$ (28)			50	45	55	45	50	40	50	40
$f_{ck.cube}$ (90)			65	50	70	50	55	40	55	40
Abrasion, mm			1.67	1.46	1.63	1.70	1.60	1.46	1.73	1.65
Water absorbability, %			4.74	2.16	2.83	1.32	4.40	2.84	2.82	1.95
Height of capillary suction, mm			18	10	22	8	13	11	16	8
Specific gravity, g/cm^3			2.494	2.532	2.621	2.614	2.564	2.558	2.614	2.614
Skeleton density, g/cm^3			2.768	2.756	2.777	2.778	2.785	2.742	2.781	2.771
Frost resistance – loss of f_c after 150 cycles, %			–8	–11	–7	–14	–6	–13	–14	–18
Water permeability - depth of water penetration, cm			W16 (4.1)	W16 (1.4)	W16 (4.7)	W16 (2.7)	W16 (4.8)	W16 (0.9)	W16 (4.2)	W16 (2.2)
Hydration degree			0.52 (0.60)	0.76 (0.73)	0.40 (0.42)	0.76 (0.73)	0.60 (0.56)	0.87 (0.90)	0.46 (0.49)	0.75 (0.84)
Corrosion resistance coefficient (CR) after:	6 mounts	CR(f_{ct})	0.82	0.91	0.91	0.91	0.97	1.17	0.80	1.34
		CR(f_c)	0.82	0.80	0.91	0.93	0.74	0.92	0.84	0.92
	9 mounts	CR(f_{ct})	0.77	0.74	0.85	0.84	0.75	0.80	0.75	0.82
		CR(f_c)	0.51	0.70	0.78	0.82	0.50	0.83	0.82	0.80
	12 mounts	CR(f_{ct})	0.72	0.72	0.85	0.83	0.75	0.81	0.80	0.84
		CR(f_c)	0.48	0.68	0.76	0.80	0.52	0.79	0.79	0.76

A characteristic feature of concretes mixed with asphalt addition is that their compressive strengths, regardless of whether they were vibropressed or not, are comparable and their strength classes remain the same both after 28 and after 90 days. The concretes are also characterized by similar hydration degrees (Table 4). A comparative analysis of the degree of cement hydration using thermal analysis and a modified Powers model (values in brackets) shows good agreement of hydration value in both cases. Other data presented in Table 4 shows that asphalt additions have an influence on the development of concrete's compressive strength, specific gravity, skeleton density, water absorbability, capillary suction, frost resistance, water permeability, abrasion and corrosion resistance.

Average values of chloride penetration into a cylindrical sample of 102 mm in diameter and thickness of 51 ± 3 mm are presented in Fig. 3. The figure gives the value of the charge penetrating the sample in coulombs [C], as well as the depth of chloride penetration into concrete fractures moistened by 0.1 mol/dm^3 $AgNO_3$ solution. According to ASTM (ASTM C 1202-97 1997) for a charge above 2000 C the penetration is maintained on a medium level, for a charge from 1000 to 2000 – on a low level, from 100 to 1000 C – on a very low level, while below 100 C chloride penetration is negligible.

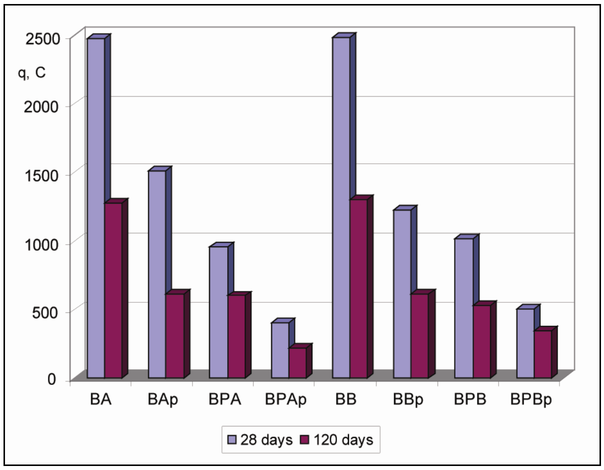

Fig. 3. Average values of chloride penetration and hardening time for different concrete series

Table 5. Content of chosen components in cement paste samples based on thermal analysis results

Symbol of sample	Contents of chosen elements, % m/m				
	Bound water	Bound water in CH	Calcium hydroxide (CH)	Loss of mass in 540÷1000°C	Loss of ignition
A–0.00 (air)	9.4	1.6	6.6	3.3	14.3
A–0.07 (nitrogen)	8.9	3.0	12.3	5.8	17.7

The lowest values of chloride penetration are observed for vibropressed concretes with asphalt addition (BPAp and BPBp), however for BAp and BPA as well as for BBp and BpB series close values of chloride penetration are obtained after 120 days of hardening. It should be noted that for BPAp series the value obtained after 120 days is almost negligible, which is important when applying vibropressed products with asphalt addition, for example, in bridge building.

Exemplary content of chosen products of hydration in cement pastes with (A–0.07) and without (A–0.00) asphalt additions are presented in Table 5.

Quantitative interpretation of thermal analysis results of the hydration of cements A and B after 90 days makes it possible to formulate the following conclusions:

- asphalt addition applied to either non-vibropressed or vibropressed concretes at the value of p/c = 0.07 accelerates the hydration process of both cements simultaneously stabilizing the content of the emitted calcium hydroxide by about 15%;
- the CH content in either non-vibropressed or vibropressed concretes is much smaller; which indicates a lower degree of hydration of cements in both types of concrete;
- the content of bound water in the hydration products in cement B with silica fume is higher than in cement A with no silica fume. There is more bound water found in both calcium silicates of the CSH type and hydrated calcium aluminosulphate;
- the total content of CaO in mortars and concrete with asphalt addition is similar and amounts to about 25%. The least of CaO (about 13%) is contained in vibropressed concrete with two types of cements.

The favourable influence of asphalt addition on the porosity structure of was determined by comparing the diameter of pores. In all compared mortars and concretes these diameters were found to be invariably smaller when asphalt addition was added, which implies an increase of the number of small pores. A particularly wide-ranging effect of this additive was observed while comparing pore shares by size (Table 3).

Another favourable result of using the addition is that the internal surfaces of all pores are covered with thin hydrophobic asphalt layers (Fig. 4).

The results obtained using scanning electron microscope show that the thickness of these asphalt layers is about 200 nm. The layers cover both the hydration products as well as tiny gel pores (Fig. 5). The hydrophobic layers of asphalt significantly hamper not only the absorbability but also capillary suction water in mortars and concretes.

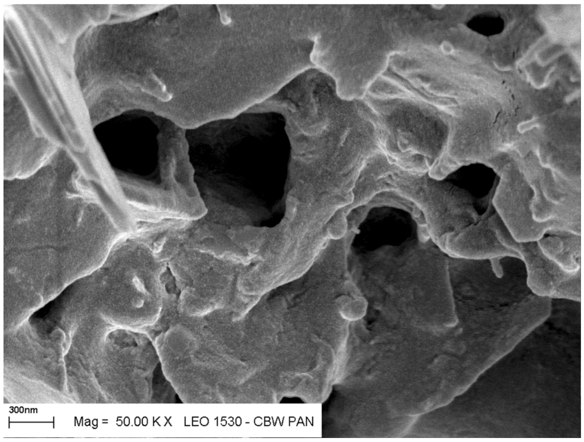

Fig. 4. CSH phase. Hydration products with visible pores about ~300 nm in diameter covered with a thin asphalt layer. Siliceous cement B (BPBp). Photo by A. Presz

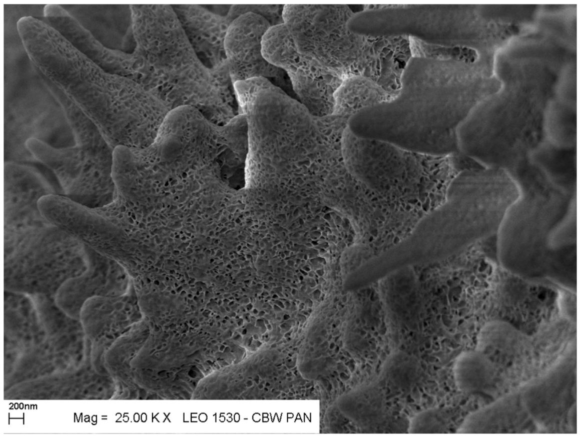

Fig. 5. BPBp-08. Asphalt coating on CSH phase. Visible, rounded off edges and craters after solvent evaporation. Photo by A. Presz

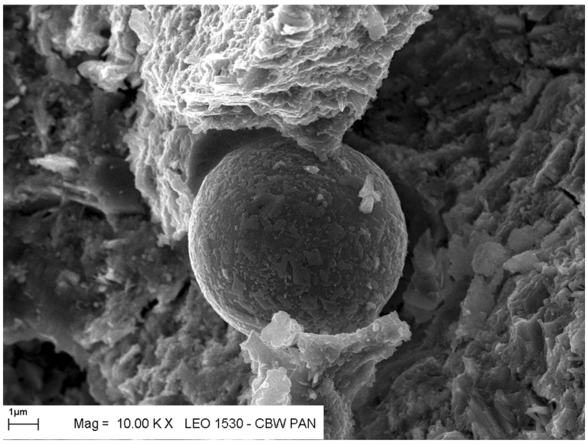

Fig. 6. BPBp-water-11. Non-hydrated silica fume grain. Close CSH phase. Photo by A. Presz

In the case of cement B with silica fume, the asphalt addition is hinders the hydration of tiny silica grains (Fig. 6). As a result, in practice, combining asphalt addition and silica fume to produce cement concrete is not recommended.

4. Conclusions

1. Asphalt can be applied as an addition to high performance concrete of high durability providing special methods of consolidation of concrete mix are applied.

2. Owing to its dispersive and hydrophobic qualities, asphalt addition improves the properties of cement concrete structures, which increases their corrosion resistance in aggressive solutions and in the presence of de-icing salts.

3. Due to a favourable layout of pores, asphalt addition decreases chloride penetration, water absorbability and capillary suction.

4. The corrosion resistance of mortars and concrete to the destructive influence of solutions of aggressive substances and de-icing salts increases with a rise of the p/c ratio. The test results have shown that the corrosion resistance is directly proportional to an increase in the degree at which the pore walls and aggregate are coated by asphalt addition. The asphalt addition dissolved in high boiling organic solvent (paraffin oil) blocks both the access of ions and other aggressive substances to the inside of the material thus making impossible or hindering destructive processes caused by chemical reactions in the material.

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6. Asphalt molecules bound to hydrocarbon chains of hydrophobic components by van der Waals force acquire the ability to moisten with batch water and approach the surface of hydrated cement with polar groups of the hydrophobic substance. As a result the asphalt effectively covers the cement hydrates with a thin layer of about 200 nm. After hardening of the cement, CSH gel, CH crystals in pores, surfaces of fine and coarse aggregate become also covered with asphalt. During the vacuum preparation of samples for examinations in the scanning electron microscope the solvent evaporates from the thin layer.

7. Small-sized vibropressed concrete elements with such asphalt addition are produced in Mazurian Manufacturing-Building Enterprise in Augustów (Poland).

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ASFALTO PRIEDŲ IR KONSOLIDACIJOS METODO ĮTAKA CEMENTBETONIO ILGAAMŽIŠKUMUI

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S a n t r a u k a

Statybinių konstrukcijų, pagamintų iš gerų eksploatacinių savybių cementbetonio, ilgaamžiškumas yra labai svarbus veiksnys. Ypač tai svarbu apibrėžiant pastato konstrukcijų patikimumą, kai jas veikia smūginės ir dinaminės apkrovos bei įvairių klasių agresyvioji aplinka. Autorių nuomone, ši problema gali būti sprendžiama taikant cheminius ir mechaninius metodus, užtikrinant geresnę statybinių konstrukcijų, naudojamų specifinėmis sąlygomis, apsaugą. Siekiant chemiškai pakeisti betono mikrostruktūrą, siūloma betono sudėtį papildyti aukštos temperatūros asfalto priedais, ištirpintais verdančiame tirpale. Kita vertus, norint pagaminti betoninę konstrukciją, buvo taikyti specialūs betono mišinio konsolidacijos metodai.

Reikšminiai žodžiai: betonas, asfalto priedas, poringumas, gniuždomasis stipris, vibracinis presavimas.

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