



Research paper

The influence of measurement conditions on the determined values of thermal parameters of different types of concrete

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Abstract: In recent years, great emphasis has been placed on the introduction of energy-saving solutions to the construction sector. Building envelopes made of concrete with a specially selected composition give great opportunities in this regard. As part of a wide-ranging experiment, the authors undertook to diagnose how much thermal conductivity, volumetric specific heat and thermal diffusivity can be improved with an aerating admixture and different types of aggregates. Three groups of composites were tested: B1 – on stone aggregate, B2 – on expanded clay aggregate, B3 – on sintered fly ash aggregate. Each of the groups was divided into 4 formulations made without an aerating admixture and with its increasingly higher content of 0.8, 1.1, 1.4% in relation to the weight of cement. The thermal parameters were measured on the top (T) and bottom (B) surfaces of 36 rectangular samples (3 samples from each of the 12 mixtures) with the ISOMET 2104 apparatus. Diagnostic tests concerning the influence of measurement conditions were carried out on dry and water-saturated samples. It has been proven that for each composite and in both conditions, the values of thermal parameters determined on the lower surfaces will not correctly describe the properties of the real structure present in the main volume of the element. Only measurements carried out on surfaces with a structure corresponding to the interior of the element provide adequate data that can be used in decision-making processes and in numerical simulations to assess the real thermal qualities of building envelopes.

Keywords: concrete, moisture content, thermal conductivity, thermal diffusivity, type of surface, volumetric specific heat

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1. Introduction

As part of the works [1, 2], carried out at the Faculty of Civil and Environmental Engineering of the West Pomeranian University of Technology in Szczecin, extensive research was carried out to assess the basic thermal parameters of a wide group of concrete composites. The issues of proper solution of external envelopes in terms of construction and material is not only to provide them with the required load-bearing capacity and durability, but also optimal thermal parameters. Under Article 5, paragraph 1 of the Construction Law [3], all buildings in Poland must be designed and built in conformity with “technical building regulations,” i.e. regulations issued by competent ministers that set out technical requirements for buildings, their location, and use. The most important of these is the Minister of Infrastructure Regulation of 12 April 2002 on technical requirements for buildings and their location (Journal of Laws 2002, item 1225) [4], which specifies detailed technical standards for buildings. The current regulations [4] require that the heat transfer coefficient of external walls (at $t_i \geq 16^\circ\text{C}$) did not exceed the limit value of $0.20 \text{ W}/(\text{m}^2 \cdot \text{K})$. Energy considerations lead not only to providing the envelopes with the required thermal insulation, but also to increasing their heat storage, improving the comfort of using the building and reducing energy consumption for its heating or cooling. This problem is now becoming particularly important, when the issue of reducing energy consumption becomes a priority challenge due to, among others, existing limitations with the availability of energy resources. These circumstances lead to research all over the world on the possibilities of improving the thermal parameters of concrete composites intended for external walls.

A very extensive review of literature relating to the thermal conductivity of concrete was carried out in [5]. The authors analyzed 117 items of world literature in the field of applied research techniques and various modifications in the composition of concrete mixes, aimed at improving their thermal conductivity. Stationary and non-stationary research techniques were discussed, with the conclusion drawn from the review that non-stationary methods were chosen much more often due to the availability of equipment, their price, duration of measurement and the possibility of testing wet samples. The most commonly used methods in measuring the thermal conductivity of concrete were considered to be the “hot wire” method and the “transient plane source” method. Material and technological factors influencing the thermal parameters of concrete were also analyzed, indicating, among others, type and amount of aggregate, type of binder used, water-cement ratio, type and number of admixtures and additives used (e.g., phase change materials) or the age of the samples. The influence of moisture and temperature on the measurement results obtained by individual researchers was also discussed extensively. In the case of humidity, the analyzed tests showed that the value of the thermal conductivity coefficient of cement composites in saturated conditions was 1.4–3 times higher than the values measured in the dry state. The analysis of the influence of temperature on thermal conductivity showed a downward trend. For example, tests carried out at 500°C gave a value of thermal conductivity that was about 50% lower than the value determined at room temperature.

Unfortunately, in this extensive review, there is not even a mention of a very important factor strongly affecting the results of thermal measurements carried out using the non-

stationary technique. This factor is the method of preparing the surface on which tests are carried out with the use of a contact probe. Creating inappropriate measurement conditions and conducting tests on surfaces that do not represent the actual structure present in the volume of the element results in a strong falsification of the results. The testing measurements presented below prove that the thermal parameters determined on the top (T) and bottom (B) surfaces of the same samples may differ in relation to each other even several times.

2. Materials and methods

A concrete composite consists of aggregate grains dispersed in a cement matrix. The aggregate is the majority component of the composite, averaging approx. 70% of the total volume. The remaining 30% of the concrete volume is cement paste, which binds the fine and coarse aggregate grains in the material with specific properties.

Therefore, by using the appropriate type of aggregate, we can most effectively affect the final properties of the obtained composite. Additional possibilities are also provided by the modification of the cement paste microstructure, obtained through the use of various types of additives and admixtures (e.g., aerating admixtures).

The extensive research program presented in the paper included three main groups of concretes divided depending on the type of aggregate used: B1 – on stone aggregate, B2 – on expanded clay aggregate, B3 – on ash-porous aggregate. In turn, each of the groups was divided into 4 formulations made without an aeration admixture and with its increasingly higher content of 0.8, 1.1, 1.4% by weight of cement. As a result, the tests covered 12 concrete composites, adopting the following designations for individual formulations, taking into account the type of coarse aggregate used and the amount of admixture introduced into the mix: B1-0, B1-0.8, B1-1.1, B1-1.4 (on stone aggregate), B2-0, B2-0.8, B2-1.1, B2-1.4 (on expanded clay aggregate), B3-0, B3-0.8, B3-1.1, B3-1.4 (on sintered fly ash aggregate).

All mixes were made with the use of Portland cement CEM I 42.5R, tap water and quartz sand with a grain size of up to 2 mm. Each of the coarse aggregates (stone, expanded clay and sintered fly ash) had the same grain size in the range of 4–8 mm.

Formulations of individual 12 mixtures, as well as strength and physical parameters of the obtained composites B1 (0, 0.8, 1.1, 1.4%), B2 (0, 0.8, 1.1, 1.4%), and B3 (0, 0.8, 1.1, 1.4%) were determined in the work [6] and presented in [7].

The recipes of all concrete composites are shown in Table 1 which is prepared on the basis of [7].

The thermal tests consisted of a total of 36 rectangular samples (three from each recipe). Molds with internal dimensions of 14×16×4 cm were used to make the samples. Initially, the molds were filled with the mixture to half the height and then placed on a vibrating table to ensure proper compaction. After the first layer was compacted, the molds were filled with another portion of the mixture and vibrated again. The excess of the mixture was removed with a trowel, sliding along the upper edge of the mold. Subsequently, the molds containing the concrete mix were placed in a climatic chamber and stored in high humidity for 24 h. Then the samples were demolded and placed back in the chamber. The total storage time of

Table 1. Mix proportions of tested concrete composites

Type of recipe	Type of coarse aggregate	Coarse aggregate kg/m ³	Quartz sand kg/m ³	Cement kg/m ³	Water kg/m ³	Aerating admixture kg/m ³
B1-0	Stone aggregate	1290.73	464.57	387.14	212.93	0.000
B1-0.8		1002.55	360.90	300.69	165.38	2.405
B1-1.1		1002.56	360.85	300.71	165.39	3.308
B1-1.4		1002.55	360.90	300.69	165.38	4.209
B2-0	Expanded clay aggregate	257.84	602.89	502.41	276.32	0.000
B2-0.8		209.72	490.41	408.69	224.79	3.268
B2-1.1		209.74	190.42	408.68	224.77	4.495
B2-1.4		209.72	490.41	408.69	224.76	5.721
B3-0	Sintered fly ash aggregate	570.00	619.64	516.36	284.00	0.000
B3-0.8		451.93	491.24	409.38	225.17	3.275
B3-1.1		451.92	491.27	409.39	225.17	4.503
B3-1.4		451.93	491.24	409.38	225.17	5.731

the samples in the climate chamber was 28 days. After this time, the samples were removed from the chamber and placed for approx. 2 months in a water bath. The samples were then transferred to a laboratory, where they were stored in air-dry conditions until a constant weight was obtained.

After the curing process was completed, the samples (with base dimensions of 14×16 cm and a height of approx. 4 cm) were subjected to mechanical processing – using a diamond disc, the top layer of each of the 36 samples was cut off. In this way, it was possible to carry out measurements on two different surfaces of the same sample – the upper one (representing the structure of the element's interior) and the lower one (formed at the interface between the mixture and the bottom of the mold). The applied measurement technique with the use of contact probes, as the required condition for the correct conduct of measurements, is the homogeneity and smoothness of the tested surfaces, which was ensured in each case. A photo of a set of samples prepared for testing is shown in Fig. 1, which additionally exposes the differences between the two surfaces (top and bottom) of the samples.

As part of the work [1, 2], thermal parameters of all 12 concrete composites were tested, in the following order:

- drying of samples in laboratory drying ovens until a constant weight was achieved,
- measurements of thermal parameters – carried out on dry samples,
- saturation of the samples to a constant weight in a water bath,
- measurements of thermal parameters – carried out on water-saturated samples.



Fig. 1. View of 36 samples prepared for thermal tests as part of works [1,2]

Directly before the drying process, all samples were weighed in an air-dry state on an electronic scale with a precision of 0.01 g. Thereafter, they were placed on grates in a dryer programmed with successive time-temperature cycles. The drying process was repeated until the weight of all samples was stabilized. The subsequent cycles were as follows: 3.5 h at 50°C and 16.5 h at 70°C; 3.5 h at 50°C and 79 h at 70°C; 2 h at 50°C and 17.5 h at 70°C; 17.5 h at 70°C and 21 h at 70°C.

After drying, each sample was wrapped in polyurethane foil and then placed in a sealed container, according to groups (B1, B2, B3). This method ensured protection against re-absorption of moisture from the surrounding environment. Subsequently, samples were systematically taken for thermal tests. Measurements were carried out on the upper (T) and lower surfaces (B) of each of the 36 samples.

After completing the tests on the dry samples, they were placed in cuvettes with distilled water. Throughout the storage period, the water in the cuvettes was systematically replenished and cyclical measurements of the samples' weight changes were carried out using an electronic balance with a precision of 0.01 g. An approx. 2 months period was sufficient to obtain full saturation of the samples with water.

Similarly to dry samples, saturated samples were also subjected to thermal tests carried out on both the upper (T) and lower (B) surfaces of each of the 36 samples.

The tests of thermal parameters of all composites were carried out by the non-stationary method using the Isomet 2104 apparatus. It is "Heat Transfer Analyzer" [8] – multifunction instrument for measurement of thermal conductivity (λ) [W/(m·K)], volumetric specific heat (C_v) [J/(m³·K)] and thermal diffusivity (a) [m²/s]. As stated in the user's guide [8]: "Measurement is based on analysis of the temperature response of the analyzed material to heat flow impulses. Heat flow is excited by electrical heating of resistor heater inserted

into the probe which is in direct heat contact with the tested specimen. Evaluation of thermal conductivity and volume heat capacity is based on periodically sampled temperature records as function of time, provided that heat propagation occurs in unlimited medium". Isomet 2104 is a portable measuring instrument for direct measurement of thermophysical properties of building and construction materials. It applies a dynamic method which reduces the time of measurements up to about 8–16 minutes [8]. This device consists of a recorder to which a properly selected surface probe (for hard materials) or a needle probe (for soft materials) is connected. In the tests [1, 2], three surface probes with the following ranges were used: 0.04–0.30 W/(m·K); 0.30–2.00 W/(m·K); 2.00–6.00 W/(m·K). The reproducibility of Isomet 2104 for thermal conductivity measurements is 3% of reading +0.001 W/(m·K) and for volumetric specific heat 3% of reading + $1 \cdot 10^3$ J/(m³·K). The measurement accuracy of Isomet 2104 is given in Table 2 which is prepared on the basis of [8]. Similar parameters also have newer types of this device, for example Isomet 2114 (compare [9]).

Table 2. Measurement accuracy of Isomet 2104, [8]

Measurement	Measurement range	Accuracy
Thermal conductivity	0.015–0.050 W/(m·K)	5% of reading + 0.003 W/(m·K)
	0.050–0.70 W/(m·K)	5% of reading +0.001 W/(m·K)
	0.70–6.0 W/(m·K)	10% of reading
Volumetric specific heat	$4.0 \cdot 10^4 - 4.0 \cdot 10^6$ J/(m ³ ·K)	15% of reading + $1 \cdot 10^3$ J/(m ³ ·K)

Figure 2 shows a photograph illustrating the course of one of the 288 measurements carried out.

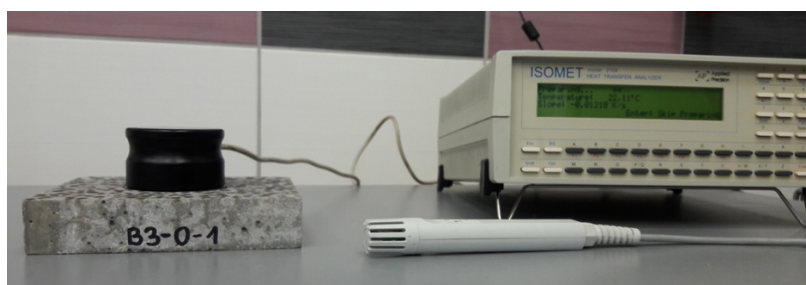


Fig. 2. Determination of thermal parameters using the Isomet 2104 apparatus with contact/surface probe [2]

Tests on both surfaces of each sample were carried out twice. Thus, for each composite, 6 individual values of λ , C_V , a – related to the interior of the element (read on the top surface exposed after cutting off the upper layer and exposing the core structure of the material) and related to its surface formed at the interface of the mixture with the mold (bottom surface) were obtained. For all 12 formulations, the tests were carried out separately on dried samples and on water-saturated samples.

Such an arrangement of the experiment made it possible to assess not only the influence of the internal material structure of each of the composites on the obtained results, but also to estimate to what extent the change in measurement conditions translates into the results recorded in a given test.

3. Research results and their analysis

Comparative compilations of all the obtained results are presented below – divided into analyzes relating to dry samples (subchapter 3.1) and wet samples (subchapter 3.2). The values of thermal conductivity, λ , volumetric specific heat, C_V , and thermal diffusivity, a , are presented in Figs. 3–5 (dry samples) and in Figs. 6–8 (wet samples). Apart from the mean values, the standard deviations of the results were also determined. In general, high repeatability of results was obtained. The coefficients of variation in most cases were at the level of a few percent. Only in a few cases did the coefficients of variation slightly exceed 10%.

The purpose of carrying out all the following analyzes was to check how and to what extent individual measurement factors (type of tested surface and moisture condition) affect the obtained values of thermal parameters (λ , C_V , a) of concretes made on the basis of different aggregates (B1, B2, B3), using different amounts of aerating admixture (0%, 0.8%, 1.1%, 1.4%).

3.1. Dry samples – comparison of the results obtained on the top and bottom surfaces

Each of the results presented in Figs. 3–5 is the arithmetic mean determined on the basis of the results from 6 individual measurements (in each of the three samples of a given composite, measurements on each surface were carried out twice). A total of 144 measurements of thermal parameters were carried out on dry samples. Only in the case of concrete B1-0.8 were the measurement results from the lower surface of the B1-0.8-3 sample rejected. The dispersion of the obtained results can be assessed by analyzing the data published in [10], which presents the components of the λ coefficient determined on the upper surfaces of 36 samples tested in a dry state.

3.1.1. Thermal conductivity of dry samples

The average values of thermal conductivity λ determined in measurements carried out on the top (T) and bottom (B) surfaces of samples of twelve composites tested in the dry state are summarized in Fig. 3.

The comparison of the results obtained on the top and bottom surfaces of individual composites shows how important it is which surface is tested. The values of the thermal conductivity coefficient determined in the measurements carried out on the upper surface differ significantly from those determined on the lower surface, regardless of the type of aggregate used or the amount of admixture. Analyzing the values from Fig. 3, it can be seen that the lower thermal conductivity in each case is noted in the tests carried out on the upper

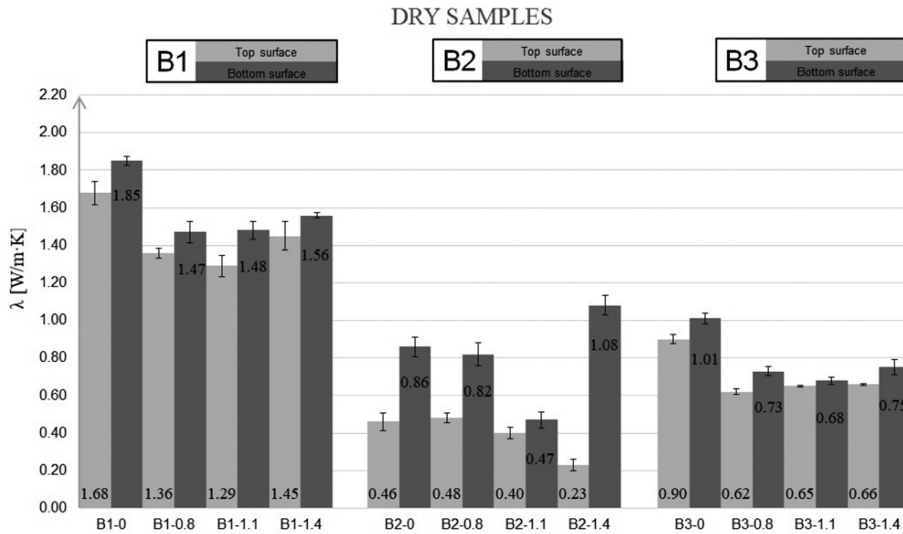


Fig. 3. Average values of the thermal conductivity coefficient λ determined on the top and bottom surfaces of dry samples

surfaces of the samples. In most concretes, the differences between the two surfaces are very large. The greatest range of variability occurs in concrete on expanded clay aggregate, especially in the one with an aerating admixture in the amount of 1.4% of the cement mass. The average value of $\lambda_{B2-1.4}^T = 0.23$ W/(m·K) obtained from the measurements carried out on the upper surfaces of the samples is almost 5 times lower than the average value of $\lambda_{B2-1.4}^B = 1.08$ W/(m·K) determined on the lower surfaces of the samples made from this formulation. The lowest variability of results was noted in the studies concerning the B3-1.1 formulation. In this case, the thermal conductivity coefficient on the top surface $\lambda_{B3-1.1}^T = 0.65$ W/(m·K) differs by less than 5% in relation to the average value determined on the bottom surface $\lambda_{B3-1.1}^B = 0.68$ W/(m·K).

Additional differences are also noted when analyzing the effects of lowering the thermal conductivity coefficient due to the introduction of an aeration admixture. For example, the tests of the top surface of concrete B1 show that the best choice is to use an admixture in the amount of 1.1% of the cement mass, which reduces the λ value to 77% compared to the B1-0 reference mix. From the analysis of the data from the bottom surface of the B1 samples, it would appear that a better option would be to use an admixture at the level of 0.8% of the cement mass, resulting in a reduction of λ to the level of 79% of the value obtained from the B1-0 formula. Data from the B2 group of concretes would also lead to different conclusions. The analysis of the results read on the top surfaces of the samples would indicate the highest efficiency of using an admixture in the amount of 1.4% (reduction the λ of B2-1.4 concrete to the level of 50% of the value obtained for the reference concrete B2-0). On the other hand, based on the data from the bottom surfaces, the introduction of the admixture in the amount of 1.1% would be considered the most effective (reduction of λ B2-1.1 to the level of 54% of the value of the reference formula B2-0). A divergence

of recommendations would also occur in the case of formula B3. Based on measurements from the top surfaces, it would be recommended to use an admixture in the amount of 0.8% (reduction of λ B3-0.8 to 69% compared to B3-0). On the other hand, based on the results collected on the bottom surfaces, an admixture of 1.1% would be preferred (reduction of λ B3-1.1 to 67% compared to B3-0).

The occurrence of differences in the assessment should also be taken into account when carrying out an analysis of the reasonableness of replacing the stone aggregate with one of the two tested types of lightweight aggregates. While the data from the top surfaces are unambiguous and indicate the highest efficiency of λ reduction in the case of using expanded clay aggregate, the data from the bottom surfaces may lead to misleading conclusions. Let's take the B2-1.4 mix as an example, in which there was a strong increasing the fluidity of the mixture in the lower zone (in contact with the mold) and significant compaction of the structure, which did not occur in the depth of the element. A different structure (at the bottom surface and inside the element) is quantitatively expressed in the values of thermal conductivity coefficients measured on the top and bottom surfaces of the B2-1.4 composite samples: $\lambda_{B2-1.4}^T = 0.23 \text{ W/(m}\cdot\text{K)}$ and $\lambda_{B2-1.4}^B = 1.08 \text{ W/(m}\cdot\text{K)}$. If the decision was based on the latter result, then the sintered fly ash aggregate could be mistyping as more effectively reducing the λ coefficient of the tested group of composites, which is not true.

3.1.2. Volumetric specific heat of dry samples

Figure 4 shows the average values of the volumetric specific heat C_V determined in the measurements carried out on the top (T) and bottom (B) surfaces of the dry samples of the twelve tested composites.

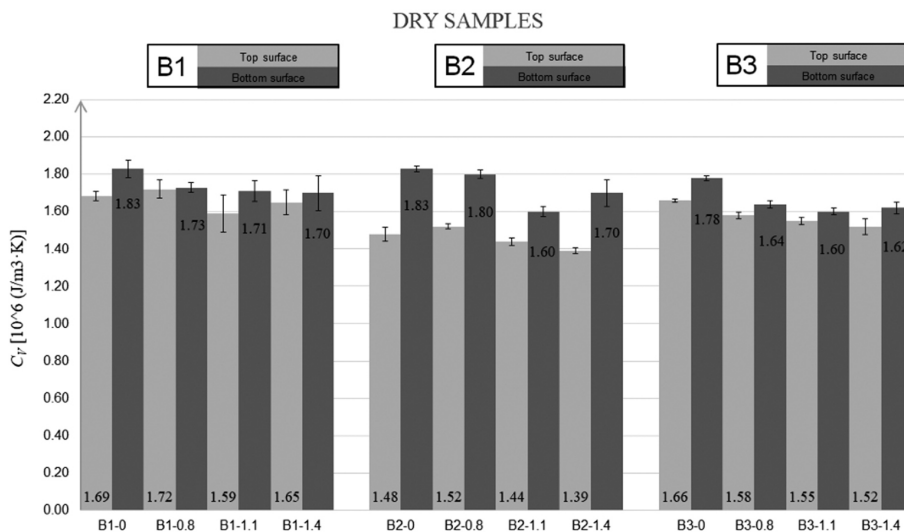


Fig. 4. Average values of volumetric specific heat C_V determined on the on the top and bottom surfaces of dry samples

Analyzing the data in Fig. 4, in which the values of the volumetric specific heat of two surfaces were compared, a uniform tendency can be observed. Well, all C_V values measured on the lower surfaces of the samples are higher in relation to the analogous values, but determined on the upper surfaces, representing the real structure inside the element. The greatest range of variability is visible in the case of non-aerated samples made on the basis of expanded clay aggregate (B2-0), where the average value of C_V measured on the upper surface is almost 81% of the value of C_V determined on the lower surface. It should be noted that a similar level of variability was also noted in the case of the most aerated samples made with this aggregate (B2-1.4), where the C_V value determined from the upper surface is about 82% of the C_V obtained from the lower surface. A clearly lower range of C_V^T/C_V^B differentiation was noted in the case of mixtures from the B1 and B3 groups. In the case of B1 mixes on stone aggregate, the differences range from 92% to 99%, while in the case of B3 mixes on sintered fly ash aggregate, the differences range from 93% to 97%. Analyzing the data from the bottom face of the samples, it can be observed that the highest values of the C_V parameter were obtained on all three reference mixtures that did not contain an aerating admixture. On the other hand, the results obtained on the upper surfaces show that the highest C_V values in all groups of mixtures (B1, B2 and B3) occurred in two cases each time – no aeration or the use of an admixture, but at the lowest level, i.e., in the amount of 0.8%. In general, dosing the aerating admixture above 0.8% of the cement mass for both surfaces give only negative effects, expressed in the reduction of the value of the volumetric specific heat, and this is the conclusion that comes from the analysis of data for both the lower and upper surfaces.

However, an analysis of the impact of the aggregate on the obtained C_V values can be strongly falsified if it were based on data from the lower surfaces, especially in the case of concretes on expanded clay aggregate. The lower zones of samples in this type of mixtures show a clearly more compact structure (with a dominant share of cement mortar) than the inside of the element (with a dominant share of highly porous expanded clay aggregate). Hence the greatest variation in the values of C_V^T/C_V^B , but also the risk of wrong interpretation of the results, if only the measurements from the bottom surface were taken into account. The C_V values of expanded clay concretes obtained on these surfaces reach a level similar to concretes on stone aggregate, which applies only to the lower zone of the element, and does not refer to the real structure inside it.

3.1.3. Thermal diffusivity of dry samples

The average values of thermal diffusivity a determined in measurements carried out on the top (T) and bottom (B) surfaces of composite samples from groups B1, B2 and B3 tested in the dry state are summarized in Fig. 5.

Comparing the resultant thermal diffusivities a shown in Fig. 5, it can be observed that the values from both surfaces differ in all concrete groups. It should be noted that the same tendency is observed for each of the formulations – data from the upper surface (referring to the inside of the element) always show lower values compared to those measured on the lower surface. The greatest range of variability was noted in the case of samples made on expanded clay aggregate, with an aeration admixture in the amount of 1.4% of the cement

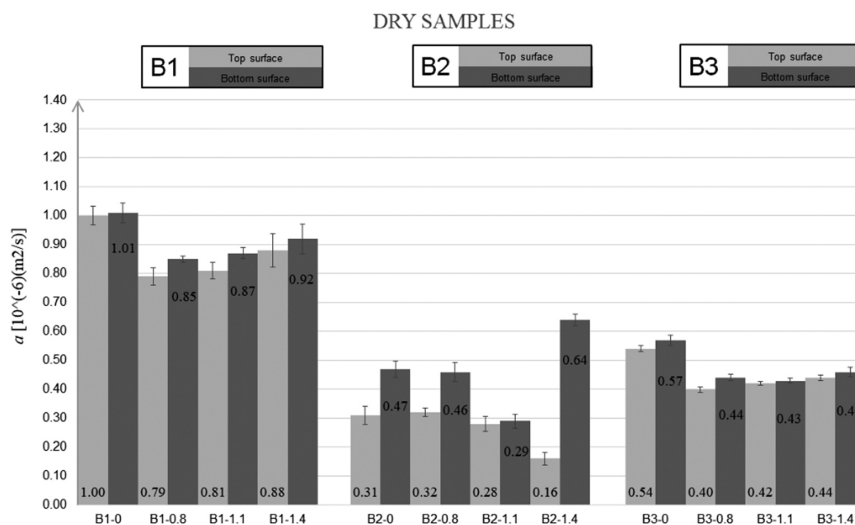


Fig. 5. Average values of thermal diffusivity a determined on the top and bottom surfaces of dry samples

mass – the value of $a_{B2-1.4}^T$ is 4 times lower than the value of $a_{B2-1.4}^B$. Generally, in the group of B2 concretes on expanded clay aggregate, there is the strongest differentiation – relations a^T/a^B oscillate in the level from 25% (B2-1.4) to 97% (B2-1.1). The results obtained for concretes from the B1 group are the least differentiated – the a^T/a^B ratio ranges from 93% (B1-0.8 and B1-1.1) to 99% (B1-0). Concretes based on ash-porous aggregate are characterized by slightly greater variability – from 91% (B3-0.8) to 98% (B3-1.1).

As the thermal diffusivity a is the ratio of the two previously analyzed parameters ($a = \lambda/C_V$), it is obvious that the conclusions regarding the dosing of the aerating admixture or the selection of lightweight aggregate will be falsified in a similar way, if the analysis is based on data from the lower surfaces only. The most impressive example is the B2-1.4 mixture. The average thermal diffusivity $a_{B2-1.4}^B = 0.64 \cdot 10^{-6} \text{ m}^2/\text{s}$, measured on the lower surfaces (characterized by a highly densified structure), turns out to be higher in relation to all other thermal diffusivities a^T and a^B determined for the group of concretes B2, but also higher in relation to all a^T and a^B values determined for the B3 group of concretes. Meanwhile, the same B2-1.4 formula, evaluated in relation to the highly porous structure obtained inside the element, gives the average value of $a_{B2-1.4}^T = 0.16 \cdot 10^{-6} \text{ m}^2/\text{s}$ by far the lowest in the entire group of concretes B2, as well as B3 and of course B1.

3.2. Samples saturated with water – comparison of the results obtained on the top and bottom surfaces

Each of the results presented in Figs. 6–8 is the arithmetic mean determined on the basis of the results from 6 individual measurements. A total of 144 measurements of thermal parameters (λ , C_V , a) were carried out on wet samples and all data were taken into account in determining their average values.

3.2.1. Thermal conductivity of wet samples

Figure 6 shows the average values of the thermal conductivity coefficient λ measured on the top (T) and bottom (B) surfaces of twelve concrete composite samples previously saturated to constant mass during storage in a water bath.

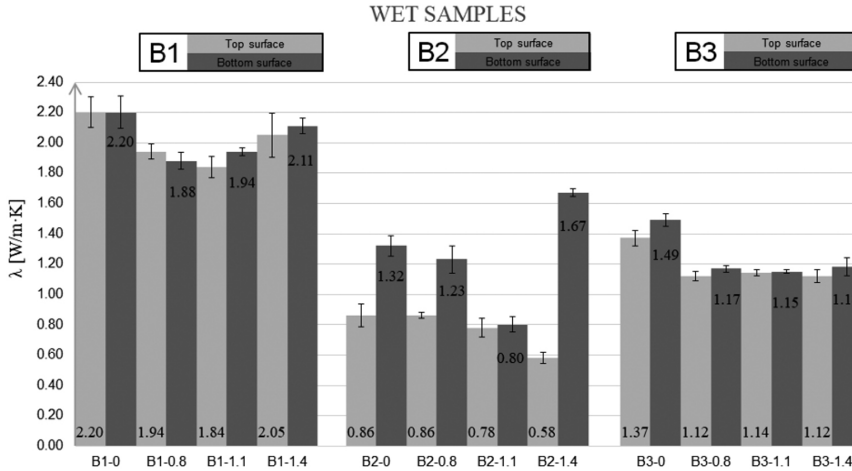


Fig. 6. Average values of the thermal conductivity coefficient λ determined on the upper and lower surfaces of wet samples

Analyzing values of the thermal conductivity coefficient λ determined on both surfaces, it can be concluded that in most cases, the thermal conductivity corresponding to the internal structure of the samples reaches lower values in relation to those determined on the lower surfaces, shaped in contact with the bottom of the mold. This situation occurs in both groups of mixes B2 and B3 made on lightweight aggregates, regardless of the amount of aerating admixture used, and in the more highly aerated mixes B1-1.1 and B1-1.4 made on stone aggregate. The only deviation from this regularity is the higher value of the λ coefficient on the top surface for samples from the B1-0.8 group and the same value of $\lambda^T = \lambda^B$ obtained for non-aerated B1-0 samples. The situation in terms of quantitative and qualitative relationships between individual groups is similar to that of dry samples. Of course, due to the presence of water, the λ values of each formulation are at a much higher level. However, as in the case of dry samples, the largest range of λ^T/λ^B variability is visible in the B2-1.4 mixtures, except that in saturation conditions the scale of variability slightly decreases – the λ^B coefficient is, in this case, about 3 times greater than the coefficient λ^T .

As in the case of dry composites, there would also be discrepancies in the recommendation regarding the selection of the optimal amount of aerating admixture – depending on whether it would be based on the values of λ^T or λ^B . For example, wet samples made on expanded clay aggregate on the upper surface show the best thermal conductivity when using an admixture at the level of 1.4% of the cement mass, but the analysis of the data on the lower surfaces would indicate the use of an admixture in the amount of 1.1% of the cement mass as the most effective.

Recommendations regarding the selection of the most favorable aggregate, if they were based on the values of λ^B , would also turn out to be wrong. Data relating to the inside of the element, i.e., obtained on the upper surfaces, clearly indicate expanded clay aggregate as the most effective in reducing the value of the λ coefficient, regardless of the admixture dosing level. However, the λ values, obtained from the lower surfaces of the samples from group B2, would indicate that with an admixture in the amount of 0.8% and 1.4% would be better to use sintered fly ash aggregate. This would not be a correct recommendation, as it would only refer to the contact zone of the mixture with the mold and not to the representative structure within the interior of the element.

3.2.2. Volumetric specific heat of wet samples

The average values of the volumetric specific heat C_V measured on the top (T) and bottom (B) surfaces of the B1, B2 and B3 composite samples tested after previous water saturation are summarized in graphical form in Fig. 7.

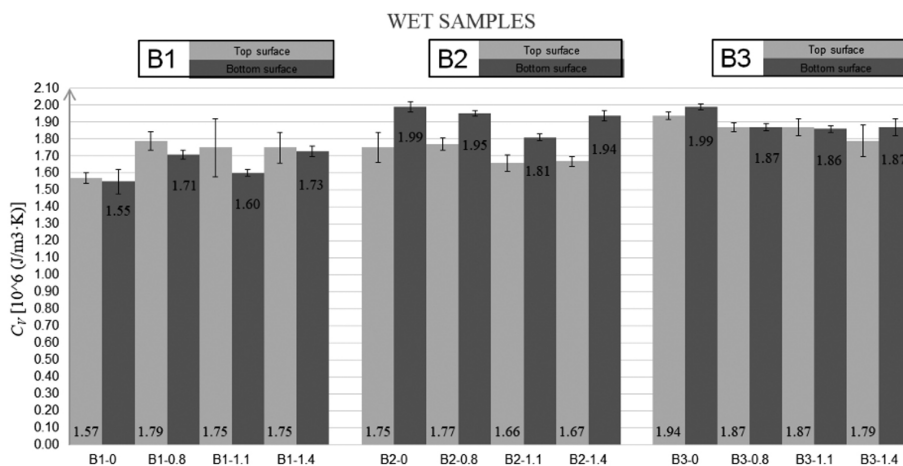


Fig. 7. Average values of the volumetric specific heat C_V determined on the top and bottom surfaces of the wet samples

Analysis of the data presented in Fig. 7 allows us to conclude that also, in the case of wet samples, there are often quite significant differences in the C_V values determined on both surfaces.

The tendency that clearly distinguishes saturated samples from dry samples is the appearance of higher C_V^T values in relation to C_V^B in all four mixtures of group B1. Thus, water filling the pores in the cement matrix (with practically non-absorbent stone aggregate) noticeably increases the C_V values corresponding to the interior of the slightly more porous element than the lower zone with a more compact structure formed in contact with the form. The percentage increase in the C_V^T/C_V^B ratio is from approx. 101% to approx. 109%. In the group of expanded clay concrete B2, the tendencies analogous to those in the case of dry samples are maintained, however, in the case of wet samples, the percentage reduction of

the C_V^T/C_V^B ratio ranges from 86% to 92%. On the other hand, trends analogous to those in the case of dry samples ($C_V^T < C_V^B$) in the B3 group of concretes occurred only in the B3-0 and B3-1.4 mixes.

It is also worth noting that due to the greater possibility of water absorption in more porous composites made of lightweight aggregates, generally higher values of both C_V^T and C_V^B are observed in concretes of the B3 and B2 groups, compared to the analogous ones, concretes from group B1.

Different values of volumetric specific heat obtained for the same composite on the upper surface C_V^T and lower surface C_V^B also, in this case, indicate the possibility of making a mistake when selecting the most advantageous amount of admixture for a given type of aggregate, which would particularly negatively affect the adequacy of the decision in the case of concretes from the B2 group, where the variation in C_V^T/C_V^B values was the most significant.

3.2.3. Thermal diffusivity of wet samples

Figure 8 shows the average values of thermal diffusivity a determined in measurements carried out on the top (T) and bottom (D) surfaces of the samples of all tested concrete composites previously saturated to a constant mass in a water bath.

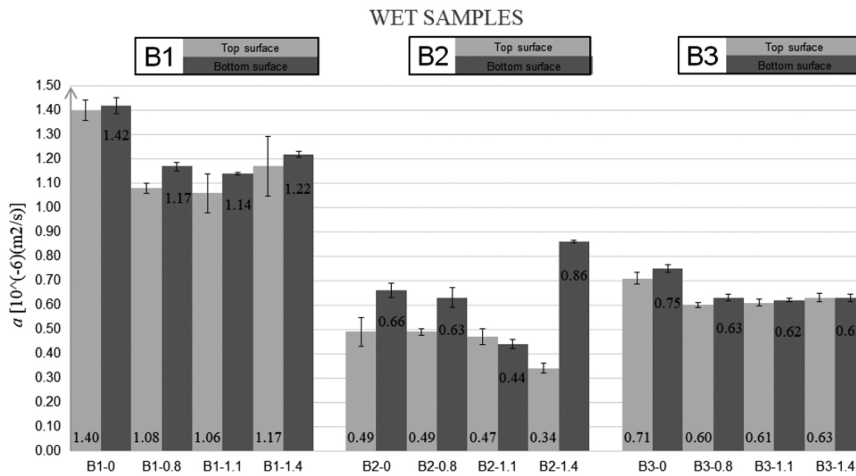


Fig. 8. Average values of thermal diffusivity a determined on the top and bottom surfaces of wet samples

The results presented in Fig. 8 prove that also, in the case of thermal diffusivity a , differences in the values read on the upper and lower surfaces of the same samples should be taken into account. The most significant differences occurred in the group of B2 concretes on expanded clay aggregate, where the relations a^T/a^B range from 39.5% (B2-1.4) to 106.8% (B2-1.1). These are the two most specific cases in the group of twelve tested composites. In formulation B2-1.4, the greatest range of variability occurred – the value of a^T was 2.5 times higher than the value of a^B . On the other hand, formulation B2-1.1 was the only one in which a higher value of a^T was obtained in relation to the value of a^B .

In all composites from group B1, there was a relationship $a^T < a^B$, and the range of variability of a^T/a^B was not significant and oscillated between 93.0% and 98.6%. Also, the differentiation of a^T and a^B values in the saturated composites of the B3 group was maintained at a moderate level – in the most unfavorable case (B3-0), it slightly exceeded 5%.

4. Summary

Conducting tests of thermal parameters on two surfaces of the samples (top “T” and bottom “B”) allowed proving that in the case of all twelve tested concrete composites, the type of surface had an unquestionable impact on the obtained values of λ , C_V , a . Differences in the results occurred both in the case of samples tested in the dry state and in the water-saturated state, although the scale of changes and the observed tendencies depended on the type of aggregate used in the three basic groups of mixes (B1, B2, B3), and in each of them on the amount of aerating admixture (0%, 0.8%, 1.1%, 1.4%).

A detailed discussion of the values of λ , C_V , a determined on both surfaces, is contained in subchapter 3.1 (dry samples) and in subchapter 3.2 (water-saturated samples).

Summing up the obtained results, it should be stated that a much greater differentiation of results appeared in the case of samples tested in a dry state. For the thermal conductivity of all 12 composites, the range λ^T/λ^B variation was from 21.3% to 95.6%. In the extreme case (mixture B2-1.4), the λ^B coefficient showed a value 4.7 times higher than the λ^T coefficient, corresponding to the real structure of the element's interior. In the case of volumetric specific heat, the achieved scope of variability C_V^T/C_V^B ranged from 80.9% to 99.4%. In the most extreme case (mixture B2-0), the value of C_V^B was 1.24 times higher than the value of C_V^T , describing the real accumulation possibilities of this composite. The diagnosed scale of thermal diffusivity a^T/a^B ranged from 25.0% to 99.0%. In the B2-1.4 composite with the greatest dispersion of results, the a^B value determined on the lower surface with a compressed structure was 4 times higher in relation to the diffusivity a^T referring to the porous interior of the element. Regardless of the type of the tested parameter, in all 12 composites, the values from the upper surfaces of dry samples were in each case lower than those determined on the lower surfaces, i.e., $\lambda^T < \lambda^B$, $C_V^T < C_V^B$, $a^T < a^B$.

Such unequivocal tendencies did not occur in the case of water-saturated samples. On the one hand, this was due to its specific properties – a high value of thermal conductivity and an exceptionally high value of specific heat. On the other hand, the more compact lower zones (shaped in contact with the mold) reacted differently to its presence than the internal zones of the sample (mostly with a more porous structure).

Regardless, however, for each of the parameters (λ , C_V , a) determined on wet samples, there were often very large differences in the parameters measured on the upper and lower surfaces of the same samples. The range of variation of λ^T/λ^B was from 34.7% to 103.2%, i.e., in the most unfavorable case (B2-1.4) the λ^B coefficient was 2.9 times higher than the λ^T coefficient. The range of variability of the volumetric specific heat C_V^T/C_V^B oscillated at the level from 86.1% to 109.4%, i.e., in the extreme case (B2-1.4) the value obtained from the lower surface was about 1.2 times higher than that corresponding to the interior of the

element. The obtained scale of variation in the thermal diffusivity of a^T/a^B ranged from 39.5% to 106.8%, with the most significant differences occurring in the above-mentioned analogous composite (B2-1.4), where a^B was found to be 2.5 times higher than a^T .

The data collected in the experiment clearly indicate the danger of collecting obviously false results if the measurements of thermal parameters (λ , C_V , a) were limited only to the surface formed in contact with the mold. Unfortunately, this is a common practice in laboratory tests because then there is no need to carry out additional mechanical treatment of the samples.

In laboratory practice, when performing tests using specific equipment, a detailed manual developed by the manufacturer is used. The manual provides guidelines on how to perform measurements effectively. For the ISOMET 2104 apparatus [8], the user's guide states that it is equipped with various types of optional probes, where needle probes are for porous, fibrous or soft materials, and surface probes are intended for hard materials. Surface probes were used in the tests presented in this paper. The user's guide [8] contains the following recommendations on how to carry out measurements with these probes: „Flat surface of at least 60 mm diameter is satisfactory for the probe. Demand for the accuracy of the surface flatness increases with increasing thermal conductivity value of the tested material. The expected minimal thickness of evaluated material is ranging from 10 mm to 15 mm depending on its diffusivity (conductivity).” Therefore, emphasis was placed on maintaining certain geometric dimensions as well as ensuring the flatness and smoothness of the surface of the samples to be tested. Therefore, in the case of, for example, concrete elements, measurements are usually carried out on surfaces formed at the contact with the mold (compare e.g. [9, 11]).

The surfaces of concrete mixes obtained in this way are smooth and ensure good adhesion of the measuring probe to the tested material. While the upper surfaces, due to their blurring after placing the mixture in the mold, are usually uneven and rough, are not suitable for direct measurements on them. In the light of the obtained results, however, it turns out to be necessary to use mechanical treatment in order to remove the boundary layer and reveal the representative structure of the element's interior so that the conducted tests serve to obtain adequate values λ , C_V , a . The risk of false results was found in all the tested composites, but it was most visible in mixes with lightweight aggregate, in particular expanded clay aggregate, and in loose mixes with a significant degree of aeration. The greatest (several times) differences in the results there were undoubtedly caused by the fact that in the lower zone formed in contact with the bottom of the mold, the share of compact cement matrix was greater, and the share of coarse aggregate was, lower than on the upper surface which has a representative structure of the mixture containing the right amount of coarse aggregate located in the aerated matrix.

A similar danger occurs during in-situ tests conducted on concrete partitions poured in the formwork. Measurements there are carried out by means of probes located on surfaces formed at the interface with the formwork, where the so-called “wall effect” appears, giving analogous distortion of the results. The thermal parameters λ , C_V , a determined in this way, do not correctly describe the properties of the real structure present in the main volume of this element, but refer to its narrow near-surface zones.

The data obtained in this way lead to incorrect conclusions made in decision-making processes and to obtaining incorrect results in numerical simulations used to assess the thermal qualities of building envelopes, or in simulations concerning the energy performance of entire building and indoor comfort. Only the use of correctly determined, e.g. thermal conductivity coefficients of all component materials of individual building partitions (external ceiling, internal wall, external wall, roof, slab on ground, compare [12]) will guarantee obtaining the correct values of their heat transfer coefficients, resulting in the adequacy of various energy and environmental analyzes.

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Wpływ warunków pomiarowych na wyznaczone wartości parametrów cieplnych różnego rodzaju betonów

Słowa kluczowe: beton, dyfuzyjność cieplna, objętościowe ciepło właściwe, przewodność cieplna, rodzaj powierzchni, stan zawilgocenia

Streszczenie:

W ostatnich latach kładzie się duży nacisk na wprowadzenie energooszczędnych rozwiązań do sektora budownictwa. Duże możliwości w tym względzie dają przegrody budowlane wykonane z betonów o specjalnie dobranym składzie. Autorki w ramach szeroko zakrojonego eksperymentu podjęły się zdiagnozowania, na ile można poprawić przewodność cieplną λ , objętościowe ciepło właściwe C_V oraz dyfuzyjność termiczną a za pomocą domieszki napowietrzającej oraz różnego rodzaju kruszyw. Badaniom poddano trzy grupy kompozytów: B1 – na kruszywie kamiennym, B2 – na kruszywie keramzytowym, B3 – na kruszywie popiołoporytowym. Równocześnie każda z grup została podzielona na 4 receptury wykonane bez domieszki napowietrzającej oraz z coraz to wyższą jej zawartością wynoszącą 0,8, 1,1, 1,4% w stosunku do masy cementu. Badania parametrów cieplnych zrealizowano techniką niestacjonarną wykorzystując aparat ISOMET 2104. Pomiar przeprowadzono na górnych i dolnych powierzchniach 36 próbek prostopadłościennych (po 3 próbki z każdej z 12 mieszanek), wykonując je na każdej z powierzchni dwukrotnie. Górne powierzchnie reprezentowały faktyczną strukturę występującą we wnętrzu każdego z badanych kompozytów. Dolne powierzchnie ukształtowane na styku z dnem formy odznaczały się na tyle zmienioną strukturą, że w bardzo istotny sposób zmieniały wartości szczytujących na nich parametrów. Badania diagnostyczne, dotyczące wpływu warunków pomiarowych, przeprowadzono na próbkach suchych i nasyconych wodą. Udowodniono, że w przypadku każdego kompozytu i w każdych warunkach wilgotnościowych, wyznaczone na dolnych powierzchniach wartości parametrów cieplnych nie będą prawidłowo opisywać właściwości realnej struktury występującej w zasadniczej objętości tego elementu.

W obszernym 2-etapowym eksperymencie zrealizowanym w ramach prac [1, 2] przeprowadzono w sumie 288 pomiarów każdego z trzech badanych parametrów cieplnych, tj. przewodności cieplnej λ , objętościowego ciepła właściwego C_V oraz dyfuzyjności termicznej a . W odniesieniu do testowanych 12 kompozytów betonowych wykonano po 144 pomiary składowe na próbkach suchych oraz po 144 pomiary składowe na próbkach nasyconych wodą. Wyznaczone wartości średnie poszczególnych parametrów cieplnych zestawiono odpowiednio na rys. 3–5 oraz na rys. 6–8. Obrazują one skalę zróżnicowania wyników pozyskanych z górnych i dolnych powierzchni, wskazując jednoznacznie, jak duże jest niebezpieczeństwo zebrania ewidentnie fałszywych wyników w sytuacji, gdyby pomiary parametrów cieplnych (λ , C_V , a) ograniczyć jedynie do powierzchni uformowanych na styku z formą. Niestety jest to częstą praktyką w badaniach laboratoryjnych, gdyż nie ma wówczas potrzeby przeprowadzania dodatkowej obróbki mechanicznej próbek. Dolne powierzchnie wylanych mieszanek betonowych są gładkie i zapewniają dobre przyleganie sondy pomiarowej do badanego tworzywa. Podczas gdy górne powierzchnie, z racji ich zatarcia po ułożeniu mieszanki w formie, są najczęściej nierówne, chropowate i nie nadają się do bezpośredniego przeprowadzenia na nich pomiarów. W świetle uzyskanych wyników konieczne okazuje się jednak zastosowanie mechanicznej obróbki, w celu usunięcia warstwy wierzchniej i odsłonięcia reprezentatywnej struktury wnętrza elementu, aby przeprowadzone badania służyły uzyskaniu adekwatnych wartości λ , C_V , a . Niebezpieczeństwo uzyskania zafałszowanych wyników stwierdzono we wszystkich testowanych kompozytach, przy czym w największym stopniu ujawniło się w mieszankach na kruszywie lekkim, w szczególności keramzytowym i w luźnych mieszankach o znacznym stopniu napowietrzenia. Występujące tam

największe (kilkukrotne) różnice w wynikach niewątpliwie spowodowane były faktem, iż w dolnej strefie uformowanej na styku z dnem formy większy był udział zwartej matrycy cementowej, a mniejszy udział kruszywa grubego, aniżeli na powierzchni górnej, na której odsłonięta została reprezentatywna struktura mieszanki zawierającej odpowiednią ilość kruszywa grubego ulokowanego w napowietrzonej matrycy. Analogiczne niebezpieczeństwo występuje w badaniach in-situ, prowadzonych na przegrodach betonowych wylanych w szalunkach. Pomiary prowadzi się tam za pośrednictwem sond lokowanych na powierzchniach uformowanych na styku z szalunkiem, gdzie pojawia się tzw. efekt ściany, dający analogiczne przekłamanie wyników. W ten sposób wyznaczone parametry cieplne λ , C_V , a nie opisują prawidłowo właściwości realnej struktury występującej w zasadniczej objętości tego elementu, tylko odnoszą się do wąskich jego stref przypowierzchniowych. Pozyskane w ten sposób dane prowadzą do błędnych wniosków podejmowanych w procesach decyzyjnych (np. co do wyboru optymalnego kruszywa, czy ilości domieszki), jak również do uzyskiwania (przy bazowaniu na niepoprawnie wyznaczonych wartościach λ , C_V , a) nieprawidłowych wyników w przeprowadzanych symulacjach numerycznych służących ocenie termicznych walorów przegród budowlanych, czy też w symulacjach dotyczących całego budynku, a służących np. wyznaczeniu jego efektywności energetycznej.

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