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Research paper

The impact of the addition of diabase dusts on the properties of cement pavement concrete

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Abstract: The aim of the paper was to analyse the possibility to use waste material which is created during the production of mineral-asphalt mixes as a side effect of the process of drying and dedusting diabase aggregate in high temperature. Experimental studies included the analysis of the influence of the addition of diabase dust on the improvement of the properties of cement concrete destined for the construction of local roads. The mineral additive in the form of diabase dust, which constitutes natural waste, was inserted into the concrete mix as a mineral additive substituting a part of the aggregate with the constant amount of cement and water, and additionally as the substitute for cement. The performed studies resulted in the conclusion that adding diabase dust significantly increased the tightness and density of concrete, which impacts the increase of compressive strength by 7, 21 and 28% in reference to model concrete. The insertion of the waste diabase dust into the concrete mix significantly improved the freeze-thaw resistance of concrete after 150 cycles of testing and reduced the water absorption by 6, 15 and 21%. Using diabase dust as a substitute in the following amount: 50, 100 and 150 kg/m^3 did not cause significant changes in the scope of density and water absorption, whereas the reduction of the compressive strength was from 8, 23 and 33% in reference to the model concrete. The application of dust as the substitute for cement resulted in the reduction of the costs of concrete by 6, 12 and 18% and resulted in the possibility to fully apply waste material, which confirms the justness of undertaking implementation research. Concrete with the use of waste rock dusts may be qualified as concrete that is environmentally friendly and compliant with the sustainable development of modern construction materials.

Keywords: recycling, mineral additive, compressive strength, concrete pavement

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1. Introduction

The fast development of technology in the area of road construction increases the expectations of investors, but, above all, of the manufacturers of construction materials, towards the wider application of materials which constitute production process waste [1–11]. Rock dust which is formed during the drying of aggregate, is such material. Despite its high technical parameters, this dust is thrown away. The mineral additive in the form of rock dust causes an increase of the volume of the cement paste, which significantly impacts the improvement of workability and the increase of the tightness of the concrete mix [12–19]. The first phase of the project also included analysing the possibility to use diabase dust to substitute limestone dust which is used for the production of mineral-asphalt mixes, and the results obtained in this experiment were very good. The second phase of the project included analysing the impact of the addition of diabase dust on the properties of cement concrete destined for road construction. The aim of those studies is the improvement of the properties of cement concrete, but also the reduction of production costs through the substitution of the cement binder with rock dust [20–22]. The reduction of the amount of cement results in the fact that cement concrete is more environmentally friendly because we use less energy for the production of cement and concrete [23, 24]. The application of materials from recycling or materials that are mineral additives, performed by [25, 26], proved their usefulness in construction.

Concrete with the use of waste rock dusts may be qualified as concrete that is environmentally friendly and compliant with the sustainable development of modern construction materials [27–32].

The main direction of construction development is the reduction of the amount of carbon dioxide and the associated carbon footprint. This can be achieved by applying mineral additives or industrial waste to the concrete mix, lowering not only the price of the mix but also the clinker index in the cement, because cement accounts for more than 50% of the energy consumption in concrete [33–39].

Numerous works on the use of mineral additives in concrete mixtures as an aggregate substitute, but also as a cement substitute, resulted in the development of this research area and the possibility of changing the perception of concrete as an environmentally sustainable materials [30, 40–52]. Therefore, an effective way to reduce the consumption of binders in concrete and to regulate their structural and technical properties is introduction of active mineral additives and finely classified fillers of various origins [1].

2. Materials and methods

2.1. Materials

All the analysed concretes were produced on the basis of Portland cement CEM I 42.5 R with sand and crushed-stone granite aggregate of the following fractions: 2/8 and 8/16 mm. The studies included using waste mineral dust which was collected during the production of mineral-asphalt mix based on diabase aggregate. The designed concrete was one of C30/37 class with the water–cement ratio equal 0.45, with the use of a plasticizing and an aerifying admixture.

The assumptions of the research project were based on determining the properties of the concrete mix and of the hardened concrete with the use of diabase dust as industrial waste, in terms of application for road concrete pavement. The requirements included in the concrete pavement catalogue [53] were used for designing the composition of the concrete mix. Minerals have the following density: granite 2.65 kg/m^3, sand 2.63 kg/m^3 and diabase dust 2.94 kg/m^3. The designed concrete mix is intended for a single-layer cement concrete surface. The mineral mix complies with curves up 16 mm included in the requirement for the concrete pavement in accordance with the general technical specification [61, 63]. The grading of individual materials is presented in Table 1.

Table 1. Graining of materials

Sieve [mm]	Screening [%]			
	Granite 8/16	Granite 2/8	Sand 0/2	Diabase dust
16.000	4.20	0.00	0.0	0.0
8.000	93.10	2.10	0.0	0.0
4.000	1.69	60.90	0.0	0.0
2.000	0.41	30.40	2.9	0.0
1.000	0.20	5.55	14.0	0.1
0.500	0.08	0.62	43.3	1.6
0.250	0.02	0.08	30.0	13.8
0.125	0.00	0.28	9.2	34.3
0.000	0.30	0.07	0.6	50.2
Sum	**100.0**	**100.0**	**100.0**	**100.0**

Diabase dust was added in the following amount: 50, 100 and 150 kg/m^3. First, the dust was added as substitution for a part of the aggregate, and subsequently a partial substitution of cement was performed in the following amounts: 50, 100 and 150 kg/m^3.

Additionally, in order to compare the properties of concretes containing diabase dust in their composition, also concrete without additives was prepared. Therefore, in total, seven series of concrete were made. The marking of particular concretes presents the content of cement and diabase dust in kg/m^3 (Table 2).

Table 2. Composition of concrete mixes

Marking of concretes	Components [kg/m^3]							
	Cement	Water	Sand 0/2	Granite 2/8	Granite 8/16	Diabase dust	Plasticizing admixture	Aerifying admixture
Control concrete	360	162	711	538	673	0	2.2	0.6
C_360_50	360	162	696	522	657	50	2.2	0.6
C_360_100	360	162	680	505	642	100	2.2	0.6
C_360_150	360	162	676	474	626	150	2.2	0.6
C_310_50	310	162	711	534	674	50	2.2	0.6
C_260_100	260	162	713	532	671	100	2.2	0.6
C_210_150	210	162	715	530	668	150	2.2	0.6

2.2. Petrographic assessment of diabase and diabase dust according to PN-EN 932-3 [62]

Diabase is a volcanic igneous rock, the mineral composition of which is similar to that of basalt. Its colour is grey-steel, with coarse grains of paleobasalt. The basic component of the rock is well preserved plagioclase, colourless and transparent, and the rarely occurring pyroxene. The structure of diabase is ophitic, holocrystalline, and its texture is massive and unoriented (Fig. 1).

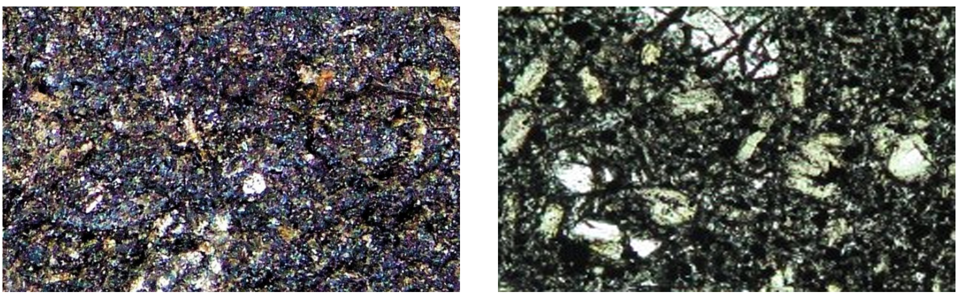

Fig. 1. Diabase structure

2.3. Analysis of the microstructure of diabase dust

The analysis of the microstructure of diabase dust specimens was performed applying scanning electron microscopy SEM Joel JSM-6610 (Joel, Tokyo, Japan). The specimen was placed on carbon film and graphite powder was applied on it. Moreover, the chemical analysis of the specimens was performed using the EDS analyser which is a part of the microscope set (Fig. 2).

a) b) c) d)

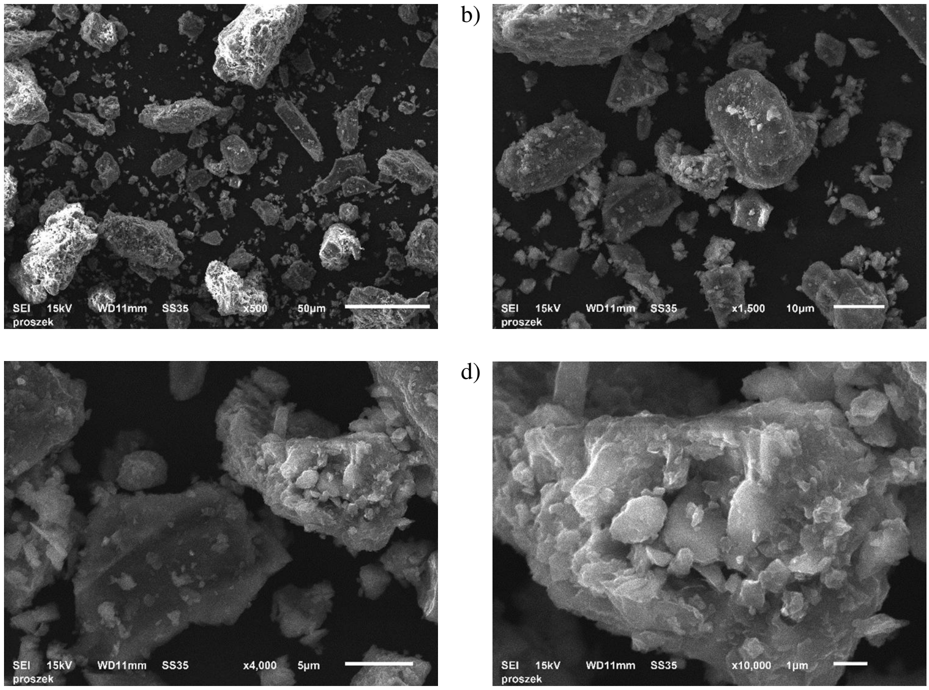

Fig. 2. The image of rock dust created using scanning electron microscopy SEM Joel JSM-6610 (Joel, Tokyo, Japan) a) 500×, b) 1500×, c) 4000×, d) 10000×

The results of the analysis of the rock dust microstructure have been presented in Table 3 (Fig. 3).

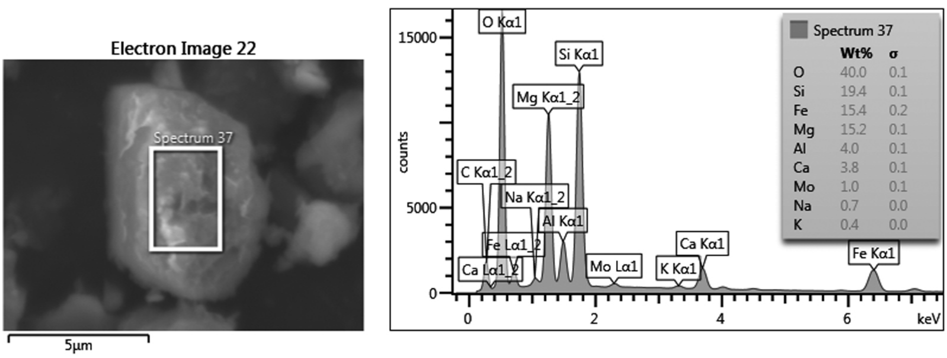

Fig. 3. The image of the chemical analysis of rock dust created using the EDS analyser which is a part of the scanning electron microscopy set SEM Joel JSM-6610 (Joel, Tokyo, Japan)

While analysing the obtained results of the rock dust microstructure analysis, which have been presented in Table 2, it is necessary to notice the high content of chemically

Table 3. The chemical analysis of the composition of diabase dust

Element	Apparent concentration	k Ratio	Wt %	Wt % Sigma	Standard label
O	16.64	0.05601	40.02	0.15	SiO_2
Na	0.23	0.00098	0.67	0.04	Albite
Mg	4.46	0.02959	15.20	0.08	MgO
Al	1.09	0.00785	4.02	0.05	Al_2O_3
Si	5.57	0.04416	19.40	0.09	SiO_2
K	0.15	0.00123	0.44	0.03	KBr
Ca	1.25	0.01117	3.84	0.06	Wollastonite
Fe	4.16	0.04163	15.39	0.15	Fe
Mo	0.22	0.00223	1.01	0.09	Mo
Total			100.00		

reactive minerals in the form of silicon dioxide SiO_2, magnesium oxide MgO, aluminium oxide Al_2O_3. The addition of diabase dust resulted in the fact that the finest fractions constitute the filling of the paste structure and, in consequence, of the concrete. Moreover, reactive silicon oxides SiO_2, magnesium oxides MgO, aluminium oxides Al_2O_3 probably go into a reaction with cement, causing the increase of compressive strength and they significantly increase the durability of the concrete.

2.4. Methods

Concrete mixes were subjected to consistency assessment performed using the concrete slump test method according to the EN 12350-2 [54] standard, and the total air content assessment performed using the pressure method according to EN 12350-7 [55] after 5 and 60 minutes from the moment the components stopped being mixed. Their density was also determined in accordance with EN 12350-6 [56]. Subsequently, specimens were formed from the concrete mixes for tests referring to compressive strength, water absorption and freeze-thaw resistance. The weight water absorption of the concretes after 28 days of curing according to the PN-B-06250:1988 [57] standard was also determined. All the specimens were made and received concrete care in accordance with the EN 12390-2 [58] standard. The compressive strength tests were performed on cubic specimens with the side length of 150 mm, in accordance with PN-EN 12390-3 [59]. The specimens for the tests received concrete care in water in the temperature of 20 ± 2°C, in accordance with PN-EN 12390-8 [60]. The density of the specimens of hardened concrete was determined in accordance with PN-EN 12390-7 [61]. The freeze-thaw resistance test was performed in accordance with PN-B-06250:1988, applying the ordinary method. In Poland this method is the basic method of assessment of the freeze-thaw resistance of concrete. Two sets of specimens of the following dimensions: 100 × 100 × 100 mm were prepared from each series of concrete.

In accordance with the requirements of the PN-B-06250 standard, concrete which should be considered freeze-thaw resistant is one which demonstrates a mass loss that does not exceed 5% and a compressive strength decrease that does not exceed 20% in reference to specimens which have not been subjected to freeze-thaw cycles. Moreover, there must not be any cracks on the specimens after freeze/thaw cycles. 24 specimens were made for every designed concrete composition. In reference to the above, in total 168 specimens were prepared for the studies.

3. Results and discussion

3.1. Properties of fresh concrete

The results of the analyses of the concrete mix have been presented in Table 4.

Table 4. The properties of the analysed concrete mixes

Marking of mixes	Concrete slump test, mm		Air content, %		Density, kg/m^3
	after 5 min	after 60 min	after 5 min	after 60 min	
Control concrete	20	20	4.8	4.6	2460
C_360_50	70	60	5.7	5.4	2468
C_360_100	100	90	5.3	5.0	2471
C_360_150	140	120	6.0	6.1	2475
C_310_50	60	40	5.4	5.0	2466
C_260_100	80	60	4.9	4.5	2459
C_210_150	90	80	4.7	4.6	2455

The addition of diabase dust, as the substitute for aggregate, in a significant degree influences the change of the concrete mix consistency. Concrete mixes that contain the addition of diabase dust demonstrate greater liquidity (greater cone slump) than a mix without dust (control). Greater consistency changes are observed after 5 minutes from the moment the components stop being mixed than after the elapse of 60 minutes. The addition of diabase dust in the amount of 150 kg/m^3 causes the greatest increase of cone slump (by 100–120 mm) compared to the mix without dust (control). While analysing the influence of the addition of diabase dust as the substitute for cement, one can notice that there was also a change of the consistency, but in a smaller degree. According to the authors, this may prove the stable behaviour of the workability parameters of the concrete mix. The total air content in the analysed concrete mixes is from 4.6% to 6.1%. On the basis of the results of the measurement of air content in the concrete mix after 5 and 60 minutes, one can conclude that in the scope of aeration the mixes meet the requirements in reference to mixes destined for road construction. While analysing the influence of the addition of dust on the properties of the concrete mix, it should be noticed that along with the increasing amount, the concrete mix underwent sealing. This can be explained by the fact that the very fine particles of the diabase filler filled the spaces between the mineral aggregate and significantly increased the amount of the cement paste.

3.2. Compressive strength

The analyses of compressive strength were performed after 7, 28 and 90 days of concrete curing. The compressive strength was calculated based on the actual dimensions of the specimens. The mean results have been presented in Table 5 and in Figures 4 and 5. Dashed line has been used to mark the minimum required value of concrete compressive strength for class C30/37.

Table 5. The influence of diabase dust on compressive strength

Parameter	Marking of mixes						
	Reference concrete	C_360_50	C_360_100	C_360_150	C_310_50	C_260_100	C_210_150
f_{c7} [MPa]	42.5	44.5	48.6	49.0	38.6	32.8	28.0
f_{c28} [MPa]	50.3	54.0	60.9	64.4	46.3	38.5	33.4
f_{c90} [MPa]	55.3	58.3	66.4	70.2	51.8	46.4	38.8

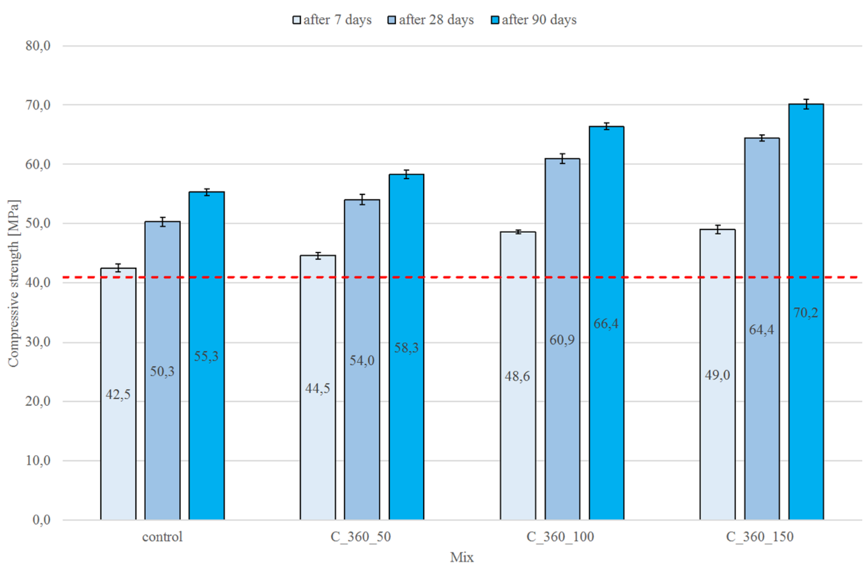

Fig. 4. The influence of diabase dust, as a filler, on compressive strength

While analysing the obtained compressive strength results one can notice that they indicate that the addition of diabase dust to concrete, as a substitute for aggregate, has

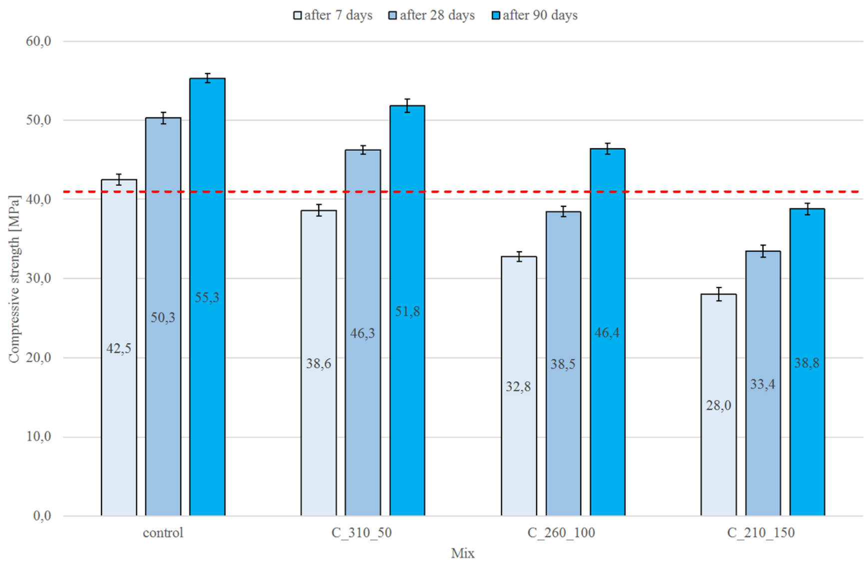

Fig. 5. The influence of diabase dust, as a substitute for cement, on compressive strength

a beneficial impact on the concrete strength. All the analysed concretes obtained the required compressive strength class after 28 days of curing. The greatest compressive strength, in all the terms of analysis, was demonstrated by concrete with the addition of diabase dust in the amount of 150 kg/m^3. The differences in compressive strength in comparison to the control concrete are.

The concrete compressive strength results proved to be different in case of the addition of diabase dust as the substitute for cement. Along with the increase of substituting cement with diabase dust, there is a decrease of compressive strength in all the terms of analysis. The assumed compressive strength class after 28 days was only obtained by two concretes: the control one and the one with the addition of 50 kg/m^3. In case of the concrete containing the addition of the dust as the substitute for cement in the amount of 100 kg/m^3 and 150 kg/m^3, the strength after 28 days was lower by% in reference to the required one (41 MPa).

3.3. Water absorption and freeze-thaw resistance

The results of the durability tests of concretes including their resistance to cyclical freezing and thawing in the scope of the F150 degree and water absorption have been presented in Table 6.

While analysing the influence of diabase dust, as a substitute for aggregate, on the resistance to the effect of freeze, one can notice that the addition has a positive influence on the durability of concrete in the conditions of freeze aggression (without the participation of de-icing agents). All the analysed concretes, except for the concrete marked as C_210_150 (the substitution of cement with diabase dust in the amount of 150 kg/m^3) met

Table 6. The results of tests of concrete water absorption and resistance to freezing and thawing for the F150 freeze-thaw resistance degree

Parameter	Marking of mixes						
	Reference concrete	C_360_50	C_360_100	C_360_150	C_310_50	C_260_100	C_210_150
Mean decrease of the strength of specimens ΔF, %	9.2	5.6	4.3	5.1	8.5	11.3	23.3
Mass change of specimens subjected to cyclical freezing and thawing ΔG, %	–0.03	–0.02	–0.02	-0.01	–0.03	–0.03	–0.04
Water absorption, %	4.7	4.4	4.0	3.7	4.6	4.6	5.1

the requirements of the freeze-thaw resistance test performed according to the standard procedure [63] which included 150 cycles of freezing and thawing. The addition of diabase dust to concrete, in the amount of 150 kg/m^3, as the substitute for aggregate, caused the reduction, by half, of the decrease of compressive strength of specimens subjected to 150 cycles of freezing and thawing. The substitution of cement with diabase dust in the amount of 100 kg/m^3 and 150 kg/m^3 causes the increase of the reduction of compressive strength. A test which was very important from the point of view of durability, was determining the concrete water absorption after 28 days. The test results included in Table 5 indicate that the water absorption of the mix with the addition of 150 kg/m^3 of diabase dust (as a substitute for aggregate) improved by 21% compared to the control concrete. The reduction of water absorption is associated with the sealing of the concrete structure by the addition of diabase dust.

3.4. Air void analysis of hardened concrete

The air void size distribution was determined according to EN 480-11:2008 [64]. The analysis was carried out on specially prepared 150×100×20 mm polished concrete sections in the laboratory of the Military University of Technology in Warsaw. Seven samples were used in the study which, after cleaning and drying, were polished and coated with a contrast agent. The following air void system parameters were determined for each of the analyzed samples of hardened concrete: (total air content A%, specific surface of the air void system α mm^{-1}, spacing factor L mm, micro air-void content (amount of air voids below 0.3 mm in size) A_{300}%, paste-air ratio R%.

A computer image analysis method is used to evaluate the microstructure of concretes and parameters of pore structure are calculated; these parameters include relative volume fraction, relative specific surface area, and pore arrangement ratios [26]. The results of research on the aeration of the samples are presented in Table 7.

Table 7. Experimentally determined air void system parameters of hardened concrete

Parameter	Reference concrete	C_360_50	C_360_100	C_360_150	C_310_50	C_260_100	C_210_150
Total traverse length, T	2464	2464	2464	2464	2464	2464	2464
Total air content, A	4.8	5.0	5.1	5.5	5.2	5.1	4.0
Total number of chords measured, N	881	870	869	923	857	839	821
Specific surface of the air void system, α	24.2	25.1	24.9	26.2	24.3	23.9	19.2
Paste/ air ratio, R	5.2	5.1	5.2	4.2	4.9	5.2	6.2
Spacing factor, L	0.17	0.16	0.17	0.18	0.20	0.22	0.27
Micro air-void content, A_{300}	1.68	1.77	1.86	1.91	1.59	1.76	1.23

The air void distribution parameters determined according to EN 480-11:2008 [16] in the laboratory of the Military University of Technology in Warsaw allow us to conclude that the tested concrete meets very high requirements that are currently specified for paving grade concrete. A negative result of the pore analysis was obtained for the formulas C_260_100 and C_210_150.

The total amount of air A ranged from 4.8 to 5.5%, the specific surface α ranged from 19.2 to 26.2 mm^{-1} and the paste/ air ratio R ranged from 4.2 to 6.2. The most important for the freeze-thaw resistance evaluation are, however, the values of the spacing factor L and the micro-air content A_{300}, which were in the ranges of 0.16 to 0.27 mm and 1.23 to 1.91% respectively.

3.5. The economic analysis of applying diabase dust

The application of a filler which constitutes waste is action which is a part of the strategy of sustainable development. A frequent accusation directed towards solutions that are ecological and environmentally friendly are the increased costs of such a solution. Therefore, the summing up of the assessment of the possibility to apply waste material in the form of rock dust which is created during the production of mineral-asphalt mixes as a side effect of the process of drying and dedusting diabase aggregate in high temperature, includes an economic assessment.

The prices of the materials have been adopted based on the assessment of the construction materials market in Poland in the period of the last year. The juxtaposition of the cost difference has been presented in Figures 6 and 7.

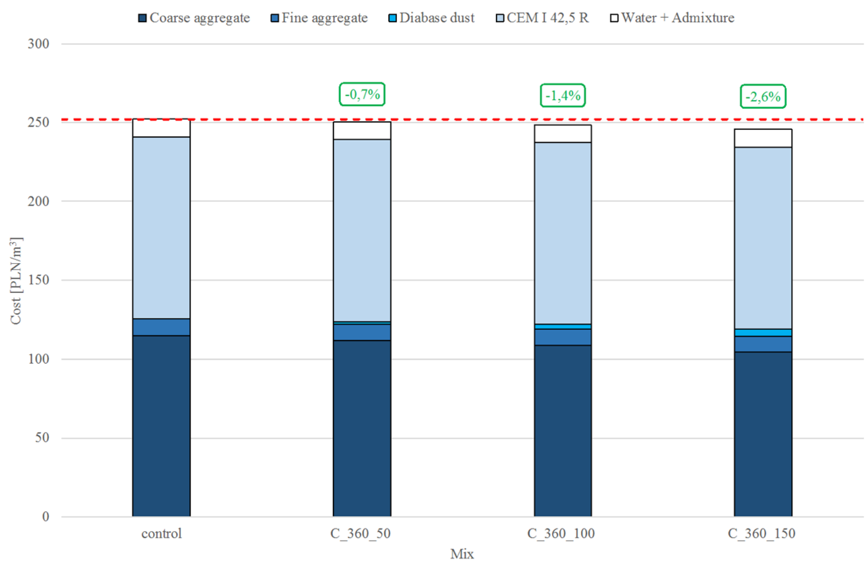

Fig. 6. The estimation of the cost of the concrete mix with various diabase dust content

The application of 150 kg/m^3 of diabase dust as a filling additive not only significantly improves the technical parameters of concrete, but also constitutes savings of 3% of the unit price of a cubic meter of concrete. If we apply the addition of diabase dust as the substitute for cement in the amount of 50, 100 or 150 kg/m^3 then there are savings of 6, 12 and 18%.

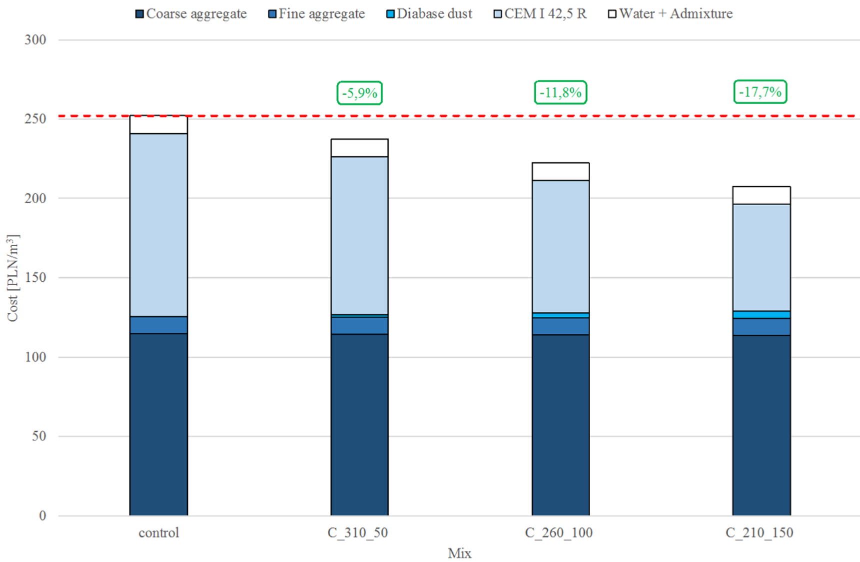

Fig. 7. The estimation of the cost of the concrete mix with various diabase dust content

4. Conclusions

On the basis of the conducted studies and analyses, it is possible to formulate the following conclusions:

– The mineral additive in the form of diabase dust increases the compressive strength by from 7 to 28% in reference to model concrete.
– The application of diabase dust as a substitute for cement in the following amount: 50, 100 and 150 kg/m^3 did not cause significant changes in the scope of density and water absorption, but it reduced the frost resistance of concrete and the reduction of the compressive strength was 8, 23 and 33% in reference to the reference concrete.
– The application of dust as the substitute for cement resulted in the reduction of the costs of concrete by 6, 12 and 18%.
– The addition of diabase dust increases the filling of the cement paste structure and, in consequence, increases the durability of road cement concrete.
– The application of diabase dust significantly improved the freeze-thaw resistance of concrete after 150 cycles of testing, and the water absorption decreased by 6, 15 and 21%. A negative result of the pore analysis was obtained for the formulas C_260_100 and C_210_150.
– Concrete with the use of waste rock dusts may be qualified as concrete that is environmentally friendly and compliant with the principles of the sustainable development of modern construction materials.

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Wpływ dodatku pyłów diabazowych na właściwości cementowego betonu nawierzchniowego

Słowa kluczowe: recykling, dodatek mineralny, wytrzymałość na ściskanie, nawierzchnia betonowa, zrównoważony rozwój

Streszczenie:

Celem pracy było zbadanie możliwości wykorzystania odpadowego materiału, który powstaje podczas produkcji mieszanek mineralno-asfaltowych jako efekt uboczny procesu suszenia i odpylania w wysokiej temperaturze kruszywa diabazowego. W ramach badań eksperymentalnych analizowano wpływ dodatku pyłu diabazowego na poprawę właściwości betonu cementowego przeznaczonego do budowy dróg lokalnych. Dodatek mineralny w postaci pyłu diabazowego stanowiącego naturalny odpad wprowadzano do mieszanki betonowej jako dodatek mineralny zastępujący część kruszywa przy stałej ilości cementu i wody oraz dodatkowo jako zamiennik cementu. W wyniku przeprowadzonych badań stwierdzono, że dodanie pyłu diabazowego znacznie zwiększa szczelność i gęstość betonu co wpływa na zwiększenie wytrzymałości na ściskanie od 7, 21 i 28% w stosunku do betonu wzorcowego. Wprowadzenie odpadowego pyłu diabazowego do mieszanki betonowej znacząco poprawiło mrozoodporność betonu po 150 cyklach badania oraz zmniejszyło w porównaniu do betonu wzorcowego nasiąkliwość o 6, 15 i 21%. Natomiast zastosowanie pyłu diabazowego jako zamiennika cementu w ilości 50, 100 i 150 kg/m^3 nie spowodowało znacznych zmian w zakresie gęstości i nasiąkliwości, ale nastąpiło zmniejszenie wytrzymałości na ściskanie wyniosło od 8, 23 i 33% w stosunku do betonu wzorcowego. W wyniku zastosowania pyłu jako zamiennika cementu uzyskano obniżenie kosztów betonu o 6, 12 i 18% i uzyskano możliwość pełnego zastosowania odpadowego materiału co potwierdza zasadność podjęcia badań wdrożeniowych. Beton z zastosowaniem odpadowych pyłów kamiennych można zakwalifikować do betonów przyjaznych dla środowiska i zgodnych z równoważonym rozwojem nowoczesnych materiałów budowlanych.

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