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Technical And Economical Efficiency for Application of Nanomodified High-Strength Lightweight Concretes

Aleksandr S Inozemtcev[1,a], Evgenij V Korolev[1,b]

[1]Moscow State University of Civil Engineering, 129337, Russia, Moscow, Yaroslavskoe hw., 26

[a]InozemcevAS@mgsu.ru, [b]KorolevEV@mgsu.ru

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Abstract. The development of construction technologies is impossible without the proper estimation of economical efficiency. Some results of technical and economical efficiency of the developed high-strength structural lightweight concretes are presented in the article. Overview concerning world practice of research and application of lightweight concrete composition are made. The main properties and advantages of developed energy efficient high-strength lightweight concretes are described. The method of calculation of economic efficiency of concrete by means of reduction of total construction weight and increasing of floors' number is proposed. Dependence between efficiency, footprint of building and number of floors is presented. It is shown that economical calculation for developed material which is based only on the cost of the material itself does not allow to obtain adequate data concerning prospect and competitiveness of the material. The authors offer method of calculating the economic efficiency of the developed high-strength lightweight concrete which takes into account the technical properties of the new material. The results of the study showed that the application of high-strength lightweight concrete is more effective than traditional kinds of the concretes.

Introduction

The development of construction technologies and scientific achievements in materials science which is directed to the improvement of pace and effectiveness of construction process are impossible without the proper economical efficiency [1-3]. The criteria related to the economic efficiency are often the most important, while the quality of the material is not. For instance, the multi-purpose construction materials with unique combination of operational properties will be unlikely used somewhere except the research lab if at the same time such materials are economic inefficient.

Table 1. Worldwide experience in development of lightweight concrete

Year	Country	Compressive strength, {MPa}	Average density, {kg/m^3}	Specific strength, {MPa}	Source
1997	Kuwait	45.0-50.0	1800-1850	25.0-27.0	7
1999	Norway	65.0-70.0	1900-1930	34.2-36.2	8
1999	Kuwait	20.0-22.0	1500-1520	13.3-14.4	9
2002	Germany	14.0-25.0	1800-1850	7.5-15.0	10
2003	Brazil	40.0-50.0	1450-1600	24.5-30.5	11
2003	Turkey	30.0-40.0	1800-1860	16.1-22.2	12
2004	Japan	47.0-54.0	1800-1850	27.5-30.0	13
2007	Russia	46.0-61.0	1800-1850	25.5-33.8	14
2007	Russia	42.0-48.0	1600-1650	25.4-28.7	15
2010	Malaysia	43.0-48.0	1870-1990	22.9-24.1	16
2011	Turkey	42.0-60.0	1840-1960	22.8-30.6	17
2011	Portugal	40.0-80.0	1500-2000	26.6-40.0	18
2012	Our HSSLWC	40.0-70.0	1300-1500	30.0-50.0	19, 20

It must be noted that the methods of preliminary estimation of the economic effectiveness based on the costs of resources (raw materials) and performance of the equipment do not allow to evaluate the prospects of practical implementation of scientific developments objectively. Thus, it is obvious that the sphere of application in construction and material properties should be taken into account during economical justification.

We have to examine the economic efficiency of the use of energy-efficient nanomodified high-strength structural lightweight concrete (HSSLWC) for construction purposes [4] – concrete with lower average density and high compressive strength. Multi-component structure of such concrete includes cement binder, mineral part, filler, additives and nanoscale modifier [5]. Filler, providing a low density concrete, is lightweight aggregates – hollow glass or ceramic microspheres produced by plasma spraying [6] or high temperature flaring of coal.

The similar concretes are known in the worldwide practice of construction [7-20]. However, the known concretes, being characterized by low average density, also have low specific strength (Table 1).

Experimental results (technical efficiency)

We have carried out the experimental research during development of the high-strength lightweight concrete. The developed HSSLWC have universal combination of properties (high strength and low average density), which makes them suitable for the manufacture of structural elements in the construction of residential and public buildings. Such concretes offer several advantages in comparison with classical heavy and light concrete (Tables 2 and 3).

Table 2. Advantages of the developed high-strength lightweight concretes (HSSLWC)

Indicator	High-strength concrete	Light-weight concrete	HSSLWC
High strength	+	–	+
Low density	–	+	+
High specific strength	+	–	+
Closed porosity	+	–	+
Low water absorption	+	–	+
Low heat conductivity	–	+	+
Low sound conductivity	–	+	+

Notes: "+" – the property is inherent for this material; "–" – the property is not inherent for this material.

Table 3. Properties of known concretes and HSSLWC

Property	High-strength concrete	Light-weight concrete	HSSLWC
Density, {kg/m^3}	2300…2500	1100…2000	1300…1500
Compressive strength ,{MPa}	30.0…40.0	12.5…30.0	40.0…65.0
Specific strength, {MPa}	13.0…18.0	11.0…15.0	30.0…55.0
Water absorption, {%}	5.0…10.0	15.0…40.0	less than 2.5
Heat conductivity, {W/(m·K)}	1.45…1.55	0.30…1.20	less than 0.60
Specific heat at 25^{o}C, {kJ/(kg·K)}	–	–	0.80…1.15
Freeze-thaw resistance	more than F200	more than F75	more than F300

As we can see from the table 2 and the table 3, developed HSSLWCs have lower average density compared to the heavy concrete (which makes possible to decrease the weight of entire construction by 40%), while maintaining the strength and structural quality. Moreover, these concretes have lower heat conductivity, thus the insulating properties of the walls can also be increased.

Due to the use of hollow microspheres as filler, the dense structure of concrete with low porosity can be created. This leads to the high of freeze-thaw resistance and increased durability of the material. Lightweight concrete with porous aggregates requires additional finishing for protection against operational impacts, but the developed HSSLWCs do not. The most of the known lightweight concretes did not have a high specific strength and thus can not be used in constructions for making bearing elements; the developed HSSLWCs can be. The net effect of the high specific strength is the consequence of the modification of the inter-phase boundary between cement stone and microspheres by means of nanoscale modifier which increases the strength of the inter-phase contact (adhesion). It was shown that for concretes with hollow microspheres characterized by average density 1300…1500 kg/m^3 the specific strength might be rather high. One of the reasons for that is the cement and mineral constituents evenly coats the aggregate particles and provides a uniform contact area. As it follows from the image of concrete structure (Fig. 1), the microspheres with radius 21.0±0.5 mkm are characterized by 13.5 mkm interlayer; thickness of the cement-mineral matrix around a single particle of aluminum silicate microspheres is 6.75 mkm.

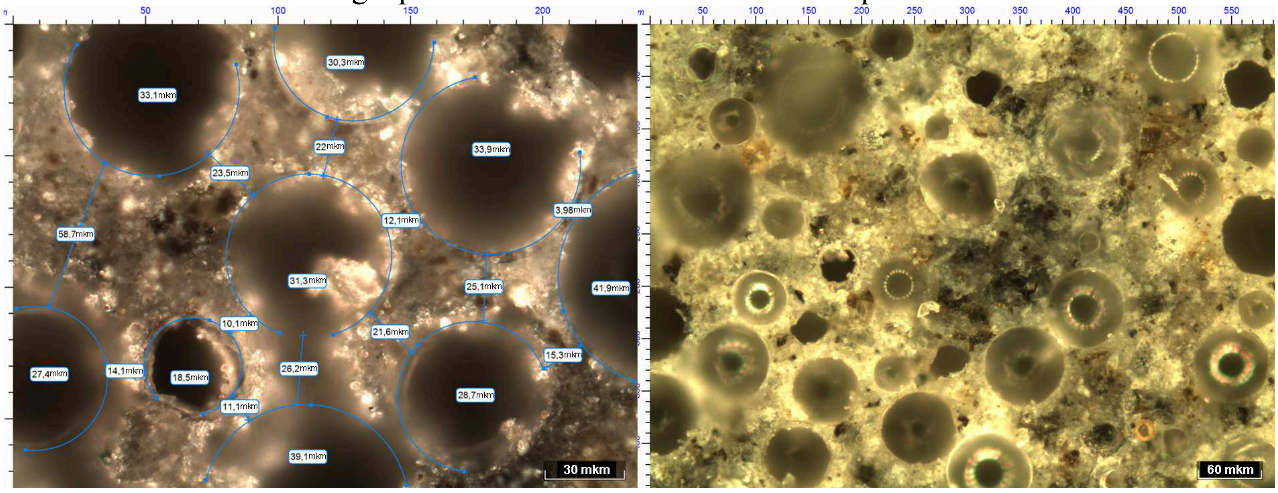

Fig. 1. Structure of the high-strength lightweight concrete a – 500×; b – 200×

Thus, the primary quality criteria for cost-effective implementation of the developed concrete, are: low average density (allows to reduce the weight of products), high strength (structural quality), low thermal conductivity.

Conditions and calculations (economical efficiency)

Determination of economic efficiency can be formalized for the design of construction or building. Calculation is based on the reduction of the total weight of heavy concrete products, which in turn based on the assumption that reducing the load on the bases and foundations allows increasing the number of floors of the building which leads to more useful ground space utilization and to the reduction of costs per construction of unit area.

Assuming that on the area of S is planned to construct buildings of N_c floors by means of using the heavy concrete of average density ρ_{av}^{c}, for the weight of the entire building we get

$$M_b^c = m_{fl}^c N_c \,, \tag{1}$$

where m_{fl}^c is the reference mass of the floor. It depends on geometry of the floor:

$$m_{fl}^c = S\bar{\delta}\rho_{av}^c \,, \tag{2}$$

where S is the area of the floor:

$$S = 2ah + 2bh + ab \,, \tag{3}$$

where a, b and h are the dimensions of the floor,

$$\bar{\delta} = \sum_{i=1}^{z} \alpha_i \delta_i \,, \tag{4}$$

where $\bar{\delta}$ is the thickness of the carcass, δ_i – thickness of the i-th concrete article, and α_i is the weighting parameter for i-th element.

For the new mark of the concrete the mass of the floor is

$$m_{fl}^{nc} = S\bar{\delta}\rho_{av}^{nc} \,, \tag{5}$$

In addition, the low average density of concrete can further allows to reduce the thickness of the wall (of sandwich panels) to provide the required resistance to heat transfer. In this case, the reduced thickness δ_i of the wall panel allows reducing the thickness of concrete and reducing the total weight of the floor:

$$\delta_{wp} = \delta_{wl_0} \frac{\lambda_c}{\lambda_{nc}}, \tag{6}$$

where λ_i is the heat conductivity.

However, in construction industry, regulations for the minimum thickness of the concrete layer allow to reduce the thickness of the concrete structure on the value of k:

$$\delta'_{wp} = k\delta_{wp_0}. \tag{7}$$

And, at the same time, this condition must be met:

$$\delta_{wp} \geq \delta'_{wp}. \tag{8}$$

By means of the substitution the experimental values for different concretes (usual high-strength and HSSLWC) we can show that total area of floors can be increased by 44%. Or, alternatively by means of using the HSSLWC the required ground surface can be decreased by factor 1.71.

The increase in the total floor areas of the building leads to the reduction in the cost per square meter, and, consequently, for the same price per unit area the higher profitability of construction can be achieved.

In addition, the better thermal properties of the HSSLWC allow to save cost for thermal insulation. HSSLWC of thermal conductivity almost two times less than that of the heavy concrete. The greatest economic effect is achieved by using HSSLWC as a material for slabs and fencing panels.

Example of calculation of cost effectiveness of high-strength lightweight concrete by means of the proposed method is presented in the table 4.

Table 4. Results of example calculation of economic efficiency of HSSLWC as a structural material and the insulation material

#	Indicator	Values for:	
		Heavy concrete	HSSLWC
Initial conditions			
1	Type of the building	Fabricated	
2	Footprint, {m^2}	1000	
3	Basic storey of building	16	–
4	Class of concrete	B40	
5	Average density of concrete, {kg/m^3}	2400	1400
6	Price of 1 m^3 of concrete, {rub.}	4500 ($135)	8500* ($260)
7	Price of 1 m^2 of building, {rub.}	50 000 ($1,535)	
Results of calculation			
7	Total mass of construction, {M_t}	13.2	
8	Factor of density change	1.714	
9	Volume of concrete, {$\cdot 10^3\ m^3$}	5.53	9.48
10	Total area of the floors, {$\cdot 10^3\ m^2$}	16	28
11	Price of materials, {millions rub.}	18.21 ($560000)	80.58 ($2480000)
12	Price of 1 m^2 of the floor**, {thousands rub.}	1.14 ($35)	2.94 ($90)
13	Cost of thermal insulation, {millions rub.}	4.02 ($123500)	3.61 ($111000)
14	Economy for thermal insulation, {%}	13.45	
15	Total revenue from the sale of buildings, {millions rub.}	610 ($18770000)	1100 ($33845000)
16	Economic efficiency, {%}	44.50	

Notes: * – the price of 1 m^3 of high-strength lightweight concrete at a cost of aluminosilicate microspheres of 11.75 rub./kg; ** – the cost of construction work taken as 200 % of the cost of materials, cost of 1 m^2 of land is 90 thousand rub.

Table 4 shows that application of nanomodified high-strength lightweight concretes provides economic benefit for more than 45%. The dependencies between economical efficiency, footprint and number of floors are presented on Fig. 2 and 3.

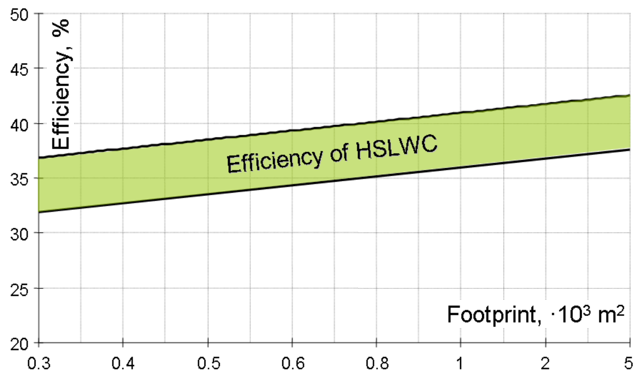

Fig. 2 – Dependence between footprint and efficiency

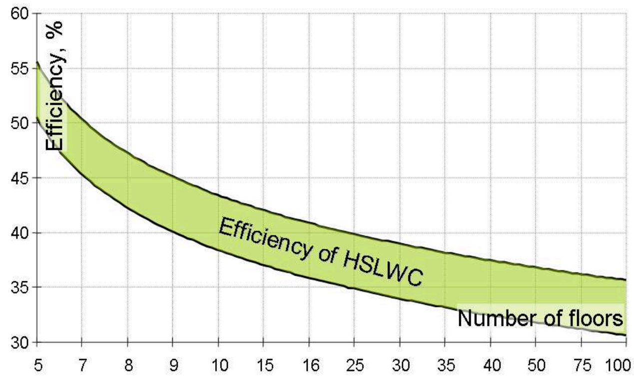

Fig. 3 – Dependence between number of floors and efficiency

Increasing the area of the building leads to an increase in profitability due to the reduction of general costs per unit area. Increasing the number of floors lowers economic effect because of higher costs for construction and installation. Together Fig. 2 and 3 show that the economic efficiency – regardless of the number of floors and the building area – is not less than 35%.

However, the proposed method for calculation of economic efficiency does not take into account the decrease of overhead costs due to reduction of the relative weight of construction. Obviously, the lower cost of transportation and installation work for lighter materials provides additional economic benefits.

There is another method which takes into account the use of high-strength concrete in the design of modular and monolithic reinforced concrete structures. The authors of the [21] have proposed optimization requirements for reinforcing steel and concrete with improved physical and mechanical characteristics.

The following expressions can be used to calculate the consumption of materials:

$$\eta_b = \sqrt{\frac{\mu_0 k_0 - 1}{\eta_s^2 \mu_0 k_0 - \eta_{s0}}}, \tag{9}$$

$$\eta_s = \frac{\eta_b \pm \sqrt{\eta_b^2 - 4\mu_0 k_0 + 4\mu_0^2 k_0^2}}{2\mu_0 k_0 \eta_b}, \tag{10}$$

where η_b, η_s are the consumed materials (concrete and steel), μ_0 is the reinforcement factor for the initial cross-section, k_0 is the parameter taking into account the initial resistance of reinforcement R_{s0} and concrete R_{b0}. The later parameter is equal to:

$$k_0 = \frac{R_{s0}}{2R_{b0}}. \tag{11}$$

Obviously, the use of materials characterized by a high strength reduces consumption required to manufacture the product. So, when using high-strength lightweight concrete of strength class B50 and A400 reinforcing steel rebar the reduction of consumption of 30% can be achieved.

For the products with a high initial ratio of reinforcement parameter η_s decreases, and thus the economic effect of reducing the cost of reinforcement will increase. Reduced consumption of reinforcement is an additional economic factor justifying the application of the developed HSSLWCs.

The proposed methodology for calculating cost effectiveness which is based on consideration of the main indicators of quality of development allows to justify the using of new building materials, raw material components for which have a narrow specificity of use. Designated approach allows us to conclude that the direct calculation of the cost of the material by the prime cost does not provide objective data concerning the prospects of the development and its competitiveness.

Conclusion

By means of using hollow microspheres and optimal combination of cement, mineral additives, quartz components and modifiers it is possible to improve the adhesion at the interphase boundary and produce concrete of high strength. The developed energy-efficient HSSLWCs have a versatile combination of properties. This combination can significantly expand the area of application of such concretes.

The calculations show that the developed HSSWLCs, despite the high cost of raw materials (compared to well-known heavy concrete), have a high prospect of production and can provide economic benefits for construction industry.

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