

Original Research

The Study on Possible Applications of Lightweight Concrete Based on Waste Aggregate in Terms of Compressive Strength and Thermal Insulation Properties

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Abstract

The leading theme of the paper was to study, how the use of lightweight concrete based on waste aggregates, characterized by significant mechanical strength and increased thermal insulation, affects the properties of building partitions and contributes to possible economic savings, so as to properly design and select materials required for the construction process.

The work presents the composition of lightweight concrete samples made of waste lightweight aggregates as well as their physical and mechanical properties. It includes calculations concerning floor loading and heat transfer coefficient of building partitions made of the presented lightweight concretes. Calculations provided the basis for assessing the impact of particular parameters on compressive strength and thermal insulation of walls and floors. The paper additionally describes concretes made of waste aggregates in the form of lytag (Pollytag) and slag. Based on the research, it was found that concrete containing Pollytag had the lowest density value and thermal conductivity coefficient. These parameters translated into reduction in the weight of the slab in question by more than 40% and allowed to save 25% of steel compared to an analogous plain concrete slab. The decrease in heat conductivity coefficient did not result in a significant increase in thermal insulation of building partitions.

Keywords: lightweight concrete, compressive strength, thermal conductivity

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Introduction

Modern construction materials, including concrete, should be differentiated with high mechanical strength, good thermal and acoustic properties, as well as pro-environmental characteristics. Waste aggregate can be used as an alternative material to produce lightweight concrete with low environmental impact [1, 2]. In order to meet the existing numerous requirements, the manufacturers of building materials have been constantly modifying the composition of concrete mix for obtaining the best possible parameters [3]. The question remains open whether such improvements might be converted into real benefits.

On the basis of the data collected weekly from commercial companies – the members of the Polish Union of Steel Distributors, there were monitored the average wholesale prices of reinforcing steel. The above changing data helped to determine an upward price trend of reinforcing bars. Therefore, it is worth considering whether the use of lightweight concrete can result in savings on reinforcement.

The situation is similar with the continuing growth in energy consumption. Currently, the fact has been drawing great attention from governments, industry and academics. The mechanical properties of lightweight concrete are satisfactory, as evidenced by numerous studies. Considering energy savings, it is also recommended to verify the thermal insulation parameters of materials [4-7].

The thermal insulation parameters of concrete in the construction industry have been undertaken as a research topic by many scientists, what finds confirmation in large amount of scientific literature: [8], [9-19]. Authors in their works emphasise the importance of proper insulation of construction materials and analyse the correlation between density, compressive strength and thermal conductivity. The popular trend of research is the use of various waste aggregates such as: fly ash, rubber aggregate, blast furnace slag, rice hush ash, palm oil fuel, pumice powder, polyethylene, volcanic ash, glass powder, paper sludge ash. There are still valid attempts to use less known light aggregates such as lytag [20, 21]. The issue of using waste aggregate obtained from coconut oil production was discussed by Alengaram [11], who compared the thermal insulation properties of the obtained concrete with traditional materials such as bricks or plain concrete. Lightweight aggregates in the form of pumice powder, expanded perlite or waste rubber aggregates were the subject of research described by Oktay [15]. The results presented in Alyousef [22] paper showed that the incorporation of sand obtained from marble waste and perlite aggregate notably improved the mechanical properties and the thermal insulation of lightweight concrete.

A significant improvement in thermal insulation has been observed depending on types and percentages of waste aggregate used in concrete.

According to the latest trends in concrete technology, lightweight concrete, which accordingly to PN-EN 206+A1:2016-12 [23] has density below 2000 kg/m³ and is included in strength classes between LC8/9 and LC80/88, is particularly desirable. The classes from LC50/55 to LC80/88 are lightweight concrete classes of high compressive strength characteristics. Owing to the use of lightweight aggregate, such concretes allow for producing lighter structural elements with, in consequence, reduced static loads and improved load-bearing capacity. Unfortunately, lower density often leads to lower compressive strength of the material and results in changes in its insulation properties. The porous structure of lightweight aggregate is responsible for differences in mechanical and thermal performance of lightweight concrete compared to normal weight concrete [24, 25].

The paper presents the comparison of compressive strength characteristics of concrete made of waste aggregates, such as slag and Pollytag, and includes a comparative analysis of the calculated floor slab made of the designed materials and the standard concrete slab of similar compressive strength parameters. It also calculates how the use of lightweight concrete with reduced thermal conductivity affects insulation properties of building partitions.

Material and Methods

Materials

Cement

Cement used for the tests was certified as CEM III 52.5. It was produced by Góraźdze Cement S.A. Heidelbergcement Group, Poland. This is a new product offered by the cement plant designed specifically for buildings exposed to significant loads and chemical corrosion risks.

Pollytag

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

Boiler Slag

The presented concrete mixes used boiler slag as an additional waste aggregate, which is a by-product of

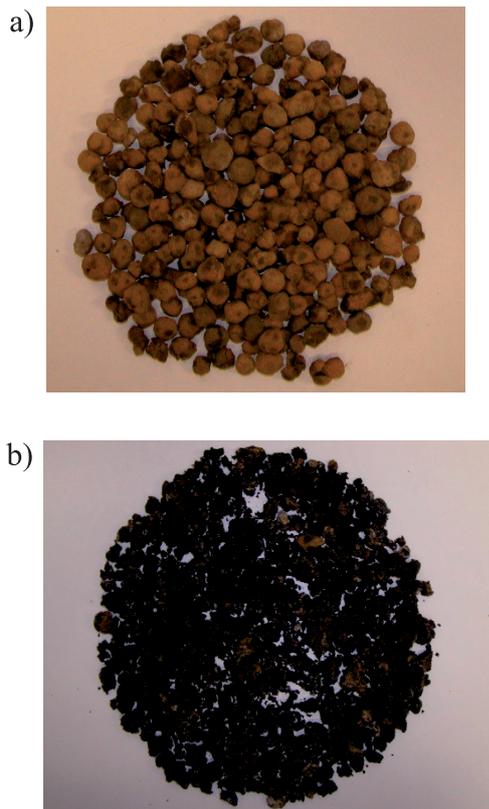


Fig. 1. Photographs of waste aggregates used in the study: a) pollytag, b) boiler slag.

hard coal incineration in grate furnaces. The material was received from an electrothermal power plant located in the city of Poznań in Poland. Its bulk density equalled 885 kg/m³, 10-minute absorbability was 19.9%, whereas 24-hour absorbability came to 22.4%. The maximum grain diameter was 16 mm. The aggregate is shown in Fig. 1b).

Omega-Spheres

Lightweight aggregate in the form of hollow ceramic micro-spheres characterised by good mechanical and thermal properties. The material used for the purpose of the study was received from Omega Minerals, Germany. The concrete mix formulas used the aggregate with the grain diameter 0.5 mm and bulk density 0.8 g/cm³.

Micro-Silica

Micro-silica is a type of waste captured in the ferrosilicon smelting process. The material used for the study was received from Huta Łaziska, in Silesia. Micro-silica exhibited pozzolanic properties. The diameter of micro-silica grain was approx. 0.5 μm, its bulk density equalled to 2.18 g/cm³.

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 cement fineness 3600 cm²/g.

Chemical Admixtures

In order to obtain concretes of the highest possible compressive strength parameters, the 4th generation superplasticizer of high-performance (SP 10 designation), based on polycarboxyl ethers was used in the study. The material was received from Schomburg, Germany.

Water

Water from the local water supply was used for the study.

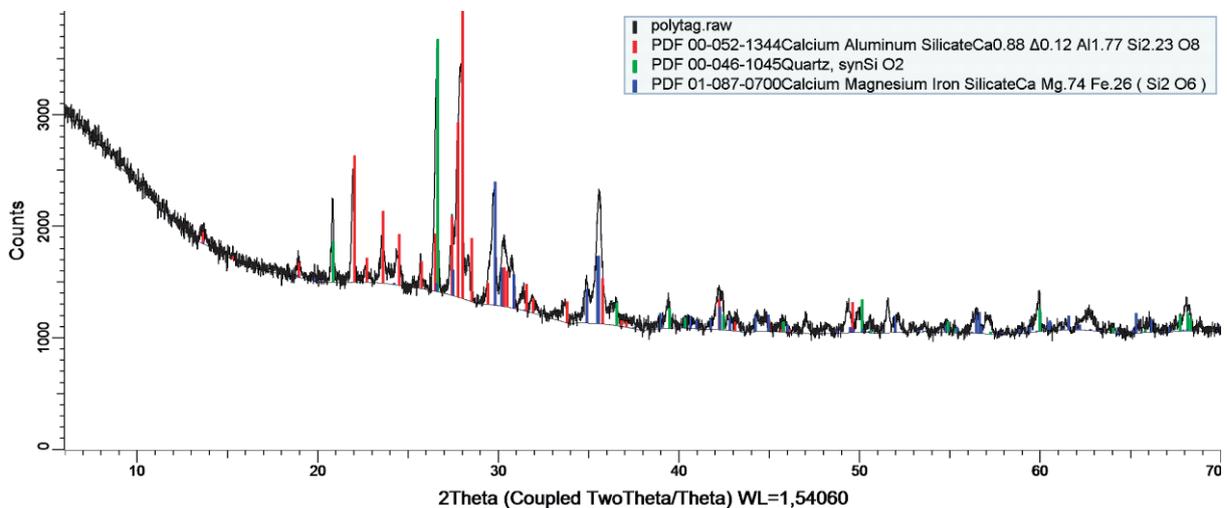


Fig. 2. Elemental XRD analysis for pollytag.

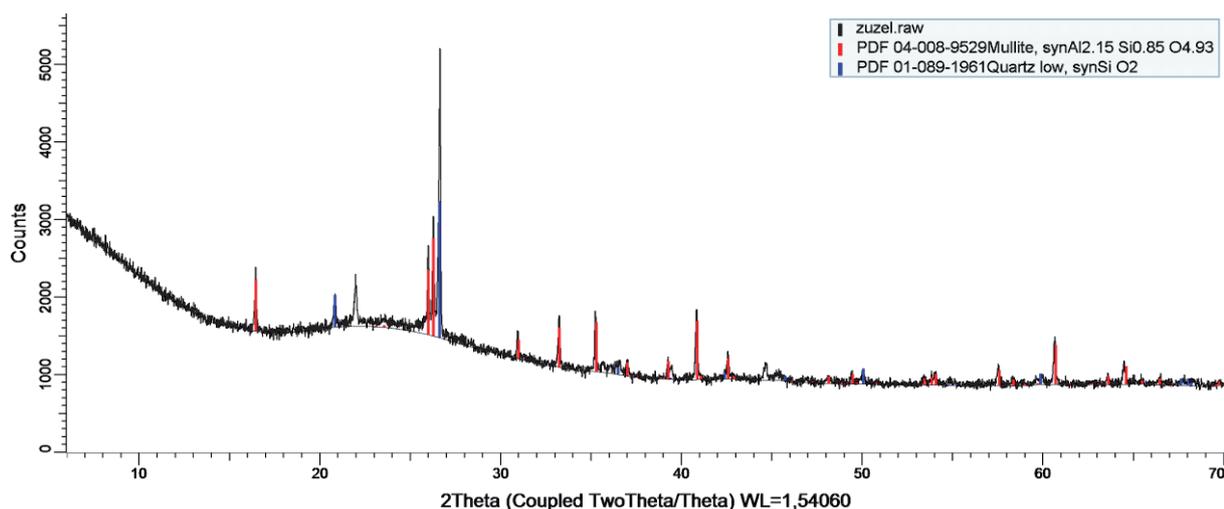


Fig. 3. Elemental XRD analysis for boiler slag.

Elemental XRD Analysis

To check the elemental composition of the additives used (Pollytag and boiler slag), a powder diffractometer test (BRUKER D8 Advance) was performed. The research was carried out at The Laboratory of Unique Chemical Equipment at Adam Mickiewicz University, Poznan, Poland. The test results are shown in Figs 2 and 3.

Elemental XRD analysis for pollytag showed the presence of Calcium Aluminum Silicate, Quartz and Calcium Magnesium Iron Silicate (Fig. 2). In the case of the boiler slag, the presence of Mullite (Al₂.15 Si_{0.85} O_{4.93}) and Quartz was detected.

Compositions of Concrete Mixes and Their Properties

The above presented components were used to prepare concrete mixes. Their detailed compositions

Table 1. Composition of concrete mixes.

Concrete mix composition	P - Pollytag [kg/m ³]	Z-slag [kg/m ³]
Cement	380	320
Pollytag (0÷2) mm	213	
Pollytag (2÷4) mm	67	
Pollytag (4÷14) mm	605	
Slag (0÷4) mm		409
Slag (4÷8) mm		607
Omega spheres	85	68
Plasticizer	3,8	5.3
Water	155	258
Micro-silica	62	60

are included in the table (Table 1). Concrete mixes with Pollytag are indicated with P, and concrete mixes with slag – Z, respectively.

The results of laboratory tests on density, heat transfer coefficient and compressive strength are summarized in the table (Table 2). The properties of concrete were tested in laboratory conditions. The compressive strength of samples was examined using a Walter+Baia 107/3000A/J press. The heat transfer coefficient was determined with the use of Isomet, a multifunctional instrument for measuring thermal conductivity.

Structural Calculations Concerning the Floor Slab

The use of lightweight concrete as a structural material can be associated with real savings in the construction process due to the possibility of reducing the self-weight of a structure while retaining high compressive strength parameters for concrete and significant cost-effectiveness for reinforcing steel.

In order to verify of this assumption, three reinforced concrete slabs made of three different concrete mixtures were designed for the study including:

- Pollytag (hereinafter referred to as lightweight concrete P),
- slag (hereinafter referred to as lightweight concrete Z),

Table 2. Summary of laboratory test results.

The scope of laboratory tests	Summary of results	
	P -pollytag	Z-slag
Average density of the sample [kg/m ³]	1400	1700
Average value λ [W/mK]	0.38	0.63
Average compressive strength of the reference samples [MPa]	36.4	45.6

– natural aggregate (hereinafter referred to as plain concrete).

The tested concrete samples were characterised by different density, therefore, the slabs – including

Table 3. Characteristic self-weight values of slabs.

Type of the slab	Characteristic value [kN/m ²]
Plain concrete	4.00
Lightweight concrete Z	2.77
Lightweight concrete P	2.29

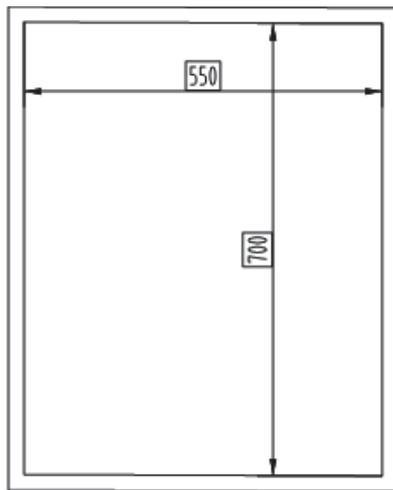


Fig. 4. Dimensions of slabs.

Table 4. Basic parameters of the designed slabs.

Lx	5.5 m
Ly	7.0 m
Concrete class	C30/37
Steel A-IIIIN	$f_{yk} = 500$ MPa
Exposure class	XC1
Structure class	S4
Height of the slab	16 cm
f_{ctm}	2.9 MPa

reinforcement – were varied in terms of weight. The values are presented in the table (Table 3).

The calculations were prepared for 16 cm thick slabs with dimensions 5.5 m (x) x 7.0 m (y) – Fig. 4. Following the compressive strength laboratory tests on concrete cubic blocks with sides equal to 15 cm, there was indicated the class of concrete as C30/37. For the calculations it was assumed that the slabs were reinforced with RB 500W steel bars of yield strength $f_{yk} = 500$ MPa. The samples included ribbed slabs with diameters $\varnothing = 6$ mm (along the longer side – direction y) and $\varnothing = 8$ mm (along the shorter side – direction x).

The authors assumed the characteristic value of live load, including the loading of partition walls, as equal to 3.25 kN/m². The layout of the slab was adopted as a structure freely supported on all its edges. Bending moments were calculated using the appropriate tables [27]. Reinforcement was designed according to PN-EN 1992-1-1:2008+A1:2015-03 [28]. The adopted parameters for the design of reinforced concrete slabs are shown in the table (Table 4)

Results and Discussion

Designed Slabs

For the assumed data (presented in section 2), the maximum bending moments were determined and the reinforcement cross-sections was calculated (Table 5).

Then, drawings of the bottom and top reinforcement of the plates were made and compiled list of reinforcing steel was made. Fig. 5 shows the reinforcement of the lightweight concrete Z slab.

By analyzing the results shown in Table 6, it may be concluded that the use of concrete based on Pollytag can save almost 25% of reinforcing steel. The use of light concrete with Pollytag is also associated with a much lower weight of the whole floor slab (over 40%), which will contribute to further savings in the construction process (Table 7).

Despite the low density of light aggregate concretes (up to 2000 kg/m³), they may demonstrate relatively high compressive strength values, depending on the type of aggregate used. Calculations on the structural floor slab confirmed that lightweight concrete had the strongest impact on the demonstrated values. The total

Table 5. Maximum bending moments and assumed reinforcement for the designed reinforced concrete slabs.

	Plain concrete	Lightweight concrete Z	Lightweight concrete P
M _{x,max}	22.282 kNm	19.077 kNm	17.833 kNm
M _{y,max}	12.756 kNm	10.921 kNm	10.209 kNm
Reinforcement (direction x)	$A_{s_{lx}} = 4.17$ cm ² Ø8 every 12 cm	$A_{s_{lx}} = 3.57$ cm ² Ø8 every 14 cm	$A_{s_{lx}} = 3.33$ cm ² Ø8 every 15 cm
Reinforcement (direction y)	$A_{s_{ly}} = 2.57$ cm ² Ø6 every 11 cm	$A_{s_{ly}} = 2.17$ cm ² Ø6 every 13 cm	$A_{s_{ly}} = 2.02$ cm ² Ø6 every 14 cm

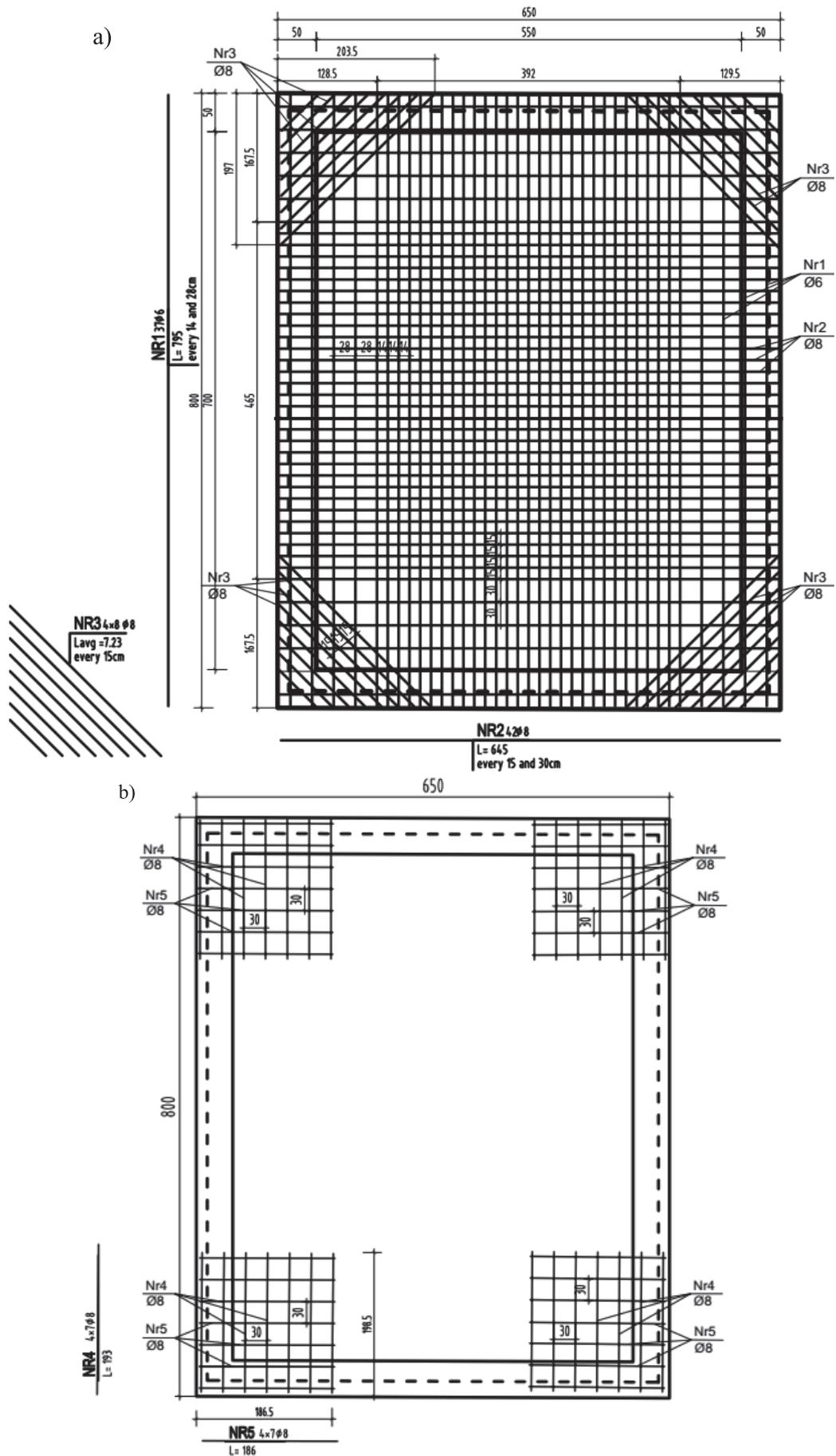


Fig. 5. Drawing of the reinforcement of the lightweight concrete Z slab, a) bottom reinforcement, b) top reinforcement.

Table 6. Total weight of reinforcement of particular slabs.

Type of the slab	Total weight of reinforcement [kg]
Plain concrete	291.08
Lightweight concrete Z	247.69
Lightweight concrete P	235.84

weight of the slab including reinforcing was reduced by 40%, and the weight of reinforcing steel was reduced by 25%.

Thermal Insulation Calculations Related to Building Partitions Made of the Developed Lightweight Concretes in Comparison to Plain Concrete

The concrete samples presented by authors were characterised not only by high compressive strength, but also by good thermal insulation parameters, since the coefficient λ was 0.38 W/mK. The averaged values of thermal conductivity coefficient for subsequent series of concrete samples are presented in the table (Table 2).

The determined thermal conductivity values of lightweight concrete samples were compared with the reference data, where plain concrete with 2400 kg/m³ density had the coefficient $\lambda = 1.7$ W/mK.

Lightweight concrete prepared in this way can improve thermal insulation parameters of walls without the necessity to make them thicker. This creates new opportunities for the use of the presented material in broadly understood construction. The table (Table 8) shows heat transfer coefficients U [W/m²K] for external

partitions made of solid concrete elements differing in density and thermal conductivity coefficients. As of January 1, 2021 [29], the heat transfer coefficient for an external wall at $t_i \geq 16^\circ\text{C}$ cannot exceed 0.20 (W/m²·K) (maximum value). Calculations were made for full partitions, except for the effect of thermal bridges.

The search for building materials with the lowest heat transfer coefficient aims to improve thermal insulation of partitions without thickening them. Unfortunately, the reduction in thermal conductivity coefficient, λ (λ), does not result in a significant change in heat transfer coefficient and, as a result, in reduction in thickness of an insulation layer. The lack of significant correlation should be borne in mind while selecting appropriate construction materials. Material characterised by higher heat transfer coefficient will not always contribute to savings on insulation, particularly when polystyrene boards are considered, which are sold in standard thickness: 5 cm, 8 cm, 10 cm, 12 cm, 15 cm, and similar. The situation is more favorable for insulation boards available in a greater range of thickness between 1÷30 cm with a difference in dimensions every 10 mm. Depending on the individual needs of customers, the required thickness of an insulation layer can be selected adequately.

Many manufacturers of building materials encourage customers to purchase their brand by highlighting the importance of lower thermal conductivity coefficient compared to other products available on the market. However, they do not provide detailed information on what amount of savings on insulating materials can actually be made. On the basis of results included in Table 3 it is readily apparent that the change in thermal conductivity coefficient even from $\lambda = 1.7$ [W/mK] (for plain concrete) to $\lambda = 0.38$ [W/mK] (lightweight

Table 7. Total slab weight and percentage gain.

Type of the slab	Weight of the slab with reinforcement [t]	Reduction in slab weight in relation to the reference slab [%]
Plain concrete	15.09	-
Lightweight concrete Z	10.30	31.7
Lightweight concrete P	8.84	41.4

Table 8. Comparison of heat transfer coefficient for external partitions made of concrete with different thermal properties (according to PN-EN ISO 6946:2008 [29]).

Structural material of external partition	Density of concrete	Thickness of concrete partition	Thermal conductivity coefficient of concrete λ	Thickness of insulation material (Styrofoam $\lambda = 0.04$ [W/mK])	Heat transfer coefficient of external partition
Units	[kg/m ³]	[m]	[W/mK]	[m]	[W/m ² K]
Plain concrete	2400	0.24	1.7	0.19	0.20
Lightweight concrete with slag	1700	0.24	0.63	0.18	0.20
Lightweight concrete with Pollytag	1400	0.24	0.38	0.17	0.20

concrete based on Pollytag) allows for reducing the thickness of an insulation layer by only 2 cm.

It should also be emphasized that obtaining very good thermal insulation of a building partition requires the elimination of as many thermal bridges as possible. To achieve it, it is necessary to use, inter alia, thin joints (called adhesive-bonded joints), counteracting the heat escape through joints between blocks. The relatively small savings in the insulation stage of works, however, should not deter customers from searching for advanced building materials with higher thermal conductivity. In accordance with the principle – even a slight improvement in building material properties can ultimately provide energy efficiency and economic benefits.

Conclusions

1. The use of lightweight concrete as a building material reduces the self-weight of slabs by 40% in comparison to plain concrete slabs, and correspondingly decreases the value of permanent loads acting on them.

2. Lightweight concretes designed on the basis of waste aggregates allow for multi-faceted savings on: reduction in reinforcement (even by 25%), and as a consequence, in transport of materials and construction time.

3. With the existing requirements for thermal insulation of buildings, the presented concretes, despite low thermal conductivity coefficient, do not allow for complete resignation from applying insulation materials. However, improved thermal properties make it possible to slightly reduce the thickness of an insulation layer.

4. An additional advantage of the presented concretes is the use of waste aggregates for their production, which raises their ecological and economic values.

Conflict of Interest

The authors declare no conflict of interest.

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