WARSAW UNIVERSITY OF TECHNOLOGY | Index 351733 | DOI: 10.24425/ace.2024.148910
FACULTY OF CIVIL ENGINEERING
COMMITTEE FOR CIVIL AND WATER ENGINEERING
ARCHIVES OF CIVIL ENGINEERING
POLISH ACADEMY OF SCIENCES | ISSN 1230-2945 | Vol. LXX | ISSUE 1 | 2024

 pp. 261 –275

Research paper

The durability of inverted roof insulation kits

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Abstract: The paper analyses the loss mechanism of roof insulation kits' performance due to dampness increase in the insulation layers. The analyzed structures were used in standard conditions for ten years and had thermal insulation made of expanded polystyrene with a hydrophobized surface. The dampness of the thermal insulation materials was determined after the referenced period for their future fitness as roof insulation, based on laboratory tests of material samples collected from the structures. They were completed with a computer simulation of heat transfer and dampness in the partition for working conditions specified for ten years, assuming the thermal conductivity was determined for the materials collected from the analyzed roofs. It was discovered that simulation-based calculation dampness values are much lower than those observed after ten years of roof utilization. Additionally, the authors attempted to determine the correlations between the period of thermal insulation materials used in real conditions and the selected properties of the products determined in laboratory tests. To that end, the collected material was dried to constant weight and then subjected to accelerated aging through total immersion in water at room temperature, for twenty-eight days, followed by 300 freeze-thaw cycles at –20°C and +20°C. The results helped conclude that the abovementioned laboratory testing cycle does not allow for assessing the fitness for the use of the referenced products for ten years. The directions of future laboratory tests were set, suggesting extending the testing cycle at least twice.

Keywords: computer simulations of partition's heat conductivity and dampness, expanded polystyrene (EPS), durability, laboratory and field tests, inverted roof

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1. Introduction

A roofing system is a relevant part of a building's construction affecting the building's service life, durability and efficiency [1, 2]. Considering the arrangement of layers in a flat roof covering, it can be divided into traditional and inverted flat roof types. In standard (traditional) roofs, a thermal insulation layer is found under the waterproofing layer. In inverted roofs, the thermal insulation layer is arranged above the roof's waterproofing layer and is not protected against moisture caused by precipitation [3, 4]. Multifunctional inverted flat roofs appeared in the USA in the 1950s with the invention of extruded polystyrene foam (XPS). In Central Europe, this type of roof came into use later, in the 1970s [5]. Innovative flat roof solutions, e.g. water-covered roofs, are now tested. Nonetheless, examples of such applications are quoted for Mediterranean countries [6]. The authors of paper [6] demonstrated that reservoir roofs, also called water-collecting roofs, present greater thermal inertia than inverted flat roofs due to the water mass they contain. This feature contributes to their improved thermal performance and higher stability at indoor air and wall surface temperatures. It seems that in the mid-European transitional climate, the solution might not be useful due to periodic exposure of roof coverings to negative temperatures reaching –15°C and positive temperatures up to +70°C. Inverted roofs are typically used as garden roofs, which results in maintaining constant dampness of the thermal insulation layer but at a level much lower than in water-covered roofs [7]. Truly enough, green roofs – also called living or vegetated roofs – can reduce heat flux magnitude through a building envelope as a result of insulation provided by the growing medium, shading from the plant canopy, and transpirational cooling [8, 9].

Considering the potential permanent moisture content in an inverted roof's thermal insulation, it should be made of materials with low water absorbability, i.e. extruded polystyrene (XPS) or expanded polystyrene (EPS) with a hydrophobised surface; EPS has been utilised only recently, and publications point out insufficient experience in that regard [9, 10].

ETAG 031 [4] (for XPS and EPS), EAD 040650-00-1201 (for XPS) [11] and EAD 040773-00-1201 (for EPS) [12] have been effective in the European Union countries for the last test years, authorising the requirements for thermal insulation products intended for application in inverted roofs. According to ETAG 031, products for whose long-term water absorption by immersion does not exceed the limit values of $\leq$ 1.0% for EPS boards and $\leq$ 0.7% for XPS boards can be embedded in the reference solutions. The EADs do not quote any limits in this regard. Since the moisture content in polystyrene boards increases during freeze/thaw cycles, ETAG 031 specifies the following acceptable moisture content limit levels after the freeze-thaw cycles: EPS boards $\leq$ 5.0% and XPS boards $\leq$ 1%.

The provisions above suggest that the applied products should guarantee resistance to variable positive and negative temperatures in dampness conditions. In the mid-European transitional climate, the outdoor temperatures cross 0°C in three seasons, which means the buildings are exposed to the loads above for most of their life. According to technical requirements concerning building structures and good building practices, products used for covering roofs and terraces should ensure the required thermal insulation during the structure's entire life. The problem of selecting the best thermal insulation solutions in the construction sector is widely discussed in the science literature [13–15].The issue is regarded as technically significant also for inverted roofs, as it considerably affects maintaining the building structure's functionality. After a few years of use, the inspections of such roofs revealed high moisture content in the insulation layer despite the originally declared low water absorbability [16–20], which reduces the partition's thermal insulation performance [21]. The issue was discussed in detail in paper [21], where after ten years of using two buildings, the dampness of the thermal insulation layer made of expanded polystyrene with hydrophobised surface used as roofing reached up to 17% by volume; in the case of extruded polystyrene used as terrace cover reached up to 4% by volume. Truly enough, in such solutions, thermal conductivity calculations of construction barriers take into account modifiers due to air voids in the insulation layer, mechanical fasteners that perforate the insulation material and, for inverted roofs, the influence of rainfall, as stormwater may flow under the insulation, causing a periodic increase in the systems' heat transfer [22]. The stormwater penetrating under the thermal insulation boards of inverted roofs contributes significantly to the heat loss through the roof's structure which should also be a subject of our interest [23].

The Building Research Institute has been researching the issue for many years. At the first stage, laboratory tests revealed that freezing and thawing of the boards, irrespective of the initial water absorption, is the main contributor to the constant and considerable increase in the moisture content [24]. Immersing the boards in water for 28 days contributes less to the moisture content increase in thermal insulation materials, whereby the most significant increase in the moisture content takes place in the first days of soaking and remains relatively consistent on subsequent days. The relationship between water absorption after 28 days of immersion and that caused by freeze and thaw cycles was not determined under the referenced tests [24]. The freeze and thaw testing was stopped after 300 cycles without discovering the results' relevance for the loads in real operation conditions. Considering the diversified temperature and precipitation distribution over the years, depending on climate conditions and the building structure's location and roof shape, unequivocal determination of such correlation requires many field observations completed with long-lasting accelerated ageing tests in laboratory conditions. In order to initiate action, the authors attempted to determine if the scope of laboratory loads assumed in the studies above [24], i.e. 28 days of the boards' total immersion in water followed by 300 freeze/thaw cycles, is a sufficient assumption for comparison with a thermal insulation layer's damage in roofs used for ten years. The research results are presented in this article, supplemented with an impact analysis of the thermal insulation layer's moisture content on reducing the thermal insulation function of the entire partition.

2. Experimental program

The research was carried out in two parallel phases, i.e.

- in buildings used for ten years, where dampness problems were diagnosed in the inverted roofs' insulation,
- in laboratory conditions; the materials used in the tests were taken from the abovementioned roofs.

The tested residential complex consisted of five buildings (five floors each) situated along the plot's edge. The roofs were inverted, bath-type constructions surrounded by high attic walls, with internal draining. Two out of five roofs in the buildings were evaluated after ten years of use. The roof layers were arranged as follows (according to their laying sequence):

- reinforced concrete floor slab, 15 cm thick,
- cement screed with a slope 1.0‰,
- PVC membrane as a roofing layer, 1.2 mm thick, reinforced with glass mesh,
- black polyethylene membrane, 0.2 mm thick,
- expanded polystyrene boards with hydrophobised surfaces, laid in two layers, 10 cm and 5 cm thick, respectively,
- geotextile,
- protective gravel layer, ca. 10 cm thick.

Expanded polystyrene board samples were collected for the tests in three places on two buildings. The thermal insulation layer's dampness was evaluated in each uncovered area, in both layers. The uncovered areas were selected considering the following aspects:

- tenants' information about frost penetration in the ceiling,
- areas sensitive from the point of view of the roofing's usage, i.e. at the inlet and the attic wall.

Figure 1 shows the views of the uncovered roof layers.

Fig. 1. View of the tested roofs

Figure 2 describes the testing procedure.

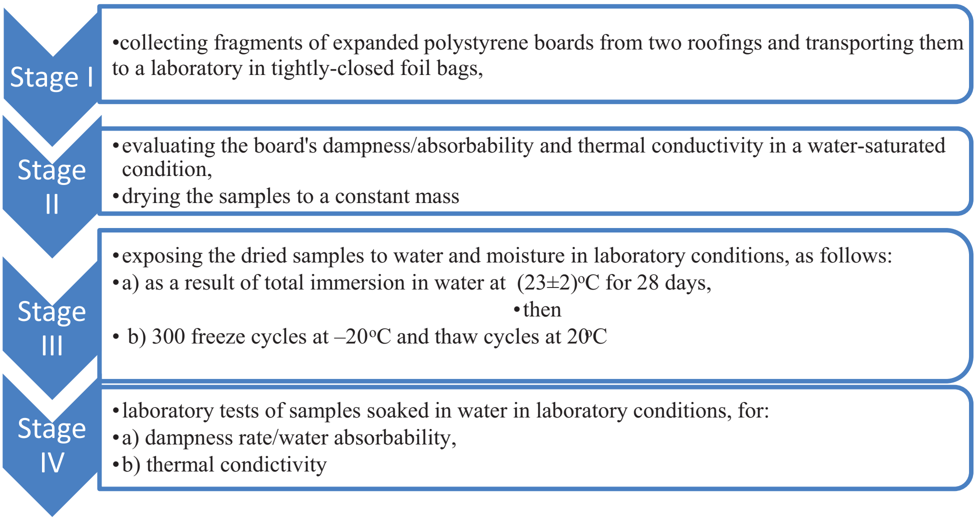


Fig. 2. Sequence of tests discussed in the paper

3. Materials and methods

3.1. Materials

The materials collected from the roofs and used in the tests were perimeter shape-moulded EPS boards with a profiled surface (compliant with EN 13163 [25]). Expanded polystyrene with a hydrophobised surface and the following functional characteristics was used on both roofs:

- thickness: 100 mm bottom layer, 50 mm top layer,
- density: 28 kg/m^3,
- compressive stress at 10% relative strain CS(10) 200 ≥ 200 kPa,
- declared thermal conductivity $\lambda \leq 0.034$ W/(m·K).

Fig. 3. View of the tested boards

The samples collected from roof No. 1 were marked as EPS E1 and those from roof No. 2 as EPS E2. The tested boards are shown in Fig. 3.

3.2. Methods of tests

3.2.1. Testing the boards' dampness

Five samples were cut out from each of the collected roof boards. The samples had the same surface sizes (300 × 300) mm and their original thickness was maintained. The initial weight of the cut-out samples was determined, and then the samples were dried to constant weight. First, drying continued for fourteen days in laboratory conditions at 23 ± 2°C and 50 ± 5% relative humidity. Then the samples were placed for about two months in a drying tunnel at 45°C until the weight differences did not exceed 0.01 g after five successive weight measurements. Dampness, in % (v/v), was calculated according to the following formula:

$$N = \frac{m_p - m_k}{V} \times \frac{100}{\rho_w} \tag{3.1}$$

where: m_p – initial weight, ca. 2 hours after collecting the sample, [kg], m_k – final weight, after reaching constant weight, [kg], V – sample's volume, [m^3], ϱ_w – water density – 1000 [kg/m^3].

3.2.2. Thermal conductivity of the boards

The samples' thermal conductivity was tested twice, i.e. for the following sample types:
– damp, immediately after collecting from the roofs,
– dried to constant weight.

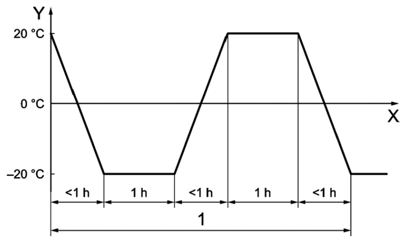
The thermal conductivity λ and thermal resistance in steady heat flow conditions were determined with a single-sample plate apparatus with heat flux density sensors according to EN 12667:2001 [26].

The sample's mean temperature in the measurements was 10°C, the temperature difference at the sample's thickness amounted to 20°C, and the heat motion was directed upward. The tests were carried out on samples sized 300 × 300 × 50 mm and 300 × 300 × 100 mm.

3.2.3. Long-lasting total immersion of the boards

Water absorbability at a long-lasting total immersion was identified according to EN ISO 16535:2019 [27] on samples cut out with a band saw, with surface dimensions of (200 × 200) mm, maintaining the board's original thickness.

Additionally, intermediate measurements were performed after 24 hours, 7 days, 14 days, 21 days and 28 days of immersion in water. After 28 days of immersion in water, the samples were subjected to 300 freeze cycles at –20°C and thaw cycles in water at +20°C, according to EN 12091:2000 [28]. A single cycle's course and view of the testing chamber are shown in Fig. 4. Intermediate water absorbability measurements were made throughout the test after 50, 88, 122, 155, 182, 201, 245 and 300 cycles.



(a)

(b)

Fig. 4. Freeze resistance testing: a) Course and duration of a single cycle, b) testing chamber

4. Results

4.1. Dampness/ water absorbability of EPS boards

Table 1 summarises the dampness test results for EPS boards with hydrophobised surfaces immediately after collecting from the roofs. Further tests on samples dried to constant weight and then exposed to water absorption through total immersion in water for 28 days, followed by 300 freeze/thaw cycles, were carried out for two samples (one for each structure) but of larger sizes (300 × 300 mm), maintaining the boards' original thickness. The test samples were selected from two structures, from the bottom layer, characterised by a middle value of dampness described as a median of the collection of all results. The water absorbability results for the boards subjected to further laboratory tests are presented in the tables below:

– Table 2 – after long-lasting immersion in water for 28 days,
– Table 3 – after 300 freeze/thaw cycles.

Table 1. Results of water absorbability for samples cut out from EPS boards collected from roofs

Board marking	Position in uncovered test layers	Layer's mean thickness, mm	Dampness, %, V/V (median)	Coefficient of variation [%]
EPS E1	Bottom layer	100	34.4*)	24.8
	Top layer	50	22.7	2.8
EPS E2	Bottom layer	100	32.2*)	14.7
	Top layer	50	18.7	1.4

**Samples selected for further testing (water absorbability and freeze resistance)*

Table 2. Results of water absorbability for samples cut out from EPS boards collected from roofs, dried to constant weight and subjected to long-lasting total immersion in water

Board marking	Water absorbability, %(v/v), for total immersion in water for				
	24 hours	7 days	14 days	21 days	28 days
EPS E1	0.29	0.53	1.71	1.77	1.80
EPS E2	0.43	0.72	1.59	1.66	1.73

Table 3. Results of water absorbability for samples cut out from EPS boards collected from roofs, dried to constant weight and then subjected to long-lasting total immersion in water followed by 300 freeze/thaw cycles

Board marking	Water absorbability, %(v/v), after freeze/thaw cycles							
	50	88	122	155	182	201	245	300
EPS E1	4.07	8.28	9.62	10.95	11.70	12.14	13.74	15.97
EPS E2	6.34	10.76	12.53	13.95	15.00	16.04	17.99	20.03

4.2. Thermal conductivity of the boards

Thermal insulating properties of EPS boards with hydrophobised surfaces were tested for samples collected from the bottom and top layers in both building structures. The samples were selected for the tests according to the same rule as described in item 4.1. Thermal conductivity and thermal resistance were determined in the tests; the samples were additionally identified by their thickness and density. The test results are presented in the tables below:

- Table 4 – immediately after collecting from the roofs,
- Table 5 – after drying the boards to constant weight.

Table 4. Results of thermal insulating properties tests on samples cut out from EPS boards immediately after collecting from roofs, in a damp condition

Sample's marking	Sample's mean thickness, mm/ Coefficient of variation [%]	Mean density, kg/m^3/ Coefficient of variation [%]	Thermal conductivity, W/(m·K)	Thermal resistance, (m^2·K)/W
EPS E1	98.8/0.3	371.5/0.3	0.113	0.88
			0.113	0.88
	49.3/0.4	358.5/2.3	0.105	0.48
			0.105	0.48
EPS E2	99.0/0.1	371.5/0.3	0.112	0.89
			0.114	0.88
	49.8/0.6	355/8.7	0.104	0.48
			0.102	0.49
			0.103	0.49

The expanded uncertainty of thermal conductivity, at k =2 and 95% confidence level amounts to 3%

Table 5. Results of thermal insulating properties tests on samples cut out from EPS boards collected from the roofs, after drying to constant weight

Sample's marking	Sample's mean thickness, mm/ Coefficient of variation [%]	Mean density, kg/m^3/ Coefficient of variation [%]	Thermal conductivity, W/(m·K)	Thermal resistance, (m^2·K)/W
EPS E1	98.8/0.1	29.0/0.0	0.0331	3.02
			0.0329	3.04
	49.3/0.1	28.0/1.0	0.0333	1.50
			0.0332	1.51
EPS E2	99.0/0.0	28.0/0.0	0.0331	3.02
			0.0330	3.03
	49.8	28.0/0.0	0.0329	1.52
			0.0334	1.50
			0.0329	1.52

The expanded uncertainty of thermal conductivity, at k =2 and 95% confidence level amounts to 3%

5. Discussion

The tests on expanded polystyrene samples with hydrophobised surfaces, collected from inverted roofs after ten years of use, revealed significant dampness values, contributing to a thirteen-fold increase in the product's density in a water-soaked condition compared to dry product and nearly four times higher thermal conductivity value against almost four times lower thermal resistance value. It results in reduced thermal insulating properties of the whole partition, which was confirmed in calculations carried out using WUFI Plus software [29] for thermal conductivity mean values, taking into consideration the values given in Tables 4 and 5. According to the results, the thermal conductivity value for the whole roof partition rose from 0.197 W/(m^{2}K) to 0.571 W/(m^2·K) at a simultaneous decrease in the total thermal resistance value from 4.9 (m^2·K)/W to 1.6 (m^2·K)/W. Considering the above, the partition's parameters deteriorated nearly three times, leading to biological corrosion hazard on the ceiling of the rooms under the roof. When building structures are used, the phenomenon is often misinterpreted as leakage through waterproofing membranes caused by their damage. Additionally, Figure 5 shows the results of the partition's dampness computer simulations [29] for the working loads determined for a ten years' period, assuming the thermal conductivity values identified for the materials collected from the analysed roofs.

The computer simulations rendered much lower water content values in the evaluated expanded polystyrene assuming a ten year's period of the reference roof's usage, at simultaneous drying of the partition, compared to real conditions of use. Based on the analysed structures,

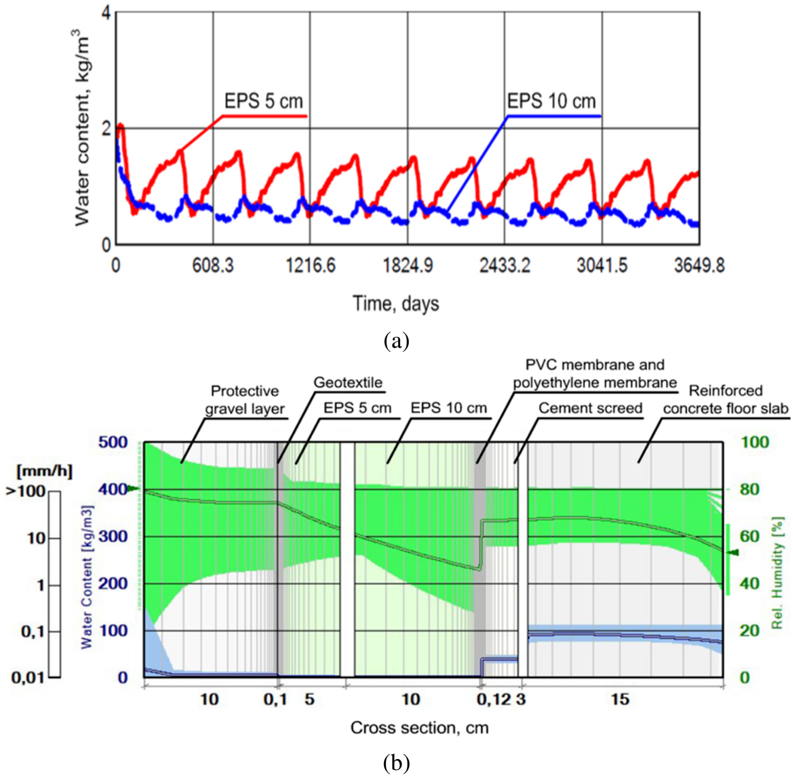


Fig. 5. Simulation of the partition's dampness change during ten years of use: a) water content in the layers of EPS, b) waveform of dampness change in the partition's layers

used in Warsaw for ten years, a gradual increase in the thermal insulation layer's dampness was observed, which is discussed further in the paper. The results for the samples collected in different roofing areas are scattered, which confirms the previous theorem about the impact of the test point's location in the roofing on the dampness development rate. Summing up, it can be concluded that numerical simulations assuming mean data for a representative year in a given location do not correctly reflect the conditions of inverted roof use as for the real dampness level of a thermal insulation layer in the roof.

Laboratory tests on the product samples collected from damp roofs confirmed the theorem above about a lack of satisfactory compatibility between the results of computer simulations of dampness development rate in inverted roofs and the real values observed in building structures. The samples were dried to constant weight and exposed to dampness in laboratory conditions, starting from soaking the samples in water as a result of their total immersion in water at (23 ± 2)°C for 28 days. The test results are summarised in Figure 6. Moreover, the Figure compares the test results for other products that had not been exposed to any operational loads before. The comparison was based on the results obtained in the first phase of the presented research, published in [24]. The absorbability increase curve for the samples collected from roofs 1 and 2 differs slightly from the curve for the boards not exposed to operational loads before. The dampness increase rate in the first two weeks for the boards previously used on the roof is higher and stabilises in the following two weeks. The end result is still lower than that obtained for the samples collected from the roof after ten years of use, which confirms the statement that long-lasting exposure to water at a positive temperature is not the fundamental cause of the thermal insulation layer becoming damp when used in a roof.

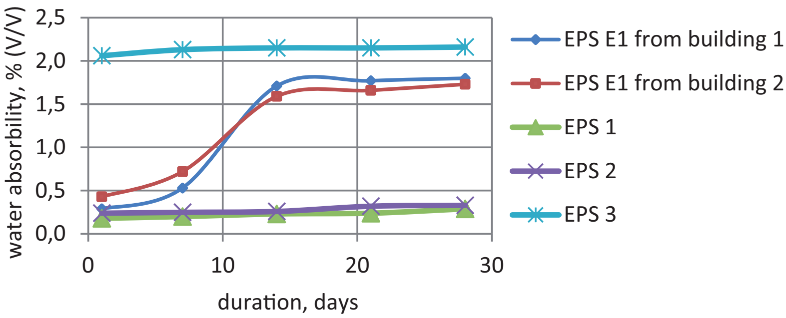


Fig. 6. Increase in the EPS boards' water absorbability during total immersion in water at (23 ± 2)°C for 28 days

Then, successive loads were simulated for the samples pre-soaked in water during their total immersion in water for twenty-eight days, followed by 300 freeze/thaw cycles at -20^{o}C and +20^{o}C, respectively. The test results are compared in Figure 7, which shows the values for the samples collected from the roofs described above and the values for stock products not exposed to operational loads, shown previously in Figure 6.

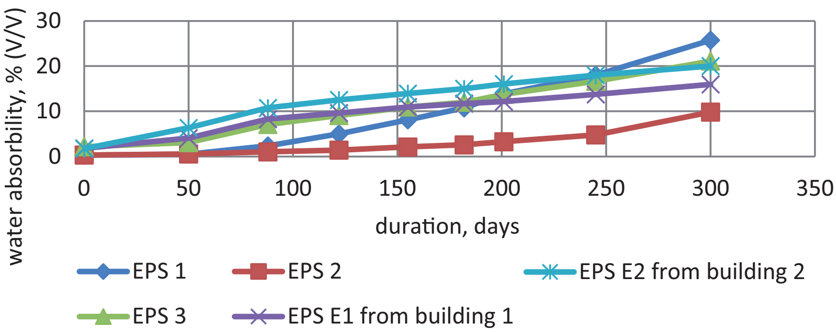


Fig. 7. Increase in EPS boards' water absorbability after 300 freeze/thaw cycles and previous total immersion of the boards in water at (23 ± 2)°C for 28 days

Although the increase in the sample's dampness during freeze/thaw cycles is disorderly for the samples previously not exposed to operational loads, for the samples collected from the roof it is rectilinear from cycle 200 to cycle 300. It shall be highlighted that after 300 freeze/thaw cycles, the samples still reveal absorbability values lower than those observed for the products immediately after their collecting from the roof, which is presented for comparison in Fig. 8.

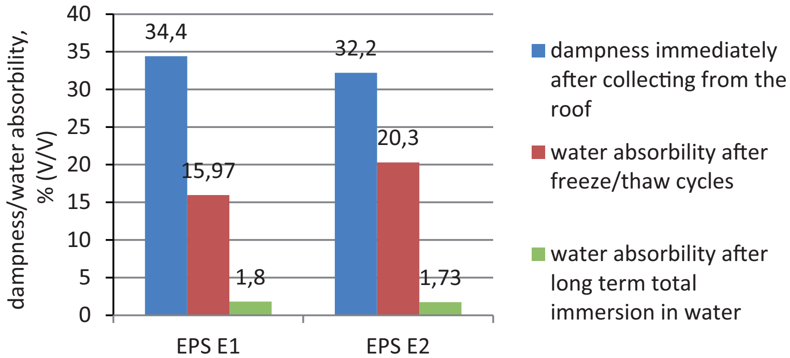


Fig. 8. Comparison of dampness level in EPS boards collected from an inverted roof, resulting from various operational loads

Considering the above, it can be concluded that the freeze resistance testing cycle assumed in EN 12091 [28] does not fully reflect the operational cycle of thermal insulation material used in an inverted roof, calculated for a ten years' period. Assuming idealistically that the curves remain rectilinear, in order to determine the dampness of the boards used in the abovementioned systems after ten years, twice more than presented above testing cycles would have to be performed in laboratory conditions, i.e. about 600 cycles. The statement above can be treated only as a hypothesis setting future research directions in this area rather than a conclusive statement. Future research shall also consider climate change, which will contribute significantly to the increase in the absorbability of thermal insulation materials used in roofs designed as described above. The temperature anomaly in winter 2022 in Poland, i.e. deviations from the long-term monthly averages in 1991–2020, ranged from –1.0°C to 3.0°C [30]. In summer 2022 (June–August) it was 19.3° C, meaning 1.3°C higher than the multi-year average temperature value for that period (climatological normal period 1991–2020). The anomaly index in the summer, i.e. deviations from the multi-year monthly averages in 1991–2020, ranged from 1.0°C to 2.0°C [31].

6. Conclusions

The paper presents the test results for thermal insulation boards made of expanded polystyrene with hydrophobised surfaces, collected from inverted roofs, used in natural conditions for ten years. On the basis of the results, the following conclusions can be drawn:

– after ten years of use, thermal insulation boards do not effectively fulfil their thermal insulation function due to a thirteen-fold increase in the product's density in a water-soaked condition compared to dry product and nearly four times higher thermal conductivity value against almost four times lower thermal resistance value. It reduces the insulation performance of the whole partition to the level causing biological corrosion hazard. The frost penetration effects in the partition are often misinterpreted as leakage through the roof with compromised tightness,

– after drying the thermal insulation material to constant weight, successive dampness develops faster than for materials not previously exposed to operational factors, and its curve takes the shape of a nearly linear function after about 200 freeze/thaw cycles.
– a laboratory testing cycle, assumed previously for functional characteristics assessment of thermal insulation materials, is too short to enable evaluation of the referenced products' fitness for at least ten years of use. The test results discussed in the article helped determine the directions of future laboratory tests, suggesting that the previously applied testing cycle should be extended at least twice,
– dampness of the thermal insulation layer significantly deteriorates the thermal insulation characteristics of the whole roof partition, contributing to an increase in the thermal conductivity value from 0.197 W/(m^2·K) to 0.571 W/(m^2·K), at a simultaneous decrease in the total thermal resistance from 4.9 (m^2·K)/W to 1.6 (m^2·K)/W, resulting in biological corrosion hazard in the rooms located under the roof,
– computer programmes used for simulating dampness development in the roof partition during its use do not reflect the operating conditions of inverted roofs.

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Trwałość przekryć dachowych o odwróconym układzie warstw

Słowa kluczowe: badania laboratoryjne, polistyren ekspandowany EPS, przekrycia dachowe o odwróconym układzie warstw, trwałość

Streszczenie:

W artykule przeanalizowano mechanizm utraty właściwości użytkowych przekryć dachowych o odwróconym układzie warstw wynikających ze wzrostu wilgotności warstwy termoizolacyjnej. Ocenę przeprowadzono analizując właściwości użytkowe obiektów eksploatowanych w warunkach naturalnych przez okres 10 lat, z izolacją termiczną wykonaną z polistyrenu ekspandowanego hydrofobizowanego powierzchniowo. Po ww. okresie użytkowania określono zawilgocenie materiałów termoizolacyjnych w funkcji ich przydatności użytkowej do dalszego pełnienia funkcji termoizolacyjnej przekrycia dachowego, na podstawie badań laboratoryjnych próbek materiałów pobranych z obiektów. Uzupełniono je o symulację komputerową przewodności cieplnej i zawilgocenia przegrody dla obciążeń użytkowych określonych również dla okresu 10 lat, przyjmując wartości współczynnika przewodzenia ciepła ustalone dla materiałów pobranych z analizowanych przekryć dachowych. Stwierdzono, że w efekcie obliczeń symulacyjnych uzyskiwane są wartości zawilgoceń znacznie niższe niż te notowane po 10 latach eksploatacji przekryć dachowych. Dodatkowo podjęto próbę ustalenia korelacji pomiędzy okresem użytkowania ww. materiałów termoizolacyjnych w warunkach rzeczywistych, a wybranymi właściwościami tych wyrobów określonymi w badaniach laboratoryjnych. W tym celu pobrany materiałwysuszono do stałej masy, a następnie poddano przyspieszonemu starzeniu polegającemu na całkowitym zanurzeniu w wodzie o temperaturze pokojowej, przez okres 28 dni a następnie działaniu 300 cykli zamrażania–rozmrażania, w temperaturach odpowiednio –20°C i +20°C. Uzyskane wyniki pozwoliły na stwierdzenie, że ww. laboratoryjny cykl badawczy również nie umożliwia oceny przydatności użytkowej przedmiotowych wyrobów w okresie 10 lat. Wytyczono kierunki dalszych badań laboratoryjnych, sugerując co najmniej dwukrotne wydłużenie ww. cyklu badawczego. Stwierdzono również, że po wysuszeniu materiałów termoizolacyjnych do stałej masy kolejne wzrost zawilgocenia następuje szybciej niż dla materiałów nie poddanych wcześniej działaniu czynników eksploatacyjnych i przyjmuje, w przybliżeniu kształt funkcji liniowej po około 200 cyklach zamrażania –rozmrażania.

Received: 2023-08-04, Revised: 2023-09-17