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Research paper

Assessment of the application of CEM III with exposed aggregate as an alternative to CEM I for road pavements

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Abstract: The article presents a results of study on the impact of replacing CEM I SR3/NA by CEM III/A LH/HSR/NA on the mechanical properties and durability of pavement concrete with exposed aggregate. Was used granite aggregate and washed sand. Water/cement (w/c) ratio in the tested concretes constituted 0.35 and 0.4 and part of the cement was replaced with a 5% addition of natural pozzolana – zeolite. Compressive strength tests were performed after 3, 7, 28 and 56 days, tests of tensile strength test by splitting method and flexural strength two-point loading tests. The characteristics of the air pores and the rate of water absorption by concrete surface of the samples cut out from the slabs with exposed aggregate were presented. The resistance of the surface to exfoliation after 56 cycles of freezing-thawing in NaCl solution was tested. Based on the results obtained, it was found that when designing the composition of the concrete intended for the upper layer of the pavement, it is necessary to ensure high tensile strength, appropriate in the XF4 environment and with the decrease in the $w/c < 0.4$, a reduction in capillary porosity of the cement paste is obtained, and the same the durability of concrete is increased due to the improved strength parameters in the contact zone between coarse aggregate grains and cement paste. The research also showed a significant influence of proper cure on the mechanical properties and durability of pavement concrete.

Keywords: road pavement, concrete, exposed aggregate, compressive strength, tensile strength, cement

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1. Introduction

Modern concrete surfaces should meet a number of requirements, concerning their durability, safety, comfort of use, cost-effectiveness of construction and impact on the environment and surroundings. It creates a necessity of a new approach to the materials used for paving promenades, walkways, bicycle lanes, pedestrian passages, parking spaces, bus bays and also road surfaces [1]. The concrete industry, due to its enormous material and energy consumption and high CO_2 emissions, may need to pay close attention to the idea of sustainable development in construction [2]. Therefore, it is advisable to introduce changes in concrete technology, for instance, choose to use composites made of the ingredients that are optimally selected in terms of quality and quantity, causing minimum environmental degradation and consumption of natural resources and maximum energy saving [3]. This goal can be achieved both by selecting alternative components while designing a concrete mix and by implementing appropriate technological solutions [4]. The basic assumption in the development of sustainable concrete for pavements is to use a synergistic approach at all times. From high-quality and expensive ingredients, it is possible to obtain a poor composite as a result of negative synergy (interaction) and technological deficiencies [5]. The aim is to achieve the opposite – to obtain a "better"" material from lower-quality and cheaper, but instantly available (and often environmentally unfriendly) ingredients as a result of concentrating on synergy in the design process [6]. Balancing pavement concrete technology is possible by designing in accordance with the so-called "performance concept", including the use of appropriate high-quality materials alongside with waste materials, e.g. blast furnace slag, being a partial replacement of Portland clinker in CEM III LH/HSR/NA cements (over 60%), and also, by optimization of technological activities. Sustainable concrete for road pavements should be designed to be durable, with relevant functional properties, allowing for satisfactory operation in the planned long service life, e.g. 30 years. This applies to both pavement finishing methods and selection of proper cure [7]. Exposed aggregate concrete is an interesting alternative and complement to the existing solutions such as: paving stones, blocks or asphalt surfaces. The visual effect, the resultant quality and durability of such surfaces may prove worthy of attention and encourage realization of innovative projects [8]. The pavement concrete upper layer with exposed aggregates should meet both load capacity requirements for the entire cross-section of the pavement and the requirements for resistance to environmental and operational factors [9–11]. To produce the pavement with exposed aggregate, it is proposed to apply an appropriate technology for deactivating the cement bond [12]. Chemical bond retardation is in most cases achieved by placing a deactivator on the upper layer of a poured concrete mix with later removal of the non-bonded layer by means of water jet or brushing. Washing off the top layer, depending on atmospheric conditions and agents applied, should begin between 6 and 24 hours from the moment of placing the deactivator. The depth of deactivation depends on the chemical agent used in the mix, the type of cement applied, water/cement ratio and ambient temperature during application [12]. It is important to select proper penetration depth in relation to the aggregate grain present in the cement mix. In order to ensure proper durability of the material, the aggregate grains should remain embedded in the cement matrix on a level of at least 3/5 of their diameter. This prevents individual grains from falling out. Aesthetic and original visual appeal is obtained in concretes utilizing mono-grade aggregate 0/2, 0/5, 2/5, 5/8, 8/11, 11/16 mm, however, it is also possible to create surfaces with aggregate grades 2/8, 8/16, 2/16, 16/32 mm. In order to avoid mistakes, the size and type of the exposed aggregate should be well researched, as its size (quantity and size of grains) strongly impacts the visual appeal of the surface [13–15].

2. Qualitative requirements for components of exposed aggregate concrete

Pavement concrete – the type used in construction of road infrastructure must be characterized by high quality, therefore, the selection of adequate components is crucial [16–18]. According to the [19], and assigning proper exposure classes to construction elements (XF3, XM1 – roads with less traffic and XF4, XM2 – high traffic roads) one must take into account the requirements concerning the minimal amount of cement, the water/cement ratio, concrete class and air content. Additionally, while designing cement mix, the requirements for cement type compatible with a given concrete type must be met. One is supposed to take into consideration the realization of works, intended use of the concrete, maintenance conditions, size of the construction, environmental factors that the construction will have to withstand and potential alkali-aggregate reaction. In Europe reference documents – norms, standards, ordinances and technical specifications – limit the range of selection of cement. Standard [20] imposes the usage of only CEM I low-alkali SR3/NA with determined mineral content. Another limitation is the assignment of cement strength class to a given concrete class. When following the national requirements, in each and every case the pavement concretes should be designed using cement CEM I SR3/NA, coarse aggregate, like granite or basaltic grit of proper parameters, fine aggregate or river sand of determined characteristics, and a water/cement ratio lower than 0.5 [21, 22]. Requirements for adequate concrete strength, resistance to cyclic freezing-thawing, and surface peeling due to the effects of de-icing agents are defined by the general guidelines for the respective country [23]. Exposure classes and environmental classes are specified in the European standard [19] and, additionally, in German and Austrian standards, namely, ZTV Beton-StB and RVS 08.17.02.

Determining the composition of concrete is empirical, often the technologist uses her/his own experience or proven archival recipes. Hardened concrete should: be resistant to frost, meet low absorbability requirements, be watertight, in many instances it is required to have flexural strength of above 4.5 MPa. Additionally, concrete surfaces should be freeze-thaw resistant in exposure to salts and meet the requirements of class TF2. Pavement concrete should also be characterized by a proper pore microstructure ($A_{300} \geq 1.5\%$, ≤ 0.200 mm) [23, 24].

3. Designing the concrete mix with exposed aggregate

Selection of the ingredients is the most crucial factor determining the final properties of concrete pavement with exposed aggregate. The features to be taken into consideration are the type and amount of traffic, the aesthetic effect, acoustic characteristics and durability [11–14]. When designing a concrete mix with individual grains being exposed, additional attention should be paid to the selection of the aggregate that not only meets the quality requirements but is also characterized by proper grain size and shape [15–17]. It is crucial to select a mono-grade aggregate 2/5, 5/8, 8/11 mm (road grade), 2/8 mm (in case of aggregate for standard concrete), or 8/16, 16/20, 16/31,5 mm. Utilizing aggregates with grain size, for example, about 0/8 and 0/16 makes the overall visual effect less appealing. Grain size up to 8 mm is recommended for the surfaces where the key aspect, apart from the quality requirements, is noise reduction [3, 25]. Limited access and principle of sustainable development in construction encourage the search for unusual solutions. For example, it is possible to lay a two-layer concrete surface with 3–4 cm layer of granite aggregate up to 8 mm and 16 mm size respectively, wet pour it onto ordinary road concrete that meets strength requirements [26, 27]. However, in this study the authors propose to apply only one layer of the exposed aggregate concrete, which should remain in compliance with durability requirements. In order to properly design the aggregate composition, a freeze-resistant aggregate should be applied, with high resistance to grinding, with continuous grain size in the quantity ranging from 1100 to 1350 kg/m^3. The fine aggregate should be free of organic contaminants, with continuous grain size in order for the mortar to be as uniform as possible [28, 29]. The chosen material should meet the quality requirements. Its content in the mix should constitute 550–700 kg/m^3, depending on the required visual effect [30, 31]. In most roads pavements the applicable specifications and ordinances impose utilization of CEM I SR3 or, under special circumstances, CEM III/A LH/HSR/NA (low-alkalia) and compressive strength class 42.5 MPa [22, 32]. The cement should be chosen in such a way as to meet the requirements concerning matrix colour. The quantity of the cement is strongly dependent on the specified water/cement (w/c) ratio and the durability requirements for the pavement concretes. In order to create visually attractive surface with the aggregate of grain size up to 16mm, cement content should not go above 350–380 kg/m^3. In case of the aggregate with grains up to 8 mm, the content should be increased to 420 kg/m^3 [32, 33]. It is advisable to use clean water without organic pollutants so as not to affect the properties and appearance of the road pavement. Every supplied batch of concrete mix should be characterized by the same water/cement ratio. It is not recommended to use recycled water in production. The deeper the aggregate's exposure, the lower the water/cement ratio of the mortar must be [34]. In order to obtain a mix of proper characteristics meeting the requirements concerning freeze-resistance, also while being exposed to de-icing salts (FT2), absorptivity (up to 5%), water-tightness, flexural strength from 4.5 to 5.5 MPa, proper macrostructure of air pores, proper kind of plasticization and aeration is essential. In some cases, for obtaining concrete of lower porosity, zeolite or metakaolinite can be utilized [7, 35–37]. An extremely important aspect when producing concrete with exposed aggregate is even distribution of aggregate grains. To avoid segregation, effect of bleeding and cracks caused by plastic shrinkage, adding synthetic fibres is recommended [38–40]. In order to increase the visual appeal of the surface, the mortar may be coloured with the dyes available on the market. The visual effect will be enhanced if the colour of the mortar is selected so as to highlight the utilized aggregate [41]. Every batch of concrete mix should be characterized by the same water/cement ratio in order to keep the colour similar. Selection of quantity and form of the chosen dye depends on its content and intensity of dyeing. It is not recommended to use more dye than 6–7% of the cement's mass. When using dyes, their impact on the water/cement ratio and freeze-resistance should be tested [42–45]. The retarding agent (deactivator) is a special layer – in the form of a paste, lacquer, liquid or sheets of infused paper – that, when placed on the surface of concrete mix just after smoothing, penetrates the mix to a determined depth. The main objective of the deactivator to delay or stop the cement bonding process in the outer layer of the concrete mix so as to expose the aggregate when removing the top unbonded layer. During the second phase the deactivator works as a finishing-protecting layer that keeps 80% of water in the mix during the first 24 hours. This preparation also acts as protection against possible rainfall in the early setting period and later as a protective layer during maintenance. The timing for washing off the deactivator depends on its type. In most cases it shall be a water solution [27, 41, 45]. In Fig. 1 shows an example of a concrete pavement with exposed aggregate.

(a) spraying the deactivator (b) washing off (c) washed-off concrete surface with aggregate up to 8 mm (gravel), grey colouring

Fig. 1. The technology of processing the surface by means of using a retarding agent

4. Materials and methods

4.1. Materials

In accordance with the above stated requirements, six concrete mixtures have been designed for the top layer of the pavement. Two types of cement CEM I 42,5N SR3/NA (CEM I) and CEM III/A 42,5N LH/HSR/NA (CEM III) according to [20] were applied in the study. In order to improve the properties of pavement concrete, zeolite in the amount of 5% of the cement mass was added to both concrete mixes. The chemical composition and physical properties of the cements and zeolite are shown in Table 1.

Table 1. Physical and chemical properties of cement CEM I, CEM III and zeolite

Cement	Setting start time [min]	Setting end time [min]	Compressive strength [MPa]		Blaine fineness [cm^2/g]	Loss on ignition [%]	Water demand [%]
			2 days	28 days			
CEM I	185	230	23.6	56.2	3273	1.8	26.5
CEM III	230	290	14.0	59.3	4630	1.4	30.5
Zeolite	–	–	–	–	18300	–	–

Content [%]

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O_{eq}	K_2O	TiO_2	Cl
CEM I	20.9	3.7	3.3	65.7	0.9	2.5	0.38	0.64	0.25	0.05
CEM III	29.2	7.6	1.4	50.0	5.8	2.1	0.6	0.52	0.12	0.09
Zeolite	73.1	13.4	1.82	3.21	1.89	–	–	0.8	1.1	–

The fine aggregate used in the tests was naturally washed sand of fraction of 0/2 mm, with volume density of 2.65 kg/dm^3. Crushed granite aggregate of the size 2/8 mm and 8/16 mm was utilized as coarse aggregate, with volume density of 2.69 kg/dm^3. The grain distribution of individual types of aggregates is presented in Fig. 2.

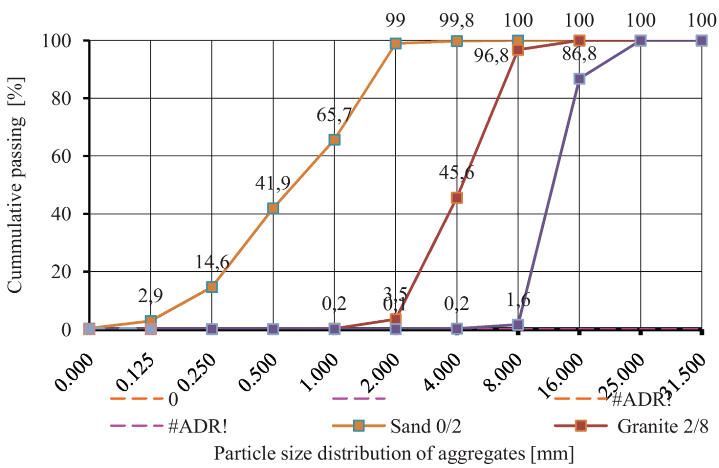

Fig. 2. Aggregate grain distribution curves: sand 0/2 (mm), crushed granite aggregates 2/8 and 8/16 (mm)

Clean water was used for the tests.

To achieve proper homogeneity and workability of the concrete mix, admixture with strong plasticizer Power Flow 2695 was added. Admixture composition is based on the newest MC-Polycarboxylatether technology. A strong plasticization results from high absorption of cement grains. Despite well-sustained consistence, a special reaction, which lies in prevention of grains from being glued in the mix, enhances the development of high initial strength. Therefore, Power Flow 2695 is suitable for the concrete mix production intended for road pavements. The mechanism of functioning caused by adding superplasticizer allows to produce concrete with extremely low water contents. In order to increase the durability and resistance of concrete to freezing and thawing, a special air-entraining admixture Centrament Air 202 was applied, which entrains very finely evenly spaced distributed air micro-pores (< 0.003 μm) into the concrete. As a result, air-pores are finely distributed within the cement paste in the structure of the concrete and are interspersed with capillary pores, naturally formed in the mix. This ensures that freezing water has enough space to expand in the whole concrete structure. Centrament Air 202 is added during mixing. When designing a concrete mix with an air-entraining admixture, it is necessary to take into account the fact that, the pore content of the concrete depends on its composition, the temperature of the mix and of the air-surroundings, consistency (water content), the type of cement, the type of powder-grain additives, type and duration of mixing and also, on transportation time.

The macro polymer fibers were used as a reinforcement. The parameters of fibers are given in Table 2. The fibers are made of polyolefin and produced as twisted bundles of a length of 24 mm (Fig. 3).

Table 2. Properties of polymer fibers

Length [mm]	Diameter [mm]	Relative density [g/cm^3]	Number of fibers per 1 kg [pcs.]	Total length of reinforcement [mb/kg]
24	0.45	0.91	250 000	13500

Fig. 3. Polymer fibers of a length of 24 mm

Six mixtures with CEM I and CEM III cements were designed with different water/cement ratios: $w/c = 0.35$ and $w/c = 0.40$. The combination of CEM I and $w/c = 0.35$ was adopted as the reference mixture for other test results. Besides, two mixtures were designed with the participation of CEM I and CEM III and $w/c = 0.40$ with the addition of 5% of zeolite, replacing a part of the CEM III/A containing 60% of blast furnace slag. In order to reduce plastic shrinkage and limit the formation of microcracks in all the mixtures, polymer fibers were added When designing the composition of concrete mixtures, the assumed fine aggregate density was 2.65 kg/dm^3, crushed granite aggregate density – 2.69 kg/dm^3, CEM I density – 3.1 kg/dm^3, CEM III density – 2.95 kg/dm^3, zeolite density – 2.1 kg/dm^3. Air content in the concrete mix was assumed on the level of min. 4% of the mix volume. The composition of concrete mixes is presented in Table 3.

Table 3. Composition of concrete mixes

Concrete designation	Type of cement	The amount of ingredient [kg/m^3]									
		Cement	Water	w/c	Aggregate			SP	LP	Zeolite	Fibers
					Sand	Granite					
					0/2	2/8	8/16				
BN I	CEM I	400	140	0.35	500	263	1054	4.0	1.0	–	0.6
BN II	CEM I	400	160	0.40	500	253	1011	4.0	1.0	–	0.6
BN III	CEM I	380	152	0.40	500	255	1020	4.0	1.0	20	0.6
BN IV	CEM III	400	140	0.35	500	261	1044	4.0	1.0	–	0.6
BN V	CEM III	400	160	0.40	500	250	1002	4.0	1.0	–	0.6
BN VI	CEM III	380	152	0.40	500	253	1012	4.0	1.0	20	0.6

4.2. Methods

The components of the concrete mix were mixed in the Testing LZ laboratory mechanical mixer. 220 dm^3 of the mixture were mixed from each of the BN I–BN VI pavement concrete recipes to make the appropriate number of test samples. At the first stage, added aggregates, cement, zeolite, fiber and part of water and superplasticizer and were mixed for 1 minute. The air-entraining admixture and some of the water which remained from the first stage mixing were then added and mixed for another 1 minute. At the last stage, the remainder of the water was added, then all ingredients were mixed for another 1 minute. After that, the mixer was stopped for 10 minutes. Then came another 1 minute of mixing and next, the consistency was tested by the Ve-Be method according to [46]. An air content meter with a capacity of 8 dm^3 was used to measure the density of the concrete mix. The air content of the mixture was determined after it had been vibrated. The air content in the concrete mix was tested by the pressure method according to [47]. Next, the concrete mixture was laid in Polyvinyl Chloride (PVC) molds in two layers and vibrated in accordance with [48]. Test specimens were stored for 24 hours in molds at the temperature of 20 ± 2°C and subsequently stored in a chamber with the humidity of 90–95% and the temperature of 20 ± 2°C, where they were protected against drying. The summary of the size and number of test specimens is presented in Table 4.

Table 4. The summary of the size and quantity of the specimens for testing

Test	Specimen size (m)	Quantity of the specimens (pieces/recipe)	Total specimens' quantity (pieces)
Compressive strength at 3, 7, 28, 56 days	$0.15 \times 0.15 \times 0.15$	$3 \times 4 = 12$	72
Tensile strength, Brazilian test by means of splitting	$\phi = 0.15$, $h = 0.3$	3	18
Porosity, characteristics of the air pores	$\phi = 0.15$, $h = 0.3$	2	12
Flexural strength two-point loading test	$0.15 \times 0.15 \times 0.70$	3	18
Plates with exposed aggregate	$0.5 \times 0.5 \times 0.05$	4	24
Water absorption (cut out samples)	$\phi = 0.1$, $h = 0.05$	3×2	36
Resistance to freezing and thawing (cut out samples)	$0.15 \times 0.15 \times 0.05$	3×2	36

The compressive strength of each concrete mix BN I–BN VI was tested by means of Advantest 9 Controls machine with a maximum pressure force of 3000 kN, according to [49] and determined as an arithmetic mean of three measurements taken at 3, 7, 28 and 56 days. Before the compressive strength test, the volume of each sample and its weight were determined. On this basis, the density of each concrete composition was determined as the average of three test results after 56 days of curing. The tensile strength Brazilian test by means of splitting was performed on cylindrical samples in accordance with [50]. The flexural strength two-point loading test was carried out in accordance with [51] on the beams of the dimensions of $150 \times 150 \times 700$ mm according to the scheme shown in Fig. 4.

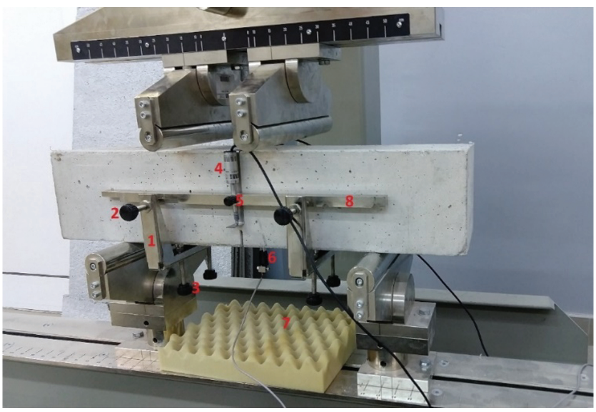

Fig. 4. Scheme of flexural strength two-point loading test

Pore structure analysis was performed by means of using a RAPID AIR 457 device. The characteristics of the air pores were determined on polished specimens cut out of the middle part of each cubic sample in accordance with [52].

For testing the speed of surface water absorption and testing pavement concrete's resistance to freezing and thawing, special elements were prepared – plates with exposed aggregate with dimensions of 500 × 500 × 50 mm. Then, samples for testing were cut out from these elements. In order to obtain a texture of concrete with exposed aggregate, for each concrete mix BN I–BN VI four sample-tiles after casting were covered with a deactivator delaying the cement binding process. After suitable time (8 to 11 hours), depending on the type of cement, the cement grout was removed with a pressure washer, exposing aggregate grains of approx. 7–8 mm. Immediately after, two plates from each sample were coated with a water-based cure agent. The cure was applied in two layers by spraying onto the surface of concrete with exposed aggregate. Additionally, two tiles from every recipe BN I–BN VI with exposed aggregate were left without curing. All plates were stored in a room with low humidity of approx. 40% and the temperature of 23 ± 2°C.

The speed of water absorption from the surface was determined in accordance with [53] on the samples of ϕ 100 mm, h 50 mm cut out of concrete slabs with exposed aggregate.

Surface salt exfoliation test of concrete with exposed aggregate was determined in accordance with [54] on samples of dimensions 150×150×50 mm. The tests were carried out after 56 days of concrete maturation. The samples were tested on their upper surface from the side of the exposed aggregate. Before testing, the samples were pre-soaked in distilled water for 3 days. Then, the surface of the samples with exposed aggregate, preliminarily placed in the molds, was flooded with 3% NaCl solution. The sample preparation scheme is shown in Fig. 5.

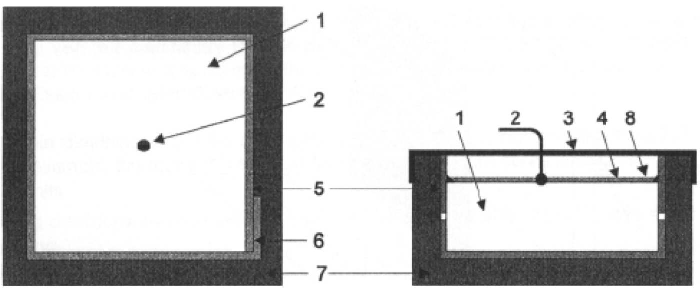

Fig. 5. Scheme of sample preparation for the surface salt exfoliation test; 1 – tested surface, 2 – frozen liquid temperature measurement by means of termocouple, 3 – foil, 4 – 3% NaCl solution, 5, 6 – side sample seal, 7 – Polystyrene thermal insulation, 8 – silicone seal

The test was performed at a period of 1 complete cycle / day. The following partial temperature cycles were adopted to make up the total cycle:

- freezing from +20°C to −4°C within 4.5 h; 5.3°C/h;
- freezing from −4°C to −18°C within 7.5 h; 1.9°C/h;
- steady temperature −18°C for 4h;
- thawing from −18°C to +20°C within 8 h; 4.8°C/h.

The total mass of the exfoliated material after 56 freeze / thaw cycles was determined using to as Eq. (4.1):

$$m_{s,n} = m_{s,\text{before}} + (m_{v+z} - m_v) \tag{4.1}$$

where:

$m_{s,n}$ – total mass of dried exfoliated material after n cycles of freezing and thawing,
$m_{s,\text{before}}$ – total mass of the exfoliated material tested at the previous check,
m_{v+z} – mass of the container with the exfoliated material,
m_v – empty container mass.

The total mass of exfoliated material per area unit after 56 cycles was determined according to the formula:

$$S_n = \frac{m_{s,n}}{A} \times 10^3 \tag{4.2}$$

where:

$m_{s,n}$ – total mass of dried exfoliated material after n cycles of freezing and thawing,
A – surface area tested.

According to the highest FT2 criterion concerning the resistance of the samples to freezing and thawing in exposure to de-icing salts specified in [53], the average weight loss after 28 cycles (m_{28}) should not exceed 0.5 kg/m^2, and after 56 cycles (m_{56}) – 1.0 kg/m^2, wherein no single result may exceed 1.5 kg/m^2, and the degree of weight loss in each case should be less than 2, as defined in the formula:

$$\frac{m_{56}}{m_{28}} \leq 2 \tag{4.3}$$

5. Results and discussion

The aim of the experimental studies conducted was to determine the effect of using CEM III containing 60% of blast furnace slag (mixtures marked BN IV, BN V, BN VI), instead of the commonly used CEM I (mixtures marked BN I, BN II, BN III) to road concretes with exposed aggregate. All the mixes contained the same type and proportions of granite aggregate and fine aggregate, naturally washed sand. In order to limit the plastic and total shrinkage and increase the tensile strength, the same type and content of polymer fibers with increased modulus of elasticity were used in all the blends. Additionally, on the basis of the obtained test results, the influence of the water / cement ratio was analyzed, assuming $w/c = 0.35$ (BN I, BN IV) and $w/c = 0.40$ (BN II, BN III, BN V, BN VI). In mixtures marked with BN III and BN VI, 5% of cement was replaced with the addition of zeolite. The effect of zeolite on the change in the concrete mix properties was observed.

The test results showed that the consistency of the concrete mix tested by the Ve-Be method in accordance with [46] after 15 minutes in all cases met V2 class requirements. Aeration of the concrete mix, determined by the pressure method, was in the range from 5.4 to 5.9% and it can be considered that it was homogeneous for all cases.

Analysis of the results of the concrete's compressive strength tests, presented in Table 5 and Fig. 6, shows significant differences in strength in the early stages of concrete maturation at 3 and 7 days depending on the type of cement, the w/c index and the use of a zeolite additive as a cement substitute.

Table 5. Properties of concrete

Concrete designation	Density [kg/m^3] after 28 days	Compressive strength at the age of days [MPa]				Flexural strength [MPa]	Tensile strength [MPa]
		3	7	28	56		
BN I	2423	24.6	43.8	57.6	61.5	5.8	3.9
BN II	2418	19.1	38.2	51.2	56.7	5.6	3.6
BN III	2402	15.1	35.4	59.9	65.9	6.1	4.0
BN IV	2412	20.1	37.2	56.4	67.5	6.0	4.1
BN V	2399	17.2	33.0	50.2	62.1	5.7	3.8
BN VI	2394	14.1	30.3	57.3	69.3	6.6	4.2

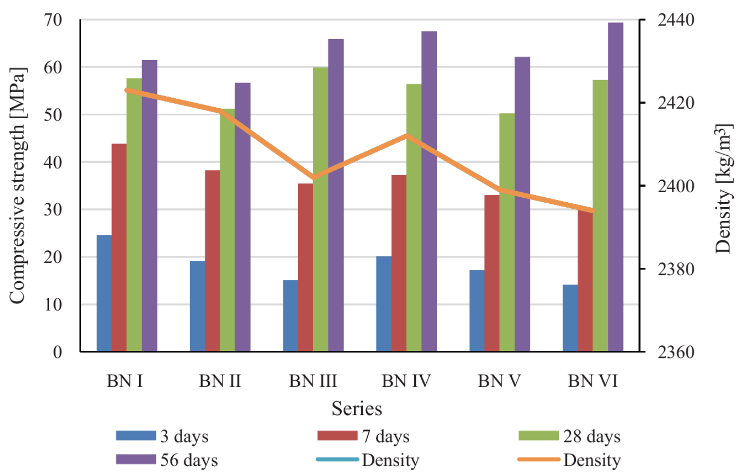

Fig. 6. Compressive strength after 3, 7, 28, 56 days vs. density after 28 days

The obtained test results confirmed that in the initial period of hardening, higher results were obtained for concretes with lower $w/c = 0.35$ (BN I, BN IV). BN I concrete with CEM I obtained 18.3% higher strength. In the case of concretes with $w/c = 0.40$, the strength of BN II was 10% higher than that of BN V. Concrete with the addition of BN III zeolite showed higher strength than BN VI by 6.6%. Very similar differences in the results were obtained after 7 days. The situation changes after 28 days, when an increase in compressive strength of concretes with zeolite is visible, BN III having higher strength than BN VI by 4.3%. After 56 days concrete BN VI obtained 5% higher strength than BN III.

It should also be noted that after 56 days concretes with CEM III (BN IV, BN V, BN VI) were characterized by higher strength than concretes with CEM I (BN I, BN II, BN III). The concrete density test showed that all concretes are characterized by similar densities from 2393 kg/m^3 (BN VI) to 2423 kg/m^3 (BN I). Concrete BN I was characterized by the highest density, and concrete by BN VI the lowest, with only 1.2%. Difference.

The tensile strength test by splitting method was carried out after 56 days. The detailed results of the tests are presented in Table 5. The relationship of the compressive strength after 56 days, the tensile strength tested by the Brazilian method and the flexural strength are shown in Fig. 7. As in the case of compressive strength after 56 days of curing, concretes with CEM III were characterized by higher strengths than concretes with CEM I. The best results for tensile strength at splitting (4.2 MPa) and for flexural strength (6.6 MPa) were obtained with concrete BN VI with CEM III, $w/c = 0.4$ with the addition of zeolite. The lowest strength was achieved by BN II with CEM I, $w/c = 0.40$ without the addition of zeolite. The highest strength results were obtained by BN VI with CEM III, $w/c = 0.40$ with zeolite. The results of the compressive strength of BN VI were higher by 22.2%, the tensile strength at splitting was higher by 16.6%, and the flexural strength – by 17.9%.

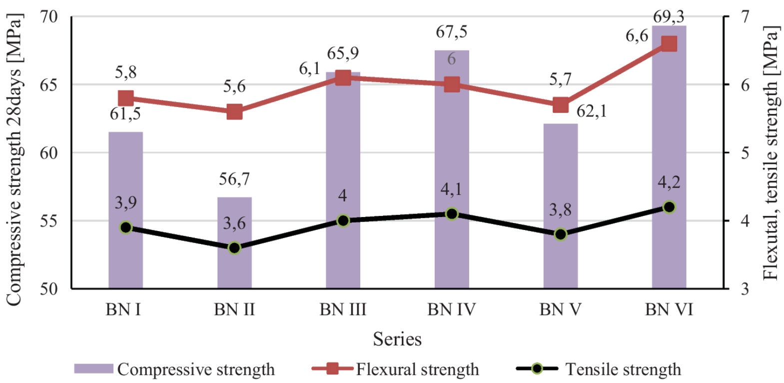

Fig. 7. Compressive, flexural and tensile strength test results

The characteristics of air pores in concrete are presented in Table 6 and Fig. 8, where according to [52]: A – total air content in hardened concrete, α – specific surface of the air pore system; – distribution indicator; A_{300} – content of micropores with diameter below 300 µm. The results obtained showed similar pore microstructure in six series of samples. Criteria for assessing compliance with the long-term durability requirements in XF4 environment: ≤ 0.18 mm, $A_{300} \geq 1.8\%$ were met for all variants. The favorable pore characteristics were also demonstrated by the proportions of the micropore content to the total pore content, exceeding 40% in all 6 types of concrete. There was no deterioration of the pore structure in the case of concrete with CEM III, which positively indicated the effectiveness of the applied admixtures. When using zeolite, the proportions of the micropore content to the total pore content exceeded 50%, which proved the beneficial effect of zeolite on the durability of concrete.

Table 6. Characteristics of air pores in concrete

Concrete designation	Pressure method	Characteristics of air pores in concrete			
		Rapid Air 457 method			
	[%]	A [%]	α [mm^{-1}]	[mm]	A_{300} [%]
BN I	5.9	6.8	33.65	0.15	3.42
BN II	5.8	6.9	35.14	0.14	3.11
BN III	5.6	6.6	34.31	0.13	3.70
BN IV	5.6	7.0	35.02	0.14	3.55
BN V	5.5	7.2	35.11	0.13	3.21
BN VI	5.4	6.7	34.23	0.14	3.78

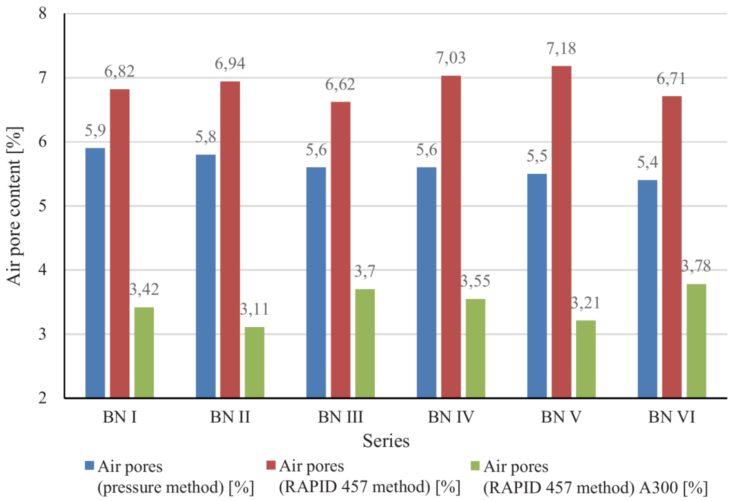

Fig. 8. Dependance of freezing – thawing resistance on a pore structure

The results of the measurements of the total air content in the concrete mix, made by means of various methods, varied from 13.2% to 23.6%. The largest difference in the measurement of the air content can be noticed in the case of BN V (CEM III, $w/c = 0.40$ without zeolite). In this case, the total air pore content measured with the RAPID 457 method was 7.2%, while standard measurements made by means of an air content meter showed the air content in the mixture at the level of 5.5%. Greater differences were found in the group of concretes with CEM III (BN IV, BN V, BN VI). Further tests, purposing at determination of the effect of the cure method on concrete properties, were carried out on the elements with exposed aggregate.

When testing water absorption on the samples of concrete BN I–BN VI, the influence of cement type, zeolite content and the curing method on the rate of water absorption from the surface of concrete with exposed aggregate was observed.

During the study, the role of slag as a component of CEM III cement was observed. The smallest initial absorption rate of ($4.4 \cdot 10^{-4}$ mm/s^{-1}) was found for BN IV with CEM III, $w/c = 0.35$, which is 10% lower than in the case of concrete BN I with CEM I, $w/c = 0.35$. An interesting observation was made concerning the role of zeolite as an additive in cement. When zeolite was used in the amount of approx. 5% of the cement mass, water absorption reduce was observed. Comparing BN I with CEM I without zeolite ($10.2 \cdot 10^{-4}$ mm/s^{-1}) and BN III with CEM I with zeolite ($8.1 \cdot 10^{-4}$ mm/s^{-1}), water absorption was reduced by 20,6% and, zeolite used as a cement additive to CEM III without zeolite BN IV ($8.8 \cdot 10^{-4}$ mm/s^{-1}) and BN VI ($7.5 \cdot 10^{-4}$ mm/s^{-1}) with zeolite, water absorption was reduced by 14,8%.

It was noticed that in the case of concrete with exposed aggregate, the type of cement and the addition of zeolite have an impact on water absorption. The biggest difference was observed while utilizing concrete BN II with CEM I, $w/c = 0.40$ without zeolite, without cure ($11.0 \cdot 10^{-4}$ mm/s^{-1}) and BN VI with CEM III, $w/c = 0.40$ with zeolite, with cure ($4.0 \cdot 10^{-4}$ mm/s^{-1}). Water absorption here was reduced by 275%. The use of zeolite in the amount of 5% of cement mass had a positive effect on reducing the initial water absorption rate. Lowering the density of the concrete did not increase the absorption. The results are presented in Fig. 9.

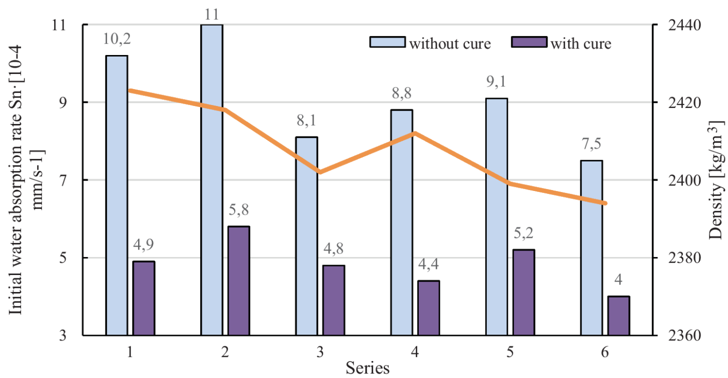

Fig. 9. Water absorption by cured and non-cured concrete samples

The Table 7 presents the results of freezing-thawing salt resistance tests of concrete with exposed. The research showed a beneficial effect of aeration of the concrete mix on freezing-thawing. The influence of the A_{300} pores content ($\leq$ 300 μm) on the durability of the concrete is visible. As the pore content of A_{300} increases, the freeze/thaw resistance in salt increases. In the case of concrete BN II with $w/c = 0.4$, the content of A300 pores constituted 3.11%, while the mass of exfoliated substance was 1.6 [kg/m^2]. In this case concrete was not subjected to additional curing to prevent moisture loss during setting and initial hardening.

As the proportion of A300 pores increases, the freeze / thaw resistance increases. The use of cure has proven to have a significant impact on the increase of resistance to exfoliation by 84% on average. Analyzing the results of the tests of BN I and BN II, we could see that

Table 7. The test results for concrete with exposed aggregate after freezing-thawing

Concrete designation	Mass of exfoliated material after freezing-thawing in salt		A_{300}
	without cure	with cure	
	[kg/m^2]		[%]
BN I	1.33	0.18	3.42
BN II	1.60	0.19	3.11
BN III	0.90	0.17	3.70
BN IV	1.12	0.17	3.55
BN V	1.43	0.18	3.21
BN VI	0.71	0.16	3.78

the weight of the exfoliated substance increased by 20% as the w/c ratio increased by 14%. The use of zeolite in the amount of 5% as a cement substitute increased A300 pore content in BN II and BN III concrete by 19%, which resulted in a decrease in the exfoliated mass after freezing-thawing by 43,8%. The obtained test results (BN IV, BN V, BN VI) indicate a beneficial effect of the use of CEM III cement on frost resistance in salt compared to the obtained results for concrete with CEM I (BN I, BN II, BN III). The tests carried out after 56 days showed that in the case of concretes with CEM III subjected to freezing-thawing cycles, the weight of the exfoliated material is 15% lower than in the case of concretes with CEM I. In Fig. 10 shows the results of the tests of concrete with exposed aggregate after freezing-thawing in salt vs. A_{300} pore content.

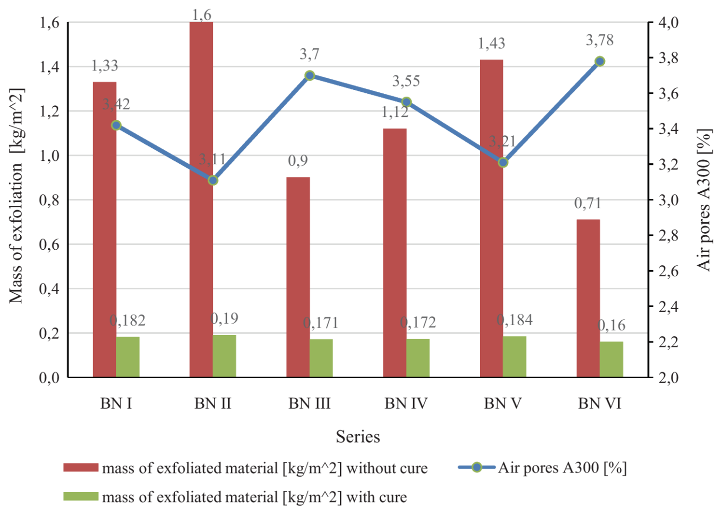

Fig. 10. The results of the tests of concrete with exposed aggregate after freezing-thawing in salt vs. A_{300} pore content

6. Conclusions

When designing a concrete composition intended for the road pavement, it is essential to make sure that the product will comply with the requirements concerning mechanical properties such as compressive strength, flexural strength, but above all, high durability and resistance to aggressive factors. These factors in the case of roads are mainly: the alternation of low and high temperatures, liquid penetration and salt action. This is possible if relevant concrete components are selected. It is important to choose the type of aggregate made of hard rock, resistant to reaction with sodium and potassium hydroxides present in the concrete pore liquid. The utilization of hard rock aggregate will allow to obtain concrete with high abrasion resistance. With a simultaneous decrease in the w/c ratio < 0.4, a reduction in capillary porosity of the hardened cement paste will be obtained. At the same time, the strength in the contact zone between aggregate grains and cement paste increases, which is desirable because of the grain's adhesion to the matrix in the surface layer.

Assessing the test results presented in the study, it can be concluded that the type of cement (CEM I and CEM II), does affect the properties of concrete. The choice of cement type may appear to be of major importance in terms of environmental protection and reduction of CO_2 emissions. CEM III contains 60% of blast furnace slag. It is a waste material, which, when stored, causes harm to the environment. Utilizing it as an additive in concrete technology helps to make reasonable use of this material and proves to be an effective method of recycling.

It is also known that the production of Portland clinker is a major emitter of CO_2 into the atmosphere. Therefore, the use of cement with additives helps reduce its content to 40% in case of CEM III (compared to nearly 90% in CEM I), which can have huge environmental impact. The tests performed by the authors of this study confirmed that it is possible to use CEM III for road pavements. Due to the properties of CEM III and its slower hydration process than that of CEM I, as well as its increase in strength over time, it is advisable to test the mechanical and durability properties of the concrete containing it after minimum 56 days. The surface cure method, which protects against water evaporation at the early stage of concrete's hardening, has a significant impact on the adhesion of grains, on the strength and, ultimately, on the durability of concrete. Lack of proper cure resulted in a fivefold increase in the water absorption rate (concrete with $w/c = 0.40$). The beneficial effect of the method of securing the concrete surface against moisture loss is visible, and the addition of zeolite in the amount of 5% has a positive effect on the internal cure of concrete and reduction of the initial water absorption rate. Positive evaluation of the pore size distribution, especially the proportion of A_{300} pores content ($\leq$ 300 µm) in the tested concrete allowed for the prognosis of the extended durability and resistance to surface exfoliation under the influence of variable temperatures, freezing-thawing process and de-icing salts. Zeolite can be described as a natural pozzolana. Like other pozzolans, it does not harden when mixed with water, but when finely ground, it reacts to water by producing soluble calcium hydroxide to form calcium compounds and compounds of calcium silicate and calcium aluminates, which contribute to an increase in compressive and flexural strength. The use of zeolite increases resistance to sulphides and chlorides. It also makes the concrete structure more airtight and less susceptible to the absorption of aggressive substances. Measurements of the water absorption rate showed difference in case of the samples cured with the conditioning agent. Proper cure and moisture loss protection enabled to obtain high flexural and tensile strength in the pavement surface area. Also, appropriate cure proved to have an impact on the contact zone between the aggregate grain and cement matrix. All above-mentioned factors boost such characteristics of the concrete as water absorption and freeze/thaw resistance.

When analysing concrete pavements from the life-cycle standpoint, compared to the asphalt pavements, concrete ones can be characterized by lower level of depletion of natural resources and lesser environmental impact. When comparing construction and repair costs of concrete and asphalt pavements within 30 years of exploitation, the total cost in case of concrete roads is lower. Concrete pavements are not prone to deformations such as ruts and pits. This results in lower repair expenditures.

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Ocena zastosowania cementu CEM III jako alternatywa CEM I do nawierzchni drogowych z eksponowanym kruszywem

Słowa kluczowe: nawierzchnia drogowa; beton; kruszywo eksponowane; wytrzymałość na ściskanie; wytrzymałość na rozciąganie; cement

Streszczenie:

W artykule przedstawiono wyniki badań wpływu zastąpienia CEM I SR3/NA przez CEM III/A LH/HSR/NA na właściwości mechaniczne i trwałość betonu nawierzchniowego z odsłoniętym kruszywem. Użyto kruszywa granitowe i płukany piasek. Współczynnik woda/cement (w/c) w badanych betonach wynosił 0,35 i 0,4, a część cementu zastąpiono 5% dodatkiem naturalnej pucolany (zeolit). Badania wytrzymałości na ściskanie wykonano po 3, 7, 28 i 56 dniach, badania wytrzymałości na rozciąganie metodą rozłupywania oraz badania wytrzymałości na zginanie dwupunktowe. Przedstawiono charakterystykę porów powietrza oraz szybkość wchłaniania wody przez powierzchnię betonu próbek wyciętych z płyt z odsłoniętym kruszywem. Zbadano odporność powierzchni na złuszczanie po 56 cyklach zamrażania/rozmrażania w roztworze NaCl. Na podstawie uzyskanych wyników stwierdzono, że przy projektowaniu składu betonu przeznaczonego na górną warstwę nawierzchni należy zapewnić wysoką wytrzymałość na rozciąganie, właściwą w środowisku XF4. Zauważono, że jeśli wskaźnik $w/c < 0,4$ nastąpiło zmniejszenie porowatości kapilarnej zaczynu cementowego, a tym samym zwiększenie trwałości betonu dzięki poprawie parametrów wytrzymał ościowych w strefie styku ziaren kruszywa gruboziarnistego z zaczynem cementowym. Badania wykazały również istotny wpływ prawidłowego utwardzenia na właściwości mechaniczne i trwałość betonu nawierzchniowego.

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