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Actual thermophysical characteristics of autoclaved aerated concrete

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Abstract. The characteristics of autoclaved aerated concrete blocks was tested and analyzed in comparing with Standards' requirements. The results of the study show that the actual thermophysical characteristics of autoclaved aerated concrete blocks, cut from product samples of the three largest manufacturers, in most cases do not coincide with the values declared by the manufacturers and presented in the standards prepared with their direct participation. The mismatch between the calculated and actual values of the thermal conductivity of materials and products used in the installation of external walling, leads to an increase in transmission heat losses through the external walls and the waste of thermal energy for heating and ventilation of buildings. In this regard, a radical review of the values declared by manufacturers, as well as the standards on the basis of which the products are manufactured, and their correct presentation in the current regulatory documents are required.

1. Introduction

Autoclaved cellular concrete products are widely used in construction [1–3]. Basically, such products in the form of autoclaved aerated concrete blocks are used in external and internal walls mortar [1, 4–7], to a lesser extent - as part of rib precast and cast-in-situ floors [8].

AAS is about four times lower, and thermal resistance is 11 times higher [9, 10]. AAC is most effective in warm and hot climates [5, 11–13]. AAC-compliant construction in hot and dry climates reduces residential energy consumption by 7 % [9]. The article [5] evaluates the energy efficiency of three types of exterior walls (prefabricated wooden frame walls, AAC and brick walls) in Southeast Europe. The results of the analysis show that the wall structure with AAC has the best environmental characteristics, while the brick wall has the best thermal characteristics in intermittent heating mode among the studied types of walls.

Unsteady heat transfer in wall structures with AAC is also considered in [14–17]. High energy-saving effect is also observed in the construction of multi-apartment buildings from AAC in three climatic zones of Greece [13]. The low cost of blocks reduces the estimated payback period of investments for reducing energy resources [18–20]. The article [1] summarizes design solutions for load-bearing and non-bearing stone walls, as well as describes construction methods aimed at increasing the efficiency and productivity of building construction, including using wall structures made of AAC.

In the manufacture of blocks used industrial waste [21–25]. This allows you to get the material with the necessary heat and humidity characteristics [21], reduce thermal conductivity [4, 22], increase thermal storage properties [26], improve the capillary-porous structure of the material [23], get high energy saving effect and reduce CO_2 emissions [24], increase moisture-proofing properties of structures [24]. Disposal in the production of AAC can significantly reduce the volume of solid waste landfill [28].

The main objective of the study [29] was to classify the properties of AAC in terms of physical (microstructure, density), chemical, mechanical (compressive and tensile strength, elastic modulus, shrinkage during drying) and operational (thermal insulation, moisture transfer, durability, fire resistance and sound

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insulation) characteristics. The articles [29, 30] present the results of theoretical studies that have shown the advantages of using AAC in wall enclosures.

However, as shown in the works [6, 7] on the example of the Central Russian Upland cold climate, the use of single-layer external walls with AAC and two-layer wall structures in the form of AAC with brick lining carries thermal risks due to the significant influence on the thermal protection of buildings of the edge zones. Such structures without additional thermal insulation have virtually no reserve for thermal protection and energy saving. To reduce the heat engineering risks in the design of buildings, it is necessary, first of all, to improve the constructive solution of the marginal zones. Another measure to increase the level of thermal protection of buildings is the use of additional thermal insulation along the entire plane of the wall.

The mismatch between the actual and declared by the manufacturer thermophysical characteristics of building materials is one of the main reasons for the deterioration of thermal comfort in the premises and the decrease in energy efficiency of operated buildings [31]. In publications does not assess the conformity of actual and declared AAC characteristics with the literature, which makes it difficult to find effective structural solutions for external walls using AAC. From this point of view, the task is certainly relevant.

This article deals with the strength and thermophysical test results made on the basis of the masonry samples of cellular autoclave curing concrete (aerated concrete blocks) with the use of polyurethane adhesive or concrete adhesives [32, 33].

In this work calculation of vapor permeability of walls from gas-concrete blocks is made [34]. The purpose of this study is to verify the thermophysical characteristics of AAC, declared by different manufacturers, as well as contained in the standards of different countries, which have a significant difference [35].

2. Materials and Methods

Tests were conducted at the St. Petersburg Polytechnic University (Russia).

As part of the study, products were selected from three different manufacturers, conventionally marked with numbers 1, 2 and 3. The lower the serial number, the greater the volume of production produced by this manufacturer:

- manufacturer 1: grade for density D 400 (declared by the manufacturer);
- manufacturer 2: grade D 500 (density declared by the manufacturer);
- manufacturer 3: D 500 grade (declared by the manufacturer).

The choice of manufacturers is due to the fact that they are the largest and are located on the territory of St. Petersburg and the Leningrad Region (Russia), and also most actively sell their products in St. Petersburg to private consumers through DIY networks.

Figure 1. Measurement of thermal conductivity of samples.

Figure 2. The excitatory method for determining the sorption moisture of samples.

Figure 3. Testing a masonry fragment in the climate chamber.

Figure 4. Determination of vapor permeability of samples.

As part of the study, the following types of tests were performed (Figures 1–4):

- determination of average density in accordance with Russian State Standard GOST 12730.1;
- determination of thermal conductivity in accordance with Russian State Standard GOST 7076;
- determination of sorption moisture in accordance with Russian State Standard GOST 24816;
- determination of vapor permeability in accordance with Russian State Standard GOST 25898;
- testing of a masonry fragment in a climate chamber according to Russian State Standard GOST 26254.

Total was made:

- 18 samples with a size of 100×100×100 mm – 6 from each manufacturer to determine the average density of the material in a dry state;
- 15 samples of size 250×250×50 mm — 5 samples from each manufacturer to determine the thermal conductivity of the material in a dry state;
- 21 samples of arbitrary shape – 7 from each manufacturer to determine the sorption moisture of the material;
- 15 samples with a diameter of 100 mm and a thickness of 30 mm – 5 samples from each manufacturer to determine the vapor permeability of the material.

To determine the thermal conductivity and humidity of the model structure in a climate chamber, a masonry fragment of AAC blocks was made on 150 mm thick adhesive. A masonry fragment is made of blocks declared by the manufacturer of the brand in average density D500 (manufacturer 2). Design tests were conducted for 66 hours. In the cold compartment of the climate chamber, the air temperature was minus 30 ± 1 °C automatically, in the warm compartment – air temperature + 20 ± 1 °C, relative humidity 50 ± 5 %. After the end of the experiment, a study was conducted of the distribution of moisture over the thickness of the test masonry fragment. For this purpose, 6 cellular concrete samples 25 mm in diameter were sequentially drilled from the central part of the fragment. The sampling step was also 25 mm.

3. Results and Discussion

3.1. AAC density test results

An analysis of the results of AAC medium density tests shows that products from only one manufacturer (manufacturer 2) correspond to the declared density brand. Products manufactured by manufacturer 1 in terms of average density (426 kg/m^3) correspond to the upper permissible density limit for products of the declared brand in density (D 400), which should not exceed 428 kg/m^3 (with a variation coefficient of 2 %). In this case, three of the six tested samples exceed the upper permissible limit. If the coefficient of variation in density of the batch produced exceeds 2 %, then the tested samples will not correspond to the declared brand in density D400. Products manufactured by manufacturer 3 with an average density of 536 kg/m^3 do not even correspond to the upper permissible limit for the average density, which, with a coefficient of variation of 2 %, should not exceed 535 kg/m^3. In fact, the products from which the samples were taken and tested correspond to the D600 density brand with the manufacturer's D500 density brand declared.

The test results show a significant variation in the density of the tested samples, which may indicate a sufficiently high value of the coefficient of variation in density for the batch of products from which the tested samples were taken. Only for products of one manufacturer, there is a slight variation in the deviation of the results of individual tests from the average density value.

3.2. AAC dry conductivity test results

AAC dry heat conductivity test results are presented in Table 1.

Table 1. The actual thermal conductivity of AAC in the dry state (at a temperature of 25 °C).

Sample	Thermal conductivity [W / (m·K)]		
	Manufacturer 1 (D400)	Manufacturer 2 (D500)	Manufacturer 3 (D500)
1	0.108	0.124	0.148
2	0.108	0.127	0.151
3	0.110	0.129	0.145
4	0.110	0.126	0.152
5	0.107	0.127	0.153
Average value	0.109	0.127	0.150

Table 2 shows the actual thermal conductivity for AAC in the dry state with a density of about 500 kg/m^3 according to foreign studies [2, 4, 9, 21, 24]. Figure 5 shows a comparison of the obtained AAC dry heat conductivity test results with foreign studies presented in Table 2. The test results are shown in Figure 5 with dashed lines for AAC manufacturers 2 and 3 (grade D500). Figure 5 shows that the obtained test results and data from foreign studies have good consistency, which indicates the reliability of the obtained experimental values of thermal conductivity.

Table 2. Actual thermal conductivity AAC (D500).

No	Author	Thermal conductivity [W/(m·K)]
1	[9]	0.140
2	[21]	0.120
3	[4]	0.124
4	[24]	0.160
5	[2]	0.130
6	Our results	0.127–0.150

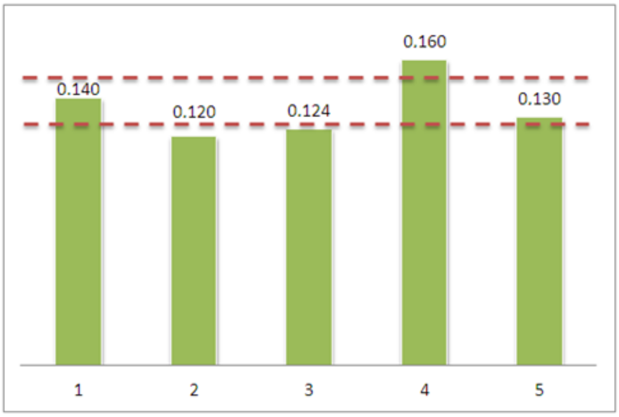
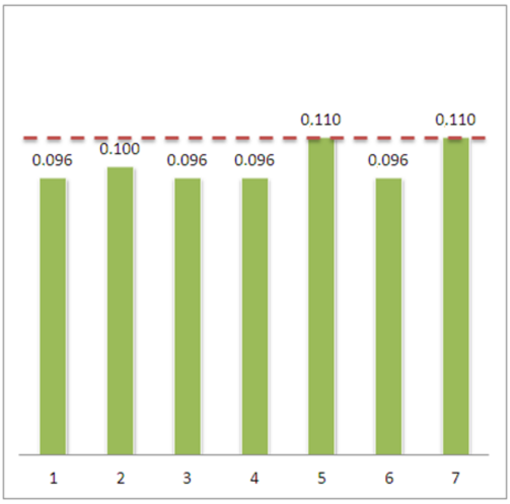


Figure 5. Comparison of the obtained results with the data of other researchers.

A comparison of the dry thermal conductivity values of dry AAC declared in Russian and international standards and the actual thermal conductivity of AAC of various grades by density is presented in Figure 6.

A.



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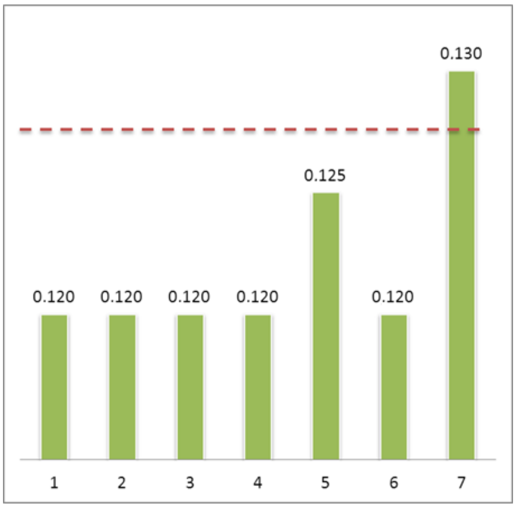


Figure 6. Thermal conductivity AAC in the dry state.

Dashed line shows measurements' results.
A – density grade D400 (manufacturer 1).
B – density grade D500 (manufacturers 2 and 3).
The bars on the bar charts show the standard requirements in accordance to:
1 – Russian State Standard GOST 31359;
2 – Russian State Standard GOST 25485;
3 – Standard 2.9.136 of National Association of Constructors (Russia);
4 – Standard 3.1 of National Association of Autoclaved Aerated Concrete Manufacturers (Russia);
5 – Russian State Building Code SP 50.13330;
6 – EN 1745 (λ50/50);
7 – EN 1745 (λ90/90).

The analysis of the results shows that the measurement results for the blocks of the brand in terms of average density D500 do not correspond to the thermal conductivity values specified in most Russian standards. The values of λ90/90, established in the international standard EN 1745, as well as the data of the Russian standard SP 50.13330, correspond to the measurement results for brand products with an average density of D400 (manufacturer 1). The λ90/90 values according to EN 1745 correspond to the actual data for the brand products in terms of average density D500 (manufacturer 2). The actual values of thermal conductivity of manufacturer's samples 3 (not shown in Figure 6) correspond to the values of λ90/90 established in the EN1745 standard for brand products with an average density of D600.

A significant difference between the actual thermal conductivity values of AAC products from the requirements of the standards is one of the main reasons for the deterioration of thermal comfort in rooms and the decrease in energy efficiency of operated buildings.

3.3. AAC thermal conductivity test results at different humidity

The results of tests of thermal conductivity of AAC grade average density D 500 at a humidity close to 2 and 5% are presented in Table 3.

Table 3. Thermal conductivity of wet products from AAC brand D 500.

Sample	First test cycle		Second test cycle	
	Humidity,% by mass	Thermal conductivity, W / (m·K)	Humidity,% by mass	Thermal conductivity, W / (m·K)
1	2.1	0.137	5.2	0.176
2	2.0	0.140	4.8	0.187
3	2.0	0.143	4.7	0.190
4	1.8	0.135	5.0	0.186
5	2.2	0.145	5.0	0.182
Average value	2.02	0.14	4.94	0.184

Figure 7 shows a generalized dependence of AAC thermal conductivity on humidity, averaged over all tested samples.

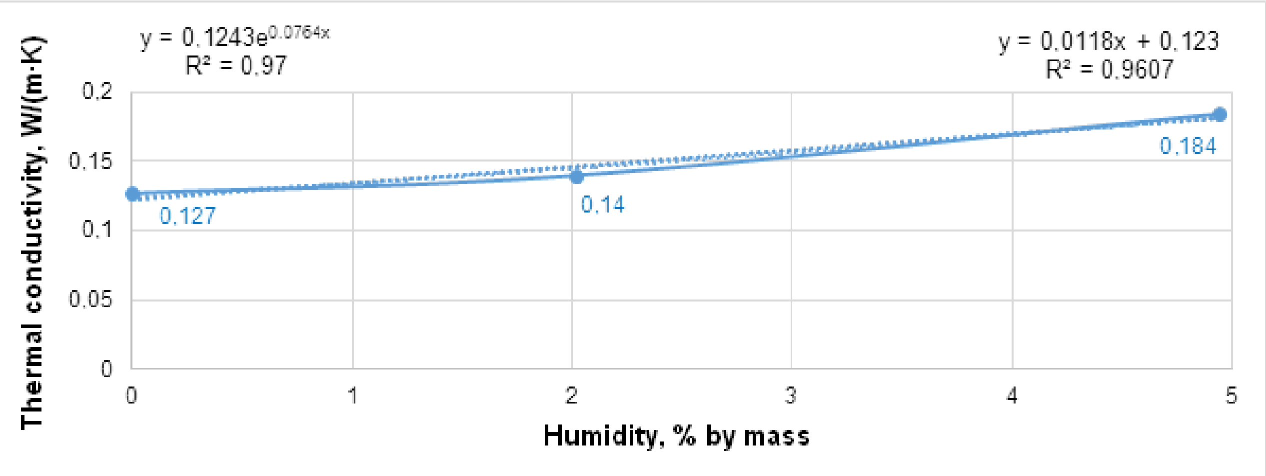


Figure 7. AAC thermal conductivity vs. humidity.

From the data presented in Fig. 7, it follows that the maximum determination coefficient (R^2) corresponds to the exponential dependence of the thermal conductivity of AAC on humidity. To compare the results, Fig. 7 also shows the linear dependence $\lambda(w)$. In the international standard ISO 10456, the dependence of the thermal conductivity of building materials on humidity is also represented by an exponential function of the form:

$$\lambda_w = \lambda_o \exp\left[f_w (w_2 - w_1) \right], \tag{1}$$

where λ_0 is the measured value of thermal conductivity in the dry state, W/(m·K); f_w is the coefficient establishing for the exponential dependence the proportionality between the thermal conductivity and humidity of the building material; w_2 is the moisture content of the material,%, for conditions 2 (for a given humidity other than 0 %); w_1 is the moisture content of the material,%, for conditions 1 (initial conditions), for example, at a moisture content of zero.

For five tested samples from one manufacturer, the experimental dependence of AAC thermal conductivity on humidity can be described by an equation of the form (see Figure 7):

$$\lambda_w = 0.1243\exp\left[0.0764(w_2 - w_1)\right]. \tag{2}$$

An analysis of the results shows that the discrepancy between the obtained experimental data and the declared values of thermal conductivity AAC at different humidity according to the Russian State Standard GOST 31359 is due to the discrepancy between the initial values of the thermal conductivity of the material in the dry state (0.1243 W/(m·K) in according to the test results of the control batch of samples, 0.12 W/(m·K) in according to GOST 31359), and the mismatch of the coefficients f_w (0.0764 % and 0.0405, respectively).

3.4. AAC sorption moisture test results

AAC sorption moisture test results are presented in Table 4.

Table 4. Sorption humidity AAC.

Manufacturer	Density grade declared by the manufacturer	Equilibrium sorption humidity,% by mass,	
		with relative air humidity at 80%	with relative air humidity at 97%
1	D400	3.3	9.3
2	D500	4.0	15.9
3	D500	2.9	9.6

From a comparison of the measurement results presented in table 4, with standard values from regulatory documents follows:

1. The AAC actual sorption humidity of all three manufacturers at a relative humidity of 80 % does not exceed 4 % specified in Russian State Standard GOST 31359, Standard 2.9.136 of National Association of Constructors (Russia), Standard 3.1 of National Association of Autoclaved Aerated Concrete Manufacturers (Russia) when establishing the equilibrium moisture content of aerated concrete by weight for operating conditions A.

2. The actual sorption humidity AAC of all three manufacturers at a relative humidity of 97 % significantly exceeds 5 % specified in Russian State Standard GOST 31359, Standard 2.9.136 of National Association of Constructors (Russia), Standard 3.1 of National Association of Autoclaved Aerated Concrete Manufacturers (Russia) when establishing the equilibrium moisture content of aerated concrete by weight for operating conditions B.

3. For products of one of the manufacturers (manufacturer 2), the AAC actual sorption humidity at a relative humidity of 97 % reaches 16 %. This can be explained by the fact that the equilibrium sorption moisture of aerated concrete depends not only on the density of the products, but also on the composition of the initial raw materials.

3.5. AAC vapor permeability test results

AAC vapor permeability test results are presented in Table 5.

Table 5. Vapor permeability AAC (average values).

Manufacturer	Density grade declared by the manufacturer	Permeance [$kg\cdot Pa^{-1}\cdot s^{-1}\cdot m^{-1}$]
1	D400	$6.39\cdot 10^{-11}$
2	D500	$4.72\cdot 10^{-11}$
3	D500	$5.00\cdot 10^{-11}$

Comparison of the data presented in Table 5 with Standards' values shows the following:

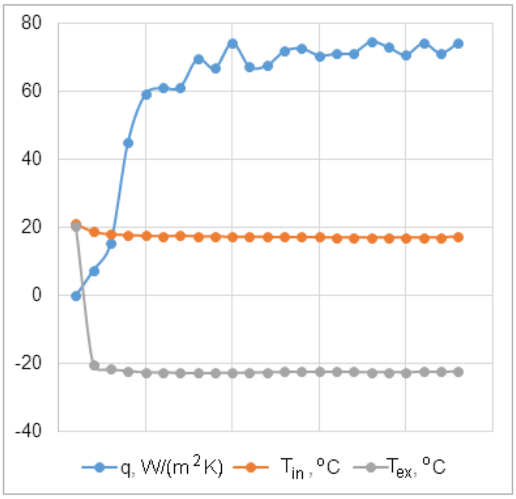
1. Actual vapor permeability of AAC of manufacturer 1 ($6.39\cdot 10^{-11}$ $kg\cdot Pa^{-1}\cdot s^{-1}\cdot m^{-1}$) coincides with the value provided by Russian State Standard GOST 31359 for the average density D400 declared by the manufacturer of the brand.

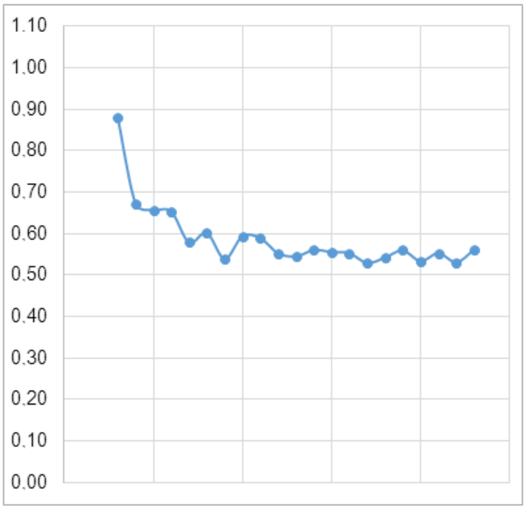
2. The actual values of vapor permeability AAC manufacturer 2 ($4.72 \cdot 10^{-11}$ kg·Pa^{-1}·s^{-1}·m^{-1}) and manufacturer 3 (0.65 ng·Pa^{-1}·s^{-1}·m^{-2}) do not match the value presented in Russian State Standard GOST 31359 for the declared brand manufacturer for the average density of D500 ($5.00 \cdot 10^{-11}$ kg·Pa^{-1}·s^{-1}·m^{-1}).

The observed difference between the actual and declared vapor permeability values of cellular concrete suggests that the properties of cellular concrete depend not only on their density, but also on the quality of the feedstock.

3.6. AAC Masonry Test Results

The test results of the AAC fragment of masonry from in a climate chamber are presented in Figures 8 and 9.





a **b**

Figure 8. The results of measurements of parameters in the climatic chamber (a) and calculation of thermal resistance, m²·K/W, of the studied fragment (b).

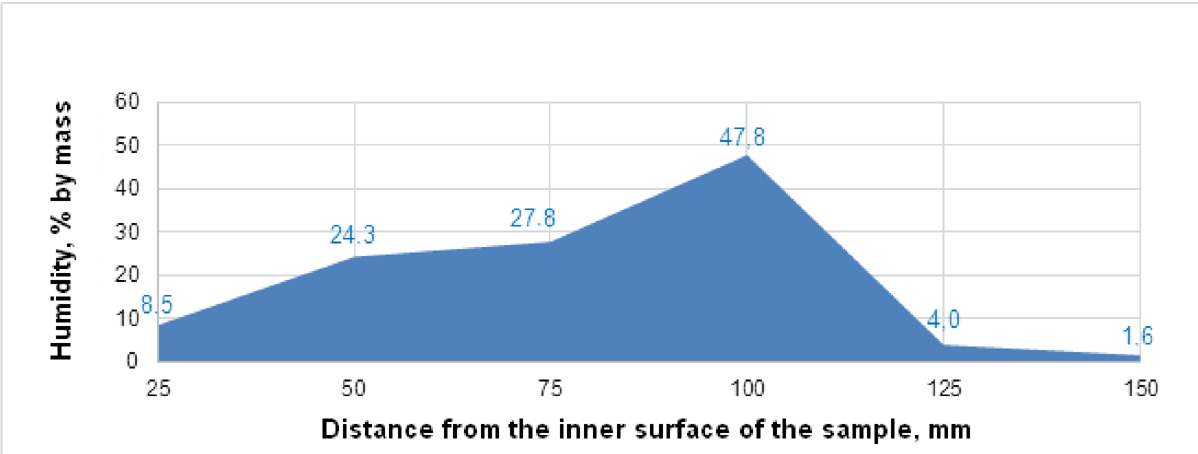


Figure 9. Moisture distribution over the thickness of the AAC wall structure.

Despite the fact that the moisture distribution over the thickness of the tested masonry fragment, shown in Figure 9, is obtained for a conditional (model) masonry with a thickness of 150 mm, this distribution is indicative from the point of view of a qualitative display of the main features of the humidity regime of real wall fencing. It can be seen from the graph (see Figure 9) that the plane of maximum wetting of the masonry is at a distance of 2/3 of its thickness when counting from the inner surface of the test fragment, i.e. correlates with the data specified in clause 9.1 of Russian State Building Code SNiP 23-02-2003 for a homogeneous (single-layer) wall.

In the plane of maximum humidification at low temperatures, moisture freezes and creates a low-permeability barrier for water vapor, which leads to further accumulation of moisture in front of it. Behind this barrier, due to the low resistance to vapor permeation of a section of the structure located between the condensation plane and the outer surface, the masonry is dried.

The initial AAC humidity measured before testing is 5.7 %. The average AAC humidity in the composition of the test masonry fragment after the experiment was 19 %.

The thermal conductivity of the masonry under these conditions can be calculated. As the calculated value of thermal resistance, we take the value of 0.54 m^2 K/W, obtained as a result of laboratory tests of a fragment of a wall enclosure in a climate chamber (see Figure 8). Then, with the thickness of the test fragment equal to 150 mm, the thermal conductivity without taking into account the influence of mortar joints of the masonry will be 0.278 W/(m·K). It is seen that an increase in operational humidity and freezing of moisture in the pores of the material leads to a significant increase in the thermal conductivity of the masonry.

4. Conclusion

The literature does not assess the conformity of the actual and declared characteristics of autoclaved aerated concrete blocks (AAC), which makes it difficult to find effective structural solutions for exterior walls using AAC.

1. The results of the study show that the actual thermophysical characteristics of autoclaved aerated concrete blocks (AAC), cut from product samples of the three largest manufacturers, in most cases do not coincide with the values declared by the manufacturers and presented in the standards prepared with their direct participation.

2. The mismatch between the calculated and actual values of the thermal conductivity of materials and products used in the installation of external walling, leads to an increase in transmission heat losses through the external walls and the waste of thermal energy for heating and ventilation of buildings. In this regard, a radical review of the values declared by manufacturers, as well as the standards on the basis of which the products are manufactured, and their correct presentation in the current regulatory documents are required.

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