

# Experimental Study on Modification of Concrete with Asphalt Admixture

Michał Boltryk<sup>1</sup>, Dorota Malaszekiewicz<sup>1</sup>, Edyta Pawluczuk<sup>1</sup>

<sup>1</sup> Białystok University of Technology, Wiejska Str. 45E, 15-351, Białystok, Poland

d.malaszekiewicz@pb.edu.pl

**Abstract.** Durability of engineering structures made of cement concrete with high compressive strength is a very vital issue, especially when they are exposed to different aggressive environments and dynamic loads. Concrete resistance to weathering actions and chemical attack can be improved by combined chemical and mechanical modification of concrete microstructure. Asphalt admixture in the form of asphalt paste (AP) was used for chemical modification of cement composite microstructure. Concrete structure was formed using special technology of compaction. A stand for vibro-vibropressing with regulated vibrator force and pressing force was developed. The following properties of the modified concrete were tested: compressive strength, water absorption, freeze-thaw resistance, scaling resistance in the presence of de-icing agents, chloride migration, resistance to CO<sub>2</sub> and corrosion in aggressive solutions. Corrosion resistance was tested alternately in 1.8% solutions of NH<sub>4</sub>Cl, MgSO<sub>4</sub>, (NH<sub>2</sub>)<sub>2</sub>CO and CaCl<sub>2</sub>, which were altered every 7 days; the experiment lasted 9.5 months. Optimum compaction parameters in semi-industrial conditions were determined: ratio between piston stress ( $Q_p$ ) and external top vibrator force ( $P_o$ ) in the range 0.4÷-0.5; external top vibrator force 4 kN. High strength concretes with compressive strength  $f_{cm}=60\div70$  MPa, very low water absorption (<1%) and high resistance to aggressive environments were obtained in this study. AP content was reduced from 10% (previous investigations) to 2-4% of cement mass thanks to the special compaction method. Excellent chloride ion penetration resistance and carbonation resistance of concrete containing AP admixture is due to the asphalt barrier formed in pores of cement hydrates against dioxide and chloride ions. Concrete specimens containing AP 4% c.m. and consolidated by vibro-vibropressing method proved to be practically resistant to highly corrosive environment. Vibro-vibropressing compaction technology of concrete modified with AP can be applied in prefabrication plants to produce elements for road, bridge and hydraulic engineering constructions.

## 1. Introduction

Concrete is a universal building material, used especially in combination with steel. Concrete and steel are vulnerable to harmful substances that penetrate into the material by means of moisture. This can result in concrete damage due to concrete and reinforcement corrosion. Durability of concrete elements depends on the quality of the used materials, design and construction quality as well as the environment to which the element will be exposed. If concrete structures are intended for chemically aggressive environment, both material and structural protections should be applied. Additional surface protection, which to some extent limits access of corrosive factors, may be used when the concrete elements are subjected to moderately aggressive environment. In highly aggressive conditions impermeable surface



protection may be required to separate completely the element from these factors. Protective measures should be applied in most exposure classes regardless whether the surface protection will be used or not. These measures consist in proper selection of the constituent materials used for concrete production and modifying concrete microstructure while constructing the structure.

The investigations related to the issue of concrete durability cover a wide range of problems concerning the causes of concrete destruction and preventive measures. Some studies discuss the mechanisms of concrete deteriorations [1-4]. Other present the results of research aiming on supplementary protection methods such as coatings [5,6,7]. Different admixtures such as corrosion-inhibiting admixtures may be used for steel protection [8]. Very popular and effective method of enhancing concrete durability is application of cementitious materials [9-14]. Polymers are also used for modification of cement microstructure [15]. Special attention is given to resistance to freezing and salt scaling [4,16,17].

This study presents the technology of vibro-vibropressing compaction of concrete modified with asphalt based admixture, which may be applied, for instance, for production of bridge, road and street curbs. Asphalt paste (AP) produced according to the Polish Patent No. 136449 was used as an admixture. It is a solution of industrial asphalt in high-boiling organic solvent (technical kerosene with additions). In previous studies [18,19] the dosage of AP exceeded 5% by cement mass. It improved significantly concrete resistance to freezing and de-icing salts, but at the same time this amount of AP resulted in considerable decrease of concrete compressive strength. In this study lower dosages of AP were applied. The technology of compaction was developed under R&D project N° R1400903 financed by The National Centre for Research and Development (Poland). Special device with adjustable parameters of vibration and pressing was designed and used in this study. It can be implemented by companies producing precast structural elements for roads, bridges or hydraulic engineering structures. The technology consisting in modification of concrete microstructure with asphalt emulsion was also developed under the same project [20].

## 2. Materials and specimen preparation

### 2.1. Materials

Portland cement specified in the Polish standard PN-B-19707:2003 as CEM I 42,5 N-HSR/NA was used. Cement physical properties, chemical and phase composition are listed in table 1.

Asphalt paste (AP) made according to Polish Patent No. 136449 was used in this investigation for chemical modification of concrete microstructure. It is a solution of industrial asphalt (Ps 85/25) in high-boiling organic solvent (technical kerosene with additions).

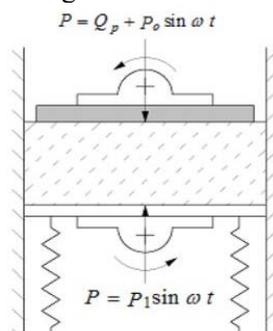
It is a homogenous, black mass with consistency of dense honey, specific gravity 1.030 kg/dm<sup>3</sup>.

**Table 1.** Properties, chemical and phase composition of cement.

Parameter	Value	Chemical composition	[% weight]	Phase composition	[% weight]
Initial setting time (min)	181	Insol.	0.29	C <sub>3</sub> S	58.82
Final setting time (min)	249	Ign. loss	0.62	C <sub>2</sub> S	16.80
Specific surface (cm <sup>2</sup> /g)	2990	CaO	64.36	C <sub>3</sub> A	1.78
Soundness (mm)	0.7	SiO <sub>2</sub>	21.34	C <sub>4</sub> AF	16.05
Compressive strength (MPa):		Al <sub>2</sub> O <sub>3</sub>	4.05		
• 2 days	17.4	Fe <sub>2</sub> O <sub>3</sub>	5.28		
• 28 days	51.8	SO <sub>3</sub>	2.21		
		MgO	1.28		
		Cl	0.004		
		Na <sub>2</sub> O <sub>eqv.</sub>	0.42		

## 2.2. Composition and preparation of specimens

Previous investigation [18,21] proved usefulness of vibro-vibropressing technique for concrete mix consolidation for prefabricated products with high corrosion resistance. The structure of the test stand used in this experiment enabled to apply vibro-vibropressing method of consolidation, which is very efficient in industrial conditions. The external vibrator with regulated force was attached to the movable piston. The vibrator structure allows to regulate the force as follows: 0.80, 2.50, 3.15, 4.00 and 6.30 kN. The pressing force of the piston can be regulated practically in any range of stresses. The diagram of the laboratory stand is given in figure 1. The optimum proportions between pressing piston stress ( $Q_p$ ) and external top vibrator force ( $P_o$ ) should be in the following range:  $Q_p/P_o=0.4\div 0.5$ . When this ratio is lower than 0.4 the vibrations of pressing piston have vibro-percussive (striking) feature, which is very efficient for consolidation concrete mix of dry consistency. When  $Q_p/P_o>0.5$  the vibrations are almost harmonic, which is sufficient to consolidate plastic concrete mix. In previous investigations [18] the dosage of AP had to exceed 5% by cement mass in order to improve significantly concrete resistance to freezing and de-icing salts. However this amount of AP resulted in considerable decrease of concrete compressive strength. Vibro-vibropressing consolidation with optimum pressing force (additional factor) allows to limit dosage of AP to 2-4% by cement mass. As a result, the microstructure of concrete is very tight without considerable loss in compressive strength.



**Figure 1.** Diagram of a stand;  $Q_p$  – pressing force,  $P_o$  – vibrator force

**Table 2.** Concrete compositions

Composition	Constituents, kg/m <sup>3</sup>						Water
	Cement	Asphalt paste	Standard sand	Basalt grit			
				2/4 mm	4/8 mm	8/16 mm	
C0	500	-	824	341	683	114	150
C2	500	10	818	229	678	113	150
C4	500	20	811	336	672	112	150

Compositions of tested concretes are given in table 2. Concrete mix was placed in cubic moulds 150 mm and after vibro-vibropressing consolidation the moulds were kept under plastic foil for 24 hours. Then the cubes were stored in moist conditions at  $80\pm 5\%$  RH and temperature  $20\pm 1$  °C until the age of 28 days. Eight specimens were prepared for each of planned 8 series. After 28 days five specimens were randomly selected for compressive strength test and three for water absorption test.

## 3. Experimental methods

### 3.1. Compressive strength and water absorption test

Cubic specimens 150 mm were prepared, cured and tested in accordance with EN 12390-3 (Testing hardened concrete - Part 3: Compressive strength of test specimens) and the Polish standard PN-88/B-06250 (Ordinary concrete). Specimens were saturated with water under atmospheric pressure.

### 3.2. Concrete freeze-thaw resistance test

Freeze-thaw resistance to cyclic freezing and thawing was conducted according to the Polish standard

PN-88/B-06250 (Ordinary concrete). Concrete specimens were saturated with water under atmospheric pressure until full absorption and then placed in automatic freezer. Control specimens were kept in water in temp.  $20\pm 1^\circ\text{C}$ . Duration of freezing in temp.  $-19\pm 1^\circ\text{C}$  was at least 5 hours and duration of thawing in temp.  $+19\pm 1^\circ\text{C}$  was at least 2 hours in each cycle. The test lasted 150 cycles. After the final cycle the specimens were weighted with accuracy 0.2% and then compressive strength of the reference specimens and those subjected to freezing and thawing cycles was tested. Concrete is freeze resistant after the required number of cycles if specimens have no cracks, total mass loss is not higher than 5% and compressive strength loss does not exceed 20%.

### 3.3. Freeze resistance in the presence of deicing salts

Freeze resistance was evaluated on the basis of surface scaling under influence of freezing in the presence of deicing salts according to the standard PN-EN 1338:2005 (Concrete pavement bricks. Requirements and test methods). Tests were performed for three concrete compositions. Specimens  $100\times 100\times 150$  mm were cut from cubes 150 mm. After 28 days of curing specimens were stored for 170 hours in the climatic chamber in temperature  $+20^\circ\text{C}$  and relative humidity 70%. Side surfaces of specimens were covered with a rubber collar. The upper surface was left for freezing. The collar edge was  $20\pm 2$  mm higher than specimen surface. Connection of the rubber collar and concrete specimen was sealed with silicon in order to prevent water penetration. After storing in the climatic chamber the tested surface was covered with water (temperature  $20^\circ\text{C}$ ), height  $5\pm 2$  mm, for testing the tightness of the connection between the collar and the specimen during 72 hours. All surfaces except for the surface subjected to freezing were insulated with polystyrene (thickness 20 mm). Water was substituted by 3% NaCl solution (thickness  $5\pm 2$  mm) before placing specimens in the automatic freezer. Specimens were covered with polyethylene foil in order to prevent evaporation. The foil was flat and did not touch the freezing solution. After 28 cycles the scalings were removed from the tested surface and collected. Solution with scalings was poured on filter paper and then rinsed with at least one liter of pure water in order to remove remains of NaCl. Filter paper with scalings was then dried for 24 hours in temperature  $+105^\circ\text{C}$ . Mass loss per surface area (with accuracy  $\pm 0.2$  g) was calculated by dividing the total mass of scalings (kg) after 28 cycles of freezing and thawing by the area of tested surface ( $\text{m}^2$ )

### 3.4. Chloride migration

Resistance to chloride migration was tested after 28, 70 and 112 days of curing in temperature  $20\pm 1^\circ\text{C}$  and relative humidity above 90%. An experimental method described in the standard NT BUILD 492 (Concrete, mortar and cement-based repair materials: Chloride migration coefficient from non-steady-state migration experiments) was applied. It allows direct and quick determination of chloride migration coefficient  $D_{\text{nssm}}$  in non-steady-state migration test.

### 3.5. Resistance to $\text{CO}_2$ (carbonation)

Accelerated test of concrete resistance to  $\text{CO}_2$  was made according to procedure given in the standard EN-13295:2005 (Products and systems for the protection and repair of concrete structures. Test methods. Determination of resistance to carbonation). Examinations of carbonation progress (the depth of neutralization) were performed on two specimens in each series. The same specimen was used several times for measurement of carbonation depth increasing with time. Thin layer of the specimen was removed before subsequent measurement. The measurements were made after 56, 112 and 168 days. The carbonation depth ( $d_k$ ) is a mean distance between the concrete surface and the border of the area where  $\text{CO}_2$  reduced alkalinity of hydrated cement – phenolphthalein index solution remained colourless. Specimens  $57\times 75\times 150$  mm were cut from cubes 150 mm and kept in temp.  $20\pm 1^\circ\text{C}$  and RH above 95% until the age of 28 days. Then for 14 days they were kept in temp.  $21\pm 1^\circ\text{C}$  and RH about 60% until the mass was stabilized. After that they were placed in carbonation chamber with 2%  $\text{CO}_2$  concentration, temp.  $21\pm 1^\circ\text{C}$  and RH  $60\pm 10\%$ . Temperature, RH and  $\text{CO}_2$  concentration were monitored every day. The carbonation depth was measured on fresh fractures of each specimen. 15 mm layer was taken for the measurement. The fresh fractures were cleaned from dust and loose particles without using water.

Then phenolphthalein index solution was sprayed on these surfaces. The neutralization depths were measured  $60 \pm 5$  minutes after spraying. Each side of specimen was divided into four even sections – in this way five measurement points were determined. The carbonation depth was measured with a ruler in each point, perpendicularly to the edge of the specimen. The mean  $d_k$  and the maximum  $d_{k,max}$  depths were measured with accuracy  $\pm 1$  mm because carbonation front in practice is irregular. The mean depth on the given specimen side ( $d_{k1}$  for instance) was calculated from five single measurements and rounded to 0.5 mm. Then the measurements were made for the remaining three sides. The mean depth from the four specimen sides is the mean carbonation depth  $d_k$ .

### 3.6. Corrosion in aggressive solutions

For this test the specimens  $40 \times 40 \times 40$  mm were cut from cubes of 150 mm. Dried specimens were placed in corrosive liquids and in water as the reference medium. 1.8% solutions of  $\text{NH}_4\text{Cl}$ ,  $\text{MgSO}_4$ ,  $(\text{NH}_2)_2\text{CO}$  and  $\text{CaCl}_2$  were altered every 7 days. Evaluation (compressive strength test) was made after 3, 6.5 and 9.5 months on 8 cubes  $40 \times 40 \times 40$  mm from corrosive solutions and 8 cubes from water each time. Visual inspection was made every time when solution was altered. Compressive strength was tested in wet state immediately after removing specimens from corrosive solution or water.

## 4. Program of optimization experiment

4-factor experiment was planned in this investigation. The following variable factors were applied (table 3):

- $X_1$  – AP content by cement mass ( $2 \leq X_1 \leq 4\%$ ),
- $X_2$  – external vibrator force  $P_o$  ( $0,8 \leq X_2 \leq 4,0$  kN),
- $X_3$  – pressing stress  $Q_p$  ( $0,05 \leq X_3 \leq 0,1$  MPa),
- $X_4$  – time of vibration ( $30 \leq X_4 \leq 60$  s).

Concrete mix composition is given in table 2. Eight series of specimens differing in AP content and parameters of compaction (table 3) were prepared. The w/c ratio was constant (w/c=0.3) and the cement CEM I 42.5 HSR/NA content was constant.

**Table 3.** Experimental plan.

Series	$X_1$ AP content [%]	$X_2$ Vibrator force [kN]	$X_3$ Pressing stress [MPa]	$X_4$ Time of vibration [s]
1	2	0.8	0.05	30
2	4	0,8	0.05	60
3	2	4.0	0.05	60
4	4	4,0	0.05	30
5	2	0.8	0.1	60
6	4	0.8	0.1	30
7	2	4.0	0.1	30
8	4	4.0	0.1	60

Regression model in the form of second degree polynomial is appropriate to describe dependency of the feature  $Y$  on the independent variables ( $X_1, X_2, X_3, X_4$ ) in the selected range of factors variations (factor space). This polynomial takes into account linear effects of all factors and first degree combined effects of factor  $X_2$  (pressing stress) with other factors. Eight 5-element random samples were used for testing concrete compressive strength (variable  $y_1$ ) at selected values of independent variables  $X_1, X_2, X_3, X_4$  (table 3). The average values of experimental results are given in table 4.

Assuming that classical linear regression model is appropriate for description of the dependency of  $y_1$  on independent variables, the parameters of this model were estimated. This is the regression function calculated for the encoded values:

$$y_1 = 58.68 - 4.15x_1 + 7.55x_2 + 1.37x_3 + 0.45x_4 - 0.37x_1x_2 + 0.45x_2x_3 - 1.80x_2x_4 \quad (1)$$

Estimation  $s^2=4,632$  which has  $v=8(5-1)=32$  degrees of freedom was obtained. Standard error of estimation of the regression equation (1) parameters was calculated  $s_{b_k} = \sqrt{\frac{4.632}{8}} = 0.76$ . The critical value  $t_{0,05;32}=2.04$  was obtained in t-Student distribution at significance level  $\alpha = 0.05$ . The regression equation for the encoded factors after excluding insignificant coefficients is as follows:

$$y_1 = 58,68 - 4,15x_1 + 7,55x_2 - 1,80x_2x_4 \quad (2)$$

It is possible to predict compressive strength of concrete specimens in the considered factor space from the equation (2). The regression function of water absorption for the experimental results is as follows:

$$y_2 = 1.817 - 0.400x_1 - 0.677x_2 - 0.117x_3 + 0.045x_4 + 0.205x_1x_2 + 0.072x_2x_3 + 0.085x_2x_4 \quad (3)$$

Estimation  $s^2 = 0.038$  was obtained. Standard errors of estimation of regression equation (3) parameters are identical and equal to  $s_{b_k} = \sqrt{\frac{0.038}{8}} = 0.069$ . The critical value is  $t_{0,05;16}=2.120$  was obtained in t-Student distribution at significance level  $\alpha=0.05$ . The regression equation for water absorption dependency for the encoded factors after excluding insignificant coefficients is as follows:

$$y_2 = 1.817 - 0.400x_1 - 0.677x_2 + 0.205x_1x_2 \quad (4)$$

The optimum levels of the factors  $X_1$ ,  $X_2$  and  $X_4$  can be calculated from the equations (2) and (4). The insignificant factor  $X_3$  (pressing stress) can be determined in the range from 0.05 MPa to 0.10 MPa and it can be accepted for instance  $X_3=0.075$  MPa. As it can be seen from the equation (2) the factor  $X_2$  (external vibrator force) should be at top level ( $X_2=4$  kN) and the factor  $X_4$  (vibration time) at bottom level ( $X_4=30$  s) in order to achieve maximum compressive strength. By substitution in the equation (2) the value of the encoded factor  $x_4=-1$  we obtain:

$$y_1 = 58.68 - 4.15x_1 + 9.35x_2 \quad (5)$$

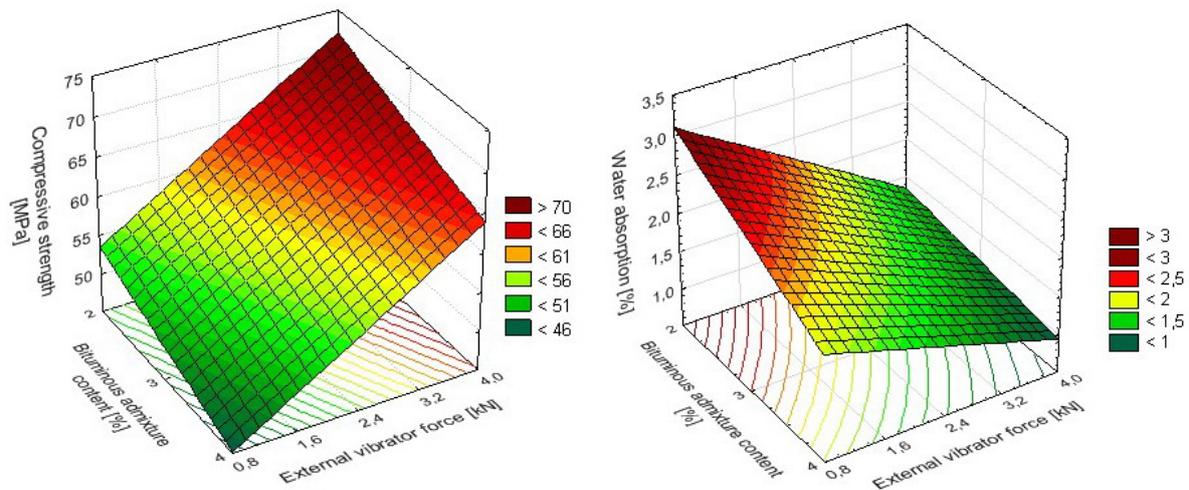
**Table 4.** Experimental plan and results of concrete compressive strength and water absorption.

Series	Encoded factors				Mean compressive strength, [MPa]	Mean water absorption, [%]
	$x_1$	$x_2$	$x_3$	$x_4$		
1	-1	-1	-1	-1	51.3	3.42
2	1	-1	-1	1	49.1	1.95
3	-1	1	-1	1	68.0	1.42
4	1	1	-1	-1	60.8	0.95
5	-1	-1	1	1	58.5	2.78
6	1	-1	1	-1	45.6	1.83
7	-1	1	1	-1	73.5	1.25
8	1	1	1	1	62.6	0.94

Both compressive strength and water absorption should be taken into consideration for determining optimum values of parameters  $X_1$  and  $X_2$ . For this purpose isolines of compressive strength and water absorption calculated from the equations (2) and (4) can be applied. The isolines are presented in figure 2. There are many pairs of  $X_1$  and  $X_2$  for which compressive strength is not lower than 60 MPa and water absorption not higher than 1.5%. For choosing the specific pair of  $X_1$  and  $X_2$  the additional condition should be stipulated, the maximum compressive strength in the area, for instance. For the pair  $X_1=2\%$  and  $X_2=4$  kN the values of other parameters are  $X_3=0.075$  MPa and  $X_4=30$ s.

a)

b)



**Figure 2.** Dependency of a) concrete compressive strength  $y_1$  on AP content ( $X_1$ ) and external vibrator force ( $X_2$ ); b) water absorption  $y_2$  on AP content ( $X_1$ ) and external vibrator force ( $X_2$ )

Optimization of the technology of forming concrete specimens showed that the further investigation should be conducted using vibro-vibropressing method of compaction with external vibrator force 4 kN, pressing stress 0.1 MPa and time of vibration 30 s.

## 5. Test results and discussion

### 5.1. Influence of asphalt paste on concrete freeze resistance test

The experimental results of concrete freeze resistance are reported in table 5. All tested concretes met requirements of Polish standard PN-88/B-06250 regarding freeze resistance after 150 cycles of freezing and thawing. Mass loss was 0.14% and compressive strength loss was 6.2% for concrete without AP. Mass losses were 0.08% and compressive strength losses were respectively 5.6% and 5.3% for concretes with 2% and 4% of AP by c.m. All concretes formed by vibro-vibropressing compaction are freeze resistant after 150 cycles of freezing and thawing in water. However better results were obtained in the case of concrete modified with bituminous admixture. Such high freeze resistance of the specimens modified with AP is associated with the very low water absorption of cement hydrates in which the impermeable hydrophobic asphalt film seals the pores.

**Table 5.** Mass and compressive strength loss after 150 cycles of freezing and thawing.

Composition	Mass of specimens [kg]		Mean mass loss (%)	Compressive strength [MPa]		Mean strength loss [%]
	Before cycles	After cycles		Control specimens	Tested specimens	
C0	5.116	5.109	0.14	95.6	89.7	6.2
C2	4.976	4.972	0.08	74.7	70.5	5.6
C4	4.902	4.898	0.08	65.8	62.3	5.3

### 5.2. Influence of asphalt paste on freeze resistance in the presence of deicing salts

Test results are presented in table 6. According to the standard *PN-EN 1338:2005* concrete freeze resistance in the presence of deicing salt is evaluated on the basis of mass of scalings after 28 cycles of freezing and thawing. The mean mass of scalings should be not higher than 1.0 kg/m<sup>2</sup> and any single result should not exceed 1.5 kg/m<sup>2</sup>. All tested concretes have good freeze resistance.

**Table 6.** Test results of concrete freeze resistance in the presence of deicing salt.

Composition	Mass of scalings after 28 cycles, [kg/m <sup>2</sup> ]
C0	0.33
C2	0.92
C4	0.34

### 5.3. Influence of asphalt paste on chloride migration and carbonation

Criteria for chloride migration coefficient after 28 days of concrete curing are given in table 7. Experimental results are presented in table 8. Applying vibro-vibropressing method of compaction enabled to produce concrete with very good resistance to chloride migration. Age of concrete influences the chloride migration coefficient  $D_{nssm}$  to considerable extent for all tested concretes. The value of this coefficient drops significantly after 70 days of curing. The value of the coefficient  $D_{nssm}$  decreased twenty times to  $0.1 \cdot 10^{-12} \text{ m}^2/\text{s}$  between 28th and 112th day of curing for concretes containing AP. It means that concrete practically impermeable for chlorides was obtained.

**Table 7.** Evaluation of concrete resistance to chloride migration

Migration coefficient	Resistance to chloride migration
$< 2 \cdot 10^{-12} \text{ m}^2/\text{s}$	Very good
$2 \div 8 \cdot 10^{-12} \text{ m}^2/\text{s}$	good
$8 \div 16 \cdot 10^{-12} \text{ m}^2/\text{s}$	Sufficient
$> 16 \cdot 10^{-12} \text{ m}^2/\text{s}$	Not acceptable

**Table 8.** Experimental results of chloride migration coefficient  $D_{nssm}$ 

Composition	Age of specimens	$D_{nssm} \cdot 10^{-12} [\text{m}^2/\text{s}]$	Resistance to chloride migration
C0	28 days	2.06	Good
C2		2.05	
C4		2.03	
C0	70 days	1.94	Very good
C2		1.66	
C4		1.04	
C0	112 days	0.70	Very good
C2		0.09	
C4		0.08	

It is difficult to establish definitely the relation between the chloride migration coefficient and AP content after 28 days of concrete hardening. It may be a result of an inaccuracy of measurement of depth of chloride migration using calorimetric method. Only after 70 days of curing the beneficial influence of AP may be very clearly noticed. Considerable decrease of the chloride migration coefficient can be observed even after 112 days in the concrete specimens containing AP compared to the control specimens. The chloride migration coefficient is very low for concretes properly designed, compacted by vibro-vibropressing and properly cured. Whereas application of the bituminous admixtures allowed to obtain the material practically impermeable for chloride ions.

Carbonation symptoms (regardless AP content) were noticed after 56 days of keeping in carbonation chamber only on the surfaces which were smoothed with a trowel:  $d_{k(1-4)}=0.5 \text{ mm}$  or  $d_{k(1-4)}=1 \text{ mm}$ ,  $d_{k,max}=2.5 \text{ mm}$ . Carbonation symptoms were not noticed on fractions. There was no carbonation progress after 112 and 168 days on any tested specimen. Such excellent chloride ion penetration resistance and carbonation resistance of concrete containing AP admixture is due to the asphalt barrier formed in pores of cement hydration products against dioxide and chloride ions.

#### 5.4. Influence of asphalt paste on corrosion in aggressive solutions

Corrosion resistance coefficient  $CR(f_c)$  (ratio of strength of specimens from corrosive solution CS to strength of specimens kept in water W) was taken as the durability criterion. Concrete for which  $CR(f_c) > 0.8$  is considered to be durable. The experimental results are reported in table 9. All concretes compacted by vibro-vibropressing have high resistance to highly corrosive environment after 3, 6.5 and 9.5 months of treatment. All specimens retained their shape and dimensions regardless the corrosive solution, there were no signs of destruction or considerable compressive strength loss. Specimens with 2% AP kept in aggressive environment had lower compressive strength than reference specimens after 3 months of treatment. Yet, the corrosion resistance coefficient was high  $CR=0.93$ . Whereas specimens with 4% AP after 3 months of exposure and with 2% AP after 6.5 months of exposure had higher compressive strength than the reference specimens - the corrosion resistance coefficient  $CR(f_c)$  was 1.20 and 1.07 respectively. After 9.5 months all concretes had lower compressive strength than the reference ones. The lowest  $CR(f_c)=0.79$  was observed for C2 composition. As indicated in table 9 concrete specimens containing 4% AP and consolidated by vibro-vibropressing method are practically resistant to highly corrosive environment.

**Table 9.** Concrete compressive strength after 3; 6.5 and 9.5 months of treatment

Composition	Time [months]	Compressive strength (MPa)		Corrosion resistance coefficient $CR[f_c]$
		water [W]	corrosive environment [CE]	
C0	3	54.3	54.8	1.01
C2		41.6	38.6	0.93
C4		34.7	41.7	1.20
C0	6.5	67.4	58.9	0.87
C2		41.1	44.0	1.07
C4		38.8	38.0	0.98
C0	9.5	62.7	52.6	0.84
C2		49.7	39.3	0.79
C4		40.7	36.8	0.90

## 6. Conclusions

It is possible to compact concrete mix of low workability (without water reducing admixture) during 30÷50 seconds using the developed vibro-vibropressing stand. Optimum concrete compositions as well as optimum method of compaction were determined on the basis of the complex examinations. Optimum compaction parameters in semi-industrial conditions were determined: ratio between piston stress ( $Q_p$ ), external top vibrator force ( $P_o$ ) in the range 0.4÷0.5, external top vibrator force 4 kN. High strength concretes with compressive strength  $f_{cm}=60÷70$  MPa, very low water absorption (<1%) and very high resistance to aggressive environments were obtained. AP content was reduced to 2 and 4% by mass of cement thanks to the special compaction method. Vibro-vibropressing compaction technology can be applied in prefabrication plants to produce elements from concrete modified with AP for road, bridge and hydraulic engineering construction.

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