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Research paper

Thermal and mechanical properties of lightweight concrete with waste copper slag as fine aggregate

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Abstract: The article presents the results of investigation of mechanical and thermal properties of lightweight concrete with waste copper slag as fine aggregate. The obtained results were compared with the results of concrete of the same composition in which natural fine aggregate (river sand) was used. The thermal properties tests carried out with the ISOMET 2114 device included determination of the following values: thermal conductivity coefficient, thermal volume capacity and thermal diffusivity. After determining the material density, the specific heat values were also calculated. The thermal parameters were determined in two states of water saturation: on fully saturated material and dried to constant mass at 65°C. Compressive strength, open porosity and bulk density are given as supplementary values. The results of the conducted research indicate that replacing sand with waste copper slag allows to obtain concrete of higher ecological values, with similar mechanical parameters and allowing to obtain significant energy savings in functioning of cubature structures made of it, due to a significantly lower value of thermal conductivity coefficient.

Keywords: lightweight concrete, waste copper slag, thermal properties, sustainable building materials

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1. Introduction

Human well-being depends, among others, on the appropriate level of humidity and temperature of the environment in which he or she lives [1]. In most climate zones, at least for a part of the year, the conditions that prevail outdoors are clearly beyond the limits defined by human well-being. These are either too low or too high temperatures, often combined with humidity that intensifies negative feelings. The growing global warming crisis makes these conditions even worse, for example, by waves of long-lasting heat, which countries that have not yet experienced them are facing [2].

A significant amount of energy is used to provide adequate indoor conditions for people's occupancy, heating or cooling, which accounts for the vast majority of the energy used by buildings in general. Energy consumption in buildings (residential and commercial) in the world is between 20% and 40% of global energy consumption [3, 4]. Residential consumption of energy in 2004 was, for example, from 15% in Spain, which has a warm climate, to 28% in the cold and rainy UK [3]. In Poland it was about 40% in 1999 [5] mainly due to lower energy efficiency of the buildings.

One way to reduce energy consumption for buildings is to use materials with low thermal conductivity. However, most of such materials are characterized by unfavourable mechanical parameters, mainly low strength and low modulus of elasticity, therefore they are mainly used for thermal insulation of structures. Few exceptions, such as high-strength aerogels [6, 7], are too expensive to consider their use as stand-alone construction materials. However, research is being conducted on their use to increase thermal insulation of construction and finishing materials [8–12]. And it is actually this direction of modifying traditional building materials, e.g. by enriching them with admixtures or materials with favourable thermal parameters without significantly reducing their mechanical and durability parameters, that seems to offer the most promising solutions at acceptable costs. In the case of concrete, one of the solutions is to replace natural aggregates with industrially produced lightweight aggregates (some with use of industrial waste [13, 14] or sewage treatment residues [15]), which are characterized by significantly lower density and thermal conductivity. The resulting lightweight concrete has much better insulating properties than normal concrete. In order to improve them even further, the density of the matrix itself can be further reduced by increasing its porosity, which leads to cellular concrete or foam concrete [16, 17]. However, the latter types of concrete have low strength, so let's stick to lightweight concrete, which is a reasonable compromise between the strength of normal concrete and the insulating properties of cellular concrete. In order to additionally improve its insulating properties, for example, microspheres (cenospheres) can be used [18], which by reducing the density of the matrix at the same time do not reduce its strength as much as in the case of cellular concrete.

However, favourable thermal properties do not reduce to low thermal conductivity alone. An equally important role is played by the material's ability to accumulate heat and give it back later, which helps to reduce the costs of maintaining thermal comfort in the building. This parameter is measured by the amount of heat that a material's unit mass (specific heat) or its unit volume (volumetric thermal capacity) can accumulate. To increase it, phase-changing materials are used, among others [19–21]. They are also used in lightweight concrete [22–25].

When assessing the impact of the applied concrete on the natural environment, it is worth taking into account also the materials from which it was produced. An increasingly significant trend is the use of waste materials in concrete production, which include, among others, metallurgical slag. Both steel slag [26] and waste copper slag [27, 28] can be used in the production of ecological and energy-saving concrete. The latter material is more and more widely used, as evidenced by the growing number of publications [29–37].

The thermal properties of concrete, including lightweight concrete, are not an important trend in material research and although articles dealing with this topic can be found [38, 39], each publication on this topic significantly increases the amount of available data. This publication presents the results of tests of thermal properties of lightweight concrete carried out using the non-stationary hot-plate method [40, 41]. ISOMET 2114 with a surface probe was used in the research. The non-stationary methods of measurement of thermal properties are more and more widely used due to the significantly shorter measurement time than in the case of stationary methods. They prove to be useful for testing the properties of building materials, which are usually characterized by considerable heterogeneity in the macroscopic scale [42–45].

The thermal properties of lightweight concrete as well as its mechanical properties (compressive and tensile strength) were examined in the tests described in this paper. In some series, instead of sand, fine waste copper slag was used as an aggregate, which made it possible to determine the effect of this material on the thermal properties of light concrete and to assess whether this effect is as clear as in the case of normal concrete [27, 28] and heavy concrete [46]. The effects of the amount of cement used (200 kg/m^3 and 300 kg/m^3) and water/cement ratio (0.50, 0.55 and 0.60) were also examined. The increase in the latter parameter causes an increase in the porosity of the concrete matrix and thus affects its ability to conduct and accumulate heat. The aim of the study was, among other things, to determine whether this effect is significant or negligible.

2. Materials and methods

2.1. Materials

For the purpose of the presented research, specimens from 12 series of lightweight concrete were prepared. River sand was used as fine aggregate in 6 series, and in the next 6 series sand was replaced by waste copper slag. The replacement was made at a mass ratio of 1:1 (with an accuracy of 2 kg). Individual series of concrete also differed in terms of water to cement ratio (0.50, 0.55 and 0.60) and in terms of cement content (200 kg/m^3 and 300 kg/m^3). The latter differentiation was assumed due to the possible influence of the amount of cement on the values of the thermal properties, which, among other things, may be related to the difference in density of the material [47].

Portland-composite cement CEM II/B-M (V-LL) 32.5 R fulfilling the requirements of PN-EN-197-1 was used for the preparation of concrete. The composition of the cement, based on the declaration of the producer, is presented in Table 1. The recipes of concrete mixtures are presented in Table 2.

Table 1. Chemical composition of the used cement (according to the producer)

Component	Content [%]
CaO	50.74
MgO	1.18
SiO_2	24.96
Al_2O_3	8.35
Fe_2O_3	3.50
SO_3	2.39
Na_2O_{eq}	0.86
Cl	0.067
LOI	7.03
Unsoluble residue	15.54

The fine aggregate fraction was river sand or waste copper slag (waste from surface blast cleaning process). Waste copper slag is a by-product of copper smelting from ore concentrate. The liquid, hot residue from this process is transported to landfill, where it is rapidly cooled, resulting in approximately 90% of its mass being the glassy phase, with the remaining crystalline phase consisting of SiO_2. Part of the slag produced is then ground. The total amount of copper slag produced in Poland in 2014 was 1.25 million of which ground slag accounted for 400 thousand tonnes with the prospect of reaching about 1.0 million tonnes within a year [48]. In Poland, ground slag is almost entirely used as an abrasive in the air-blast cleaning process, most of which in the shipbuilding industry. Besides, it is also used as a component of hydraulic backfill for filling underground workings, as well as in reclamation works [49] and as bedding in road construction. After its use as an abradant, copper slag is partly cleaned and reused in this role, and partly stored as waste. In the concrete mixes investigated in this paper, waste copper slag after air-blast cleaning was used, which was not cleaned and was not intended for reuse.

The chemical composition of the copper slag is given in Table 2, based on the tests reported in [50], excluding secondary components. This is the composition of the material after the copper smelting process and does not take into account impurities found in the material used for air-blast cleaning (e.g. remains of paint coatings and rust).

Table 2. Chemical composition of copper slag (based on [50])

Component	Average content [%]
LOI	1.12
SiO_2	40.45
Fe_2O_3	14.34
Al_2O_3	11.39
CaO	23.95
MgO	5.22
SO_3	0.15
Na_2O	0.92
K_2O	2.87

The results of investigations of its physical and mechanical properties can be found e.g. in the work by Rzechuła [51]. As this is an industrial waste characterised by increased radioactivity and heavy metal content, including lead (0.85–0.89% [50, 52]), copper (0.55–0.63 [50, 52]), chromium (0.038% [50]), or arsenic (0.007% [52]), the issues of the safety of its use become important. No leachability and radioactivity studies were carried out as part of the research described in this paper, but such studies are available in the literature. According to Rzechuła [51], the concentration of leachable metals hazardous to health after elution with distilled water is within acceptable limits. Investigations of radioactivity of the copper slag itself show that according to the classification presented in the Decree of the Council of Ministers of 2 January 2007 (Journal of Laws 2007, no. 4, item 29 § 3) it qualifies to the 2. group of materials, as the activity indices obtained in tests are within the ranges: 2.0 Bq/kg > f_1 > 1.2 Bq/kg and 400 Bq/kg > f_2 > 240 Bq/kg [50]. On the other hand, studies of materials made with the use of slag show activity allowing to classify them into the 1. group, as the indices meet the criteria $f_1 < 1.2$ Bq/kg and $f_2 < 240$ Bq/kg [29,50]. Guided by these results, it can be assumed that also the tested lightweight concrete will belong to the 1. group. due to the relatively low content of waste copper slag.

Fig. 1. Waste copper slag

Coarse aggregate consisted of two fractions of lightweight aggregate shown in Fig. 2. of which the 4–8 mm fraction was a material called Certyd, which is sintered fly ash produced in the process of burning coal dust (Fig. 2a). And the 8-16 mm fraction was a material called Keramzit (Fig. 2b), which is thermally expanded clay.

Fig. 2. Lightweight aggregate used in the tested concrete mixes: a) sintered fly ash, b) thermally expanded silty clay

Tap water was used as mixing water. The total amount of water applied in the recipes takes into account the absorbability of lightweight aggregates, which was tested before the recipes were prepared, so the values of water to cement ratio given in Table 3 are the assumed effective values.

Table 3. Recipes of concrete mixtures

	S2-50	S2-55	S2-60	S3-50	S3-55	S3-60	C2-50	C2-55	C2-60	C3-50	C3-55	C3-60
Cement CEM II/B-M (V-LL) 32.5R	200	200	200	300	300	300	200	200	200	300	300	300
River sand 0–2 mm	664	656	648	599	587	575	–	–	–	–	–	–
Waste copper slag	–	–	–	–	–	–	662	654	646	597	585	573
Fine light aggregate (Certyd - sintered fly ash)	409	404	400	369	362	354	322	319	315	291	285	279
Coarse light aggregate (Keramzyt - expanded clay)	446	440	435	402	394	386	546	539	533	492	482	473
Water	230	238	247	267	280	293	236	244	252	272	285	297
w/c	0.50	0.55	0.60	0.50	0.55	0.60	0.50	0.55	0.60	0.50	0.55	0.60

Concrete mixes were prepared in such a way that first aggregate and cement was mixed in a concrete mixer and then water was added. The mixing was divided into two stages so that in the interval between them the excess water could be absorbed by lightweight aggregate. The concrete mix was laid in two layers in the moulds. Each layer was compacted using a vibrating table.

From each concrete mixture 8 specimens were prepared in the form of cubes with 100 mm long edges and 2 specimens in the form of cylinders with 150 mm diameter and 300 mm high. The cubic specimens were used to test the compressive strength and the cylindrical specimens were cut 28 days after concreting into slices about 25–30 mm thick. On the specimens prepared in this way the thermal properties were tested with the ISOMET device and a surface probe.

2.2. Thermal parameters measurements

The thermal properties were tested using slices with a diameter of 150 mm and a thickness of about 25–30 mm. They were cut from two cylindrical specimens of the same diameter that were stored in water until they were cut. Nine specimens were cut from each cylinder (except for one case, when only 8 specimens were prepared). To examine the properties of concrete in two different extreme saturation states, the specimens obtained from one cylinder were placed, after cutting, in water until the test, and the specimens from the other cylinder were placed in the dryer. Drying process took place at 65°C until the specimens reached stable mass.

Thermal properties were measured using a non-stationary method with the ISOMET 2114 device equipped with a surface probe. The measurement consists of a preliminary phase, during which the device examines the tested material and selects the appropriate parameters, and then the actual measurement takes place. It consists of three phases: establishing a stable temperature (its changes over time must be less than the assumed threshold), heating the specimen with constant power and cooling it down. During the whole measurement process the temperature of the specimen is continuously recorded and its changes in time are the basis for calculating thermal conductivity, thermal volume capacity and thermal diffusivity.

The number of measurements in one measurement cycle (i.e. in this case on one specimen) was assumed to be 3. The duration of one measurement depends on the time necessary to achieve a stable temperature during the first phase. This time is the longer the lower the thermal diffusivity of the material. The next two measurement phases last a total of about 400 seconds. The whole measurement usually takes between 12 and 18 minutes.

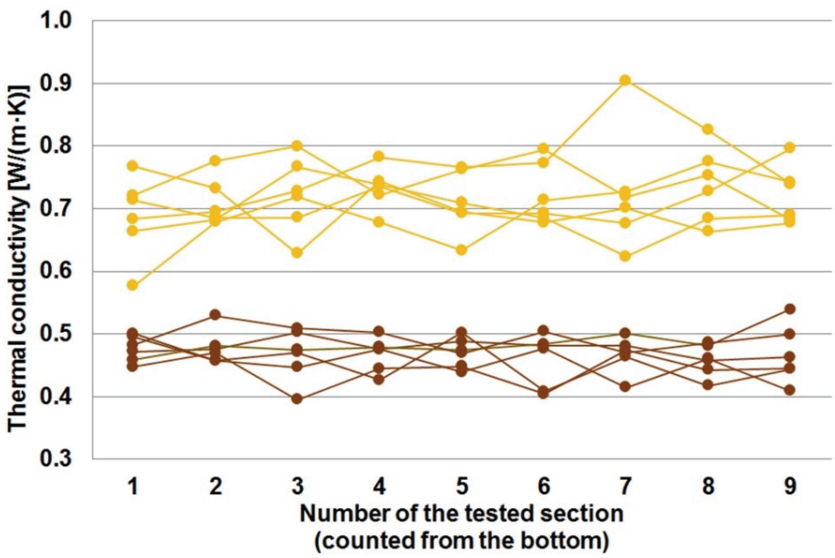

Fig. 3. Differentiation of thermal conductivity values at the height of exemplary concrete specimens with sand (yellow markers) and waste copper slag (brown markers)

Despite the significant difference in the density of coarse (light) and fine aggregates, especially waste copper slag, which has a density of 2.99 kg/dm^3, no segregation of aggregates took place, as evidenced by the thermal conductivity results obtained on individual specimens cut from the same roller. Figure 3 shows the results obtained on dry specimens to illustrate only the variability of the results at the height of the prepared cylinders. Successive numbers from 1 to 9 indicate the consecutive number of the specimen cut counted from the bottom of the cylinder. As it can be seen, in the course of the variability of the thermal conductivity coefficient values, no trend can be distinguished, which indicates that there is no aggregate separation phenomenon that could affect the results.

2.3. Significance analysis

The obtained values of thermal properties were subjected to statistical analysis in order to determine whether the differences between individual series are significant. Due to the large amount of data, the analysis of mutual interactions between factors differentiating individual series was not performed and the analysis was limited to a single-factor analysis of variance (ANOVA), in which it was determined whether a given thermal parameter shows significant differentiation. Since for each of the analysed variants the analysis showed that the obtained differences between the series are statistically significant, a post-hoc analysis was then carried out in order to determine which of the following parameters has a significant impact on the differentiation of the obtained values: type of fine aggregate, w/c ratio or amount of cement. Conclusions resulting from the analyses were given when discussing the results of each of the parameters. Regardless of the analyses described above, the values obtained for specimens saturated with water and dried to constant mass were compared. In this case, the significance of the obtained differences was assessed by arbitrarily comparing the obtained values and the measurement uncertainty values calculated on their basis. The results of these analyses were also presented in detail when discussing the obtained values of particular thermal parameters.

3. Results and discussion

3.1. Compressive strength

The compressive strength was tested using specimens in the form of 100 mm cubes. All the specimens were stored in water from the time of demoulding until the test. The strength test was carried out in accordance with PN-EN 12390-3 on 8 specimens from each concrete series. The results obtained were analysed for outliers and an average of the results that were not rejected was calculated. In addition to the average strength value, a standard deviation was calculated from which the expanded uncertainty of the result was calculated. The values of the compressive strength are listed in Table 4. In addition to the mean value, the uncertainty value is also given.

Table 4. Results of the compressive strength test

	S2-50	S2-55	S2-60	S3-50	S3-55	S3-60	C2-50	C2-55	C2-60	C3-50	C3-55	C3-60
Compressive strength [MPa]	17.5 ±0.6	19.3 ±0.3	17.8 ±0.4	23.6 ±0.4	19.1 ±1.1	18.0 ±0.7	17.7 ±0.4	19.8 ±0.3	18.4 ±0.3	20.4 ±0.5	18.4 ±0.2	17.9 ±0.4

The values of compressive strength of the tested concretes were presented and discussed in more detail in the conference publication [33]. It can be seen that, with two exceptions, concrete in particular series shows the expected tendency to decrease its strength with an increase in the w/c coefficient and higher values of the strength in case of series with more cement used. The influence of the applied fine aggregate is not unequivocal, because in the case of half of the series, the exchange of sand for waste copper slag caused an increase in the strength, and in the case of the remaining series, its decrease.

3.2. Bulk density and open porosity

The values of open porosity and volumetric density are also presented and discussed in the publication [33], as is the method of determining these values. Quoting these results in this paper is justified for two reasons. Firstly, the values of bulk density are necessary to calculate the specific heat of concrete, as the ISOMET device gives the value of volumetric heat capacity. The latter parameter is used much less frequently with regard to building materials, including concrete, and therefore its values have been converted into specific heat values. Secondly, the porosity of the material, not only of concrete, is one of the factors influencing the values of thermal parameters, especially if one compares the results of measurements of these parameters made in the case of concrete saturated with water and dried concrete, when the pores are filled with fluids of very different thermal parameters (water and air). The method of determining the values of volume density and open porosity is described in the paper [33].

Table 5 shows the results obtained. There are values of volumetric density in two states of concrete saturation with water and the values of open porosity. Since these results were obtained after drying the specimens at 65°C, it is not the total porosity. But since the thermal properties of concrete were tested on such dried specimens, the porosity value determined in this way is suitable for analysing the relationship between the content of pores and the differences in the values of thermal parameters measured on specimens saturated and dried to constant mass at 65°C.

Table 5. Average values of the bulk density and open porosity of the concrete

	S2-50	S2-55	S2-60	S3-50	S3-55	S3-60	C2-50	C2-55	C2-60	C3-50	C3-55	C3-60
Bulk density of the saturated specimens [kg/dm^3]	1.76 ±0.01	1.799 ±0.02	1.82 ±0.01	1.84 ±0.02	1.84 ±0.01	1.83 ±0.05	1.77 ±0.04	1.83 ±0.02	1.88 ±0.01	1.83 ±0.04	1.88 ±0.02	1.87 ±0.03
Bulk density of the dried specimens [kg/dm^3]	1.55 ±0.01	1.58 ±0.02	1.59 ±0.01	1.59 ±0.02	1.58 ±0.01	1.54 ±0.06	1.53 ±0.05	1.6 ±0.02	1.63 ±0.01	1.59 ±0.04	1.6 ±0.02	1.58 ±0.03
Porosity	20.9% ±0.2%	22.2% ±0.6%	23.0% ±0.2%	23.8% ±1.0%	26.2% ±0.3%	28.2% ±0.4%	23.0% ±0.7%	22.9% ±0.5%	24.3% ±0.7%	24.6% ±0.5%	27.4% ±0.4%	28.6% ±0.2%

The analysis of porosity results indicates that it increases with the amount of cement in concrete and the w/c ratio. Moreover, concrete made with the use of waste copper slag as a fine aggregate shows slightly higher porosity than concrete made with the use of sand with the same other parameters (w/c ratio and amount of cement).

3.3. Thermal properties

3.3.1. Coefficient of thermal conductivity

The results of the thermal conductivity coefficient test are summarised in Table 6. The values given are averages obtained from the results of individual measurements, from which outliers were rejected. For each of the series, 27 measurements were made and the final number of results included in the calculation of the average in the individual series, given in Table 5, ranged from 15 to 27. Due to the different convergence of the results obtained on dry and wet specimens, the number of values adopted for the calculation of the average and the measurement uncertainty for some series varies according to the state of saturation.

The obtained results indicate significant differences in the value of thermal conductivity of light concrete depending on the state of saturation with water. Dried specimens are characterized by the value of thermal conductivity coefficient lower by 49% to 61%. A greater variation of values in the two tested saturation levels can be seen in the case of a series with the use of sand. In this group there is also no correlation between porosity and differentiation of results obtained on wet and dry specimens. Concrete series made with the use of waste copper slag show a correlation between a decrease in thermal conductivity and porosity. This correlation is the opposite of what one would expect. As the porosity increases, the influence of the saturation state of the specimens decreases.

Table 6. Average values of the coefficient of thermal conductivity of concrete

	S2-50	S2-55	S2-60	S3-50	S3-55	S3-60	C2-50	C2-55	C2-60	C3-50	C3-55	C3-60
Dried specimens [W/(m·K)]	0.669 ± 0.016	0.709 ± 0.018	0.713 ± 0.014	0.748 ± 0.015	0.784 ± 0.033	0.708 ± 0.018	0.446 ± 0.001	0.454 ± 0.013	0.475 ± 0.004	0.479 ± 0.002	0.495 ± 0.007	0.454 ± 0.011
Saturated specimens [W/(m·K)]	1.151 ± 0.016	1.436 ± 0.016	1.391 ± 0.016	1.383 ± 0.016	1.384 ± 0.016	1.410 ± 0.016	0.820 ± 0.016	0.840 ± 0.016	0.898 ± 0.016	0.909 ± 0.016	0.945 ± 0.016	0.885 ± 0.016

The analysis of the obtained results in terms of the influence of the type of fine aggregate used indicates that there is a very clear correlation with the thermal conductivity coefficient values. Series of concrete with sand are characterized by a thermal conductivity coefficient from 0.669 W/(m·K) to 0.784 W/(m·K) in dry state and 1.151–1.436 W/(m·K) in saturated state. In the case of series made of waste copper slag, the corresponding ranges of variation of the thermal conductivity coefficient are as follows 0.446–0.495 W/(m·K) (dried specimens) and 0.820–0.945 W/(m·K) (saturated specimens). The difference is significant and indicates that the use of fine waste copper slag instead of sand as an aggregate allows to obtain lightweight concrete with better thermal insulation properties.

The amount of cement used in only 5 of the 12 pairs of the series under analysis proved to be a factor causing significant changes in the thermal conductivity coefficient values. In all these cases, a higher amount of cement (i.e. 300 kg/m^3 compared to 200 kg/m^3) resulted in an increase in thermal conductivity by 7% to 17%.

An attempt to find a trend of changes in the value of thermal conductivity coefficient along with a change in the w/c ratio did not lead to success. This influence turned out to be statistically significant in a vast minority of cases, but even in this small set of series no regularities could be found.

The decrease in thermal conductivity coefficient as a result of replacing sand with waste copper slag is an effect that has also been observed in other cases where such an exchange has taken place. This effect was also seen when such an exchange was partial [27]. The decrease in thermal conductivity ranged from 3 to 15%, depending on the cement used and additional technological treatments (use of a plasticiser facilitating thickening of the structure). The results presented in [28], where sand was replaced with waste copper slag in increasing proportions, also indicate a gradual decrease in thermal conductivity of the material as more and more waste was incorporated. Here the decreases ranged from 8% up to 44%. The trend of decreasing thermal conductivity values as a result of waste copper slag application was also observed for concrete using recycled aggregate, which was made as a reference concrete to compare its properties with heavy concrete [46]. Two batches of the reference concrete, one made with sand and the other with waste copper slag, showed a difference in thermal conductivity values of 27–29 % (test carried out on specimens saturated with water and dried at 65°C).

3.3.3. Volumetric heat capacity and specific heat

The values of the volumetric thermal capacity are given in Table 7. As in the case of the thermal conductivity coefficient, both average values are given for dried specimens and for specimens saturated with water. In addition to the average values, the measurement uncertainty and the number of specimens included in the analysis are given.

Table 7. Average values of volumetric heat capacity of the concrete

	S2-50	S2-55	S2-60	S3-50	S3-55	S3-60	C2-50	C2-55	C2-60	C3-50	C3-55	C3-60
Dried specimens [MJ/(m^3·K)]	1.53 ± 0.01	1.56 ± 0.01	1.50 ± 0.01	1.57 ± 0.01	1.59 ± 0.02	1.52 ± 0.03	1.50 ± 0.02	1.54 ± 0.01	1.51 ± 0.01	1.55 ± 0.01	1.58 ± 0.00	1.54 ± 0.01
Saturated specimens [MJ/(m^3·K)]	1.63 ± 0.06	2.14 ± 0.03	1.75 ± 0.08	1.91 ± 0.07	1.82 ± 0.11	2.15 ± 0.01	1.65 ± 0.04	1.80 ± 0.05	1.78 ± 0.05	1.98 ± 0.02	1.87 ± 0.06	1.92 ± 0.05

The results obtained in two different states of concrete saturation are significantly different. Considering the high porosity of the material, such variation was to be expected. However, there is no correlation between the content of pores in concrete and the value of volumetric thermal capacity.

The analysis of the obtained results in terms of the influence of the type of fine aggregate used showed that the volumetric thermal capacity is almost completely insensitive to this parameter. In all the compared pairs of concrete series that were tested after drying the specimens, the differences in the values obtained for concrete with sand and concrete with waste copper slag proved to be statistically insignificant. The results obtained in the case of concrete specimens saturated with water showed significant differences only in the case of two out of six analysed pairs of the series.

The results of the analysis of the influence of the amount of cement used lead to other conclusions. In the case of the results obtained on dried specimens, significant differences were recorded in four out of six pairs of the compared series, although the differences in numbers are small, as they range from 2.3% to 2.7%. The higher amount of cement increases the value of volumetric thermal capacity. The results obtained on specimens saturated with water show much greater variability, as here the differences range from 7.2% to 18.5%, and five out of six pairs of the compared series show statistically significant differentiation. In one case, a larger amount of cement resulted in a decrease in volumetric heat capacity, but this should be considered as an exception to the rule, as in other cases the effect was the opposite.

Differentiation of the value of the w/c ratio did not lead to a clear relationship between this parameter and the value of volumetric thermal capacity. Both water saturated and dried specimens in five out of twelve cases showed statistically significant differences. However, they do not follow any trend, as exactly half of the significantly different results showed an increase in their volumetric thermal capacity along with an increase in the w/c index and half a decrease.

Table 8 presents the results of concrete specific heat calculations. These calculations were carried out on the basis of the measured values of concrete density and volumetric heat capacity. Similarly to the previously discussed thermal parameters, also in this case average values, measurement uncertainty values and the number of specimens included in the calculations were given.

Table 8. Average values of specific heat of the concrete

	S2-50	S2-55	S2-60	S3-50	S3-55	S3-60	C2-50	C2-55	C2-60	C3-50	C3-55	C3-60
Dried specimens [mm^2/s]	987 ±8	988 ±5	938 ±10	985 ±8	997 ±20	993 ±17	960 ±24	935 ±17	923 ±8	973 ±10	978 ±10	969 ±8
Saturated specimens [mm^2/s]	925 ±32	1197 ±15	958 ±48	1010 ±60	978 ±54	1162 ±18	922 ±33	977 ±30	946 ±29	1061 ±24	998 ±33	1029 ±25

The analysis of the obtained results of the specific heat calculation shows that this parameter is slightly correlated with the factors which influence was analysed. The influence of the concrete saturation level is most evident, as the specific heat of water saturated specimens is in most cases higher than that of dried ones. Exceptions to this rule should be explained by the large variation in the parameters taken into account for the calculation, i.e. density and volumetric heat capacity, since the specific heat value was calculated for each specimen separately to calculate the value of its standard deviation directly from the results obtained. Due to the high heterogeneity of the material, both of these parameters were characterised by a large variation, which was reflected in the obtained values of specific heat.

The results of volumetric heat capacity testing performed on concrete with waste copper slag presented in other publications are rather ambiguous. It can be seen both that there is no effect of sand replacement on waste copper slag, as in the case of the results presented in [27], but also that

there is a rather clear and significant decrease, as in the case of the results presented in [28]. In the latter case, only two concrete series were compared with each other, in two states of saturation, so it is difficult to consider these results as conclusive. In the case of a larger number of series tested in the study [46], a decrease in the volumetric heat capacity value after the introduction of waste copper slag into the concrete can be noticed when testing wet specimens, but the trend is no longer clear as the proportion of the waste increases. In the case of dry specimens, the differences obtained are smaller than the measurement uncertainty value and it can be assumed that the individual series do not differ significantly from each other in terms of volumetric heat capacity. The differences in the case of wet samples can be explained by differences in porosity. Material with a larger pore volume can store more water in the saturated state. Water has a high volumetric heat capacity value and the differences noted can be attributed to its influence. The type of fine aggregate used itself does not seem to have a significant effect on the volumetric heat capacity value.
Results of specific heat calculations were not compared with other cases due to significant differences in bulk density.

3.3.4. Thermal diffusivity

The last analysed thermal parameter obtained from the tests is thermal diffusivity. Its average values and measurement uncertainty are given in Table 9.

Table 9. Average values of thermal diffusivity of the concrete

	S2-50	S2-55	S2-60	S3-50	S3-55	S3-60	C2-50	C2-55	C2-60	C3-50	C3-55	C3-60
Dried specimens [J/(kg·K)]	0.455 ± 0.007	0.450 ± 0.003	0.463 ± 0.005	0.476 ± 0.008	0.492 ± 0.021	0.457 ± 0.015	0.291 ± 0.004	0.299 ± 0.007	0.316 ± 0.003	0.312 ± 0.003	0.316 ± 0.004	0.297 ± 0.007
Saturated specimens [J/(kg·K)]	0.703 ± 0.026	0.677 ± 0.009	0.752 ± 0.037	0.733 ± 0.036	0.744 ± 0.027	0.655 ± 0.020	0.496 ± 0.008	0.459 ± 0.012	0.508 ± 0.013	0.467 ± 0.008	0.503 ± 0.014	0.466 ± 0.009

Among the results obtained, the variation due to the degree of saturation of the material is very pronounced, with a lower diffusivity value being obtained for dried specimens. Also, a comparison of the values characterising series groups made with two types of fine aggregate indicates very clear and large differences. In this case, a lower thermal diffusivity value was obtained in the group of series of concrete made using waste copper slag. In the case of the other two analysed parameters, i.e. the amount of cement used and the w/c ratio, there is no clear correlation between them and the differences in thermal diffusivity values. Although statistically significant differences were obtained for some of the series, they do not form any consistent relationship.

4. Summary and conclusions

The obtained results indicate that it is possible to produce lightweight concrete of good quality and favourable thermal properties using a minimum amount of cement. Such concrete can be described as ecological for several reasons. Lightweight aggregate made from ashes and waste copper slag are industrial waste. The material itself saves energy due to its favourable thermal properties. The same effect is achieved by using a minimum amount of cement, the production of which is associated with high CO_2 emissions to the atmosphere.

Apart from the above, the following specific conclusions can be drawn from the results obtained.

1. The use of waste copper slag significantly modifies two interrelated thermal parameters of lightweight concrete: thermal conductivity and thermal diffusivity. Both of these values significantly decrease in relation to concrete of the same composition prepared using sand.
2. Differentiation of thermal conductivity and diffusivity of lightweight concrete prepared with the use of waste copper slag is independent of the level of concrete saturation with water. In both analysed saturation states (material fully saturated and dried at 65°C to constant mass) the differences are significant and large.
3. Usage of sand or waste copper slag in lightweight concrete has little influence on the properties determining the material's ability to accumulate heat. The values of volumetric heat capacity and specific heat in both variants differ slightly from each other and these differences result more from the heterogeneity of the material than from its composition.
4. In the case of lightweight concrete prepared with a low cement usage (up to 300 kg/m^3), the open porosity of the material, determined after it has been dried to a constant mass at 65°C, varies slightly with the change in the w/c ratio, as the lightweight aggregate used is responsible for most of this porosity.
5. There is no clear correlation between the open porosity value of the tested lightweight concrete and the values of its thermal parameters.

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Właściwości mechaniczne i cieplne betonu lekkiego z odpadowym żużlem pomiedziowym jako kruszywem lekkim

Słowa kluczowe: beton lekki, odpadowy żużel pomiedziowy, właściwości cieplne, ekologiczne materiały budowlane

Streszczenie:

W badaniach opisanych w niniejszej pracy określono właściwości termiczne betonu lekkiego oraz jego właściwości mechaniczne (wytrzymałość na ściskanie i rozciąganie). W części serii zamiast piasku jako kruszywo drobne zastosowano odpadowy żużel pomiedziowy, co umożliwiło określenie wpływu tego materiału na właściwości cieplne betonu lekkiego oraz ocenę, czy wpływ ten jest równie wyraźny jak w przypadku betonu zwykłego i ciężkiego. Zbadano również wpływ ilości użytego cementu (200 kg/m^3 i 300 kg/m^3) oraz stosunku woda/cement (0,50, 0,55 i 0,60).

Wykonano łącznie dwanaście serii betonu. W sześciu z nich jako kruszywo drobne zastosowano piasek rzeczny, a w kolejnych sześciu zastąpiono go odpadowym żużlem pomiedziowym. Wymiany dokonano w stosunku masowym 1:1. Zastosowano cement portlandzki wieloskładniowy CEM II/B-M (V-LL) 32,5 R. Kruszywo grube składało się z dwóch frakcji kruszywa lekkiego. Frakcją 4–8 mm był kruszywo Certyd, a frakcję 8-16 mm stanowił keramzyt. Całkowita ilość wody zastosowanej w recepturach uwzględniała chłonność kruszywa lekkiego, którą badano przed przygotowaniem receptur.

Właściwości cieplne badano na próbkach o średnicy 150 mm i grubości ok. 25–30 mm. W celu zbadania właściwości betonu w dwóch różnych stanach granicznego nasycenia, część próbek przechowywano w wodzie do momentu przeprowadzenia badań, a pozostałą część umieszczono w suszarce w temperaturze 65°C do momentu osiągnięcia stabilnej masy.

Wytrzymałość na ściskanie badano na kostkach 100 mm. Wpływ rodzaju zastosowanego kruszywa drobnego nie był w tym przypadku jednoznaczny, gdyż w przypadku połowy serii, wymiana piasku na odpadowy żużel pomiedziowy spowodowała wzrost wytrzymałości, a w przypadku pozostałych serii jej spadek.

Określono również porowatość materiału. Analiza wyników wykazała, że zwiększa się ona wraz z ilością cementu w betonie i współczynnikiem w/c. Ponadto beton wykonany z wykorzystaniem odpadowego żużla pomiedziowego wykazuje nieco wyższą porowatość niż beton wykonany z wykorzystaniem piasku o tych samych pozostałych parametrach (stosunek w/c i ilość cementu).

Właściwości cieplne zmierzono metodą niestacjonarną za pomocą urządzenia ISOMET 2114 wyposażonego w sondę powierzchniową. Uzyskane wartości właściwości cieplnych poddano analizie statystycznej. Ze względu na dużą ilość danych analizę ograniczono do jednoczynnikowej analizy wariancji (ANOVA). Ponieważ w przypadku każdego z rozpatrywanych wariantów analiza wykazała, że otrzymane różnice między seriami są istotne statystycznie, przeprowadzono następnie analizę post hoc. Niezależnie od wymienionych powyżej czynników różnicujących

poszczególne serie analizie poddano również wartości otrzymane w przypadku próbek nasyconych wodą i wysuszonych do stałej masy.

Wyniki badania współczynnika przewodności cieplnej wskazują na istotne różnice w wartościach tego parametru w zależności od nasycenia betonu. Próbki wysuszone charakteryzują się niższą wartością współczynnika przewodnictwa cieplnego. Większe zróżnicowanie tego parametru w zależności od poziomu nasycenia betonu wodą dało się zaobserwować w przypadku serii z wykorzystaniem piasku. W tej grupie nie ma również korelacji pomiędzy porowatością a zróżnicowaniem wyników uzyskanych na próbkach nasyconych i wysuszonych. Serie betonu wykonane z wykorzystaniem odpadowego żużla pomiedziowego wykazują korelację pomiędzy spadkiem przewodności cieplnej a porowatością. Korelacja ta jest jednak przeciwna od tej, jakiej należałoby się spodziewać. Wraz ze wzrostem porowatości zmniejsza się wpływ stanu nasycenia próbek.

Analiza uzyskanych wyników pod kątem wpływu rodzaju zastosowanego kruszywa drobnego wskazuje na bardzo wyraźną korelację z wartościami współczynnika przewodności cieplnej. Różnice są duże i wskazują, że zastosowanie w roli drobnego kruszywa odpadowego żużla pomiedziowego zamiast piasku pozwala na uzyskanie betonu lekkiego o wyższej izolacyjności termicznej. Próba znalezienia trendu zmian wartości współczynnika przewodności cieplnej wraz ze zmianą współczynnika w/c nie doprowadziła do sukcesu. Wpływ ten okazał się istotny statystycznie w zdecydowanej większości przypadków, ale nie stwierdzono wśród nich żadnych prawidłowości.

Wartości objętościowej pojemności cieplnej uzyskane w dwóch różnych stanach nasycenia wody są istotnie różne. Biorąc pod uwagę wysoką porowatość materiału, należało się spodziewać takiego zróżnicowania. Nie ma jednak korelacji pomiędzy zawartością porów w betonie a wartością objętościowej pojemności cieplnej. Analiza tego parametru wykazała, że różnice w wartościach uzyskanych w przypadku betonu z piaskiem i betonu z odpadowym żużlem pomiedziowym okazały się nieistotne statystycznie. Natomiast większa ilość cementu zwiększa wartości objętościowej pojemności cieplnej wysuszonego betonu i zmniejsza je w przypadku betonu nasyconego. Zróżnicowanie wartości wskaźnika w/c nie doprowadziło do wyraźnej zależności pomiędzy tym parametrem a wartością objętościowej pojemności cieplnej.

Wartości ciepła właściwego betonu zostały obliczone na podstawie zmierzonych wartości gęstości betonu i objętościowej pojemności cieplnej. Z analizy uzyskanych wyników wynika, że parametr ten jest w niewielkim stopniu skorelowany z branymi pod uwagę czynnikami. Wpływ stopnia nasycenia wodą jest najbardziej widoczny, ponieważ ciepło właściwe próbek nasyconych wodą jest w większości przypadków wyższe od ciepła właściwego próbek wysuszonych.

Ostatnim analizowanym parametrem cieplnym uzyskanym z badań jest dyfuzyjność cieplna. Spośród uzyskanych wyników bardzo wyraźna jest zmienność związana z poziomem nasycenia materiału, przy czym niższa wartość dyfuzyjności uzyskiwana jest dla próbek suszonych. Również dwa rodzaje drobnego kruszywa wskazują na bardzo wyraźne i duże różnice. Niższą wartość dyfuzyjności cieplnej uzyskano dla serii betonów wykonanych z wykorzystaniem odpadowego żużla pomiedziowego.

Uzyskane wyniki wskazują, że możliwa jest produkcja betonu lekkiego o dobrej jakości i korzystnych właściwościach termicznych przy użyciu minimalnej ilości cementu. Beton taki można określić jako ekologiczny co najmniej z kilku powodów. Ze względu na zastosowanie lekkiego kruszywa z popiołów i odpadowego żużla pomiedziowego jako drobnego kruszywa, materiał ten pozwala zagospodarować odpady przemysłowe. Dzięki swoim korzystnym właściwościom termicznym pozwala na oszczędność energii. Ten sam efekt jest osiągany poprzez zastosowanie minimalnej ilości cementu, którego produkcja wiąże się z wysoką emisją CO_2 do atmosfery.

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