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The effect of the aggregate type on the properties of pavement concrete

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Abstract. This paper presents the results of laboratory tests on the properties of cement concrete containing various types of aggregate. The purpose of the tests was to determine the effect of aggregate on compressive strength, indirect tensile strength, air pore characteristics, frost resistance and the modulus of elasticity of concrete for road surfaces. The aggregate that meets the requirements for road concrete was determined on the basis of the tests.
Keywords: road concrete, frost resistance of aggregate, frost resistance of road concrete
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1. Introduction

The paper presents the results of experimental research aimed at determining the effect of aggregate available on the market on the properties of cement concrete for road surfaces.

According to data published by the General Directorate for National Roads and Motorways [3], almost 2,200 kilometres of national roads will be built in Poland between 2014 and 2023. Nearly one third of these roads, i.e. approx. 810 kilometres, will be concrete surface roads, not asphalt surface roads. According to a study by the Association of Cement Manufacturers [6], with the current technical requirements, the cost of 1 cubic metre of asphalt pavement (so-called flexible pavement) for light traffic varies from approx. PLN 92 to approx. PLN 124, depending on the type of pavement. The cost of the same volume of concrete pavement (so called rigid pavement) varies from approx. PLN 105 to approx. PLN 134. Concrete pavement for heavy traffic is even cheaper — the cost of 1 cubic metre of rigid pavement is PLN 200-225 while the cost of 1 cubic metre of flexible pavement is PLN 244-271. Considerably lower construction costs and the availability of materials on the domestic market is the reason for the increase in the share of concrete pavement roads in newly planned investments, as illustrated in Figure 1.

At the same time, it should be noted that cement concrete pavements are much more susceptible to errors occurring at the stage of selection of materials, mainly aggregate and cement of proper quality, design errors or errors occurring at the pavement construction stage, including incorrect treatment of the pavement concrete.

Fig. 1. Proposed types of pavements for the network of Polish expressways to be built by 2020, according to the General Directorate for National Roads and Motorways [7]

2. Motivation for the research

Due to the situation on the Polish market, especially in the private sector, contractors very often try to save money on building materials. The same applies to concrete pavements used in storage yards or car parks.

The PN-V-83002 standard, which is no longer in force, recommended the use of granite aggregate with a homogeneous petrographic composition for concrete road pavements. This aggregate is characterised by the lowest water absorption and high frost resistance. The concrete pavements containing this aggregate showed adequate compression strength and frost resistance, which is extremely important in Polish climatic conditions.

The current PN-EN 206+A1:2016-12 standard concerning concrete does not impose the type of aggregate that should be used for the construction of road pavements. The standard specifies only the requirements for the properties of aggregates. These requirements are met by the majority of aggregates available on the Polish market. This contributed to the fact that contractors looking for savings decide to use cheaper aggregates, and they very often use non-crushed aggregates. The use of unsuitable aggregate adversely affects the durability of pavement, mainly its frost resistance, and contributes to quick degradation of pavement mainly in the formation of splinters (Fig. 2a). Figure 2b shows a core sample from a storage yard pavement containing a non-crushed aggregate.

a) b)

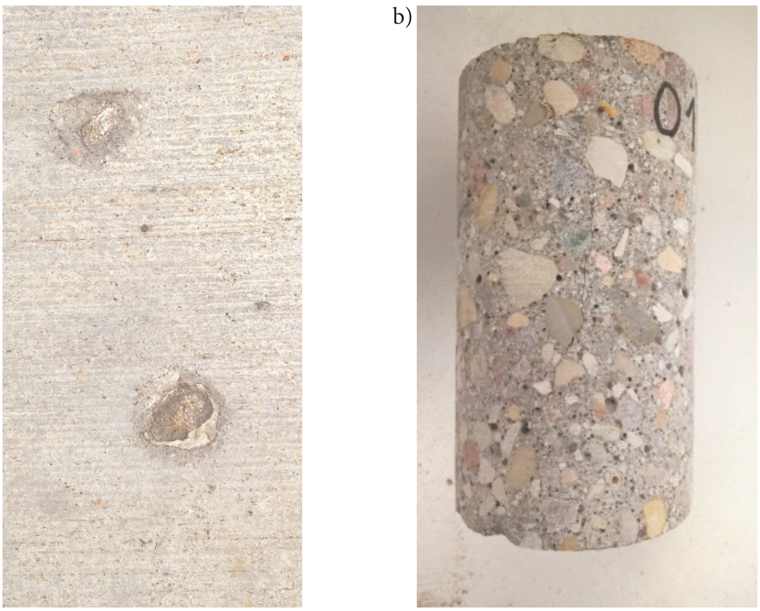

Fig. 2. Natural aggregate in concrete pavement

The aim of the experimental research was to compare the properties of cement pavement concrete containing granite aggregate, basalt aggregate and gravel. A mineral mix was designed based on guidelines [2, 5] and limit curves of recommended particle size distribution [4]. The concrete mix composition is specified in Table 1, while the summary of particle size distribution curves for the analysed aggregates is shown in Figure 3. The quantities of samples for testing individual cement concretes are given in Table 2. The designed cement concrete was a C30/37 strength class concrete of plastic consistency and XF4 exposure class.

Table 1

Concrete mix components

Concrete mix components per 1 m^3	Content	
	[%]	[kg]
Cement	11.6	360.0
Water	14.2	142.2
Coarse aggregate	53.9	1481.0
Fine aggregate	20.3	538.3
Total aggregate content	74.2	2019.3

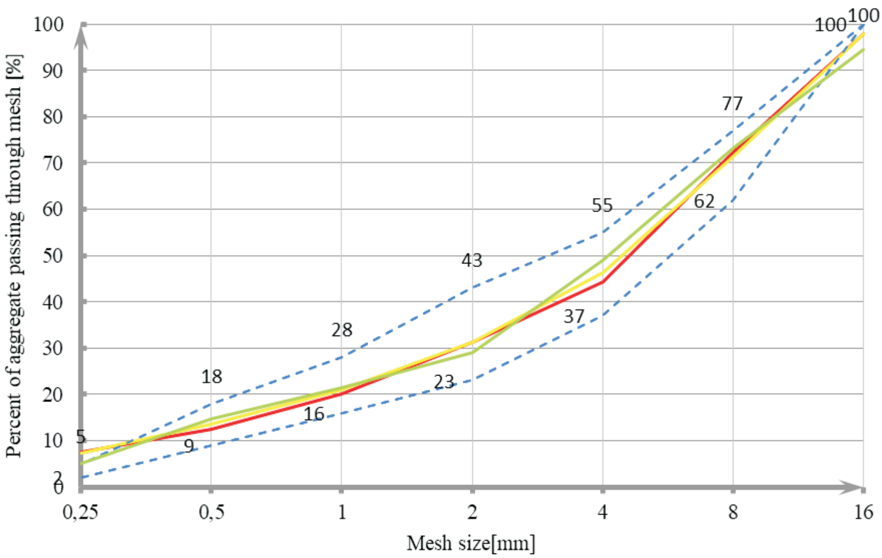

Fig. 3. Particle size distribution curves for aggregate (colour: green — gravel, red — granite, yellow — basalt)

Table 2

Quantities of test samples

Test	Sample shape	Sample dimensions [cm]	Sample quantity
Compression strength	Cube	150 x 150 x 150	5
Split tensile strength	Cube	150 x 150 x 150	5
Characteristics of air voids	Cube	150 x 150 x 150	2
Frost resistance	Cube	100 x 100 x 100	12
Modulus of elasticity	Cylinder	150 x 300	2

3. Laboratory test results

3.1. Compression strength

According to the PN-EN 206-1 standard, the compression strength of concrete should be tested after 28 days of curing in laboratory conditions using cubic samples (150 mm side) or cylindrical samples (150 × 300 mm). After removing the samples from water, excess moisture should be wiped off from their surface. The cubic samples should be positioned so that the load is applied perpendicularly to the direction of sample formation, the plane which was levelled after forming should be on the side. Compression strength test results are presented in Table 3.

On the basis of the presented results, it should be stated that the cement concrete containing basalt aggregate has the highest compression strength of 90.4 MPa. The cement concrete containing gravel has the smallest compression strength. The results obtained are directly related to the compression strength of rock used to make aggregate. Basalt, with its compression strength exceeding 250 MPa, is the strongest. The compression strength of granite is approximately 150 MPa, while the compression strength of gravel, depending on its type, is up to 120 MPa.

Table 3

Compression strength test results

Aggregate	Sample number	Weight [g]	Apparent density [kg/m^3]	Destructive force [kN]	Compression strength [MPa]	Average strength f_c [MPa]
Basalt	1	9084.7	2690	2077.1	92.3	90.4
	2	9163.6	2710	2003.9	89.1	
	3	9287.2	2750	2139.2	95.1	
	4	9046.1	2680	1975.7	87.8	
	5	8979.4	2660	1975.8	87.8	

cont. tab. 3

Aggregate	Sample number	Weight [g]	Apparent density [kg/m^3]	Destructive force [kN]	Compression strength [MPa]	Average strength f_c [MPa]
Granite	1	8252.9	2450	1886.9	83.9	83.9
	2	8316.7	2460	1907.1	84.8	
	3	8172.4	2420	1892.8	84.1	
	4	8215.7	2430	1838.5	81.7	
	5	8172.4	2410	1915.4	85.1	
Gravel	1	8082.1	2390	1535.8	68.3	73.9
	2	8287	2460	1719.7	76.4	
	3	8160	2420	1660.0	73.8	
	4	8152.2	2420	1788.4	79.5	
	5	8123	2410	1611.6	71.6	

3.2. Split tensile strength

The split tensile strength test is otherwise referred to as the Brazilian test method. The test according to the PN-EN 12390-6:2000 standard consists in subjecting a cylindrical or cubic sample to action of compression force applied in a narrow area along the length of sample. The resulting tensile force causes the destruction of the sample. The test is carried out by applying the force through washers with a width of 0.1d, where d is the width or diameter. The test should be carried out using cubic samples (150 mm side) or cylindrical samples with a diameter of 150 mm and a height of 300 mm. Split tensile strength test results are presented in Table 4.

TABLE 4

Split tensile strength test results

Aggregate	Sample number	Weight [g]	Destructive force [kN]	Tensile strength [MPa]	Average strength f_{ct} [Mpa]
Basalt	1	8706	192.4	5.45	5.15
	2	9175.6	172.9	4.90	
	3	9016.5	183.1	5.20	
	4	9143.6	178.2	5.05	

cont. tab. 4

Aggregate	Sample number	Weight [g]	Destructive force [kN]	Tensile strength [MPa]	Average strength f_{ct} [Mpa]
Granite	1	8331.2	175.1	4.95	5.03
	2	8286.9	177.4	5.00	
	3	8195.2	186.6	5.30	
	4	8247.3	175.2	4.95	
	5	8194.3	174.3	4.95	
Gravel	1	8069.4	133.6	3.80	4.13
	2	8125.5	132.9	3.75	
	3	8075.2	151.2	4.30	
	4	8179.3	148	4.20	
	5	8024	162.9	4.60	

The concrete containing basalt aggregate also has the highest split tensile strength. The split tensile strength test result for the concrete containing granite aggregate was lower by only 2.3%. The concrete containing gravel has split tensile strength lower by as much as 19.4%. This difference is very important for durability of the pavement structure.

3.3. Characteristics of air voids in hardened concrete

Characteristics of air voids in hardened concrete are determined according to the PN-EN 480-11 standard. In order to make measurements, prepare test plates with dimensions of 100 × 150 × 20 mm. Clean and dry the samples and then grind them repeatedly in order to obtain an appropriate polished section. The sample preparation process is completed by contrasting the tested surface in order to isolate the air voids. The spatial arrangement of air voids in concrete can be described on the basis of the observation of flat cross-sections. Characteristics of air voids are determined according to the traverse method, assuming the total length of the measurement line on a single concrete sample of at least 2400 mm, regardless of the aggregate grain size. At least two samples of the same material should be tested. The air-voids intersected by the traverse-line (i.e. the air void chords determined in this way) are counted and the lengths of air void chords are measured. Following the measurements, individual air void chords are classified into appropriate length classes. The air void size distribution is assessed using static analysis. The results of the test of air void content in hardened concrete are shown in Figure 4.

The highest air void content was found in the concrete containing basalt aggregate. The average air void content in this concrete was 5.7%. A similar air void content (5.5%) was found in the concrete containing granite aggregate. A significantly lower air void content (3.3%) was found in the concrete containing a sand-gravel mix.

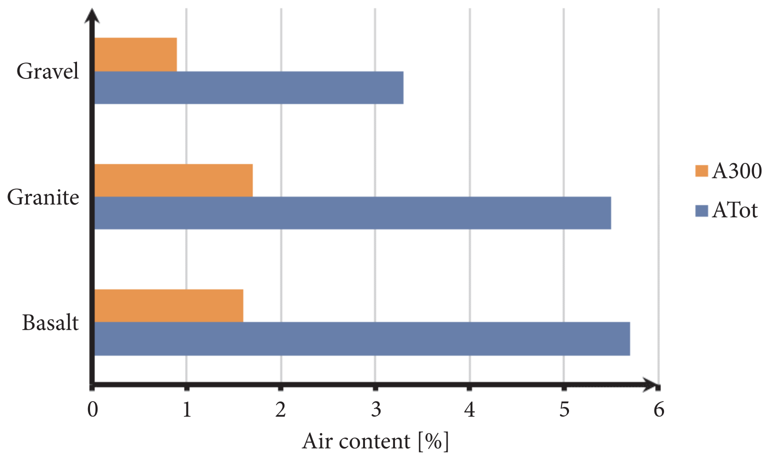

Fig. 4. Air content in cement concrete

3.4. Frost resistance

The standard method makes it possible to assess the resistance of concrete to freezing water, taking into account both the degree of internal compaction due to decrease in compression strength as well as the external compaction due to weight loss and change of external appearance. Cubic samples with a side not shorter than 100 mm should be used for the test. The test should be carried out after 28 days of concrete curing using 12 samples from one batch of concrete. All samples should be saturated with water. The saturation time should be at least 7 days. Six comparative samples, so-called witnesses, should remain in water at a temperature of 18 ± 2°C throughout the test. Wipe water off the samples intended for freezing and weigh them with an accuracy of 0.2%. The number of freezing and thawing cycles should correspond to the degree of frost resistance of the samples. After the last thawing cycle, wipe water off the samples and weigh them. Then, the tested samples and the comparative samples should be tested for compression strength. The samples must not be cracked. The total weight of losses should not exceed 5% of the weight of samples. The decrease in compression strength should not be greater than 20% in relation to unfrozen samples. The frost resistance test results are presented in Table 5. During laboratory tests, the samples were subjected to 150 freezing and thawing cycles. Since the purpose of the test is to check the decrease in compression strength of samples subjected to freezing cycles, the obtained compression strength results were not recalculated for cubic samples with a side length of 150 mm.

Table 5

Frost resistance test results

	Tested sample		Comparative sample				
Aggregate	Sample number	Compression strength [MPa]	Sample number	Compression strength [MPa]	Decrease in strength [MPa]	Decrease in strength [%]	Average Decrease in strength [%]
Basalt	1	53	1	76.5	23.5	31	40
	2	44.8	2	75.6	30.8	41	
	3	46.9	3	73.7	26.8	36	
	4	43.3	4	75.6	32.3	43	
	5	43.9	5	76.2	32.3	42	
	6	40.6	6	78.5	37.9	48	
Granite	1	78.1	1	85.6	7.5	9	13
	2	73.2	2	86.9	13.7	16	
	3	70.4	3	83.8	13.4	16	
	4	73.4	4	89.1	15.7	18	
	5	71.9	5	85.8	13.9	16	
	6	80.8	6	86	5.2	6	
Gravel	1	60.8	1	78.9	18.1	23	31
	2	56.5	2	85.7	29.2	34	
	3	65	3	77	12	16	
	4	43.7	4	84.9	41.2	49	
	5	44.5	5	82.7	38.2	46	
	6	69	6	82.7	13.7	17	

The only aggregate that meets the standard requirements is the granite aggregate. After the frost resistance test, the average decrease in strength of the cement concrete containing granite aggregate was 13%. The largest decrease in strength of granite aggregate did not exceed 20%. Basalt was found to be the least frost resistant aggregate. The decrease in strength of basalt aggregate was 40%. The decrease in strength of concrete containing gravel aggregate was 31%.

3.5. Modulus of elasticity

The following load levels were assumed for determination of modulus of elasticity: the upper level $\sigma_g = 0.4\, f_{c,cyl}$ and the lower level $\sigma_d = 0.5$ MPa. The load was applied by a testing machine that can automatically increase and decrease the force applied in time. The displacement measurement was carried out mechanically using displacement sensors with a 150 mm-long measuring base, arranged symmetrically along three generating lines at the height of the sample. Modulus of elasticity test results are presented in Table 6.

Correct assumption of modulus of elasticity is very important at the stage of the pavement structure design [1].

Table 6

Modulus of elasticity test results

Sample number	Type of aggregate		
	Basalt [MPa]	Granite [MPa]	Gravel [MPa]
1	35857	36114	41354
2	34743	37515	40210
Average	**35300**	**36815**	**40782**

Analysing the results presented, it should be stated that the highest value of modulus of elasticity was found in the cement concrete containing gravel aggregate. The values of modulus of elasticity for granite aggregate and basalt aggregate are similar (approximately 36 GPa). In road pavements, the increase in the modulus of elasticity increases the stress in concrete slabs. It is therefore desirable that cement concrete for road pavements should not have a high modulus of elasticity.

4. Conclusion

Based on the analysis of the laboratory tests presented, it should be stated that only the cement concrete containing granite aggregate meets all the requirements for concrete intended for road pavements. The frost resistance test was the decisive criterion. Although the concrete containing basalt aggregate had the highest compression strength, the highest split tensile strength and air void content similar to that of the concrete containing granite aggregate, its frost resistance was the smallest. This is mainly due to the fact that basalt and gravel aggregate is much more absorbent than granite aggregate. However, it should be borne in mind that the properties of aggregates from different mines may differ significantly and some basalt or gravel aggregates may provide adequate frost resistance of road concrete. It should also be considered whether it would be justifiable to introduce the recommendation, included in outdated standards, to use granite aggregate in road pavement concrete.

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Wpływ rodzaju kruszywa na właściwości betonu nawierzchniowego

Streszczenie. W artykule przedstawiono wyniki badań laboratoryjnych właściwości betonu cementowego z różnym kruszywem. Celem badań było określenie wpływu kruszywa na wytrzymałość na ściskanie, rozciąganie pośrednie, charakterystykę porów powietrznych, mrozoodporność oraz moduł sprężystości betonu przeznaczonego na nawierzchnie drogowe. Na podstawie przeprowadzonych badań wyznaczono kruszywo, dla którego spełnione zostały wymagania stawiane dla betonów drogowych.

Słowa kluczowe: beton drogowy, mrozoodporność kruszywa, mrozoodporność betonu drogowego
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