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A report on the fabrication of concrete pavement with the application of anionic bitumen emulsion

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HIGHLIGHTS

- Beneficial effect of bitumen emulsion on the concrete frost resistance was noticed.
- Bitumen emulsion enhances the concrete waterproofness.
- Anionic emulsion profitably changes the structure of concrete porosity.
- Concrete composition suitable for the most severe exposure classes was selected.
- Laboratory research results were verificated in practice.

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ABSTRACT

The problems of concrete degradation in pavements occur around the world, regardless of climatic zones, which is one of the chief factors in environmental corrosion. This article describes the final stage of Development Project No. 14 009 03 carried out by the Ministry of Science and Higher Education in Poland regarding the verification of laboratory research results with the construction of the Multimodal Reload Terminal within the Duty Free Zone in Małaszewicze, Poland. The Terminal concrete pavement was designed to expand and doweled in accordance with the national requirements and the paving layers was based on existing solutions. Concrete in the slab was modified with an anionic bitumen emulsion to reduce its water absorption and improve resistance to environmental aggression. To achieve the required consistency of the concrete mix superplasticizers were used. The use of bitumen emulsion allowed to achieve the concrete water absorbability to below 4% in comparison to reference concretes while at the same time retaining high F200 frost resistance. The technology of cement composites modified with anionic bitumen emulsion was successfully tested under real operating conditions with the creation of a concrete pavement capable of bearing high mechanical pressure in a corrosive environment.

1. Introduction

Concrete is a widely used composite material in the construction industry; however, due to its heterogeneous and porous structure, there are a number of problems related to maintaining its durability over a standard lifetime [1,2]. This is particularly true of structures exposed to corrosive conditions such as chlorides, cyclical freezing and thawing, corrosive chemicals and abrasion [3–6]. Numerous scientific facilities haves been researching how to improve concrete durability for many years. Many approaches have been applied including: different methods of thickening concrete [7], various curing methods [8], as well as protection of the surface layer [9–13]. Thus far, however, the use of chemical and mineral additives has played the most significant role in modifying the properties of concrete [14–17]. Different mathematical models have been developed to represent the relationship between strength and maturity of concrete. The linear relationship between double logarithmic strength and logarithmic maturity was implemented in practice to monitor the in-place strength gain and time of opening under variable temperature conditions [18].

One of the ways of minimizing the deficiencies of cement composites has been to produce high compression strength concrete: so called high performance concrete (HPC) or ultra-high performance concrete (UHPC). In modern engineering practice, cement composites with compression strengths in excess of 60 MPa are being used ever more frequently [19,20]. Unfortunately, high compressive strength does not always correspond to concrete in engi-

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neering structures with other equally outstanding properties. In particular, with an increase in strength it is not always possible to obtain the optimum resistance to a corrosive environment for a reinforced cement composite or adequate stiffness for thin-walled widely spaced engineering structures. The key challenge is to assure that concrete has durability in road surfaces, airport aprons and vehicle manoeuvring areas, which are exposed to significant mechanical loads as well as to corrosive environments. Some researchers analysed behaviour of concrete surrounding dowel bars what is a major problem in jointed plain concrete pavement. In some studies, using the finite-element method, a distribution of stresses around dowel bars was analyzed with special attention to compressive and tensile stresses, which are responsible for cracks initiation and propagation [21]. The cracks in concrete pavements are formed at early-age as consequence of internal stresses in the concrete. According to Pradena and Houben [22] the stress relaxation has an essential influence on the cracking process. The authors proposed a new equation of the relaxation factor, based on a theoretical and practical analysis of the transversal cracking in jointed plain concrete pavements. Can et al. [23] described the most appropriate method of rehabilitation of composite pavements and assessed the effect of various factors on the development of cracks in the composite pavement through survival analysis. Different mathematical models have been developed to represent the relationship between strength and maturity of concrete. The linear relationship between double logarithmic strength and logarithmic maturity was implemented in practice to monitor the in-place strength gain and time of opening under variable temperature conditions [18].

The aim of the study was determining the applicability of anionic bitumen emulsion in cement composites and establishing its effect on the properties of concretes exposed to an aggressive environment. In this article, the authors present research into optimizing the proportion of the ingredients for cement composites resistant to significant mechanical loads and corrosive environments as well as what has been learnt from the use of a cement composite in the construction of a concrete pavement for a 11,076 m^2 manoeuvre yard in Multimodal Reload Terminal within the Duty Free Zone in Małaszewicze near Terespol, Poland.

2. The research

The problems of concrete degradation in pavements occur around the world, regardless of climatic zones, which is one of the chief factors in environmental corrosion. In the example, Fig. 1, cracks in an airport apron can be seen caused by the insufficient stiffness of the concrete as well as the varying mechanical properties of the ground.

The next picture, Fig. 2, shows the loss of the upper layer of concrete after a 20-year usage period on a manoeuvring area on an industrial premises in Poland. The flaking of the concrete pavement is due to insufficient resistance to frost and the use of natural rounded aggregate.

The PN-EN 206:2014 standard [2] classifies levels of environmental corrosion including in regard to concrete pavements:

- XC – corrosion of the reinforcement caused by carbonization at the XC4 hazard level;
- XD – corrosion of the reinforcement caused by non-seawater chlorides at the XD2 hazard level;
- XF – damage caused by alternating freezing/thawing cycles together with de-icing agents at the XF4 hazard level;
- XA – chemical corrosion of concrete at the XA2 hazard level;
- XM – concrete erosion caused by abrasion at the XM1 hazard level.

In practice, the corrosion levels mentioned above occur with concrete structures in all Northern and Middle European countries, and in particular with concrete pavements.

The concrete pavement in the Multimodal Container & Reload Terminal in Terespol was designed to expand and doweled in accordance with the requirements specified by national and foreign regulations [24–26]. The design of the paving layers was based on a solution taken from a German catalogue [25]. The slab and substructure thicknesses were designed to accommodate the existing loads and comprised a concrete slab of 40 cm of at least C30/37 class modified with bitumen emulsion, a 20 cm layer of broken drainage aggregate, and ground stabilized with 15 cm of cement (Fig. 3).

In the underlying soil, some bearing grounds were present in the form of fine sand, and medium-condensed sand (resistant to frost and water). The soil was mixed and thickened with sand in order to obtain the following properties: $Is \geq 1.03$, $EV_1 \geq 60$ MPa, $EV_2 \geq 120$ MPa, $EV_2/EV_1 \leq 2.2$ [27]. Due to varying test results, the soil was stabilized with a 15 cm layer of cement of $f_{cm} = 1.5\div2.5$ MPa [28]. The main base course comprised broken aggregate stabilized mechanically. The primary and secondary deformation

Fig. 1. Cracks in an airport apron – Airport Santa Cruze de Tenerife (photo. K. Falkowski).

Fig. 2. The loss of the upper layer of concrete after a 20-year usage period (photo. K. Falkowski).

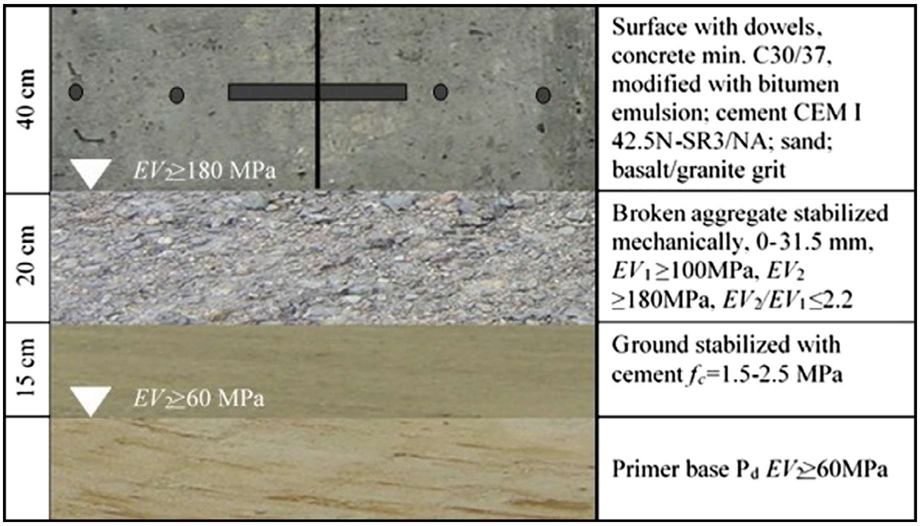

Fig. 3. The design for the intersection of concrete pavement.

modulus was determined with a VSS probe in accordance with attachment B to the standard [29].

The structure was designed to bear the load of a Reach Stacker travelling crane model SC 4531 TA5. The maximum load transferred to the front axle while lifting a container is 101 500 kg. All outstanding load parameters comparable to the load of a Boeing 787 Dreamliner are shown in Fig. 4.

Establishing the dimensions of the concrete pavement was based on the method of the Westergaard modulus [30,31]. RXF Floor Design Software v.0.2 was used to calculate the load bearing capacity for three variants: one-wheel load, two-wheel load, and front axle load.

3. Materials and experimental methods

3.1. Materials

3.1.1. Cement

A special Portland cement CEM I 42.5N-SR3/NA with a high sulphate resistance and a low alkali content specified in Polish standard PN-EN 197–1:2012 Cement – Part 1: Composition, specifications and conformity criteria for common cements was used both during laboratory testing and for the construction of the pavement at the terminal. Cement physical properties, chemical and phase composition are listed in Table 1.

This cement is characterized by a number of valuable performance properties (e.g. a low alkali content and a high resistance to sulphate corrosion) that are important in civil engineering for the construction of bridges, tunnels, flyovers and road surfaces, airports, manoeuvring areas, as well as for buildings and prefabricated elements exposed to corrosive environments.

3.1.2. Anionic bitumen emulsion

Anionic bitumen emulsion (AE) resistant to alkalis and most acids was used as the admixture. Its properties are presented in [32]. It is a ready product meeting the Technical Specification of Polish Road and Bridge Research Institute No. AB 426TW 21998/W469. It was distributed in mixing water and then added to cement and aggregate.

3.1.3. Concrete

A C35/45 formula concrete was selected for the given usage and corrosion conditions. This concrete formula meets the requirements used for the most severe exposure classes: XF4, XD3, XC4, XA3 and XM3 as per [2]. CEM I 42.5 N-SR3/NA Portland cement (Table. 1) was used for making the concrete mixtures in an amount of 360 kg/m^3. The fine aggregate comprised rinsed quartz sand, while the coarse aggregate was 2–8 mm and 8–16 mm granite grit in accordance with the requirements laid out in Table 2. These aggregates complied with the requirements determined in PN-EN 12620 + A1:2010 [33].

Tare weight: 71 100 kg
Container max. weight: 45 000 kg
Max. load on front axle: 101 500 kg
Max. weight incl. container: 116 tons
Height: 17.9 m

Tare weight: 101 000 kg
Fuselage diameter: 5.74 m
Wing span: 60 m
Max. take-off weight: 227 930 kg
Length: 57 m
Height: 17 m

Fig. 4. Comparison of loads on concrete pavement from Reach Stocker (left) and Boeing 787 Dreamliner (right).

Table 1
Cement physico-chemical properties and phase composition.

Parameter	Requirements	Test results	Standard
Specific surface (cm^2/g)	–	3 820	PN-EN 196-6
Initial setting time (min)	$\geq$60	150	PN-EN 196-3
Final setting time (min)	–	215	PN-EN 196-3
Water demand (%)	–	29.2	
Soundness (mm)	$\leq$10	1.1	PN-EN 196-3
Compressive strength (MPa)			
2 days	$\geq$10	23.0	PN-EN 196-1
28 days	42.5–62.5	52.5	
Chemical composition (%):			
Insol.	$\leq$5.0	0.49	PN-EN 196-2
Ign. loss	$\leq$5.0	2.36	PN-EN 196-2
Na_2O_{eq}	$\leq$0.6	0.46	PN-EN 196-21
Al_2O_3	$\leq$5.0	3.48	PN-EN 196-2
SO_3	$\leq$3.5	3.12	PN-EN 196-2
Cl	$\leq$0.1	0.078	PN-EN 196-21
Value of the expansion in Na_2SO_4 solution after 52 weeks (%)	$\leq$5.0	0.206	PN-B-19707
Phase composition (%):			
C_3A,%	$\leq$3.0	1.78	PN-EN 196-2
$C_4AF + 2C_3A$,%	$\leq$20	16.94	PN-EN 196-2
C_3S,%	$\leq$60	58.48	PN-EN 196-2

Table 2
Requirements for broken aggregates to concrete pavement.

Parameter	C35/45÷C40/50	C25/30÷C30/37
Max. abrasion in Los Angeles (%)	25	
Max. water absorption (%):		
a) for aggregates of igneuos and transformed rocks		
4–8 mm	1.5	2.0
>8 mm	1.2	2.0
b) for aggregates from sedimentary rocks	2.0	3.0
Max. frost resistance (%):		
a) for aggregates of igneuos and transformed rocks	2.0	4.0
b) for aggregates from sedimentary rocks	2.0	5.0
Max. content of compound of sulphur (SO_3) (%)	0.1	0.1
Max. content of shapeless grains (%)	20	25
Max. content of pollutants (%)	0.1	0.2

Grains smaller than 0.25 mm (of cement and sand) in 1 m^3 of the mixture did not exceed 460 kg/m^3 of the content (taking into account the limitation of water demand and the w/c ratio). The concrete was modified with the addition of anionic bitumen emulsion in order to decrease its absorbability and enhance its corrosion resistance. Bitumen emulsion also adds plasticizing properties to the concrete mixture. In order to obtain the required class of concrete mixture consistency, liquefaction additives were used in the form of new generation superplasticizers. The mixture's consistency was checked each time prior to its use on the site. To maintain its pumping properties and its densification with an immersion vibrator, the mixture had to have a V4 consistency (according to the Vebe test) with a reading of $s \leq 110$ mm according to the slump test.

3.1.4. Reinforcement and dowels

In order to increase resistance to cracking and eliminate shrinkage scratches, 52 mm long synthetic fibres were used as diffusion reinforcement in the proportion of 2.0 kg/m^3 of concrete mixture. To improve slab mating, dowels were used in the expansion gaps (to limit slab faulting). These were made of St3S steel and inserted at a height of half the thickness of the slabs and spaced 40 cm apart. The diameter of each bar was 40 mm with a length of 64 cm. One half of each dowel was coated with a layer of bitumen to prevent it setting to the concrete of the opposing slab.

3.1.5. Expansion joints

The spaces between the expansion joints did not exceed 5.0 m. The first 3 mm cut at 1/3 height of slabs were made, depending on the ambient temperature, between 8.00 and 24.00 h after the concrete was laid. The gaps were expanded to a width of 8 mm after the concrete in the structure had been cured for a period of 28 days and the edges of gaps were bevelled at 3 × 3 mm. The gaps were filled with a cold pourable sealing material that is characterized by good flow properties, stability at high temperatures, good adherence to primed gap walls, high elasticity at low temperatures, and resistance to chemical corrosion from de-icing agents, fuels and diesel oils. Prior to being filled, the gaps were carefully cleaned and primed.

3.2. Experimental methods

3.2.1. Laboratory testing

The selection of the optimum concrete content for the terminal surface was carried out according to planned experimental tests using three input quantities:

- X_1 – anionic bitumen emulsion, ($0 \leq X_1 \leq 4.0\%$ of cement mass),
- X_2 – superplasticiser, ($0 \leq X_2 \leq 1.1\%$ of cement mass),
- X_3 – w/c ratio, ($0.30 \leq X_3 \leq 0.44$),

as well as an assumed function in the form of a second degree polynomial:

$$y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{23}x_2x_3 \quad (1)$$

Laboratory testing was carried out with the three following formats:

a Latin square – an array of 9 for 3 elements with 3 variants (basic design),
Hartley's matrix Ha3 – an array of 11 for 3 elements with 5 variants (a planned correction for some of the data acquired from the Latin square),
Hartley's matrix Ha3 – an array of 15 for 3 elements with 5 variants (to verify the data by checking for factors that would interfere with the results of the experiment).

The output data y_i included the frost resistance of the concrete calculated on the basis of the loss of its durability and weight through flaking after 200 freezing and thawing cycles, as well as its compressive strength, water absorption, density and porosity.

3.2.2. Testing methods for base load capacity and deformability

- The testing of the primary EV_1 and secondary EV_2 compression moduli was carried out with VSS apparatus [29]:

$$EV_1 = \frac{3\Delta p_1 D}{4\Delta s_1} \quad (2)$$

$$EV_2 = \frac{3\Delta p_2 D}{4\Delta s_2} \quad (3)$$

where:

EV_1 – the primary compression modulus, MPa; EV_2 – the secondary compression modulus, MPa; D – the diameter of the surface plate $\sim$ 0.3 m; $\Delta p_{1,2}$ – the difference in stress between the first and the second stress cycles within a 0.05–0.15 MPa range for the primed primary base and within a 0.15–0.25 MPa range for the improved base; $\Delta s_{1,2}$ – the increase in relocation over the first and second stress cycles corresponding to the above stated range of loads [m].

The VSS testing describes the soil zone to a depth of 30–50 cm below the surface plate. The measuring cycle lasts approx. 2 h, $EV_2/\ EV_1 \leq 2.2$.

- Testing dynamic modulus E_d [MPa/m] for base deformation

The testing was carried out with a light dynamic deflectometer with the following properties:

- mass of falling weight 10.0 kg,
- pulse duration: 17 ± 1.5 ms,
- max. impact force 7.07 kN (0.1 MPa),
- diameter D = 300 mm,
- max. E_d value = 225 MPa,
- measurement duration: 3 min/point.

The modulus is determined as follows:

$$E_d = \frac{3pD}{4s} \quad (4)$$

where:

E_d – base dynamic modulus; p – load 7.07 kN; D – plate diameter 0.3 m; s – measured relocation, m.

- The reaction coefficient of the base K, MPa/m

The coefficient is determined on the basis of increasing trial loads p (MPa) with a plate diameter of D = 0.762 m until a relocation of $s = 1.27 \times 10^{-6}$ m is achieved calculated with the following relationship:

$$K = p/s \quad (5)$$

with a minimum plate diameter of D = 0.3 m, then:

$$K = \frac{D_0}{D_{76.2}} K_o \quad (6)$$

where:

K – the reaction coefficient of the base with a plate diameter of D = 0.762 m, MPa/m; K_o – the reaction coefficient of the base with a D_o diameter plate; $D_{76.2}$– a 0.762 m diameter plate; D_o – the testing plate.

In practice, correlations between the EV_2, E_d and K base parameters are used as follows:

$$EV_2 = 600 ln \frac{300}{300 - E_d} \quad (7)$$

$$K = \frac{EV_2}{0.762(1 - v^2)} \quad (8)$$

The correlations that may be found in the literature are:
EV_2 = 10 CBR – correlation used by the company Shell,
$EV_2 = 17.6\ CBR^{0.64}$ – correlation used in the UK,

Table 3
The results for concrete mixture in a Hartley's Ha3 matrix (15 elements).

Series	X_1 bitumen emulsion content (%)	X_2 superplasticizer content (%)	X_3 w/c ratio	Consistency S (slump test)	Air content (%)	Density of concrete mixture (kg/dm^3)
1	0.845	0.232	0.33	1	2.7	2.37
2	3.155	0.232	0.33	1	1.8	2.37
3	0.845	0.868	0.33	1	2.8	2.40
4	3.155	0.868	0.33	1	2.8	2.40
5	0.845	0.232	0.41	2	2.7	2.39
6	3.155	0.232	0.41	2	3.2	2.40
7	0.845	0.868	0.41	5	1.6	2.41
8	3.155	0.868	0.41	5	3.4	2.30
9	0	0.550	0.37	3	1.9	2.45
10	4	0.550	0.37	3	3.4	2.31
11	2	0.000	0.37	1	3.4	2.35
12	2	1.100	0.37	5	1.7	2.41
13	2	0.550	0.30	1	2.5	2.45
14	2	0.550	0.44	4	3.0	2.35
15	2	0.550	0.37	3	2.8	2.43

Table 4
The results for concrete in a Hartley's Ha3 matrix (15 elements).

Series	Density (kg/dm^3)	Water absorption WA (%)	$f_{cm,28}$ (MPa)	$f_{cm,F200}$ (MPa)[a]	$f_{cm,120}$ (MPa)[b]	$\Delta f_{cm,F200}$ (%)[c]
1	2.37	2.92	56.67	47.17	58.67	19.6
2	2.36	1.79	56.33	56.33	61.0	7.65
3	2.42	2.84	61.0	52.33	66.33	21.11
4	2.40	1.98	59.0	53.66	58.17	7.75
5	2.34	3.87	54.0	51.33	63.67	19.37
6	2.33	2.82	52.0	53.67	59.0	9.04
7	2.35	4.06	50.67	46.0	62.17	26.01
8	2.30	3.41	46.33	46.83	50.67	7.57
9	2.45	3.56	66.33	59.5	71.67	16.98
10	2.31	1.39	49.33	49.16	52.0	5.46
11	2.32	2.31	52.33	49.5	56.0	11.61
12	2.37	2.53	50.17	55.33	59.5	7.00
13	2.42	1.62	60.0	59.67	66.33	10.05
14	2.34	4.05	48.5	45.25	50.33	10.10
15	2.39	2.62	58.33	56.83	63.83	10.97

[a] Compressive strength after 200 cycles of concrete freezing and thawing.
[b] Compressive strength of control concrete.
[c] Loss of compressive strength after 200 cycles of concrete freezing and thawing.

Table 5
Regression equations describing changes in particular characteristics of concrete.

Feature	Regression equations	R^2
Density (kg/dm^3)	$D = 1.86 + 0.03X_1 + 0.65X_2 + 2.40X_3 - 0.004X_1^2 - 0.17X_2^2 - 3.11X_3^2 - 0.02X_1X_2 - 0.08X_1X_3 - 1.08X_2X_3$	0.87
WA (%)	$WA = 11.71–0.95X_1 - 2.66X_2 - 53.66X_3 + 0.02X_1^2 + 0.05X_2^2 + 86.74X_3^2 + 0.23X_1X_2 + 0.78X_1X_3 + 6.58X_2X_3$	0.94
$f_{cm,28}$ (MPa)	$f_{cm,28} = -65.91 + 2.88X_1 + 85.28X_2 + 632.63X_3 - 0.12X_1^2 - 23.34X_2^2 - 828.68X_3^2 - 1.36X_1X_2 - 10.82X_1X_3 - 157.23X_2X_3$	0.88
$f_{cm,F200}$ (MPa)	$f_{cm,F200} = -130.57 + 12.52X_1 + 80.22X_2 + 892.39X_3 - 0.93X_1^2 - 18.61X_2^2 - 1133.57X_3^2 - - 3.18X_1X_2 - 19.81X_1X_3 - 144.06X_2X_3$	0.53
$f_{cm,120}$ (MPa)	$f_{cm,120} = -113.42 + 11.77X_1 + 86.18X_2 + 849.69X_3 - 0.41X_1^2 - 18.95X_2^2 - 1053.23X_3^2 - 5.89X_1X_2 - 27.98X_1X_3 - 144.06X_2X_3$	0.84
$\Delta f_{cm,F200}$ (MPa)	$\Delta f_{cm,F200} = 60.98–2.12X_1 - 9.91X_2 - 229.08X_3 + 0.7X_1^2 + 2.89X_2^2 + 323.14X_3^2 - 3.24X_1X_2 - 9.36X_1X_3 + 34.98X_2X_3$	0.75

EV_2 = 16 CBR – correlation used in Poland for clay and sandy grounds ($0.97 \leq I_L$ - ≤ 1.0) with lower than optimum moisture content,
where: CBR –% load capacity of the base.

4. Laboratory test results and discussion

4.1. Test results for physical-mechanical properties of concrete mixture and concrete

The purpose of the laboratory testing was to obtain data on the impact of a bitumen mixture, fluidization agents, and the w/c ratio on the properties of concrete, especially its frost resistance, waterproofness, and water absorption that ensure its durability for the manoeuvring area paving surface at the Multimodal Container and Reload Terminal in Terespol. In the end, on the basis of statistical analysis of the test results, the best concrete recipes were determined for the terminal's pavement.

An example of the test data and the results obtained for concrete mixture and hardened concrete in a Hartley's Ha3 matrix (15 elements) are shown in Tables 3and 4 successively.

Table 5 presents regression equations describing changes in particular characteristics of concrete in regard to the results in Table 4.

In the authors' opinion, the following factors had the most critical impact on the particular characteristics of the concrete: X_1 –bitumen emulsion content to the cement mass, and X_3 – the w/c coefficient, which indirectly tells us the amount of water bound within the concrete.

In Figs. 5–7, surface diagrams are shown. These show the following relationships, respectively: water absorption, compressive strength after 28 days of concrete curing ($f_{cm,28}$), and compressive strength after 200 cycles of concrete freezing and thawing ($f_{cm,F200}$) to X_1 (bitumen emulsion content) and X_3 (w/c ratio).

The diagram shown in Fig. 5 shows the beneficial impact of bitumen emulsion on the water absorption of the concrete. With a w/c ratio equal to 0.30, the presence of 4% bitumen emulsion resulted in a near threefold decrease in the concrete's water absorption (to approx. 1%) in comparison to concrete that did not contain emulsion. This impact gradually lessens with a rise in the w/c ratio.

Fig. 6 shows the reduction in compressive strength after a 28 day curing due to the presence of bitumen emulsion. This reduction is particularly visible when the w/c exceeds 0.36. Due to this effect, the emulsion content should not exceed 2% of cement mass when the w/c is equal to 0.30–0.36.

The diagram in Fig. 7 shows the significant impact of bitumen emulsion on concrete durability after 200 cycles of freezing and thawing, particularly when the emulsion content is 1.5–4% of the cement mass with a correspondingly low w/c ratio. The concretes that are most resistant to freezing are obtained with a w/c of

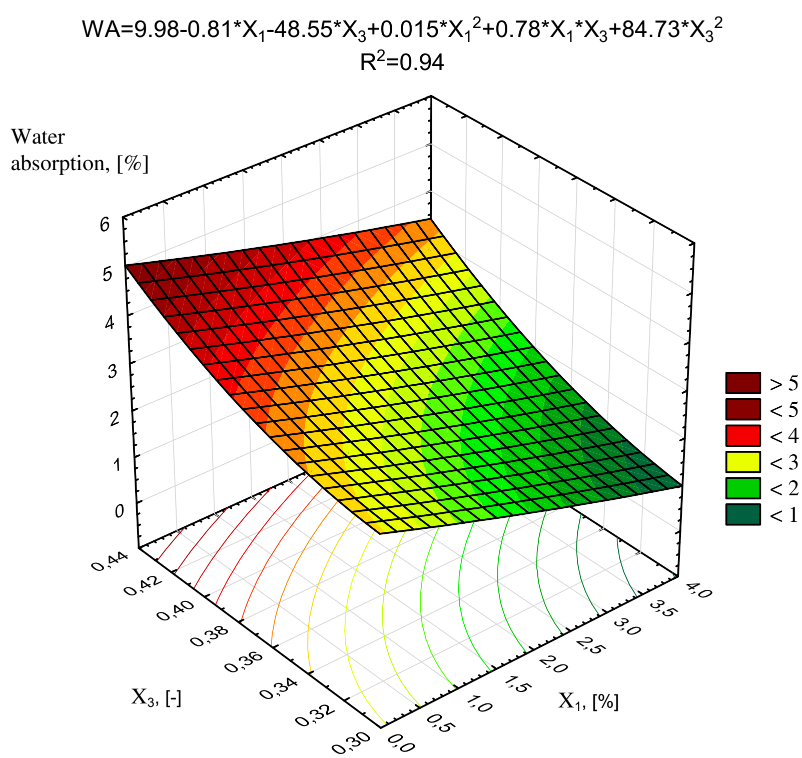

Fig. 5. The relationship between WA (%) and bitumen emulsion content (X_1) and w/c ratio (X_3).

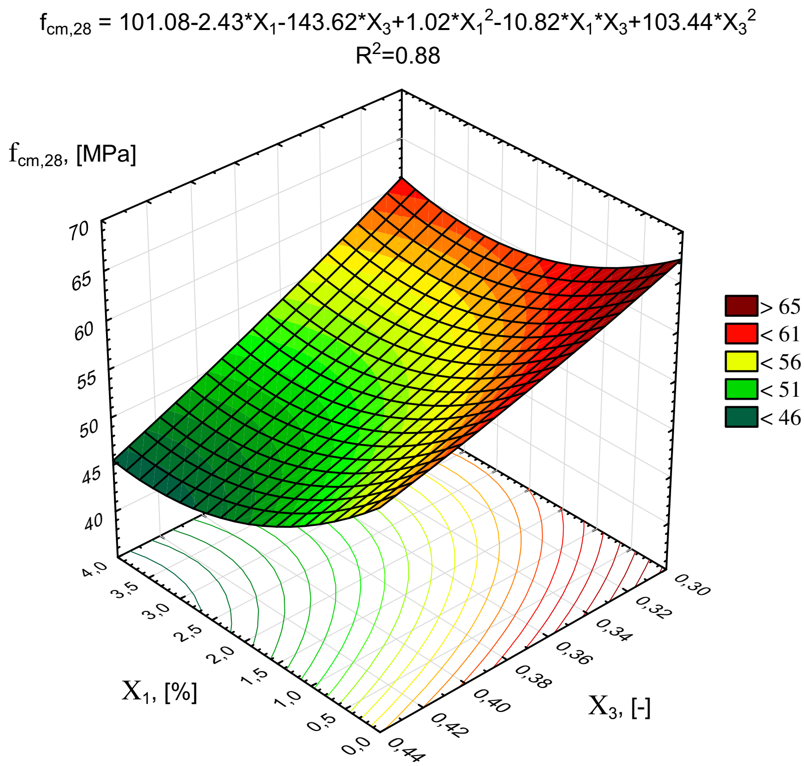

Fig. 6. The relationship between $f_{cm,28}$ (MPa) and bitumen emulsion content (X_1) and w/c ratio (X_3).

between 0.30 and 0.36 and a bitumen emulsion content in excess of 2% of the cement mass when the following method of consolidating the concrete mixture is used. Concrete samples of 10 × 10 × 10 cm were consolidated with vibrations of 50 Hz, an amplitude of 0.5 mm, and 5 g (g = 9.81 m/s^2) acceleration.

Concretes intended for paving are particularly exposed to aggressive environmental classes. Consequently, in order to protect the reinforcement from corrosion, it is necessary to improve the tightness of the concrete structure. The research results indicated that modification of the concrete mix with an anionic bitumen emulsion allows to achieve a new construction and insulation material with increased resistance in highly aggressive environments. Due to hydrophobic properties the bitumen emulsion improves the tightness of concrete, what also has a beneficial effect on composite durability. The emulsion does not contain solvent in its composition and is easily spread in cementitious composites. It can be stated that it is ecological material. Contrary to the aeration admixtures, it does not significantly reduce the concrete compressive strength, because it does not aerates the concrete. Due to the hydrophobic effect, bitumen emulsion prevents the penetration of water and other fluids into composite structure. By using this emulsion in combination with a plasticizer it is possible to obtain concrete with a compressive strength of up to 60 MPa and very low absorbability of less than 2%. Bitumen emulsion-modified concrete is characterized by especially high resistance to environmental aggression, in particular for multiple freezing and thawing.

4.2. Mercury intrusion porosimetry (MIP)

For the porosity structure examinations, the Autopore 9229 computer-aided measuring unit was used. It allowed to determine:

- Total porosity (cm^3/g), $p_{t(skeleton)}$.
- Total pore area under the acceptance a model of cylindrical pores (m^2/g), S_{total}.
- Median pore diameter by volume (μm), $\overline{\phi_{vol}}$.
- Median pore diameter by area (μm), $\overline{\phi_{area}}$.
- Average pore diameter (μm), ϕ_{subst}.

The range of measured pores was 0.003–0.360 μm.

The results for selected concrete series with different content of bitumen emulsion 0, 2% and 4% of the cement mass (series: 9, 15, 10 (Table 3)) created with the units stated above are laid out in Tables 6 and 7.

As shown in Table 6, the samples tested have a similar total porosity despite the presence of the bitumen emulsion.

The results shown in Table 7 demonstrate that the addition of bitumen emulsion in the proportions of 2% and 4% of the cement mass, had a slight impact, altering the concrete's porosity structure. The beneficial changes include an increase in the number of small capillary pores (3÷30 nm) with a simultaneous decrease in the number of macro pores in concrete structure (>3000 nm).

The porosity results presented demonstrate that the modification of cement concretes through the addition of bitumen emulsion results in a material with a porosity similar to the porosity of non-modified concretes with a slight increase in the proportion of smaller capillary pores.

Figs. 8 and 9 show the porosity characteristics of a selected series of concretes with and without bitumen emulsion.

Upon careful analysis of the relationships obtained from experimental tests, the following conclusions have been reached:

- The frost resistance of cement concretes significantly increases along with a decrease of w/c ≤ 0.37 for concretes that have been successfully consolidated;
- Concrete mixtures can be successfully consolidated on a vibration table with standard vibration parameters at w/c ≤ 0.37 through the addition of liquefaction additives and bitumen emulsion, which also has plasticizing properties;

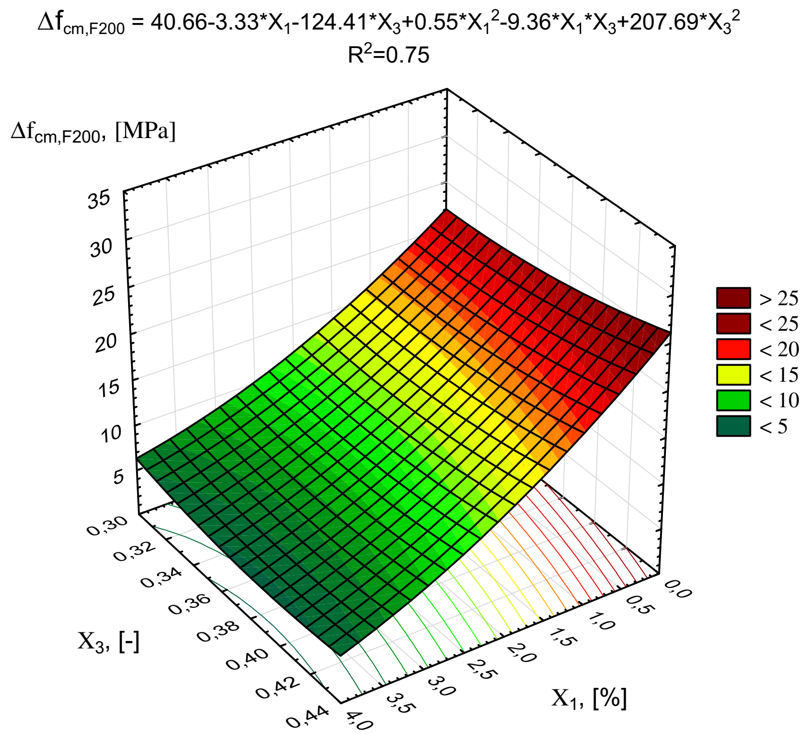

Fig. 7. The relationship between $\Delta f_{cm,F200}$ (MPa) and bitumen emulsion content (X_1) and w/c ratio (X_3).

Table 6
MIP tests results.

Bitumen emulsion content	Bulk density ρ_o	Apparent density ρ_w	Total porosity $p_{t(skeleton)}$	Total pore area S_{total}	$\overline{\phi_{vol}}$	$\overline{\phi_{area}}$	ϕ_{subst}
%	g/cm^3	g/cm^3	cm^3/g	m^2/g	nm		
0 (s.9)	2.545	2.762	0.0328	4.6520	90.0	4.7	22.1
2 (s.15)	2.495	2.757	0.0342	5.4630	91.7	5.1	22.6
4 (s.10)	2.490	2.705	0.0367	6.4097	100.1	5.3	23.3

Table 7
Porosity structure of tested concrete specimens.

Bitumen emulsion content	Total porosity	Pores by size (%)						
		3/10	10/30	30/100	100/300	300/3000	3000/30,000	30,000/300,000
%	cm^3/g	nm						
0 (s.9)	0.0328	8.6	10.1	36.1	11.3	17.8	7.8	8.3
2 (s.15)	0.0342	9.8	10.4	32.3	12.8	21.5	6.7	6.4
4 (s.10)	0.0367	12.7	11.6	26.4	13.2	24.3	6.5	5.3

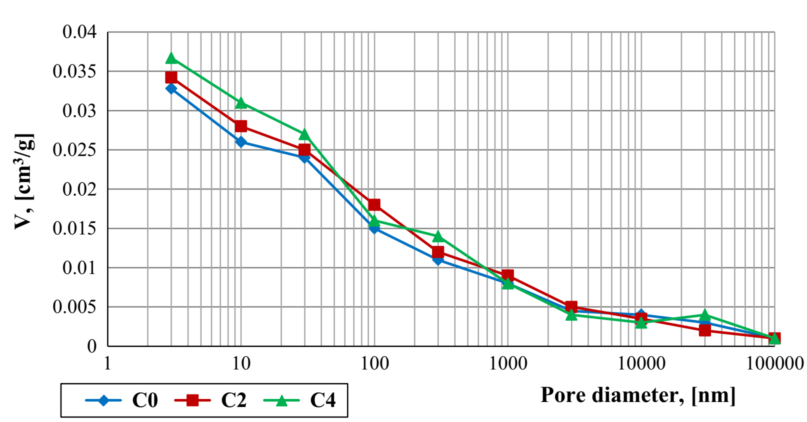

Fig. 8. Pore characteristics of concretes with and without bitumen emulsion.

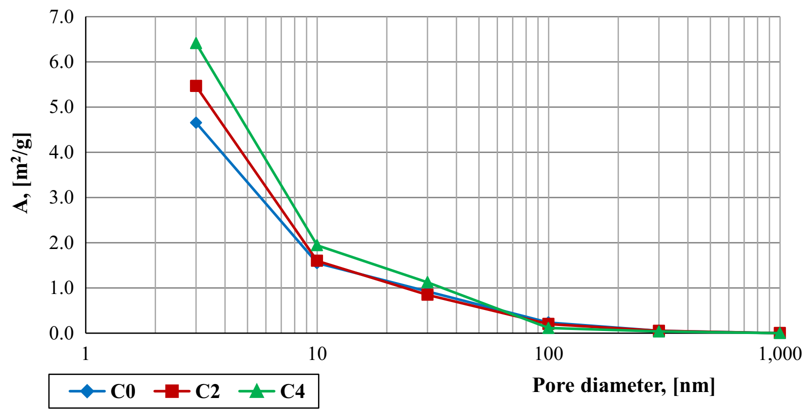

Fig. 9. Cumulative pore area in concretes with and without bitumen emulsion.

- The addition of new generation fluidizing additives enables the w/c coefficient to be decreased by 30% while retaining the same consistency;
- The highest frost resistance was obtained with concretes that had a w/c = 0.30 and contained bitumen emulsion additives as well as fluidization additives. The same types of concretes without such additives were destroyed after 200 cycles of freezing and thawing;
- Bitumen emulsion enhances the waterproofness of concrete through its hydrophobic properties and this in turn has a beneficial impact on its frost resistance;
- Cement concretes modified with bitumen emulsion and fluidization additives did not demonstrate any weight loss after 200 cycles of freezing and thawing (Table 4).

On the basis of the laboratory tests, three concrete mixtures with a w/c = 0.35 were selected for the creation of the concrete pavement at Innovative Reloading Terminal in Terespol (Table 8).

The contents (Table 8) were selected with regard to the unit prices of granite and basalt grit during the laying down of the pavement, the prices of concrete additives, as well as taking into account the average temperature over the 24-h period of the pavement laying and also taking into account the location of the structure.

5. Construction of the concrete pavement

5.1. Ground improvement – Stabilization with cement

A 15 cm layer of soil was stabilized with CEM II/B-V 32.5R Chełm cement in a proportion of 110 kg/m^3 of soil. After 7 days, an average strength of 1.34 MPa (with a requirement of 1.0÷1.6 MPa) was obtained, and after 28 days the average strength was 2.08 MPa (with a requirement of 1.5÷12.5 MPa).

5.2. Substructure – mechanically stabilized broken aggregate

A 0–31.5 mm dolomite ductile broken aggregate layer was applied and stabilized mechanically. After consolidation the thickness of the layer was 20 cm (Fig. 3). Load capacity testing produced the following average results:

$EV_1 \geq 155$ MPa; $EV_2 \geq 280$ MPa; $EV_2/EV_1 = 1.81 < 2.2$;
The minimum results were:
$EV_1 \geq 100$ MPa; $EV_2 \geq 180$ MPa; $EV_2/EV_1 = 1.8 < 2.2$.
The requirements were:
$EV_1 \geq 100$ MPa; $EV_2 \geq 180$ MPa; $EV_2/EV_1 \leq 2.2$.

5.3. Creation of the concrete slab

The concreting was divided into 5 stages, each lasting 4 weeks: excavation, stabilization, subsurface work, concreting. Ready-mixed concrete was delivered by truck. Each time prior to use, the consistency of the concrete mixture was tested. It demonstrated a homogeneous V4 consistency (Vebe test). Samples of concrete mixture were taken at random for moulds of 15 × 15 × 15 cm (144 pcs.), 15 × 15 × 75 cm (12 pcs.) and 10 × 10 × 10 cm (6 pcs.) as well as comparative samples without bitumen emulsion (16 pcs.). The samples were consolidated and stored in identical environments in the form of concrete slabs. After 28 days of curing, the samples were forwarded to two independent laboratories, at Bialystok University of Technology and the Chelm Cement Plant. The

Table 8
The specifications of three formulated concretes with a w/c = 0.35 to be used for the concrete pavement at Innovative Reloading Terminal in Terespol.

	Concrete mixture I	Concrete mixture II	Concrete mixture III
CEM I 42.5 N HSR NA	360	360	360
Sand 0–2 mm	690	649	665
Basalt grit 2–8 mm	488	–	–
Basalt grit 8–16 mm	782	–	–
Granite grit 2–8 mm	–	464	506
Granite grit 8–16 mm	–	743	702
Isola BV*	3.15	3.15	–
Isola BV/FM 74/30*	2.45	2.45	–
Centrament Rapid 610**	–	–	2.1
Muraplast FK44***	–	–	3.85
Bitumen emulsion	6.66	6.66	6.66
Fibres RXF 54	2	2	2
Water (w/c = 0.35)	125	123	127

* A plasticizing additive that reduces the water volume and improves the workability of the concrete mixture.
** A non-chloride additive that accelerates hardening.
*** A superplasticizer that may be re-applied on the site. It is compatible with other additives manufactured by MC-Bauchemie.

two laboratories tested the compressive strength in accordance with PN-EN 12390–3:2009, the bending strength in accordance with PN-EN 12390–5:2009, the depth of water penetration under 0.8 MPa pressure in accordance with PN-EN 12390–8:2009, the water absorption and frost resistance after 200 cycles of freezing and thawing according to PN-B-06250:1988 (ordinary concrete). A 40 cm thick concrete slab was consolidated with 6000 vibrations/min immersion vibrators equipped with 45 mm and 60 mm pokers. 4430 m^3 of ready-mixed concrete and 29,500 kg of bitumen emulsion were used to create an 11,076 m^2 concrete pavement.

5.4. Surface float finishing and its maintenance

Slab surface float finishing was carried out mechanically after which the surface was roughened with jute broaching and transverse brushing. The texture should be homogeneous. With jute broaching, the depth of texture equalled 0.2÷0.6 mm, while with the brushing it equalled 1.0÷1.5 mm. Surface maintenance was carried out immediately after texturing. The surface was covered with maintenance cloth and then sprayed with water. The systematic maintenance lasted 21 days (in the summertime).

5.5. Surface dehydration and inserting expansion joints

Rainwater drainage was provided by a 124 m F900 class Faserfix BIG BL200 linear drain and a 56 m D400 class linear drain. An 86.0 m KKŻ drainage channel was used together with an SK 2 BP 20/200 separator and a Ø500 culvert. The concrete pavement divided into 5 × 5 m expansion fields. The first expansion cuts of 3 mm were made along the lines defined by the layout of the dowels (5 × 5 m) going down to one third the thickness of the plate with the cuts being made depending on the ambient temperature within 8–24 h of the hardening of the concrete. After 28 days, the gaps were widened by 8–10 mm and deepened by 24 mm; the edges were bevelled at 3 × 3 mm, the gaps were carefully cleaned, primed, and then filled with cord and SABA Sealer Field sealant. The minimum thickness of the sealant was 8 mm. The sealant should be 2–3 mm deeper than the surface of the plate. 28 days after the laying down of the concrete the pavement was handed over for use (Fig. 10).

The tests of the technical properties of the concrete laid down at the Innovative Reload Terminal are shown in Table 9.

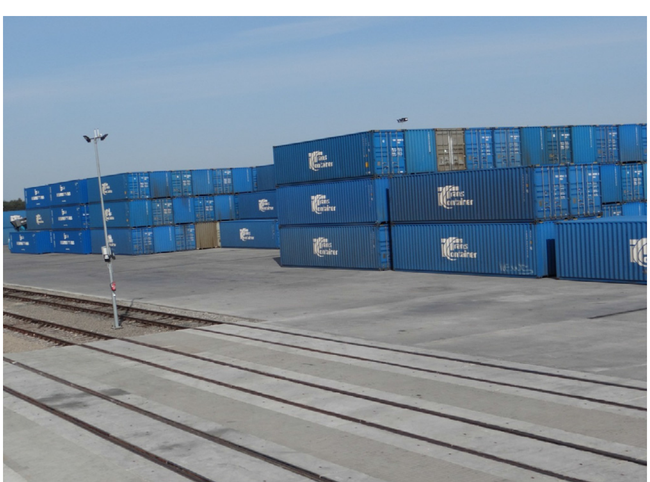

Fig. 10. The completed pavement 28 days after the concrete was laid down (photo. K. Falkowski).

Table 9
Technical properties of the concrete laid down at the Innovative Reload Terminal.

Properties	Białystok University of Technology laboratory	Chełm Cement Plant laboratory
Compressive strength, $f_{cm,28}$ (MPa)	53.31	53.19
Bending strength, f_{ctm} (MPa)	5.3	–
Max. depth of water penetration under pressure 0.8 MPa (mm)	34	26 (14.33 average)
Water absorption (%)	3.62	–
Loss of compressive strength after 200 cycles of concrete freezing and thawing, $\Delta f_{cm,F200}$ (%)	11.37	–

When comparing the above stated properties with the same type of concrete without the bitumen emulsion we find:

- a 10% increase in compression strength for the concrete with asphalt emulsion;
- a 25% increase in bending strength,
- a decrease of at least 80% in water penetration,
- a 30–50% in decrease in water absorption,
- a decreased loss of strength after 200 cycles of 0–50%.

6. Conclusion

The most frequent damage to pavements is caused by the repetitive freezing and thawing of water in concrete pores as well as corrosion from defrosting agents. Frost damage appears as cracking and flaking, which occur as a result of the water in the pores increasing its volume by approx. 9% as it freezes. This is accompanied by significant tensile stress, which is a major factor in the formation of scratches within the material structure.

Previously damage of this type was reduced by applying aeration additives. Increasing the aeration of concrete improves its frost resistance but, at the same time, causes a significant reduction in its waterproofness and decreases its durability, sometimes even by as much as 20–30%. It is not hard to see that this runs contrary to the principles of concrete fabrication. On the one hand, concrete with the lowest possible w/c multiplier is used resulting in a decrease in its porosity but on the other hand by applying aeration, an extra portion of pores is added at the same time. Admittedly in regard to frost damage, these extra pores add beneficial properties to the structure, but still they increase the total porosity of the cement composite. For this reason the authors proposed the application of anionic bitumen emulsion with hydrophobic and frost resistant properties, since it does not additionally aerate the concrete and so does not decrease its durability or any of its other properties. The anionic bitumen emulsion additive has not only hydrophobic properties but also causes the dispersal of bigger bubbles in the mixture and later in the hardened concrete. Previous tests carried out by the authors [32,34] have confirmed that anionic bitumen emulsion causes the formation of micro pores with a diameter of no more than 30 nm with the loss of macro pores, which is an important occurrence in regard to frost resistant properties. Both the waterproofing of the pores as well as the formation of a new set of micro pores minimize the probability of water ingress into all the capillaries and thus minimizes the probability that it will freeze causing critical stress and damage to concrete structure.

Previous tests have shown that when the w/c ratio is reduced to below 0.5, the total amount of frozen water at −20 °C does not exceed 18% of the total volume of water in the concrete. Hence, concretes laid down in site conditions, which have been modified with bitumen emulsion and new generation fluidizing agents, allow for the w/c multiplier to be reduced to 0.30–0.37 giving greater durability and waterproofness while decreasing absorbability to below 4% in comparison to reference concretes (without bitumen emulsion) while at the same time retaining high F200 frost resistance.

Having been developed and tested under site conditions, the technology for fabricating concrete pavements that face high mechanical loads as well as damage from frost and chloride corrosion can now be applied in engineering practice with the use of cement composites modified by anionic bitumen emulsion. These may be manufactured in existing concrete manufacturing plants and consolidated either by immersion vibrators or with special vibrating plates.

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