

Thermal and mechanical properties of lightweight concretes based on waste aggregates

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The aim of this study is to identify a construction material ensuring good mechanical properties and thermal insulation. The study also aimed at assessing the suitability of lightweight aggregates of waste origin such as lytag, boiler slag and omega spheres. On the basis of these components, using chemical admixtures, we tried to produce concrete with the lowest possible W/C ratios, but accordingly characterised by high compressive strength, low density and thermal conductivity parameters. The paper presents 8 mix formulas of lightweight concrete based on waste aggregates. An interesting aspect of the work was to compare different concrete formulas to determine the most advantageous parameters for future use. Substantial changes in formulas consisted in replacing lytag with boiler slag and introducing such components as omega spheres, micro-silica and fly ash. The use of waste aggregates (lytag, boiler slag) improved concrete characteristics. All presented formulas ensured high compressive strength and good thermal insulation performance. Significant porosity of the aggregates allowed for maintaining low density (1332-1749 kg/m³) and very good thermal properties of the material (0.388- 0.6 W/mK). After 28 days the compressive strength testing of the samples, depending on the composition of concrete mix, provided significant results as for lightweight concrete parameters reaching even 65 MPa.

Keywords: Lightweight concrete, Mechanical properties, Density, Thermal conductivity, Lightweight aggregate, Lytag, Boiler slag, Omega spheres

From the point of view of modern engineering solutions, concrete should ensure high mechanical strength and good thermal insulation properties. According to the latest trends in concrete technology, lightweight concrete, which in accordance with the PN-EN206-1: 2003 has density below 2000 kg/m³, is particularly desirable¹⁻⁵. Owing to the use of lightweight aggregate, such concretes enable the manufacturer to produce lighter structural elements, which reduce static loads and improve load-bearing capacity. In addition, the use of lightweight concretes also minimizes the cost of transportation and heavy-duty equipment⁶. Unfortunately, lower density often leads to lower compressive strength of the material.

Currently, the energy consumption has been drawing considerable attention from governments, industries and scientists⁷. Although the mechanical properties of lightweight concretes are satisfying, having in mind energy saving trends there are also other properties that should be taken into account, in particular thermal conductivity⁸.

The studies on thermal conductivity of building materials are still valid and willingly undertaken by various researchers^{2,5,9-19}. The research emphasises the importance of proper insulation of building materials and analyses the correlation between density, compressive strength, and thermal conductivity. Depending on waste aggregates used and their percentage in concrete, a significant improvement in thermal insulation has been observed with respect to conventional materials like blocks, bricks and concrete⁵.

Materials ensuring suitable thermal performance offer a greater scope of application in residential and agricultural constructions¹⁰. To that end, lightweight aggregates such as lytag (Pollytag), boiler slag, and omega spheres (ceramic aggregate) are added to concrete mixes. Detailed information on the concrete mix components used in the study is given in Table 1.

Pollytag material that was used for the purpose of the study was manufactured in the process of granulation and sintering of fly ash at temperature values between 1000°C and 135°C. Thanks to Pollytag aggregate, the weight of lightweight concretes is reduced significantly without

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Table 1 — Concrete mix components

Concrete mix components [kg/m ³]	Samples code and components of each formula							
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8
Pollytag (4-14 mm)	500	500	500	500	485	-	400	-
Boiler slag (4-16 mm)	-	-	-	-	-	60 7	-	515
Boiler slag (0-4 mm)	410	410	410	410	395	390	325	325
Cement	330	330	330	330	320	320	380	380
Omega spheres	68,2	68,2	-	-	-	-	-	-
Micro-silica	50	-	50	50	-	-	-	-
Fly ash (kg)	-	50	-	-	130	130	250	250
Ground slag	-	-	210	270	260	260	220	220
Plasticizer	5,3	5,3	5,3	5,3	5	5	5	5
Water	345	345	345	345	265	260	260	260

* The numbers in parenthesis mean aggregate sizes

compromising their structural integrity. The reduced dead load results in significant savings in the cost of buildings, due to the reduction in a total volume of concrete as well as the costs of formwork and scaffolding²⁰. The aggregate is characteristic for its lightweight, refractoriness and compressive strength. These features make it possible to manufacture lightweight fire-resistant concrete with high load bearing capacity. In Europe the aggregate is well known and fairly common in constructing residential and public buildings, roads and bridges⁶.

In concrete mixes discussed in this paper, boiler slag was additionally used as a waste aggregate. Boiler slag is a by-product of hard coal incineration in grate furnaces. In the past grate slag concrete was fairly common. Nowadays it is used to a much lesser extent, mostly due to low availability of fine quality material. As a result, its use in the construction industry has been limited mostly to manufacturing small-size wall elements^{11,21}.

Another lightweight aggregates analysed by the authors were omega spheres, or hollow ceramic microspheres. These hollow ceramic spheres have been developed for electronic uses in piezoelectric transducers and low dielectric constant substrates, for structural applications in syntactic and metal foams, for fluid transport uses in filters and radiant burners, as well as for acoustic insulation²². The manufacturer declares that the product ensures good mechanical, thermal and acoustic performance. The use of hollow ceramic microspheres in lightweight concrete is an innovation. Their application enables to reduce material density without compromising compressive strength of the final product.

Materials and Methods

Cement

Cement used for the tests was certified as CEM III A 52.5. The material was produced by Gorazdze Cement S.A. HEIDELBERGCEMENT Group, Poland.

Lytag

Lytag (Pollytag) used for the purpose of the study was a light type of aggregate manufactured by granulation and sintering of fly ash at temperature values between 1000°C and 1350°C. The aggregate is characterised by its high refractoriness and particularly high compressive strength. The material applied in the study was manufactured by POLLYTAG, Gdańsk, Poland. The grain diameter ranged from 4-8 mm to 8-14 mm, having a bulk density of 770 kg/m³. 10 min absorbability was 23.6% and 24 h – 27.9%. (Fig. 1).

Boiler slag

In the present concrete mixes, boiler slag is additionally used as a waste aggregate. It is a by-product of hard coal incineration in grate furnaces. The aggregate used in the study was crushed in a jaw crusher so that the maximum grain size did not exceed 16 mm. The material for the purpose of the study was received from an electro-thermal power plant located in the city of Poznań, Poland. The combustion process carried out in the electro-thermal power plant also included the process of extinguishing hot slag with water, so the aggregate did not require additional rinsing. A bulk density was 885 kg/m³, and 10 min absorbability was equal to 19.9% and 24 h – 22.4%. Figure 1b depicts the boiler slag used.



Fig. 1 — Photographs of the materials used (a) lytag and (b) boiler slag

Omega-spheres

Lightweight aggregate in the form of hollow ceramic micro spheres is characterised by good mechanical and thermal properties. For the purpose of the study the material was received from Omega Minerals, Germany. The aggregate grain used for the concrete mix formulas had a diameter of 0.5 mm, with a bulk density of 0.8 g/cm^3 .

Nm Fly ash

Fly ash used for the production of the lightweight concrete was obtained from a thermal power plant in Poznań, Poland. It was silica fly ash, which means that amorphous silica prevailed in the composition. The average grain size was approx. $50 \mu\text{m}$, and a bulk density was equal to 2.18 g/cm^3 .

Micro-silica

Micro-silica is a type of waste captured in the ferrosilicon smelting process. Micro-silica used for

the study was received from Huta Łaziska, in Silesia. The composition of micro-silica was similar to the composition of fly ash, and comparably to fly ash it showed the pozzolanic properties. The diameter of micro-silica grains was about $0.5 \mu\text{m}$, while a bulk density was equal to 2.18 g/cm^3 .

Ground slag

Ground slag was received by grinding boiler slag (described in the study). The process was carried out in a ball mill to the fineness of cement achieving $3600 \text{ cm}^2/\text{g}$. The material prepared in this way also showed pozzolanic properties, similarly to micro-silica and fly ash.

Chemical admixtures

In order to obtain concretes of the highest possible compressive strength, there were used high-performance 4th generation superplasticizers on the basis of polycarboxylate ethers. German company from Schomburg was the producer of the material designated as SP 10.

Water

Potable water was used for the mixing of concrete.

Lightweight Concrete Mix Formulation for Thermal Insulation

Developing suitable concrete mixes with parameters assumed by the authors constituted the basis for conducting a number of experiments. Physical and mechanical properties of each test specimen were determined. Thermal conductivity coefficient for various lightweight concrete samples were investigated and compared based on pre-prepared formulas, so that the final product met all requirements of contemporary residential and agricultural constructions

The components of formulas for lightweight concretes ensuring properties sought by the authors are presented in Table 1. Each formula is marked with a symbol: L-1, L-2, L-3, L-4, L-5, L-6, L-7, L-8. Six test specimens were made for each series.

One of the main objectives of the study was to produce light, insulating and durable concrete. In practice this meant the development of formulas meeting the criteria for self-compacting concretes (SCC). Obtaining the above assumptions, however, was associated with numerous problems. Majority of them, both in design and construction, were due to the fact that light aggregates absorb water very easily. It was

considered in the study and determined how much water and at what time it would be absorbed by the aggregate. It should be emphasised that the water absorbed is inactive and does not affect the size of the W/C ratio. However, its presence has a positive effect on cement and during the bonding process it is an element of internal concrete care. Initial 10 min pre-soaking of the aggregate prevented the loss of mixing water in the study. Consecutively, in order to prevent the segregation of aggregate, the amount of plasticizer used was carefully determined so that the viscosity of matrix consisting of cement, powder additives and the finest aggregate fractions was optimal. In the course of the study, it turned out that it was more preferable to obtain a consistency considered as almost self-compacting. The mix was slightly vibrated to increase its bleeding.

The study presents eight different concrete mix formulas, each of which was used to make cubical specimens of 150×150×150 mm. In the concretes discussed, furnace slag was pre-crushed by means of a jaw crusher and subsequently fractionated on sieves. Coarse phases were used as the basis for the mix skeleton. The remaining phases were used for gradation improvement in order to ensure greater tightness of the material. Part of the slag was ground in a ball mill to the fineness of cement and then added to the formula as a pozzolanic additive improving cement binding efficiency.

The most important variations in the presented concrete mix formulas involved the substitution of Pollytag (L-1, L-2, L-3, L-4, L-5, L-7) with coarse slag (L-6, L-8). The change was primarily due to the economic considerations. The use of coarse slag reduced the cost, however increased concrete density.

The other modifications between the formulas included inter alia the use of micro-silica (L-1, L-3, L-4) and fly ash (L-2, L-5, L-6, L-7, L-8). To reduce concrete density, fine aggregate was replaced with a lightweight filler, i.e., omega spheres with good mechanical and insulating properties. Yet, due to the high cost, the next stage involved substitution of omega spheres with ground boiler slag (L-6, L-8).

An analysis of each lightweight concrete formula presented in Table 1 shows that series L-6 and L-8 correspond to series L-5 and L-7, where Pollytag and coarse slag were used alternatively, with all other components being the same.

Research Methodology

In laboratory tests of all eight series of concrete specimens with different formulas (see Table 1), the

following parameters were determined: volumetric density, thermal conductivity λ (W/mK) and compressive strength. The specimen dimensions were 150×150×150 mm. After a 28-day maturation process in a climate chamber (min 95% relative humidity and 20°C), the samples were dried at 105°C. Subsequently, the samples were weighed and subjected to thermal conductivity and compressive strength tests. For the purpose of comparison, 6 test specimens were prepared for each formula.

A density measurement was carried out based on PN-EN 12390-7:2001: "Testing hardened concrete – Part 7: Density of hardened concrete". In its turn, compressive strength was measured on the basis of PN-EN 12390-3:2002: "Testing hardened concrete – Part 3. Compressive strength of test specimens" using a Walter+baia 107/3000A/J press (Fig. 2).

Determination of the thermal conductivity coefficient was carried out with the help of a purpose-adapted Isomet device (Fig. 3). Similar research method was also used by same authors¹⁷.

The measurement was based on an analysis of the material's temperature response generated by heat transfer induced by means of an electric heater²³. The heating element was located inside a probe placed on the test specimen's surface. There were used surface probes dedicated to porous materials. To minimize the adverse effect of external factors that could distort the measurement, care was taken to ensure good quality contact between the probe and the specimen, uniformity of the measured material and consistent moisture content throughout the specimen. The measuring time was about 8-16 min. The samples were dried in oven at 105°C until the weight loss of



Fig. 2 — Compressive strength test using a Walter+baia 107/3000A/J press

no more than 1% at 24 h¹⁷. For each sample, 3 different axes were tested. All tests were performed in laboratory conditions at 23°C and 35% air humidity.

Results and Discussion

Results of laboratory tests of density, thermal conductivity and compressive strength are presented in Table 2.

Concrete density and compressive strength tests

During the design of concrete mixtures it was decided to use cement certified as CEM III 52.5. The use of blast furnace cement enabled to obtain highly resistant concrete to chemical aggression and characterised by low hydration temperature.

During the search for concrete with low density, high compressive strength and insulation parameters, 8 different formulas were prepared which, depending on the aggregate used, had different properties. The first formulas L-1, L-2, L-3, L-4 and L-5 were prepared on the basis of lytag lightweight aggregate (Pollytag). This component allows for producing concrete that meets construction requirements while maintaining low weight. Depending on the components used, the density of lightweight concretes ranged from 1326 kg/m³ to 1581.7 kg/m³. The lowest densities were recorded for samples L-1 and L-2 containing Pollytag. In the samples designated as L-1

and L-2, an additional light aggregate was omega-spheres, i.e., hollow ceramic micro balls. The use of omega spheres enabled to reduce material density to 1326 kg/m³ and 1410 kg/m³ (Ref.22). The introduction of slag into the formulas resulted in greater weight L-6=1707.7 kg/m³ and L-8=1749.7 kg/m³. Nonetheless, the threshold weight of lightweight concretes was never exceeded.

Table 2 also presents the average results of compressive strength tests. Cubical concrete specimens were subjected to compression in the strength testing machine presented in Fig. 2.

The lowest compressive strength value was recorded for Pollytag-based series L-1, and the highest compressive strength value was recorded for series L-8, whereby the introduction of coarse slag resulted in a significant improvement in compressive strength. The tests allowed for comparing the importance of individual components in forming concrete mixtures. Comparing the compositions and results for L-1 and L-2 samples, the positive effect of micro-silica was clearly visible. Replacement of fly ash with micro silica allowed the density to drop to 1326 kg/m³, while compressive strength increased from 28.5 MPa for L-2 to 30.7 MPa for L-1. The composition of micro-silica is similar to the composition of silica fly ash. Similarly to ashes, micro-silica exhibits pozzolanic properties. Fly ash captured from exhaust gases of large power plants is today a commonly applied mineral additive in concrete technology²⁴. The significant difference between these components is that micro-silica diameter is 100 times smaller than fly ash diameter, within the limits of 0.5 µm. This translates into a significant specific surface area of grains, and consequently into the fact that micro-silica is characterised by high chemical activity. The use of micro-silica guarantees achieving concretes of the highest performance. Thus adequately, L-3 and L-4 specimens containing micro-silica provided better characteristics than L-5 sample containing fly ash.

The fundamental change in the materials used in the study was to replace Pollytag with slag and to



Fig. 3 — Thermal conductivity coefficient measurement using an Isomet device

Table 2 — Summary of laboratory test results.

Tested parameter	Results for each series							
	L-1	L-2	L-3	L-4	L-5	L-6	L-7	L-8
Oven- dry density (kg/m ³)	1326.4	1410.7	1457.6	1547.6	1545.2	1707.7	1581.7	1749.7
Thermal conductivity coefficient λ (W/mK)	0.388	0.479	0.442	0.522	0.469	0.652	0.506	0.6
28-day compressive strength (MPa)	30.7	28.5	31.4	42.8	36.9	42.4	45.6	56.9

resign from using fly ash so as to use micro-silica. These modifications were aimed at not using aggregates that were the result of production processes, but opting for waste materials generated by incineration plants, with maintaining current good results. Compressive strength of the concrete samples prepared in this way proved to have even better characteristics L-6=42,4MPa, L-8=56,9MPa (Fig. 4). A specific shape of slag grains allows for achieving higher compressive strength values. The penetration of cement into slag grains increases compressive strength of these samples, providing them with quite interesting characteristics. After grinding them in a ball mill to the finesse of cement, they show pozzolanic properties similar to fly ashes. It might be assumed that this also had impact on compressive strength of concrete samples. The difference was observed while comparing the following twin series: L-5 with L-6 and L-7 with L-8. Substitution of Pollytag with boiler slag resulted in a significant improvement in compressive strength. However, it must be remembered that the said improvement was accompanied by greater density (Fig. 4).

The results obtained in this study in terms of compressive strength seem to be very promising in comparison to other experimental results achieved during the studies on lightweight concrete based on waste materials. The work of Alengaram *et al.*¹⁶ presents lightweight concrete produced on the basis of oil palm shell – a lightweight aggregate with very similar parameters. In other studies, the results of strength tests carried out after 28 days are lower and do not exceed 35 MPa for density of 1300-1700 kg/m³ (Ref.5).

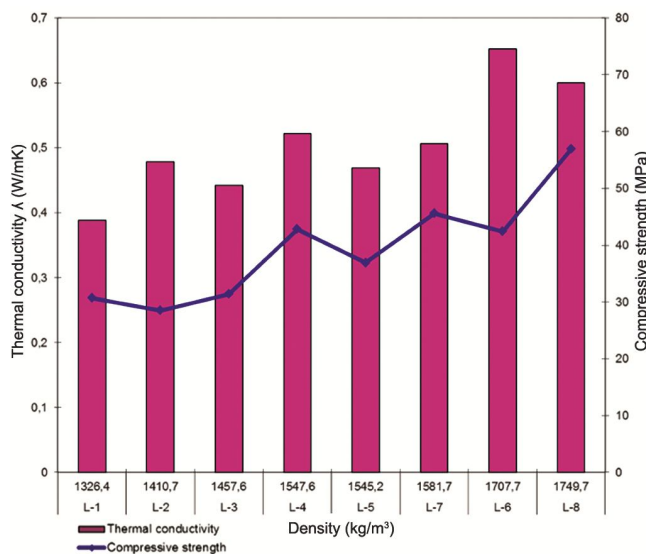


Fig. 4 — Graphic representation of laboratory test results

The comparison of values for boiler slag aggregates, which is a specific product characteristic for the local hard coal-based economy, is the most problematic. These aggregates cannot be compared in any way to furnace slag aggregates frequently described in the literature because the material is obtained from the steel-making process²⁴. According to Hiraskar and Patil²⁵ the results of compressive strength tests for furnace slag are significantly improved (reaching even 93 MPa) comparing to results for boiler slag.

Thermal insulation properties of lightweight concretes

The contemporary construction industry demands solutions that not only ensure good mechanical strength, but also provide adequate thermal insulation. The latter is determined by means of the thermal conductivity coefficient (W/mK). The coefficient value corresponds to the amount of heat conducted through the material perpendicularly to its surface in the presence of a pre-set difference in temperatures.

The average values of the thermal conductivity coefficient for each series of lightweight concrete specimens are presented in Table 2. The test results were compared with the reference data¹¹ showing that standard concrete, designated in Fig. 4 by the symbol X, with a density of 2300 kg/m³ has a thermal conductivity coefficient $\lambda=1.8$ W/mK. The percentage comparison of obtained results is shown in Fig. 5.

It needs to be emphasized that concrete specimens presented in this paper – apart from high mechanical strength – exhibited good thermal insulation properties ranging from 0.38 W/mK to 0.6 W/mK (Fig. 4). It is known that thermal conductivity depends on density, moisture content and components of the material¹⁵. The obtained results confirm the decrease in thermal insulation with the increase in material density. For the lightest L-1 sample the average density was 1326.4 kg/m³, and $\lambda=0.388$

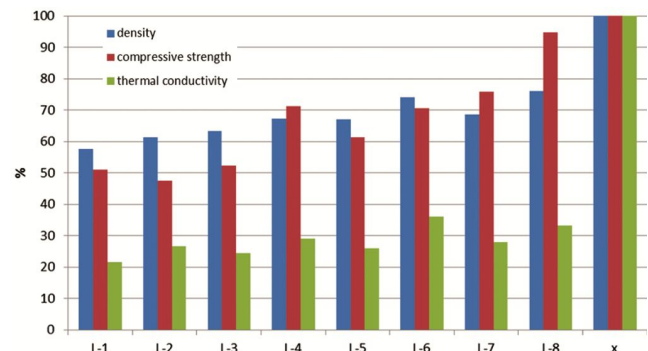


Fig. 5 — Percentage comparison of obtained results

W/mK. The highest density concrete samples (L-6 and L-8) had the thermal conductivity coefficient of at least 0.6 W/mK. As thermal conductivity is mostly a function of density, it does not really matter whether the product is moist preserve or autoclaved as far as thermal conductivity is concerned³.

The results indicate excellent insulation properties of omega spheres. The coefficient of thermal conductivity according to the manufacturer is $\lambda < 0.09$ W/mK. Aggregates with low thermal conductivity give concrete with lower thermal conductivity¹¹. The aggregate with omega spheres in L-1 and L-2 samples provided the end product with low density and the most promising thermal conductivity L-1=0.388 W/mK. Thus, considering the concrete composition, this particular aggregate seems to have played a decisive role on the above properties. In this context Pollytag aggregate ensures superior thermal insulation comparing to boiler slag aggregate. The construction of Pollytag in the form of sealed spheres guarantees air entrapment in the porous structure of the material, which primarily resulted in good insulation $\lambda = 0.14$ W/mK. Slag, on the other hand, exhibited worse thermal insulation properties ($\lambda = 0.25$ W/mK for boiler slag). Due to non-uniform grain structure mortar can penetrate not only between but also inside slag grains, filling all empty spaces. Samples with the highest density L-6 1707 kg/m³ and L-8 1749 kg/m³ have the highest thermal conductivity. It might be also stated that the higher the compressive strength, the worse is the result of thermal insulation - the correlation also indicated by other researchers in their studies¹⁶.

Other researchers have also seen very good thermal insulation properties of fly ash^{14,24}. L-5 concrete samples containing fly ash demonstrated a 10% increase in coefficient λ in comparison to twin L-4 samples. The results obtained in the study for the thermal conductivity coefficient from 0.388-0.6 W/mK do not differ from the data presented in the literature for lightweight concretes on waste aggregate^{5,14-17,24}. However, a direct comparison of these values is very challenging. It should be noted that each waste material, such as rubber aggregate, silica fume, pumice, fly ash, oil palm shell, furnace slag, metakaolin, volcanic ash and many others, has different properties. Lightweight concretes produced on the basis of such diverse components have their specific characteristics mainly related to density and porosity parameters, and thus exhibit various and unequal insulating properties.

Lightweight concrete formulas similar to those developed by the authors can improve thermal insulation properties of walls without increasing their thickness, which obviously offers new opportunities for using the presented materials in constructing residential and public buildings. Based on compressive strength test results it might be concluded that these concretes have potential to be used in numerous structures. However, other engineering properties must be considered, especially when waste materials are used in the mix proportions of concrete. Performing additional tests on tensile strength and modulus of elasticity will provide more answers on the potential use of the presented concrete for construction purposes. At the present stage of the study, the objective was to find the lightest possible concrete based on waste aggregate with low thermal conductivity and high durability. Such concretes do not necessarily have to be used as construction materials. They may also find other applications such as thermal insulation or heat resistant flooring in livestock buildings.

Conclusions

The aim of the project was to develop lightweight concrete ensuring high mechanical strength and improved thermal insulation properties based on aggregates produced from waste. On the basis of a series of tests followed by an analysis of test results, the following conclusions have been formulated:

- (i) All presented formulas ensured high compressive strength and good thermal insulation performance. The use of waste aggregate (lytag, boiler slag) did not worsen but even improved concrete properties.
- (ii) Significant porosity of the aggregates (lytag, omega spheres) allowed for keeping low density and very good thermal properties of the material. The use of omega spheres gave the most promising results for thermal conductivity at low density of the concrete.
- (iii) The use of waste aggregates provides obvious benefits for the environment and the economy, but not all components of concrete mixes are equally available. Replacement of lytag and omega-spheres with boiler slag does not significantly compromise the parameters of lightweight concrete. The use of slag improves mechanical strength (L-6, L-8), however at the cost of density and thermal insulation performance.

- (iv) Replacement of fly ash with micro-silica allowed for reducing density while increasing compressive strength and insulation performance. The use of lightweight concretes based on the above formulas can deliver tangible savings in the construction and operation of buildings. Such savings will be observed in the cost of transportation, machinery, reinforcements, foundation size, etc.
- (v) Thermal conductivity factor $\lambda = 0.6$ W/mK allows for a significant reduction in the thickness of insulation materials in composite walls. If $\lambda = 0.388$ W/mK, it is possible to eliminate insulation materials.
- (vi) Adequate thermal insulation performance of lightweight concrete combined with high mechanical strength pave a way not only for new structural solutions, but also for new applications in residential constructions – by ensuring the required load-bearing capacity and thermal insulation of the building.

The results of laboratory tests are very promising. Lightweight concrete developed using the above formulas can be successfully used for multiple applications in residential and agricultural constructions.

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