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Rational Compounds of Low-Strength Concrete with Improved Coefficient of Efficiency of Cement Use

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Abstract. The purpose of the research findings, given in article, is aimed to determine the rational compounds of concrete with an average cubic compressive strength less than 20 MPa with minimum required expenditures of cement. To reach the goal, mathematical planning of the experiment was used with variability of cement consumption from 90 to 190 kg / m^3 in the compositions of the concrete mixture, and for the fine-grained filler from tails of processed ores, the consumption was like at 100 to 400 kg / m^3. The result of processing experiments has shown us the dependences of the change in strength and coefficient of efficiency of the use of cement of the factors involved. Optimized values increase most intensively with minimum cement consumption and a change in the consumption of fine filler within the limits of the study. The highest coefficient of efficiency of use of cement is expressed by the ratio of the achieved strength per unit mass of used cement in the concrete mix and it was obtained at a cement consumption of 90 kg / m^3 and a filler of 400 kg / m^3. Using the obtained dependences of optimized values on the factors under study, the composition of concrete may be predicted with a strength up to 20 MPa with the required amount of filler.

1. Introduction

Environmental problems, in the twenty-first century, remain top priorities. Lack of timely decision-making may threaten the possibility of further comfortable human existence on the globe. One of the most important environmental problems is a significantly contaminated of the environment by secondary products of the industry because of the irrational non-integrated use of natural resources.

Furthermore, the high-energy intensity of products leads to the exhaustion of non-renewable natural resources. In addition, when they burn into the atmosphere, a substantial amount of carbon dioxide and other pollutants is released.

This problem is also important for the civil engineering complex. One of the main building materials for construction is concrete. By its rational use, it is possible to solve environmental problems to a large extent. This material will remain one of the main structural materials for the near future. The use of concrete is constantly increasing. As a part of concrete, the energy intensity of cement is approximately 70-80% of the total energy required to produce the concrete. The consumption for every ton of cement is about 290 kilograms of fuel equivalent and up to one and a half tons of carbon dioxide emits into the atmosphere (according to some data). Therefore, when we determine the compound of concrete, the main attention must be paid to the minimum necessary amount of cement to ensure the required physical and mechanical characteristics. It is necessary to raise the efficiency of the use of cement in concrete. Besides, it is important to utilize as much as possible secondary products of the industry, especially fine-grained ones, which occupy considerable areas of tailing pits and appear to be very dangerous to the environment.

2. Analysis of Literature Data and Problem Statement

Researchers give much attention to the design of concrete compositions that provide the required physical and mechanical characteristics of concrete for various structures and their operating conditions [8]. This is the key issue of Concrete Science. Concretes are composite materials, so the patterns of construction of their structure, the dependencies of the main physicomechanical characteristics of the compositions and structure are almost the same [1]. Many fundamental works are devoted to studying the influence of the structural features of concrete on the properties of concrete [3, 6, 12, 13]. An effective strand of ongoing research in order to improve the structure and properties of concrete is the use in their compositions of secondary products of industry [4]. The work [5], in which the authors justify the need and ways to reduce the energy intensity of concrete and other composite materials, belongs to the same strand. The author [9] recommends reducing the energy intensity of certain types of concretes by incorporating a significant amount of fine-grained secondary products of industry into their compositions that can pollute the environment. The same problem is proposed to be solved by the authors [2] in a much way of disposing of waste mining and processing plants in concrete. The modification of concrete by incorporating the complex additives, including through secondary products of the industry, provides a significant improvement of the properties of concrete [7, 10]. The publication [11] is devoted to the same problem, in which the authors propose a solution to similar problems for high-strength concrete. In the work [14], the regularities of the influence of a mixture of various mineral complexes, including using secondary products of the industry, on the most important characteristics of concrete are presented. The effect of superplasticizers on the properties of concrete mixes is very specific in concrete, derived from t secondary products of industry, including high-strength [15]. In addition, we have carried out studies on the effect of the number of input tailings of iron ore concentration on the properties of low-strength concrete [16, 17]. The above analysis of the results of the conducted research successfully solves the problem of improving the efficiency of the use of cement in concrete by using in them fine-grained secondary products of the industry. However, it is not possible to find a uniform regularity of their quantitative and qualitative application for the most effective increase in the efficiency of the use of cement in concrete with the maximum possible utilization of secondary products in them. This is due to the variety of properties of components used in concrete, including plasticizing agents. Therefore, it is necessary to solve such problems for certain types of components, determining their rational number depending on the required physical and mechanical characteristics of concrete. The solution of this problem is especially important for low-strength concrete, in which the efficiency of using cement is much lower than in medium and high-strength concrete. As a working hypothesis of the conducted research, one should accept the hypothesis about the expediency of ensuring a rational grain composition of the concrete mix components, which ensures the minimum voidness of the mixture. Consequently, in hardened concrete, it is possible to reduce the imperfection of the structure and the concentration of tensile stresses dangerous for concrete.

3. The goals and Objectives of the Study

The goal of the study is to determine the rational composition of concrete with an average cubic compressive strength less than 20 MPa with minimum required expenditures of cement. To achieve this goal, it is necessary to determine the required amount of filler from the tailings of iron ore in the concrete mix, by introducing which it is possible to ensure a rational granulometric composition of its components. To assess the effectiveness of the use of cement in the projected compositions of concrete, it is necessary to determine and analyze the coefficient of efficiency of use of cement, which expresses the ratio of the achieved concrete strength per unit consumption of cement in the concrete mix. In order to measure the effective use of cement in the projected compositions of concrete, it is necessary to determine and analyze the coefficient of efficiency of use of cement, which expresses the ratio of the achieved concrete strength per unit consumption of cement in the concrete mix.

4. Materials and Research Methods

4. 1. Materials and equipment used in experiments

In order to solve the problem, Krivoy Rog Portland Cement CEM 41.7 was used, coarse aggregate - crushed granite with a maximum grain size of 20 mm. Quartz river sand with an average rock density of 2630 kg / m^3, bulk density of 1550 kg / m^3, hollowness of 41%, size fraction is 1.56 was used as fine aggregate. The content of detrimental inclusions is within normal parameters. The results of the screening can be seen in table 1.

Table 1 The Results of sieving of the Dnieper river quartz sand

the remainder at sieves, %	Sizes of openings sievs, [мм]					
	2,5	1,25	0,63	0,315	0,14	less 0,14
Private	1,0	2,4	7,85	37,9	42,05	8,8
Complete	1,0	3,40	11,25	49,15	91,2	100

As a mineral additive, tailings of iron ore concentration at the Southern Mining and Processing Plant (GOK) were used, which met the required standards. The peculiarity of the tails of processed ores of the Southern Mining Plant is about that an uneven grain composition, which significantly depends on the place of their selection, may consist of both larger fractions belonging to fine aggregate (sand), and smaller, related to mineral additives fillers. The fractional composition of the tails of processed iron ores of the Southern Mining Plant, which was used in this experiment, is presented in table. 2, and the chemical composition is shown in table 3.

Table 2 Granulometric composition of the tails of processed iron ores of the Southern Mining Plant

Content in% by weight fractions size, [mkm]								
less 5	6-10	11-20	21-30	31-40	41-50	51-66	67-100	more than 100
4,13	3,54	7,93	15,71	19,7	12,41	11,48	15,39	9,71

Table 3 The chemical composition of the tails of processed iron ores of the Southern Mining Plant

Chemical composition, %					
SiO_2	Al_2O_3	FeO	Fe_2O_3	CaO	MgO
62,1	1,3	6,56	8,34	4,64	6,69

To improve the technological properties of the concrete mix, a complex additive of local proceeding PLCP-2 was used. This additive is made of the basis of secondary products of coke production. The additive mainly contains thiosulfates, radonides, sodium sulfates and some other substances. To improve the plasticizing properties, an additive C-3 was imposed. Experimental studies were conducted on certified equipment. The concrete mixture was stirred at a laboratory forced-action concrete mixer with a capacity of 25 liters. The components were doled out by mass, the mixing time of one batch with a volume of 7 liters was 3 minutes. Control samples of cubes with a side size of 10 cm were compacted on a standard laboratory vibroplatform with a vibration frequency of 50 Hz, an amplitude was in range of 0.35-0.5 mm. Compressive strength was evaluated by a standard method at 28 days old after hardening under standard conditions on a PSU-50 press.

4. 2. Methodology for measuring indicators of sample properties

The mathematical planning of the experiment with the subsequent processing of the test results was carried out. We took expenses on a cubic meter of concrete mix, which are cement (f1), tailings of iron ore concentration (f2), plasticizer PLCP-2 (f3) as variable factors. The range of variation of these three variables is presented in table 4, and the orthogonal plan of the experiment is given in table five. The optimized parameters are based on the average cubic strength of concrete samples of various compositions at the age of 28 days and the coefficient of efficiency of use of cement in these compositions.

Table 4 Variable factors

Code	Natural values		
	C, kg (f_1)	Tails, kg (f_2)	D, % (f_3)
-1	90	100	0,5
0	140	250	1,0
+1	190	400	1,5

Table 5 Orthogonal plan of the experiment

№ of experience	Variable factors		
	f_1	f_2	f_3
1	+1	+1	+1
2	+1	+1	-1
3	+1	-1	+1
4	-1	+1	+1
5	-1	-1	-1
6	-1	-1	+1
7	-1	+1	-1
8	+1	-1	-1
9	+1	0	0
10	-1	0	0
11	0	+1	0
12	0	-1	0
13	0	0	+1
14	0	0	-1
15	0	0	0

The evaluation of the mathematical model of the experiment and the construction of graphical dependencies was done by using a special program. The equation that can describe the three-factor model is:

$$Z_1(f_2,\ f_3)=b_1+b_2\cdot f_1+b_3\cdot f_2+b_3\cdot f_2+b_4\cdot f_3+b_5\cdot f_1^2+b_6\cdot f_2^2+b_7\cdot f_3^2+b_8\cdot f_{12}+b_9\cdot f_{13}+b_{10}\cdot f_{23} \quad (1),$$

where Z – model response (optimized parameter);

b_1 – polynomial free member;

b_i– coefficients for individual members of the polynomial;

f_i – variable factors in code form.

All the coefficients of this polynomial for orthogonal planning are not only determined, but also evaluated independently of each other. After determining the coefficients of the model, the adequacy (identity) of the process description by a third degree polynomial by the F criterion (Fisher criterion) was checked. To analyze the obtained polynomials of the third degree (1), nomograms were constructed, representing the isopole and isolines of the dependence of the optimized characteristics on variable parameters (fig. 1, 2).

5. The results of the Study of the Strength of Concrete and the Effectiveness of the Use of Cement

According to the above presented orthogonal plan, 15 batches were formed into three cube samples with a side size of 10 cm. Samples were tested at 28 days old after hardening under standard conditions. Visual observations of the process of preparation and molding of samples noted that in samples with a total content of cement and filler 190 and 240 kg / m^3 per cubic meter of concrete mix water separation was observed, they were compacted much worse than samples of other compositions. Most easily and quickly compacted samples that were molded from concrete mixes with a total content of cement and filler more than 500 kg per cubic meter of concrete mix.

The test results of all 15 series of samples can be seen in table 6

Table 6 The compositions and results of testing samples of concrete

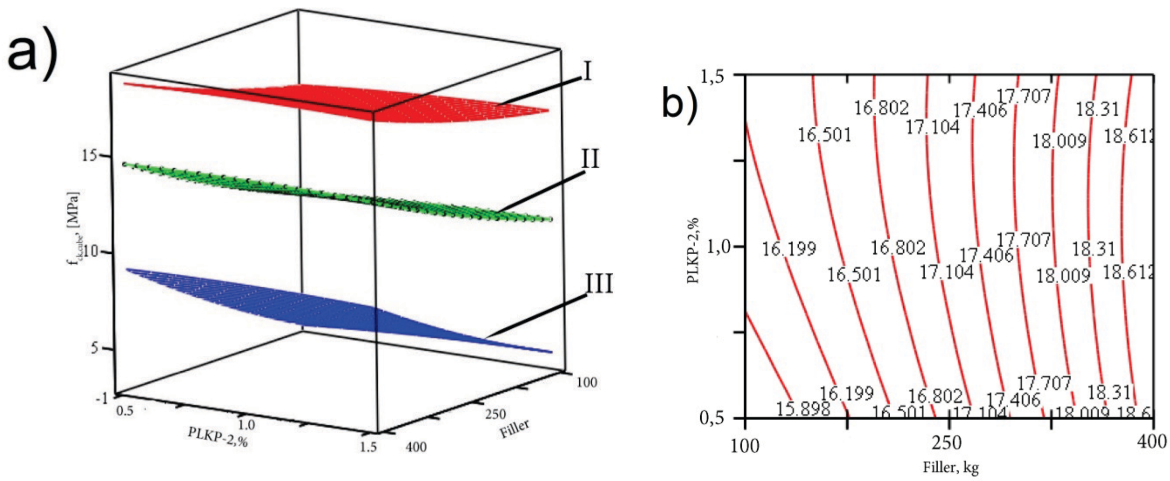
№ of composition	Material consumption per m3, kg						Density,kg/м^3		$f_{ck,cube}$, [MPa]	$f_{ck,cube}$C
	C	F	R	S	W	PLKP-2,%	fresh.	hard.		
1	190	400	1150	500	190	1,5	2410	2395	18,5	0,97
2	190	400	1150	500	190	0,5	2396	2381	19,1	1,0
3	190	100	1250	700	190	1,5	2341	2322	16,3	0,86
4	90	400	1150	600	190	1,5	2385	2371	9,5	1,05
5	90	100	1250	800	190	0,5	2274	2261	3,5	0,39
6	90	100	1250	800	190	1,5	2285	2278	3,4	0,38
7	90	400	1150	600	190	0,5	2396	2379	9,1	1,01
8	190	100	1250	700	190	0,5	2381	2375	15,2	0,8
9	190	250	1150	650	190	1,0	2418	2391	17,5	0,92
10	90	250	1250	650	190	1,0	2345	2326	5,7	0,63
11	140	400	1150	550	190	1,0	2397	2378	14,3	1,02
12	140	100	1250	750	190	1,0	2328	2311	10,7	0,76
13	140	250	1250	600	190	1,5	2391	2378	12,4	0,88
14	140	250	1250	600	190	1,0	2389	2375	11,8	0,84
15	140	250	1250	600	190	0,5	2397	2379	12,5	0,89

According to the table. 6 test results of samples The calculation of mathematical models of the experiment was made and third-degree polynomials (1) were obtained for optimized average strength of samples at the age of 28 days and the coefficient of efficiency of using cement. The coefficients of the polynomials for each of the optimized parameters - the average strength at 28 days old ($f_{ck,cube}$, MPa) and the coefficient of efficiency of cement use ($10f_{ck,cube}$ / C) are presented in table. 7

Table 7 Polynomial coefficients (1) optimized average strength at 28 days old (fck, cube, MPa) and cement efficiency ratio (10fck, cube / C)

Optimized parameters	Polynomial coefficients (1)									
	b_0	b_1	b_2	b_3	b_1^2	b_2^2	b_3^2	b_{12}	b_{13}	b_{23}
$f_{ck,cube}$ [MPa]	12,278	5,54	2,14	0,14	-0,622	0,278	-0,122	-0,7	0,025	-0,15
$10f_{ck,cube}$/C	0,063	-0,11	0,014	$2{,}4\cdot 10^{-3}$	$7{,}778\cdot 10^{-4}$	$1{,}278\cdot 10^{-3}$	$7{,}778\cdot 10^{-4}$	$7{,}5\cdot 10^{-4}$	$10\cdot 10^{-4}$	$7{,}5\cdot 10^{-4}$

Graphical dependences of concrete strength on variable factors, obtained from the results of calculations of mathematical models of the experiment and the obtained third-degree polynomial (1) are presented in fig.1. And graphical dependence of the coefficient of efficiency of use of cement from variable factors, obtained from the results of calculations of mathematical models of the experiment and the resulting polynomial of the third degree (1) are presented in fig. 2



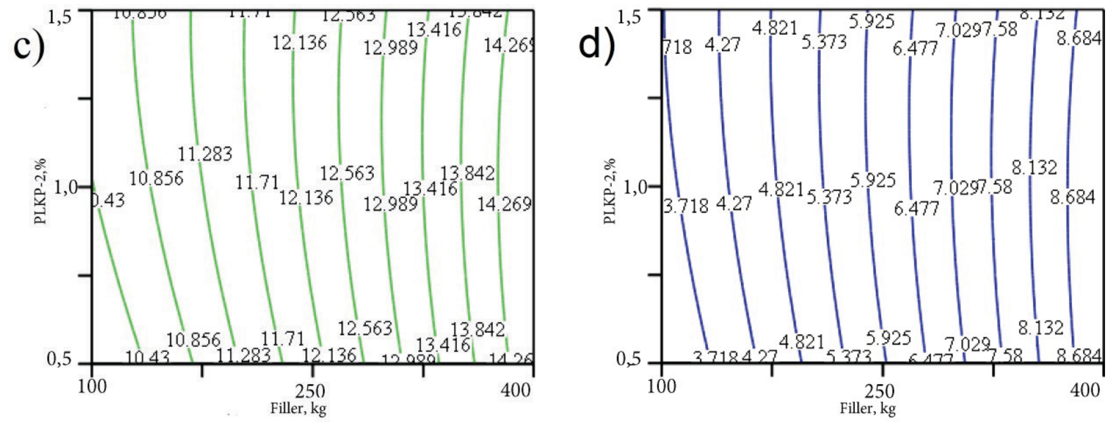
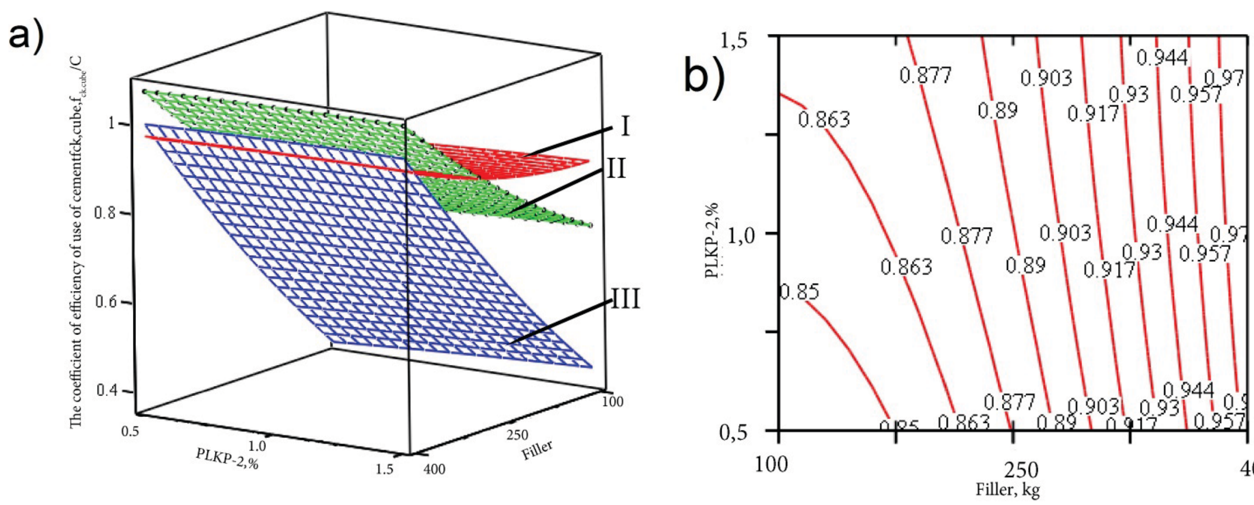


Fig. 1. Dependences of durability of concrete on the varied factors: a) - to isoplane durability of concrete : I - at the expense of cement 190 kg on the cubic meter of concrete mixture; II - the same 140 kg; III - the same 90 kg; b) are isolines of durability of concrete at the expense of cement 190 kg on the cubic meter of concrete mixture; c) - the same 140 kg; d) - the same 90 kg

Presented in fig. 1 and 2, the graphical dependencies of the optimized values on variable factors make it possible to determine the main laws governing the increase in the efficiency of the use of cement when disposing of local secondary products of industry in concrete.

6. Discussion of the Results of Studies of Concrete Strength

By results of the analysis presented in fig. 1 and fig. 2 graphical dependencies of the values to be optimized on variable factors, we can determine the following patterns. The strength of concrete is most dependent on the consumption of cement in the concrete mixture and increases significantly as its content increases in the studied limits (see fig. 1, a). But with the maximum content of cement in the concrete mix, the strength of concrete with increasing content of filler in the concrete mix increases to a much lesser extent than with a minimum cement content in the studied limits. The strength of concrete, and accordingly the coefficient of efficiency of use of cement, with an increase in the content of filler in the investigated range increases the more, the lower the cement content in the composition of the concrete mix. So, when the cement content in the concrete mix is at 190 kg / m^3 and the filler content increases from 100 to 400 kg / m^3, the strength of concrete and, accordingly, the efficiency of cement use increases at about 16% (see fig. 1, b and 2, b). And when the content of cement in the concrete mix is at 90 kg / m^3 and the increase in the content of filler in the same range, the concrete strength, and, accordingly, the efficiency ratio of cement use, increases by about 2.3 times (see fig. 1, d and fig. 2 , d).



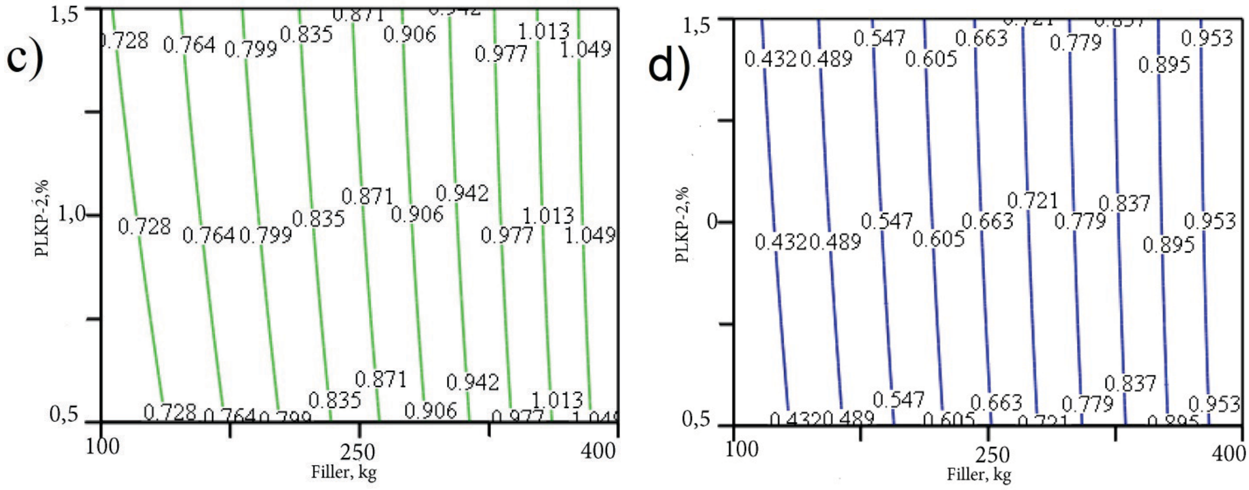


Fig. 2. Dependences of coefficient of efficiency of the use of cement on the varied factors: a) - isoplanes coefficient of efficiency of the use of cement : I - at the expense of cement 190 kg on the cubic meter of concrete mixture; II - the same 140 kg; III - the same 90 kg; b) are isolines of coefficient of efficiency of the use of cement at the expense of cement 190 kg on the cubic meter of concrete mixture; c) - the same 140; d) - the same 90 kg

The highest efficiency ratio of cement use, at any consumption of the latter within the limits considered, is observed in compositions with a total consumption of cement and filler of about 500 kg per cubic meter of concrete mix and more. And the increase in the efficiency ratio of cement use is the largest (approximately 2.2 times) in compositions with a cement consumption of 90 kg / m^3 and an increase in filler consumption from 100 to 400 kg per cubic meter of concrete mix (see fig. 2, a and fig. 2, d). Explain the results obtained from the standpoint of structural theories of concrete strength. In compositions with a filler consumption of 100 kg per cubic meter of concrete mix, even with cement consumption of 190 kg, and even more so 90 kg per cubic meter of concrete mix, there is an insufficient amount of the smallest component. Because of the irrational grain composition of the components, it is impossible to obtain its dense packing; therefore, the concrete has an increased defect structure. This leads to a significant concentration of stresses near these structural defects and destruction at lower external loads than in concrete with a filler consumption of 400 kg per cubic meter of concrete mix. In the latter case, the grain composition of the components of the concrete mix is close to rational, therefore, the defect structure and stress concentration is much less. Therefore, the strength and efficiency of the use of cement in these concretes is higher than in compositions with a filler consumption of about 100 kg per cubic meter of concrete mix. Concrete mixes with a high utilization rate of cement of the investigated range can only be used in non-reinforced reinforced concrete structures. For example, in accordance with the requirements of DSTU B.V.2.6-108: 2010 for the construction of foundations, basement walls, standard foundation blocks are not reinforced and must have strength with security of 95% from 3.5 to 15 MPa, therefore, the average cube strength with with a side size of 10 cm from 5 to 20 MPa. Significant volumes of concrete with an average strength of about 5 MPa are also required for the underlying layer for foundations, floor slabs with their formless plates the underground floors and some other similar structures. When designing the compositions of such concretes, it is necessary to use the obtained research results, providing savings of cement and disposing of a significant amount of fine-grained secondary products of the industry.

7. Conclusions

The compositions of concrete with an average strength of less than 20 MPa with an increased coefficient of efficiency in the use of cement must be obtained by introducing the required amount of fine-grained filler from secondary products of the industry. To provide the raised efficiency ratio for the use of cement, it is necessary for the total content of cement and fine-grained aggregate to be doled out at 500-550 kg per cubic meter of concrete mix. The implementation of the proposed formulations provides significant savings in cement and the disposal of a significant amount of secondary products of the industry. Hence, in this way it is possible to successfully solve topical problems of reducing the energy intensity of concrete and environmental pollution.

8. Summary

The purpose of the research findings, given in article, is aimed to determine the rational compounds of concrete with an average cubic compressive strength less than 20 MPa with minimum required expenditures of cement. To reach the goal, mathematical planning of the experiment was used with variability of cement consumption from 90 to 190 kg / m^3 in the compositions of the concrete mixture, and for the fine-grained filler from tails of processed ores, the consumption was like at 100 to 400 kg / m^3. The result of processing experiments has shown us the dependences of the change in strength and coefficient of efficiency of the use of cement of the factors involved. Optimized values increase most intensively with minimum cement consumption and a change in the consumption of fine filler within the limits of the study. The highest coefficient of efficiency of use of cement is expressed by the ratio of the achieved strength per unit mass of used cement in the concrete mix and it was obtained at a cement consumption of 90 kg / m^3 and a filler of 400 kg / m^3. Using the obtained dependences of optimized values on the factors under study, the composition of concrete may be predicted with a strength up to 20 MPa with the required amount of filler.

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