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Research paper

Management of the Properties of Shipbuilding Expanded Clay Lightweight Concrete

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Abstract

The purpose of the research was to improve the strength and durability of shipbuilding expanded clay lightweight concrete by using modifiers, fibers and optimizing the composition of concrete. The four-factor experiment was carried out according to the optimal plan. The experiment varied, the amount of sulfate-resistant Portland cement, silica fume and polypropylene fiber. The content of expanded clay gravel in concrete also varied. Strength, watertighness, frost resistance and average density of ship-building expanded clay lightweight concrete of various compositions are investigated. The rational quantity of modifiers and fibers is determined. It is shown that shipbuilding expanded clay concrete has high watertighness and frost resistance, which ensures their durability when operating afloat. The use of lightweight concrete allows increasing the load carrying of floating structures and improving the working conditions of personnel. Normative documents for the production of concrete for floating reinforced concrete structures in Ukraine have been developed.

Keywords: *expanded clay, experimental-statistical modeling, lightweight concrete, modifiers, reinforced concrete ships.*

1. Introduction

Reinforced concrete vessels and floating structures are being built in different countries for about a hundred years [1]. Presently, mainly large floating structures are being constructed from reinforced concrete: floating docks and berths, oil and gas platforms, houseboats and hotels [2]. Floating structures are operated in the seas and other water bodies in different climatic conditions. They are subjected to a constant water pressure, periodic freezing and thawing, heating and cooling, acting sulfates and microorganisms, dynamic influences of waves and ice. In such difficult conditions, reinforced concrete floating structures are much more durable than metal. Moreover, reinforced concrete structures require repairs much less often than metal [3].

For the construction of floating concrete structures, heavy and lightweight shipbuilding concrete are used. In recent years, lightweight concrete has been increasingly used. International Federation for Structural Concrete (fib) in 1995 formulated recommendations on the full transition to the using in the construction of floating oil platforms of high-strength lightweight concrete [4]. For such concrete it is recommended to use artificial porous aggregates, as well as natural porous aggregates from volcanic or sedimentary rocks.

Ukraine is one of the few countries that possess technology of reinforced concrete shipbuilding. At the Kherson factory of reinforced concrete shipbuilding "Pallada" floating docks, hotels and berths on reinforced concrete pontoons today are under construction [5]. Figure 1 shows a floating composite dock built at the Pallada plant. The dock consists of a reinforced concrete pontoon and metal towers.

Fig. 1: Floating dock on a reinforced concrete pontoon, built at the Pallada plant

In Ukraine there is also experience of using shipbuilding expanded clay lightweight concrete. In the 70s of the last century several expanded clay concrete floating docks were built, which showed high durability during exploitation in different seas [3]. For reinforced concrete floating structures (docks, hotels, houses, berths, oil and gas production platforms), using lightweight concrete allows reducing their weight, thereby increasing the carrying capacity. In addition, the use of such materials improves the comfort of people's stay and the operating conditions of equipment in the premises of a floating structure.

2. Materials and Methods

Properties of shipbuilding expanded clay lightweight concrete have been investigated. The 4-factor experiment was carried out according to the 18-point optimal plan [6]. In the experiment, the following factors of the composition of expanded clay concrete varied:

X_1 – amount of sulphate-resistant Portland cement, from 500 to 600 kg/m^3;

X_2 – the amount of silica fume, from 0 to 40 kg/m^3;

X_3 – percentage of expanded clay gravel in concrete from 650 to 700 l/m^3;

X_4 – amount of polypropylene fibers Baucon (diameter 18.7 µm, length – 12 mm.), from 0 to 1,2 kg/m^3.

The plan of the experiment is shown in the table 1.

Table 1: Plan of the experiment

№ plan point	Levels of factors			
	x_1 (cement)	x_2 (silica fume)	x_3 (expanded clay gravel)	x_4 (fiber)
1	0	0	0	0
2	-1	-1	1	-1
3	-1	1	-1	1
4	1	-1	-1	1
5	1	1	1	1
6	1	1	-1	-1
7	0	1	1	-1
8	0	-1	-1	-1
9	0	-1	1	1
10	1	0	1	-1
11	-1	0	-1	-1
12	-1	0	1	1
13	1	-1	0	-1
14	-1	1	0	-1
15	-1	-1	0	1
16	1	-1	1	0
17	-1	1	1	0
18	-1	-1	-1	0

All mixtures had equal concrete-mix consistency P2 (cone slump from 6 to 8 cm), which by selecting the amount of water was achieved. In all mixtures superplasticizer S-3 was introduced in the amount of 0,8 % of the mass of cement, which was taking into account the results of previous researches [7]. The amount of silica sand in the mixture was adjusted according to the quantity of other components (gravel, cement, silica fume, water, fiber) to provide the same volume of all investigated concretes. Namely, the factor X_3 actually showed the spreading action of granules of a coarse aggregate. As a coarse porous aggregate, expanded clay produced by the Odessa Keramzite factory of 5-10 mm grade with packed density of gravel 550 kg/m^3 of grade P125 was used. As a fine aggregate – the silica sand with Mcr=2.4. As a binder – sulphate-resisting Portland cement SRPC 400.

Compositions of 18 expanded clay concrete, which were investigated in the experiment according to the plan shown in table 1, are given in table 2. Paddling of the mixtures was carried out with preliminary treatment of the gravel with a cement suspension, which was carried out as follows. Water was added to the mixer with additive and cement. After one minute of mixing this mixture, a cement suspension was formed, and further, expanded clay was giving into the mixer and mixing was continued for another two minutes. Quartz sand was added last to the mixer and the mixture was mixed until homogeneity. This technology of preparation provided hardening of the surface layer of a large porous aggregate and the transitive zone between the aggregate and a soluble part of concrete [8].

Table 2: Compositions of 18 expanded clay lightweight concrete, which were investigated in the plan shown in Table 1

№	Compositions of expanded clay lightweight concrete						
	Cement (kg/m^3)	Expanded clay (l/m^3)	Sand (kg/m^3)	Silica fume (kg/m^3)	Fiber (kg/m^3)	S-3 (kg/m^3)	Water (l/m^3)
1	550	675	638	20	0,6	4,4	186
2	500	700	675	0	0	4	176
3	500	650	697	40	1,2	4	186
4	600	650	660	0	1,2	4,8	205
5	600	700	538	40	1,2	4,8	211
6	600	650	609	40	0	4,8	206
7	550	700	597	40	0	4,4	196
8	550	650	689	0	0	4,4	188
9	550	700	646	0	1,2	4,4	191
10	600	700	561	20	0	4,8	204
11	500	650	723	20	0	4	186
12	500	700	653	20	1,2	4	189
13	600	675	605	0	0	4,8	204
14	500	675	666	40	0	4	180
15	500	675	717	0	1,2	4	180
16	600	700	583	0	0,6	4,8	205
17	500	700	631	40	0,6	4	187
18	500	650	745	0	0,6	4	182

3. Results and Discussion

As noted above, all mixtures had concrete mix consistency P2, which meets the requirements of the technology of reinforced concrete shipbuilding. Accordingly, water demand and W/C ratio of light concrete mixtures depended on their composition. Similarly, the rest of the properties depended of the concrete composition. Levels of W/C ratio, compressive strength ($f_{ck.cube}$), bending tension strength (f_{ctk}), watertighness (W) and average density of expanded clay lightweight concrete (in the dry condition) at the experimental points are given in Table 3.

Table 3: The properties of 18 investigated in the experiment of shipbuilding expanded clay lightweight concrete compounds

№	W/C	$f_{ck.cube}$ (MPa)	f_{ctk} (MPa)	W (atm)	Average density (kg/m^3)
1	0,339	41,4	6,76	12	1755
2	0,352	34,6	5,87	8	1696
3	0,371	37,1	6,35	8	1701
4	0,341	41,5	6,94	10	1750
5	0,351	41,9	7,10	12	1756
6	0,343	43,1	6,83	14	1785
7	0,356	38,6	6,57	12	1716
8	0,342	38,4	6,49	12	1758
9	0,347	38,3	6,64	10	1729
10	0,340	41,7	7,01	14	1760
11	0,372	35,8	5,93	10	1726
12	0,378	36,4	6,14	8	1695
13	0,340	41,7	6,89	12	1734
14	0,359	37,2	5,97	10	1721
15	0,359	35,5	6,01	8	1707
16	0,342	40,9	6,98	10	1727
17	0,373	35,6	6,04	8	1724
18	0,364	35,1	5,97	8	1737

According to the data obtained at 18 experimental points, an experimentally static (ES) model of the influence of four composition factors on the W/C mixture of equal mobility was created. When creating the model, the transition from the full-scale values of the variables to the coded ones in the range from -1 to +1 [6]. Insignificant coefficients were reduced in the construction of the ES-model:

$$\begin{aligned} W/C = 0{,}340 &- 0{,}012x_1 + 0{,}008x_1^2 - 0{,}002x_1x_2 \pm 0x_1x_3 - 0{,}002x_1x_4 \\ &+ 0{,}003x_2 \pm 0x_2^2 + 0{,}003x_2x_3 \pm 0x_2x_4 \\ &\pm 0x_3 + 0{,}008x_3^2 + 0{,}003x_3x_4 \\ &+ 0{,}002x_4 \pm 0x_4^2 \end{aligned} \quad (1)$$

According to the ES-model (1), one-factor dependencies were constructed, reflecting the effect of varying composition factors in the maximum and minimum zones on the W/C. These diagrams are shown in Fig 2. When creating diagrams, the levels of three factors, not reflected in each of them, were fixed on the values that provide the maximum and minimum value of the W/C mixture. Namely, all the dependencies in Fig. 2 pass through the zones of the maximum and minimum W/C [6].

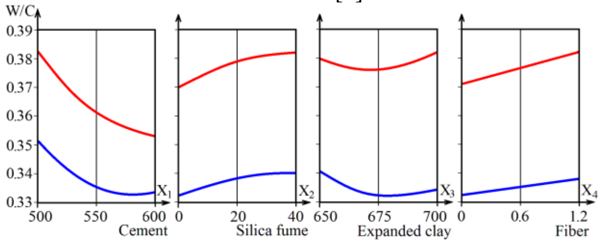

Fig. 2: Influence of variable composition factors on W/C lightweight concrete mixtures of equal mobility in the zones of minimum and maximum

As can be seen from the diagrams, within the experimental space of the experiment, the greatest effect on W/C mixtures is provided by the amount of Portland cement. The content of expanded clay gravel and the amount of polypropylene fiber have the least impact on W/C. As the amount of fiber grows in the composition (as a fiber reinforcement), the W/C mixture increases linearly. However, even with the maximum amount of fiber (1,2 kg/m^3), the W/C increases by only 4%. Accordingly, for a more detailed analysis of the effect of the amount of Portland cement, silica fume and the content of expanded clay gravel on the W/C of lightweight concrete mixtures according to the ES-model (1), a diagram was created in the form of a cube in Fig. 3. When it was created, the amount of polypropylene fiber was fixed at an average level of 0,6 kg/m^3 (x_4 = 0 in coded form).

Analysis of the diagram shown in Fig. 3 shows that with an average content of expanded clay gravel (660-680 l/m^3), the W/C of the mixtures investigated was the smallest. This is explained by the fact that when the content of expanded clay gravel changed, the amount of sand in the composition of concrete proportionally changed to ensure an equal volume of material. Namely, with an increase in the content of expanded clay gravel, the expansion of the coarse aggregate in the mixture was reduced by reducing the amount of sand. On the W/C mixture of equal mobility affects the amount of porous gravel and quartz sand in the mixture, and the ability of the components of the mixture to move during laying. Accordingly, for the mixtures studied, the best ability to move the components was at an average expended clay gravel content. This, in turn, makes it possible to obtain a more cohesive structure and better physical and mechanical properties of lightweight concrete.

With an increase the amount of Portland cement, the W/C mixture is expected to decrease, and when silica fume is introduced, it increases insignificantly. In general, all the mixtures studied in this experiment had a sufficiently low W/C (0,38 and lower) due to the use of a rational amount of superplasticizer S-3 - 0.8% of the binder mass.

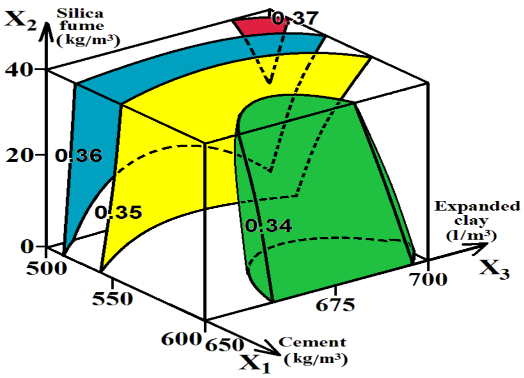

Fig. 3: Effect of Portland cement, silica fume and expanded clay gravel content in concrete on W/C of lightweight concrete mixtures of equal mobility

The ES-model, which describes the effect of 4 variable composition factors on the strength of expanded clay lightweight concrete under compression, has the form:

$$\begin{aligned} f_{ck.cube}\,(\text{MPa}) = 41{,}3 &+ 3{,}2x_1 - 0{,}6x_1^2 \pm 0x_1x_2 - 0{,}2x_1x_3 \pm 0\,x_1x_4 \\ &+ 0{,}8x_2 - 0{,}8x_2^2 - 0{,}3x_2x_3 + 0{,}1x_2x_4 \\ &- 0{,}5x_3 - 1{,}1x_3^2 \pm 0\,x_3x_4 \\ &+ 0{,}3x_4 - 0{,}3x_4^2 \end{aligned} \quad (2)$$

The analysis of the influence of concrete composition on compressive strength (2) showed that for the investigated concrete was in the range of 34 to 45 MPa. On the compressive strength compression of modified expanded clay lightweight concrete, the amount of polypropylene fibers practically does not affect and when changing the factor x_4 within the factor space of the experiment, the value of $f_{ck.cube}$ will change no more than 1 MPa. The effect of low impact of fiber reinforcement on the strength of concrete compression is well known in building material science, however, the main purpose of the use of fiber is to improve other composite quality indicators. To analyze the influence of the amount of Portland cement, silica fume and expanded clay gravel content in concrete on its strength under compression using the ES-model (2), a diagram in the form of a cube was drawn in Fig. 4. On the diagram the amount of polypropylene fiber was fixed at an average of 0,6 kg/m^3 (x_4=0).

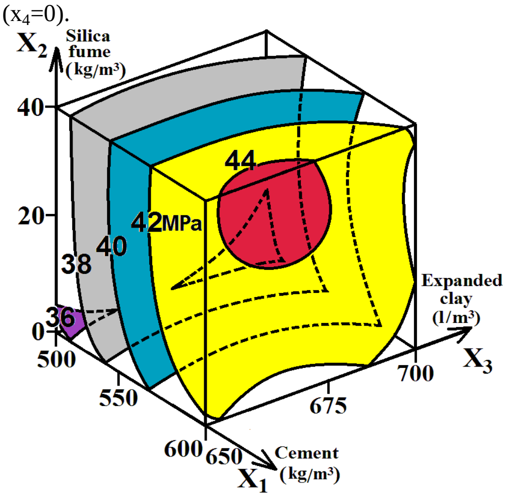

Fig. 4: Effect of Portland cement, silica fume and expanded clay gravel content on the compressive strength of expanded clay lightweight concrete

The analysis of this diagram shows that as the Portland cement increases, the strength of expanded clay concrete naturally increases. The addition of silica fume in the amount of 35-38 kg/m^3 increases the strength of lightweight concrete by 2-2,5 MPa. Due to the variation of the expanded clay gravel consist, the strength of the investigated lightweight concrete varies by up to 1,5 MPa. The greatest strength has mixtures with expanded clay gravel content of 660-680 kg/m^3, which corresponds to a lower W/C mixture.

The influence of the varied factors of the modified expanded clay lightweight concrete on its bending tension strength is described by the following ES-model:

$$\begin{aligned} f_{ctk}\,(\text{MPa}) = 6{,}76 &+ 0{,}47x_1 - 0{,}17x_1^2 - 0{,}03x_1x_2 + 0{,}03x_1x_3 - 0{,}02x_1x_4 \\ &+ 0{,}06x_2 - 0{,}07x_2^2 - 0{,}02x_2x_3 + 0{,}04x_2x_4 \\ &\pm x_3 - 0{,}02x_3^2 \quad 0{,}04x_3x_4 \\ &+ 0{,}10x_4 - 0{,}02x_4^2 \end{aligned} \quad (3)$$

The analysis of ES-model shows that within the framework of a multivariate experiment, the gravel content, that is variation of grains of the porous aggregate, practically does not affect the bending tensile strength of the investigated expanded clay lightweight concrete. This can be explained by the ability to withstand the tension stresses of the soluble part of the concrete and porous gravel. Accordingly, for a more detailed analysis, the effect of the amount of Portland cement, silica fume and polypropylene fibers on tensile bending tension of the investigated expanded clay lightweight concrete for (3) was drawn in Fig. 5, the diagram is in the form of a cube. When it was drawn, the gravel content in concrete was fixed at the average ($x_3 = 0$).

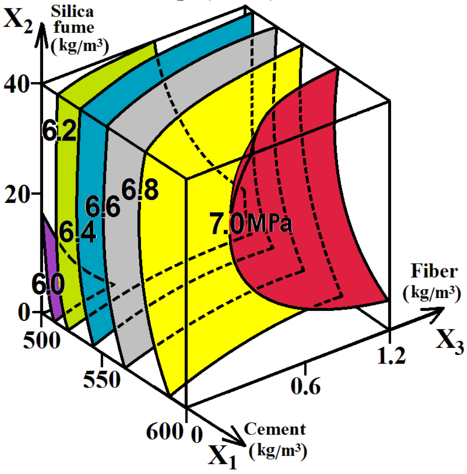

Fig. 5: Effect of Portland cement, silica fume and polypropylene fibers on the tensile strength of expanded clay lightweight concrete

The analysis of the diagram shows that, as the Portland cement increases, the tensile strength of the bending of the expanded clay lightweight concrete naturally increases, although this effect has a nonlinear appearance. The addition of silica fume in the amount of 30-35 kg/m^3 is insignificant, at 0,2-0,3 MPa, increases the strength of lightweight concrete to extension. Due to the use of disperse reinforcement, the value of f_{ctk} of investigated concrete increases by about 0,3 MPa, which can be considered as a positive, but rather limited result. The effect of increased tensile strength of expanded clay lightweight concrete in the use of fibers can be attributed to the rather good work of composites on porous fillers in tension. This is due, first of all, to the good adhesion of the cement paste (soluble component) to the filler. Accordingly, additional techniques, in particular, fiber reinforcement, in comparison with heavyweight concrete, have a lower effect to increase the strength of lightweight concrete in tension. Though in general, the positive effect of fiber remains.

Since ensuring the durability of shipbuilding expanded clay lightweight concrete was one of the main tasks of the studies, the experiments determined the watertightness and frost resistance of these materials. The ES-model, which describes the effect of variable composition factors on the watertightness of modified expanded clay-concrete, looks like:

$$\begin{aligned} W\ (atm) = 11{,}9 &+ 1{,}8x_1 - 1{,}2x_1^2 + 0{,}4x_1x_2 + 0{,}1x_1x_3 - 0{,}1x_1x_4 \\ &+ 0{,}7x_2 - 0{,}9x_2^2 \pm 0x_2x_3 \pm 0x_2x_4 \\ &- 0{,}2x_3 - 0{,}5x_3^2 \pm 0x_3x_4 \\ &- 0{,}8x_4 + 0{,}5x_4^2 \end{aligned} \qquad (4)$$

It should be noted that the accuracy of the ES-model (4) is significantly limited due to the discrete technique of determining the grade of watertightness. Values of grade W, which actually shows pressure in the atmosphere, according to the technique can only be even. However, this does not affect the general trends in the influence of factors that varied.

Analysis of the ES-model (4) shows that the amount of polypropylene fiber does not significantly affect the watertightness of expanded clay lightweight concrete. It can be noted that the compositions of lightweight concretes with fiber have a W level slightly lower than those without fiber. However, the oscillations of the exponent W practically do not differ from the accuracy of its measurement. The greatest influence on the watertightness of the material is provided by the amount of Portland cement. For a more detailed analysis of the effect of the amount of Portland cement, silica fume and the content of expanded clay gravel on the watertightness of expanded clay concrete, a diagram was created according to (4), which is shown in Fig. 6. While creating the diagram, the factor level x_4 was fixed at the minimum value ($x_4 = -1$).

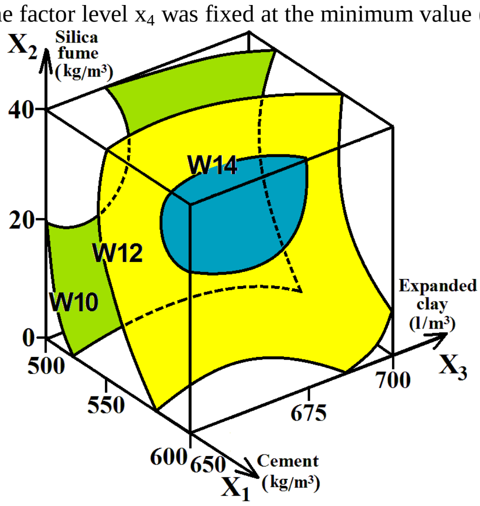

Fig. 6: Effect of Portland cement, silica fume and expanded clay gravel content on the watertightness of expanded clay lightweight concrete

As can be seen from the diagram, the watertightness of concrete varied in the range from W8 to W14. A sufficiently high level of this indicator is ensured by the introduction of a rational amount of superplasticizer S-3 (0.8% of the mass of cement) into all compositions. With an increase in the amount of cement from 500 to 600 kg/m^3, the watertightness of concrete grows by more than one grade. Due to the introduction of silica fume into the composition of 30-38 kg/m^3, the watertightness of expanded clay concrete increases by almost one grade. The content of expanded clay gravel, which actually shows the expansion of a large aggregate in the mixture, affects the level of W not very significantly. At the same time, the maximum watertightness was observed with the amount of gravel 660-670 l/m^3. Thus, the watertightness of the modified shipbuilding expanded clay lightweight concrete makes it possible to ensure their high durability. Fig. 7 shows a photo of a sample of a cylinder with a diameter and a height of 15 cm, which was split in half after the watertightness test. The photo clearly shows the fusion and homogeneity of the structure of shipbuilding expanded clay lightweight concrete. The white line shows the front of water advancement in the sample at a pressure of 10 atmospheres.

Also, researches have shown that the frost resistance of modified shipbuilding expanded clay concrete was in the range from F400 to F600, which ensures the durability of these concrete during freezing and thawing. By introducing polypropylene fiber, the frost resistance of lightweight concrete increases by approximately 50 cycles. Also, for approximately 50 cycles, the frost resistance of expanded clay lightweight concrete increases with the introduction of 30-35 kg/m^3 of silica fume.

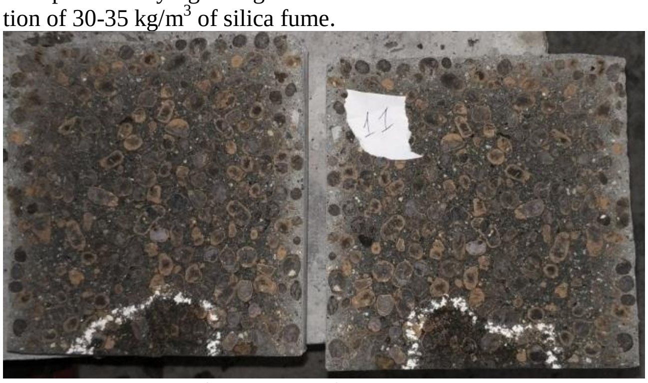

Fig. 7: An example of a structure of shipbuilding expanded clay lightweight concrete (a cylinder that was split in half after a watertight test)

As noted above, one of the main reasons for the use of lightweight concrete in shipbuilding is the reduction in the weight of reinforced concrete structures. Accordingly, within the framework of the studies, the average density of modified expanded clay lightweight concrete was investigated. The ES-model, which describes the effect of varying factors of composition on the average density of expanded clay lightweight concrete (in a state dried up to a constant mass) has the form:

$$\rho\ (kg/m^3) = 1733{,}7 + 19{,}8x_1 - 17{,}6x_1^2 + 7{,}3\ x_1x_2 \pm 0x_1x_3 \pm 0x_1x_4 + 6{,}8x_2 - 6{,}9x_2^2 \pm 0x_2x_3 \pm 0x_2x_4 - 10{,}3x_3 + 6{,}8x_3^2 \pm 0x_3x_4 - 4{,}5x_4 \pm 0x_4^2 \quad (5)$$

Analysis of the ES-model (5) shows that the amount of polypropylene fiber does not significantly affect the average density of shipbuilding expanded clay lightweight concrete. The coefficients at the factor x_4 are the smallest. To analyze the effect of the amount of Portland cement, silica fume and the content of expanded clay gravel on the average density of expanded clay concrete, a diagram was created according to (5), which is shown in Fig. 8. When creating the diagram, the factor level x_4 was fixed on the average value ($x_4 = 0$).

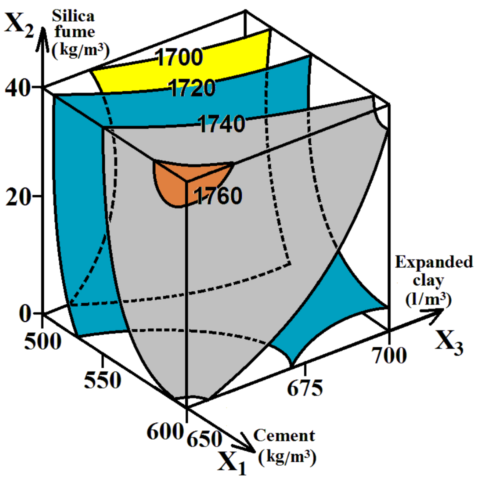

Fig. 8: Effect of Portland cement, silica fume and expanded clay gravel content on the average density of expanded clay lightweight concrete

As can be seen in the diagram shown in Fig. 8, with an increase in the amount of cement to 600 kg/m^3, the average density of expanded clay lightweight concrete is increased by 30-45 kg/m^3. With an increase in the content of porous expanded clay gravel from 650 to 700 l/m^3, the average density of the material decreases by 20-30 kg/m^3 due to a decrease in the amount of heavier quartz sand. Due to the introduction of silica fume, the average density of expanded clay is increased by 10-15 kg/m^3. In general, the average density of lightweight shipbuilding expanded clay lightweight concrete is 500-550 kg/m^3 lower than the average density of heavy shipbuilding concretes. Due to this, floating structures made of expanded clay concrete have a higher carrying capacity. Also expanded clay lightweight concrete structures provide the best conditions of stay of people and equipment operation inside placements of floating structure.

Based on years of research of the properties and technologies of shipbuilding concretes with the participation of our scientific team [3,7-9], normative documents have been developed for the production of concrete for the construction of floating reinforced concrete structures in Ukraine. In particular, the draft state standard of Ukraine "Concrete shipbuilding. Technical requirements. Technology of preparation". The standard consists of two parts: "Heavyweight shipbuilding concrete" and "Lightweight shipbuilding concrete". This state standard is now at the stage of technical expertise.

4. Conclusion

Shipbuilding expanded clay lightweight concrete is an effective material for structures of floating hydrotechnical structures: floating docks, berths, oil and gas platforms, floating houses and hotels. It has sufficient compression strength for most structures and high bending tension strength. Also shipbuilding expanded clay lightweight concrete is durable due to high watertightness and frost resistance. Floating structures made of expanded clay concrete have a higher load-carrying capacity in comparison with structures made from heavyweight concrete due to the lesser average density of lightweight ship-building concrete.

Researches of the properties of shipbuilding expanded clay lightweight concrete carried out according to the optimal plan made it possible to determine the optimum amount of silica fume (about 35 kg/m^3) and the content of expanded clay gravel of 5-10 mm (660-670 l/m^3) in lightweight concrete. The results of the research are put into manufacture. The project of the state standard of Ukraine "Concrete shipbuilding. Technical requirements. Technology of preparation" is developed.

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