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GRANITE DUST AS A MINERAL COMPONENT OF A DRY CEMENT MORTAR MIXTURES

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In this study, the results of experiment research on building mortars based on dry mixtures with the use of granite dust are given. It also shows the possibilities of their industrial release. In the conditions of energy resources shortage, gradual exhaustion of natural raw materials, aggravation of environmental problems, an important direction in the production of building mixtures is the development of mixes with waste materials from various industries. In particular, granite dust, which simultaneously allows to rationally use natural mineral material and solve environmental problems. Based on the obtained data, experimental and statistical models of physical and mechanical properties of fresh and hardened mortar are constructed and ways of optimizing their compositions and improving the properties of mortars are analyzed. It is established that the use of granite dust and some additives provides high standardized parameters for mortar mixture and bricklaying process, including plasticity, compressive strength and others at the low level of cement consumption. Fresh mortar mixtures have a prolonged slump retention.

*Keywords***:** granite dust, cement mortar, compressive strength, flexural strength, adhesion, superplasticizer.

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1. INTRODUCTION

In recent years, the trend of using energy-saving building materials has been clearly defined in modern construction. There was a significant increase in their use associated with the necessity to expand the resource base for the production of building materials. The development of material production, in particular materials utilizing of man-made waste [1-3], is to a large extent determined by the availability of the raw material base.

Nowadays, using dry cement mortar mixtures is becoming more and more popular. Their application leads to increased efficiency and quality of work, lower transport and storage costs and acceleration of technological processes. This positively distinguishes dry mixtures from traditional solutions. Nowadays, it is possible to easily control the properties of dry mixtures. A wide range of such materials is created by changing the content of different components and modifiers, so that they can be used in a variety of works.

Basalt powder can be use as an effective substitute of fine aggregate in cementitious mortar and concrete. Use of the basalt powder as a partial substitution of sand improves some properties (absorptivity, capillary rise of water and softening factor) of mortar and concrete and enable for the management of industrial waste [4]. Basalt dust added to the mortar in exchange for sand, sealing structure of the cement matrix, resulting in improved strength and the frost resistance of mortars [5]. Results of tests show that replacement of sand by waste basalt powder in amount of up to 20% improves concrete durability [6].

The use of marble powder as mineral addition for mortars and concretes, in the presence of a superplasticizing admixture provided maximum strength at the same workability level, comparable to that of the reference mixture after 28 days of curing [7]. The use of ternary cements, containing an adequate combination of marble filler and natural pozzolana, can lead to the energy saving and reduction of CO_2 emission without worsening of the mechanical properties of cement [8].

The combined use of quarry rock dust and fly ash exhibited excellent performance due to efficient microfilling ability and pozzolanic activity. The decrease in early strength by the addition of fly ash is ameliorated by the addition of quarry dust [9]. Water permeability of concrete decreased as the dust content percentage increased [10]. Industrial by-product – stone slurry is capable of improving hardened concrete performance, enhancing fresh concrete behavior and can be used in architectural concrete mixtures containing white cement [11].

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The investigations showed an improvement in strength of mortars containing limestone dust at early ages, while water demand and porosity increased with increasing dust content. This gain of strength is attributable to the acceleration of the cement hydration at early ages due to effect of the stone dust [12]. The addition of limestone reduces the initial and final setting time, as well as total porosity, whereas the free lime and combined water increase with limestone content [13].

The granite dust from the crushing screenings can be used as a filler for the production of dry building mixes for flooring [14]. Granitic quarry sludge waste, if ground to sufficient fineness, produces a denser matrix promoting up to 38% reduction in expansion due to alkali–silica reaction and almost 70% improvement in resistance to chlorides, without compromising workability and strength [15]. The addition of granite polishing waste to replace 15% to 20% sand by volume would increase the strength by 31,2% to 70,9% and improve the rheology and impermeability [16]. The compressiv strength of mortar containing waste materials significantly increases under high curing temperatures [17]. The introduction of granite dust into the concrete mixture leads to a reduction of water absorption by 25% and water penetration by 30% [18]. The addition of granite dust as paste replacement would increase the superplasticizer dosage needed to achieve the required workability, whereas the addition of granite dust as cement replacement has little effect on the superplasticizer dosage needed [19]. Superplasticizers can eliminate most disadvantages caused by using granite stone waste, particularly negative effects on the mechanical properties. They can even improve some properties of concrete and mortars, including electrical resistivity by up to around 90% [20]

The stone crushing plants produce large quantities of granite dust, which is captured by the sleeve filters in process of crushing granite. It is characterized by a very large specific surface area and does not require drying. In many quarries, granite dust is currently not used and is deposited in landfills, polluting the environment.

The current demand for energy-efficient materials has become widespread due to the rapid increase in energy prices. The production of such materials is possible with the use of industrial waste. This waste is increasingly being used in the production of building materials. This means that the development of technology for making dry mixtures for cement mortar with the use of granite dust is now justified.

2. MATERIALS AND EXPERIMENTAL INVESTIGATION

In the investigation following materials were used:

Cement: CEM II/A-S 42,5 N according to EN 197-1: 2011 [26].

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The chemical and mineralogical composition of the clinker used in the study is given in Table 1 and its physical and mechanical properties are presented in Table 2.

Table 1. Chemical and mineralogical composition of the cement clinker.

Indicator	CaO	SiO_2	Al_2O_3	Fe_2O_3	FeO	MgO	Cl	C_3S	C_2S	C_3A	C_4AF
Quantitative content, %	64,49	20,32	5,28	4,05	-	0,74	-	66,95	13,15	7,42	12,48

Table 2. Physical and mechanical properties of cement CEM II/A-S 42,5 N.

Property	**In accordance with EN 197-1: 2011**	**CEM II/A-S 42,5 N**
Grinding fineness, sieve residue №008, %	<15	6,0 – 9,0
Specific surface area, m^2/kg	-	240 – 280
Density of cement paste, %	-	27,5
Setting time: - beginning, min - ending, hr	 >60 <10	 190 – 120 5 – 6
Strength at the age of 2 days, MPa: - flexural - compression	 - >10	 1,0 – 1,2 10,2 – 12,1
Strength at the age of 28 days, MPa: - flexural - compression	 - >42,5	 4,2 – 4,8 42,9 – 46,7
Volumetric constancy, expandability, mm	<10	5
Gypsum content converted to SO_3	3,5	3,3

Granite dust: the chemical composition of dust is presented in Table 3 and the physical and mechanical properties are presented in Table 4.

Table 3. Chemical composition of granite dust.

Indicator	SiO_2	Al_2O_3	Fe_2O_3	FeO	CaO	MgO	TiO	Na_2O	K_2O	P_2O_5	H_2O
Quantitative content, %	72,97	13,60	0,98	0,58	1,29	0,46	0,30	3,91	5,18	0,08	0,15

Table 4. Physical and mechanical characteristics of granite dust.

Property	**Value**
Specific surface area, m^2/kg	220 – 250
Volumetric density, kg/m^3	920 – 970
Grain size, %:	
- up to 20 µm	15,5
- 20 – 40 µm	36,5
- 40 – 80 µm	33,5
- 80 – 160 µm	14,5
Content of clay particles, %	0,2 – 0,5
Moisture content, %	0,3 – 0,5

- quartz sand, fineness modulus 1,9, the content of dust and clay particles is 1.5%;
- superplasticizer of the polycarboxylic type, water reducing effect 30%;
- admixture: cellulose ether, viscosity 2% in 20^0C, 20°GH Brookfield RV, 20 rpm, sp. 2 mPas (Range) 38000-40000, active substance content less than 91,5%, NaCl content not more than 1.5%.

Experimental research was carried out using mathematical modelling of the experiment (MME), which enabled the algorithmization of the execution of experiments according to the scheme. It is an optimal process from the point of view of both the scope of experimental research and statistical requirements [21].

In order to construct linear and incomplete square models, a full factorial experiment was used, in which all possible combinations of factors at three levels were presented. For technological analysis and selection of significant factors, together with verification of equation adequacy, the significance of regression coefficients was also estimated.

To carry out the experiments, a three-level four-factor plan B4 was used, which is similar to the D-optimal plan B_4 [21]. A characteristic feature of these plans is the high accuracy of forecasting the output parameter in terms of factors. Quadratic regression equations allow to trace the individual and combined influence of factors on the examined output parameters in order to determine the necessary and optimal values of factors.

The results of the experiments were processed with the use of mathematical statistical methods, obtaining the equation of square regression in general form for the coefficients *k*. After the models were constructed, algebraic coefficients were calculated and supplemented with statistical (regression) analysis.

Scanning electron microscopy and microanalysis were performed using scanning microscope type JSM-5500 LV. The flexural strength test was performed on a MII-100 type device, compression strength on a FP-100/1 type press and adhesion (bond strength) on Proceq DY-216 Pull-off Tester.

3. PROCEDURE AND RESULT ANALYSIS

In order to examine the influence of the composition of mortar mixtures on their properties, analyses were carried out using algorithms according to the three-level four-factor plan B_4 (mathematical modelling). The variable components in this plan were:

- cement content;
- granite dust content;
- superplasticizer content;
- cellulose ether content.

3.1. EXPERIMENTAL METHODS

The conditions for planning an experiment are given in Table 5

Table 5. Conditions for planning an experiment in kg per m^3 of the mortar mixture.

Impact factors		**Variation levels**			**Range**
Factor name	**Coded name**	**-1**	**0**	**+1**	
Cement content, kg/m^3	X_1	150	200	250	50
Dust content (GD), kg/m^3	X_2	0	50	100	50
Superplasticizer (SP) content, % of cement mass	X_3	0,3	0,4	0,5	0,1
Cellulose ether (EC) content, kg/m^3	X_4	1,0	1,5	2,0	0,5

The output parameters of planning experiment were: compressive strength, flexural strength and adhesion (bond strength) of hardened mortar mixtures containing from 0 to 100 kg of granite dust at the age of 28 days.

All the basic properties of the binder and mortar mixtures based on granite dust have been tested in accordance with the applicable standards [22-25].

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- Mortar components were mixed with water in laboratory mixer according to PN-EN 196-1 [22] standard at 145 rpm. The mixing time was 180 seconds. Consistency tests were started 5 minutes after the components were mixed. After this time the mortars were additionally manually mixed for about 15 seconds and the consistency measurements were taken.
- The consistency of the mortars were determined by PN-85/B-04500 [23] standard. The test consists in determining the immersion depth of the measuring cone in the mortar, measured in cm.
- Tests of the properties of hardened mortars were carried out on 4x4x16 cm samples, except for the adhesion test. The mortar was laid into the form in two layers. Each layer was compacted with a shaker (60 shakes in 60 seconds). After 24 hours moulds are removed and test specimens are put into the climatic chamber with humidity of 95±5% and temperature 20±2°C for curing.
- Flexural strength: determined on beam specimens after 28 days of hardening according to PN-EN 1015-11 [24]. Each of the samples was subjected to the loading until breaking with a concentrated force applied in the middle of the span, at a support spacing of 10 cm. To determine the flexural strength of hardened mortars, three samples of each of the mixtures shown in Table 6 were tested.
- Compressive strength: was calculated as the arithmetic value of six specimens (half a beam) from flexural strength tests according to PN-EN 1015-11 [24]. If a unit value from six samples had a deviation of more than 10% from the arithmetic mean, it was rejected and the values were calculated from the other five samples.
- Adhesion (bond strength): was determined as a "pull-off test" according to PN-EN 1015-12 [25]. Mortars were applied manually on the previously prepared concrete substrate. The thickness of the mortar layer was 1,2 cm ± 10%. Adhesion is defined as the maximum tensile stress caused by a tearing load applied perpendicularly to the mortar surface. The tearing load is applied by means of a tear-off plate glued to the surface of the mortar being tested.
- The specimens for SEM analysis were curing in a climatic chamber with humidity 95%±5% at temperature 20°C. At the age of 28 days samples were mechanically divided into smaller parts measuring about 1-2 cm. These parts were fixed to the metal table with epoxy glue and subjected to microscopic analysis.

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3.2. EXPERIMENTAL RESULTS

On the basis of the obtained data, graphical dependencies and response surfaces were prepared, showing the influence of composition factors on mortar strength. In each chart, the values of two from the four variables were considered constant (level 0), while the other two variables varied from -1 to +1. The planning matrix and the results obtained are presented in Table 6.

Table 6. Planning matrix and research results*.

№	Coded factors				Mixture composition in kg/m³ of mortar						Strength, MPa		
	X_1	X_2	X_3	X_4	CEM,	GD	SP	EC	Sand	Water	compression	flexural	adhesion
1	1	1	1	1	250	100	1,25	2,0	1442	258	17,4	5,9	1,10
2	1	1	1	-1	250	100	1,25	1,0	1450	250	18,6	6,1	0,95
3	1	1	-1	1	250	100	0,75	2,0	1410	310	14,5	4,8	0,69
4	1	1	-1	-1	250	100	0,75	1,0	1400	300	15,3	5,1	0,61
5	1	-1	1	1	250	0	1,25	2,0	1550	250	11,8	4,9	0,84
6	1	-1	1	-1	250	0	1,25	1,0	1560	240	12,3	5,4	0,76
7	1	-1	-1	1	250	0	0,75	2,0	1496	334	12,5	4,3	0,53
8	1	-1	-1	-1	250	0	0,75	1,0	1504	326	12,6	4,5	0,48
9	-1	1	1	1	150	100	0,75	2,0	1568	232	14,6	4,1	0,58
10	-1	1	1	-1	150	100	0,75	1,0	1576	224	13,3	4,8	0,53
11	-1	1	-1	1	150	100	0,45	2,0	1518	292	9,5	2,7	0,45
12	-1	1	-1	-1	150	100	0,45	1,0	1526	284	10,5	2,8	0,42
13	-1	-1	1	1	150	0	0,75	2,0	1676	224	8,0	3,4	0,31
14	-1	-1	1	-1	150	0	0,75	1,0	1684	216	6,8	3,7	0,26
15	-1	-1	-1	1	150	0	0,45	2,0	1638	262	6,0	2,2	0,29
16	-1	-1	-1	-1	150	0	0,45	1,0	1646	254	7,6	2,3	0,26
17	1	0	0	0	250	50	1,00	1,5	1500	250	16,0	5,1	0,64
18	-1	0	0	0	150	50	0,60	1,5	1592	258	10,0	3,3	0,40
19	0	1	0	0	200	100	0,80	1,5	1506	244	14,2	4,2	0,57
20	0	-1	0	0	200	0	0,80	1,5	1614	236	12,0	3,0	0,46
21	0	0	1	0	200	50	1,00	1,5	1552	248	10,5	4,1	0,42
22	0	0	-1	0	200	50	0,60	1,5	1510	290	10,2	3,2	0,41
23	0	0	0	1	200	50	0,80	2,0	1518	282	11,2	3,9	0,46
24	0	0	0	-1	200	50	0,80	1,0	1526	274	11,8	4,0	0,41

*the consistency of all mixtures were between 6 and 8 cm using the cone fall method.

Statistical analysis of the research results was used to obtain regression equations for the tested parameters, coded variables given below (Eq. 3.1-3.3):

Compressive strength:

$$f_{cm} = 11{,}51 + 2{,}56 \cdot x_1 + 2{,}26 \cdot x_2 + 0{,}18 \cdot x_3 - 0{,}25 \cdot x_4 + 0{,}97 \cdot x_1^2 + 0{,}57 \cdot x_2^2 - 1{,}18 \cdot x_3^2 - 0{,}64 \cdot x_4^2 - 0{,}18 \cdot x_1 x_2 - 0{,}24 \cdot x_1 x_3 - 1{,}16 \cdot x_1 x_4 + 0{,}87 \cdot x_2 x_3 - 0{,}04 \cdot x_2 x_4 + 0{,}27 \cdot x_3 x_4 \tag{3.1}$$

Flexural strength:

$$f_{tf} = 3{,}74 + 0{,}94 \cdot x_1 + 0{,}38 \cdot x_2 + 0{,}59 \cdot x_3 - 0{,}14 \cdot x_4 + 0{,}45 \cdot x_1^2 + 0{,}15 \cdot x_2^2 + 0{,}10 \cdot x_3^2 + 0{,}20 \cdot x_4^2 - 0{,}15 \cdot x_1 x_3 + 0{,}09 \cdot x_2 x_3 - 0{,}01 \cdot x_2 x_4 - 0{,}06 \cdot x_3 x_4 \tag{3.2}$$

Adhesion:

$$f_{adh} = 0{,}44 + 0{,}17 \cdot x_1 + 0{,}10 \cdot x_2 + 0{,}09 \cdot x_3 + 0{,}03 \cdot x_4 + 0{,}08 \cdot x_1^2 + 0{,}07 \cdot x_2^2 - 0{,}03 \cdot x_3^2 - 0{,}01 \cdot x_4^2 - 0{,}01 \cdot x_1 x_2 + 0{,}07 \cdot x_1 x_3 + 0{,}01 \cdot x_1 x_4 + 0{,}02 \cdot x_2 x_3 + 0{,}01 \cdot x_2 x_4 + 0{,}01 \cdot x_3 x_4 \tag{3.3}$$

Graphical dependence of compressive strength and adhesion of cement mortars with granite dust as a function of their composition are shown in Fig. 1-4.

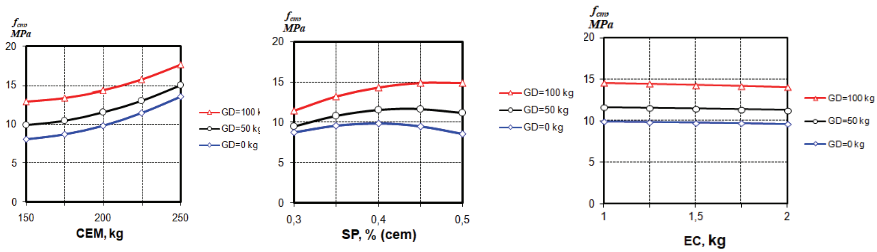

Fig. 1. Compressive strength dependence of 28-day cement mortars modified by granite dust as a function of cement, superplasticizer and cellulose ether.

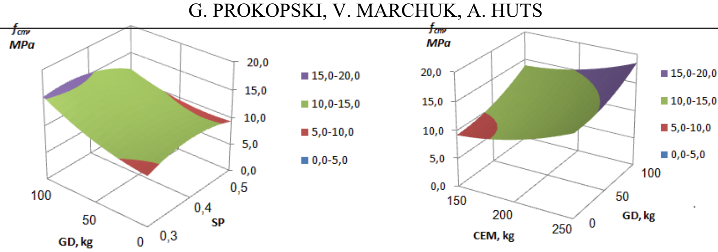

Fig. 2. Compressive strength response surface area of mortars

As shown in Figures 1 and 2, Table 6 and Eq. 3.1, 3.2 both the amount of cement and the amount of granite dust have a significant impact on the compressive strength of the mortar samples. The introduction of granite dust into a mixture is accompanied by an increase in the compressive strength by 15–20% in comparison with compositions without dust. With a further increase in the amount of dust to 100 kg, a mixture with a compressive strength of 30–40% higher than that of dust-free samples can be obtained.

The introduction of SP additive allow does not increase the amount of water. When using 100 kg of granite dust, the highest compressive strength is shown by mixtures containing 250 kg of cement, 0,5% of superplasticizer and 1 kg of cellulose ether (f_{cm}=18.6 MPa).

Granite dust, which is actively involved in the formation of the microstructure of the mixture, positively influences the compressive strength of the mortar after hardening, especially at the introduction of a superplasticizer. Conditions of satisfactory strength can be achieved with different proportions of the content of main components. In this case, the combined introduction of SP and very fine fillers has a positive effect on the strength of mortar, which can be explained by the creation of better conditions for the physical and chemical interaction between the particles in the hardening mixture. This is due to the "micro-particle effect". This effect manifests itself when the concentration of very fine filler increases in volume, which leads to a reduction in the porosity of the cement paste.

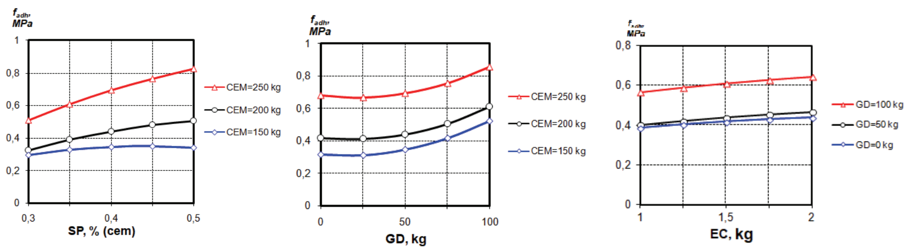

Fig. 3. Dependences of adhesion of cement mortars modified by granite dust as a function of cement, superplasticizer and cellulose ether content.

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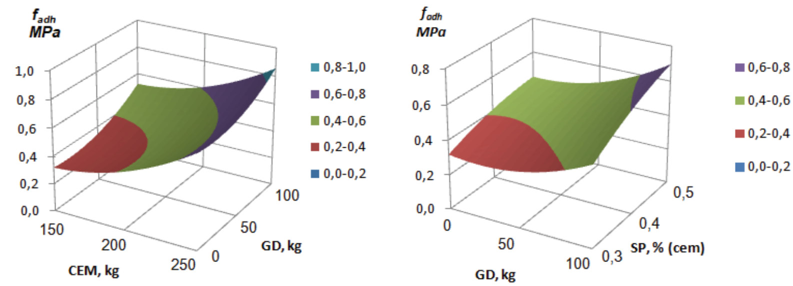


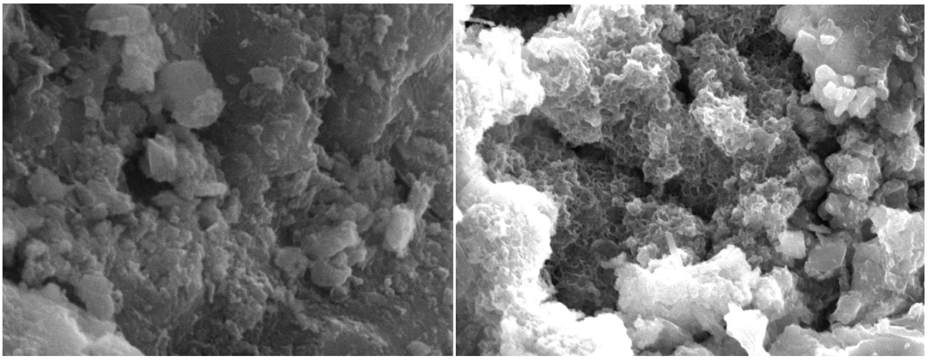
Fig. 4. Response surface of adhesion resistance

Figures 3 and 4, Table 6 and Eq. 3.3 show that with increasing cement content, the adhesion of the composition increases with a gradual increase in the proportion of granite dust. The introduction of superplasticizer in the amount of 0,4–0,45% of cement mass has a positive effect on adhesion, but with a further increase in its content to 0,5% in the composition, adhesion slightly decreases with a minimum content of CEM and GD. Positive results are obtained with cellulose ether - its influence on adhesion in comparison with the superplasticizer gives more satisfactory results, with the content of this admixture amounting to 1,3–1,8 kg/m^3 of mortar. The addition of water retention additive has a stabilizing effect on the consistency decrease. This essentially extends the service life of mortar mixtures containing superplasticizer.

Microscopic analysis of samples without and with granite dust in amount 100 kg/m^3 at the age of 28 days was performed to assess the effect of granite dust on the microstructure of mortar. The dominant mineral phases in the samples under study were C-S-H phase and portlandite. The first of them is found mainly in a small number of needle-shaped crystals. Portlandite, which is the result of the hydration of alite (C_3S) and belite (C_2S), forms massive hexagonal crystals. Influence on the microstructure of mortar depending on the amount of granite dust dosage is visible from the results of pore structure assessment. In this cement system with fine filler, granite dust does not isolate the surface of new phases and does not block the formation of compounds while it has contact with crystalline hydrates. This condition can be fulfilled by optimizing the volume fraction of the dispersion material in the mixed system. In the case of an inert filler, a volume comparable to the pore volume of capillaries may be the optimum quantity for filling cavities and compacting the structure. Hydration products settle on fine dust particles form in the crystallization center.

The "micro-particle effect" is based on the properties of fine particles that act as the centre of crystallization, i.e. accelerate the initial stage of chemical hardening. There are several points of view about the nature of the "micro-particle effect". According to one of them, the "micro-particle effect" is manifested by increasing the volume concentration of the fine filler, which leads to a decrease in the porosity of the hardened cement paste. However, if pozzolanic activity is manifested in any methods of addition of dust, the "micro-particle effect" – only when increasing the content of dispersed particles in the mixture [27]. At a high degree of filling after reaching its maximum, the strength of the concrete decreases, despite the continued decrease in the porosity of the hardened cement paste. Such curing conditions are also called "compressed" [28].

The introduction of granite dust results in a tighter microstructure of hardened mortar (Fig.5a) in comparison to dust-free mortar (Fig.5b). Granite dust fills free spaces between sand and cement grains. The resulting structure increases the strength both in the early and later stages of hardening.



a) b)

Fig. 5. Microstructure of cement paste with granite dust in amount 100 kg/m^3 of the mortar (a) and without (b) using granite dust at the age of 28 days (1000 times magnification)

4. CONCLUSIONS

On the basis of the test results of mortars containing granite dust, the following conclusions are made:

- Use of a granite powder in dry mortar mixes increases workability.
- Addition of granite dust to the composition together with superplasticizer and water retaining additive allows to improve the properties of the mixtures and regulate their characteristics in order to achieve the necessary properties of fresh and hardened mortar.
- Addition of granite dust in the amount of 50–100 kg/m^3 of mortar mixture increase the average compressive strength by 15–40%.
- The adhesion of the hardened mortars increases with a gradual increase in the proportion of granite dust.

- On the photos of the microstructure of hardened cement paste with granite dust obtained by scanning microscope is visible that the small particles act as center of crystallization, i.e. accelerate the initial stage of chemical curing.
- Addition of disperse granite dust in mortar mix can significantly decrease the porosity.
- Granite dust is useful as a component of dry cement mortar mixtures. In many cases, this allows to simplify the technology of producing such mortars in practice without compromising their quality.

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Tab. 5. Warunki planowania eksperymentu w kg na m^3 mieszanki zaprawy.

Tab. 6. Planning matrix and research results.

Tab. 6. Macierz planowania i wyniki badań.

PYŁ GRANITOWY JAKO KOMPONENT MINERALNY SUCHYCH MIESZANEK ZAPRAW CEMENTOWYCH

Słowa kluczowe: pył granitowy, zaprawa cementowa, wytrzymałość na ściskanie, wytrzymałość na zginanie, przyczepność, superplastyfikator

STRESZCZENIE:

Obecnie coraz bardziej powszechne staje się stosowanie suchych mieszanek zapraw cementowych. Ich użycie prowadzi do wzrostu wydajności i jakości pracy, obniżenia kosztów transportu i magazynowania oraz przyspieszenia procesów technologicznych. Jednym ze składników suchych mieszanek jest rozdrobiony wypełniacz, który bierze czynny udział w procesach twardnienia mieszanek. W warunkach niedoboru zasobów energetycznych, stopniowego wyczerpywania naturalnych surowców oraz zaostrzania problemów środowiskowych, ważnym kierunkiem w produkcji mieszanek jest rozwój zapraw wykorzystujących odpady z różnych działalności gospodarki. Badania wykazały, że jako wypełniacz można z powodzeniem stosować materiały o pochodzeniu antropogenicznym, takie jak pył granitowy, co jednocześnie pozwala na racjonalne rozwiązywanie problemów środowiskowych. Na właściwości reologiczne zapraw cementowych i mieszanek betonowych pozytywnie wpływa dodatek pyłu bazaltowego czy marmurowego, a nawet mączki wapiennej. Wytrzymałość zapraw cementowych na ściskanie zwiększa dodatek mączki granitowej i bazaltowej. Częściowa zamiana cementu pyłem marmurowym zwiększa wytrzymałość początkową zaprawy. Drobne kruszywo wypełnia przestrzeń między ziarnami piasku i tworzy sztywną strukturę, poprawiając szczelność oraz właściwości reologiczne zaprawy cementowej.

W zakładach kruszenia kamienia powstają duże ilości granitowego pyłu, który jest wychwytywany przez filtry rękawowe w czasie kruszenia granitu. Charakteryzuje się on dużą powierzchnią właściwą (220-250 m^2/kg) i nie wymaga suszenia. W wielu kamieniołomach pył granitowy nie jest obecnie wykorzystywany i zalega na składowiskach zanieczyszczając środowisko.

Jako materiały do badań zastosowano cement CEM II /A-S 42,5 N, pył granitowy, piasek kwarcowy, superplastyfikator typu polikarboksylowego, domieszkę zwiększająca więźliwość wody - eter celulozy i wodę. Przeprowadzono badania eksperymentalne przy zastosowaniu matematycznego planowania eksperymentu (MPE), który umożliwił algorytmizację wykonania eksperymentów według schematu. W celu skonstruowania liniowych i niekompletnych modeli kwadratowych zastosowano pełny eksperyment czynnikowy, w którym przedstawiono wszystkie możliwe kombinacje czynników na trzech poziomach. Wyniki eksperymentów zostały opracowane przy użyciu metod statystyki matematycznej, uzyskując równania regresji kwadratowej w postaci ogólnej.

W celu zbadania wpływu składu mieszanek zapraw na ich właściwości, przeprowadzono analizy z wykorzystaniem algorytmów zgodnie z trójpoziomowym czteroczynnikowym planem B4 (modelowanie matematyczne). Zmiennymi w tym planie były zawartość cementu (od 150 do 250 kg/m^3 zaprawy), zawartość pyłu granitowego (od 0 do 100 kg/m^3 zaprawy), zawartość superplastyfikatora (od 0,1 do 0,5% masy cementu) i zawartość domieszki eteru celulozy (od 1 do 2 kg/m^3). Parametrami wyjściowymi były: wytrzymałość na ściskanie, wytrzymałość na zginanie oraz przyczepność mieszanek do powierzchni elementów. Wyznaczono wytrzymałość na zginanie i ściskanie oraz przyczepność zapraw w

wieku 28 dni. Skaningową mikroskopię elektronową i mikroanalizę wykonano za pomocą mikroskopu skaningowego typu JSM-5500 LV. Całość podstawowych właściwości spoiwa i mieszanek zapraw uzyskanych na ich bazie została zbadana przy użyciu obowiązujących norm. Badanie wytrzymałości na zginanie było wykonywane na urządzeniu typu MII-100, wytrzymałości na ściskanie na prasie typu FP-100/1, a pryzczepność na Proceq DY-216 Pull-off Tester.

W każdym punkcie planu eksperymentu wykonano mieszanki zapraw, które dojrzewały przez 28 dni w komorze klimatycznej w temperaturze 20±5°C, przy wilgotności względnej 95±5%. Wytrzymałość zapraw na zginanie określono na trzech próbkach (40×40×160 mm), wytrzymałość na ściskanie – na 6 próbkach (polówkach beleczek po zginaniu). Badanie przyczepnośći wykonano metodą "pull-off", która polega na określeniu maksymalnego naprężeniea rozciągającego wywołanego przez obciążenie odrywające przyłożonego prostopadle do powierzchni zaprawy. Obciążenie odrywające jest przykładane za pomocą płytki odrywającej przyklejanej do powierzchni licowej badanej zaprawy.

Analiza statystyczna wyników badań posłużyła do uzyskania równań regresji badanych parametrów. Stwierdzono, że znaczący wpływ na wytrzymałość na ściskanie próbek ma zarówno ilość cementu, jak i ilość pyłu granitowego. Wprowadzenie pyłu granitowego do zaprawy cementowej powoduje wzrost wytrzymałości na ściskanie o 15–20% w porównaniu ze stwardniałymi zaprawami bez pyłu. Przy dalszym zwiększaniu ilości pyłu granitowego do 100 kg możliwe było uzyskanie zapraw o wytrzymałości o 30–40% wyższej, niż w przypadku próbek bez pyłu. Przy zastosowaniu 100 kg pyłu granitowego, najwyższe wartości wytrzymałości otrzymano stosując 250 kg cementu portlandzkiego, 0,5% superplastyfikatora i 1 kg eteru celulozy (f_{cm}=18,16 MPa). Wraz ze wzrostem zawartości cementu następuje wzrost przyczepności przy stopniowym zwiększaniu udziału pyłu granitowego. Wprowadzenie superplastyfikatora w ilości 0,4–0,45% masy cementu ma pozytywny wpływ na przyczepność, ale z dalszym wzrostem jego zawartości w zaprawie do 0,5%, przyczepność nieznacznie zmniejsza się przy minimalnej zawartości cementu i pyłu granitowego. Pozytywne wyniki uzyskuje się po zastosowaniu eteru celulozy - jego wpływ na przyczepność w porównaniu z zastosowaniem samego superplastyfikatora daje bardziej satysfakcjonujące wyniki, przy udziale tej domieszki wynoszącej 1,3–1,8 kg/m^3 zaprawy. Z obserwacji mikroskopowych wynika, że próbki z pyłem granitowego mają bardziej szczelną strukturę (zmniejszona ilość porów) w porównaniu do próbek, wykonanych bez dodatku pyłu, ponieważ pył granitowy wypełnia wolne przestrzeni pomiędzy ziarnami piasku i cementu.

Udowodniono eksperymentalnie możliwość otrzymywania zaprawy na bazie suchych mieszanek, gdy jako wypełniacz stosuje się pył granitowy. Wprowadzenie do zaprawy pyłu granitowego wraz z superplastyfikatorem i dodatkiem zatrzymującym wodę pozwala poprawić właściwości mieszanek i regulować ich właściwości w celu osiągnięcia niezbędnych wskaźników jakościowych. To w wielu przypadkach pozwala w praktyce uprościć technologię wykonania takich zapraw bez pogorszenia ich jakości. Otrzymane modele eksperymentalne i statystyczne właściwości wytrzymałościowych umożliwiają zaprojektowanie składów mieszanek zapraw cementowych modyfikowanych dodatkiem pyłu granitowego.

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