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Development of Prefabricated Additional Insulation Elements for the Renovation of High-Rise Apartment Buildings

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Abstract

Prefabricated additional insulation elements have demonstrated success in renovating up to 5-storey apartment buildings. However, the unique challenges posed by high-rise buildings necessitate a closer examination of installation and long-term performance. In this study, we developed an additional insulation element specifically tailored for renovating high-rise apartment buildings and analysed its hygrothermal performance. To test the performance of the insulation elements, we installed a prototype and measured its performance at critical points along the external envelope. We calibrated a calculation model and applied building performance simulation software to explore various combinations of prefabricated elements. Our goal was to compare the associated risks and the key hygrothermal properties of these different material combinations within the insulation element. Critical points between the insulation layer and the wind barrier, as well as between the surface of the existing concrete panel wall and the vapour control layer of the additionally insulated exterior wall were analysed. The study's results indicate that the thermal resistance and water vapour permeability of the wind barrier layer, and the presence of an appropriate vapour control layer primarily influence the performance and moisture dry-out of a structure. Additionally, the study results indicate that the weather component has a higher impact than in lower buildings as the wind-driven rain loads are considerably higher in the upper parts of the high-rise buildings. The initial moisture (w = 110 kg/m^3 at the height of the 9th storey and w = 117 kg/m^3 at the height of the 16th storey) dry-out can last more than 3 years depending on the building type and materials used. This study underscores the importance of tailored solutions and vigilant moisture safety management in high-rise apartment building renovations, particularly when utilizing prefabricated additional insulation elements.

Keywords: prefabricated additional insulation elements; hygrothermal performance; moisture safety; nZEB deep renovation; energy performance.

Introduction

Prefabrication has been a widely used construction method for many decades as it enhances the quality and efficiency of construction. The technology of prefabricated concrete large panel (PCLP) construction has been used in apartment buildings throughout various European countries since the 1960s (Hall & Vidén, 2005; Lahdensivu, 2012). The first PCLP building was constructed in Estonia in 1961, using production technology imported from France. Currently, over 70% of residential buildings in Europe are more than 30 years old, and over 35% are over 50 years old (Balaras et al., 2005; Miniotaite, 2015). This has led to an increasing focus on improving their condition. The European Commission introduced its Renovation Wave Strategy (EC COM 662, 2020) to enhance buildings' energy efficiency, reduce emissions, and prolong their lifespan. The strategy aims to double renovation

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rates in the coming decades. A cost-effective approach to meeting these targets involves renovating apartment and public buildings using prefabricated additional insulation elements.

Several pilot projects have demonstrated that nearly Zero Energy Buildings (nZEB) renovation measures are viable for enhancing the quality of residential buildings in Croatia (Teni et al., 2019), Italy (Malacarne et al., 2016), Spain (Patiño-Cambeiro et al., 2016), Poland (Firląg & Piasecki, 2018), the Mediterranean climate (Ferrante, 2014; Tsirigoti et al., 2021), Sweden (Mjörnell, 2016), Finland (Cronhjort, 2011), and Estonia (Pihelo et al., 2020). The results demonstrate significant energy and cost savings potential while supporting the requirements for extensive energy renovations.

A highly insulated building envelope is essential for renovating buildings towards nZEB requirements in all climates. Meeting upcoming nZEB standards requires higher insulation levels compared to older building designs (Kalamees et al., 2016). In cold climates, additional thermal insulation is crucial to significantly enhance the energy efficiency of buildings. Renovations for high-rise buildings present unique challenges and solutions (He et al., 2020; Šadauskienė et al., 2016; Sağlam et al., 2017; Turkington et al., 2021). Particularly with high-rise buildings, special consideration is needed for increased moisture exposure from wind-driven rain (Nath et al., 2015). Compared to lower apartment buildings, high-rise buildings are relatively less deeply renovated. For example, in Tallinn, Estonia, only 5% of Soviet-era high-rise apartment buildings are renovated (Hess et al., 2022).

The aforementioned studies and literature review indicated that several development projects have focused on increasing energy efficiency and cost-effectiveness using the cutting-edge technology of prefabricated insulation elements for deep energy renovations. However, many of these programs have not documented or analysed the hygrothermal performance of the existing building envelope of high-rise buildings. In this study, we analyse the hygrothermal performance of prefabricated additional insulation elements and provide respective solutions for renovating high-rise apartment buildings to fulfil nZEB standards in a cold and humid climate.

To ensure the hygrothermal performance of the renovation solutions mentioned above, the current study aims to answer the following research questions:

- What is the critical level of initial moisture content in the external concrete large panel of the high-rise apartment building?
- What are the thresholds for water vapour resistance of the vapour control layer of the prefabricated additional insulation elements mounted on the high-rise building's external walls?
- What limitations exist for materials in the mentioned solutions in terms of their sensitivity to mould growth?

Methods

Reference building

High-rise apartment buildings (9 stories and higher) in Estonia were built mainly in the 1970s to 1980s with prefabricated concrete large panels (PCLP) in typical mass production series 111-121 (mostly in Tallinn) and 111-133 (mostly in Tartu). The original (non-renovated) PCLP wall with a thickness of 250–300 mm consists of two concrete sections and insulation layers: 50–65 mm exterior reinforced concrete slab + 100–125 mm woodchip, phenolic foam, or EPS insulation layer + 75–125 mm interior reinforced concrete slab. The thermal transmittance of the original envelope varies, being U = 0.9–1.2 W/(m^2·K), and primary energy consumption before renovation is ~250 kWh/(m^2·y). Depending on the building and its construction quality, performance, dimensions, and insulation materials may vary.

Connections of the building envelope contain serious thermal bridges (see Fig. 1; insulation layers are highlighted in yellow and brown (installed in PCLP factory) and green (installed in situ) and reinforced concrete in light grey). Because of apparent thermal bridges, mould growth on interior surfaces, especially in the junctions of exterior–interior walls, and intermediate floors, may occur in top-floor apartments. Buildings of this type typically share common issues found in many older buildings, such as high energy consumption, poor ventilation, winter overheating, and inadequate thermal comfort.

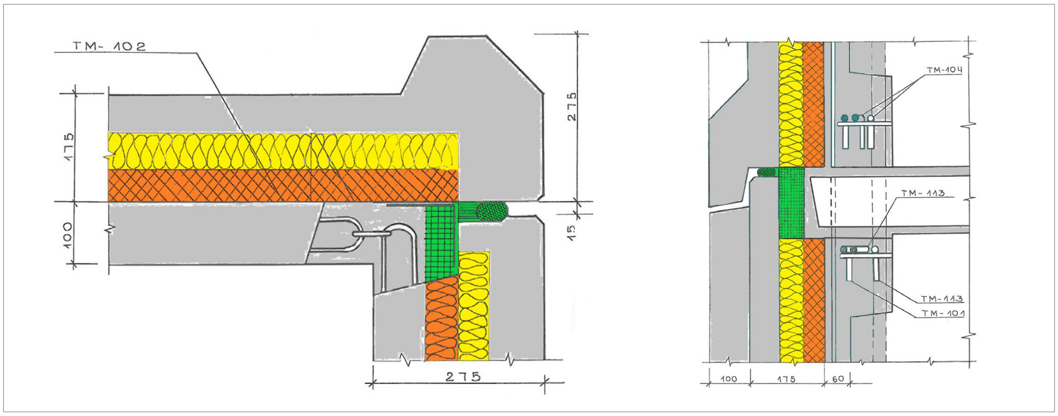


Fig. 1

Horizontal section of connection of walls (left) and vertical section (right) of connections of wall and intermediate floor with the PCLP elements in apartment building series 111-133 (based on original drawings from Estonian State Archives 1980)

The specific case study 9-storey PCLP apartment building (type 111-133) with a total area of 4990 m^2 was constructed in 1989 and is located in Tartu, Estonia (58°22'25.8"N, 26°46'40.0"E) (see Fig. 2).

Fig. 2

9-storey case study apartment building in Tartu, Estonia (left). Installation of the prefabricated test elements in February 2023 onto the apartment building studied (right)

Assessment of the hygrothermal performance

The Finnish mould growth model (Ojanen et al., 2010; Viitanen et al., 2015) was implemented as a criterion to evaluate the risk of moisture damage and fungus growth in critical spots of the structures studied. The total exposure time for the growth of mould is affected by both high and low humidity conditions, as well as the humidity and temperature levels. When simulating mould growth, it is crucial to determine the minimum (threshold) levels required for fungal growth on different materials. The duration of these conditions is also significant. There are specific minimum and maximum levels of moisture content, water activity, or temperature that allow fungi to grow. Under these favourable conditions, mould growth may continue at different rates. The onset of mould growth and growth intensity is mainly dependent on water activity, temperature, exposure time, and the surface of the substrate (Hukka & Viitanen, 1999; Ojanen et al., 2010). The boundary curve for the risk of mould growth in the range of temperature between 5 and 40 °C on a material can be described by a polynomial function, see Eq. (1):

$$RH_{\mathrm{crit}} = \begin{cases} -0.00267 \cdot t^3 + 0.16 \cdot t^2 - 3.13 \cdot t + 100 & \text{when } t \leq 20\ ^\circ\mathrm{C} \\ RH_{\mathrm{min}} & \text{when } t > 20\ ^\circ\mathrm{C} \end{cases} \quad (1)$$

where t is the temperature (°C) on the investigated material surface and RH_{min} represents the minimum level of relative humidity (%) at which mould growth is possible (varies according to the sensitivity of the material, see Table 2 (Ojanen et al., 2010).

The safe value of the mould index was set in the current study at level M < 1 (no mould growth) and the critical value at level M = 2 (several local mould growth colonies on the surface) (see Table 1). Therefore, the mould index 1 ≤ M < 2 is considered a low risk of mould growth (small amounts of mould on the surface, initial stage of growth) (Viitanen et al., 2015). According to this model, the mould growth sensitivity class 'sensitive' was used for planed wood, wood-based materials, and gypsum board with paper (see Table 2). Untreated wood (sapwood), in the class of 'very sensitive', was not used in the structures analysed. For other materials, the class 'medium resistant' was set.

Table 1

Description of mould indexes

Mould index (M)	Description of mould growth
0 ... 1	No growth
1 ... 2	Small amounts of mould on the surface (microscope), the initial stage of local growth
2 ... 3	Several local mould growth colonies on the surface (microscope)
3 ... 4	< 10% coverage, or < 50% coverage of mould (microscope)
4 ... 5	10–50% coverage, or > 50% coverage of mould (microscope)
5 ... 6	Plenty of growth on the surface, with> 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Table 2

Description of sensitivity classes

Sensitivity class	Materials	RH_{min}
Very sensitive	Untreated wood, sapwood	80%
Sensitive	Glued wooden boards, polyurethane (PUR) with the paper surface, planed pine, and planed spruce	80%
Medium resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85%
Resistant	PUR polished surface	85%

Measurements

The long-term hygrothermal performance was measured at the different locations of the external envelope of the apartment building.

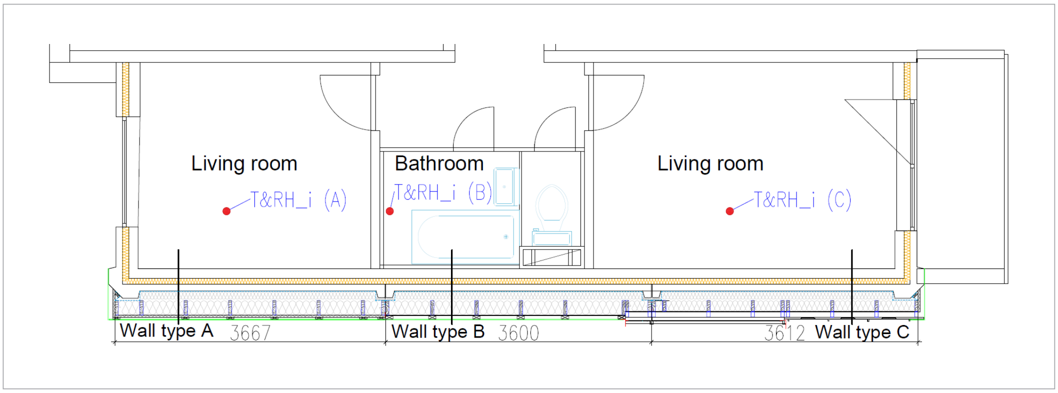
Relative humidity and temperature were measured at 30/60-minute intervals at various locations of the external envelope (see Fig. 5 left) with temperature and relative humidity external-sensor data loggers Onset HOBO UX100-023A: temperature measurement range -20...+70°C with accuracy ±0.21°C, and RH in the range 1%...100% with accuracy ±2.5% from 10%...90% RH and ±5% above 90% RH. Indoor climate in apartments was measured with integrated-sensor data loggers Onset HOBO MX1101: temperature measurement range -20...+70°C with accuracy ±0.21°C, and RH in range 1%...90% with accuracy ±2.0% from 20%...80% RH and ±6.0% below 20% RH and above 80% RH. Outdoor air and surface temperatures were measured with Onset HOBO MX2302A external-sensor data loggers: temperature measurement range -40...+70°C with accuracy ±0.20°C, and RH in the range 1%...100% with accuracy ±2.5% from 10%...90% RH and ±5% above 90% RH. The thermal transmittance of the walls was measured with the heat flux plate using the Hukseflux HFP03 sensor (Ø 17 cm, measurement range ±2000 W/m^2, accuracy +5...-15%).

Test elements

After the final design of the renovation with prefabricated elements, the test elements with sizes 3.6×3.7 m were installed on the exterior wall of the SW side of the case study building (see Fig. 2 right and Fig. 3) to practice the installation and find possible gaps in the planned design, to introduce the principle and aesthetics of the elements for the house owner and to participating in further planning and building phases designers and subcontractors.

Fig. 3

Location of the wall test elements, types A, B, and C, and indoor temperature and RH sensors



Modelling

The model was calibrated using measurement results, and prefabricated elements were analysed using building performance simulation software Delphin (Grunewald et al., 2015) to compare hygrothermal risks and the main properties of the different sets of materials in the insulation element. See the properties of the materials in Table 3.

Table 3

Materials in structures studied

Material	Thermal conductivity λ, W/(m·K)	Water vapour resistance factor μ, at RH 75%	Density ρ, kg/m³	Water absorption coefficient A_w, kg/(m²·s$^{0.5}$)
Concrete (PCLP)	1.500	110	2320	0.0200
Expanded polystyrene (insulation of the PCLP)	0.045	50.0	25	0.0001
Timber (planed spruce)	0.130	40.0	450	0.0155
Glass wool (GW) insulation	0.035	1.20	22	
GW wind barrier board with windtight facing	0.031	1.80	105	
RW wind barrier board with windtight facing	0.033	1.40	120	
Fiber cement board	0.260	17.5	1350	0.0569
Wood fibreboard	0.050	5.00	270	0.0120
Gypsum board without paper	0.190	7.90	774	0.0760
Oriented strand board (OSB)	0.130	165	595	0.0018
Sheathing membrane (S_d≤0.015 m) *	0.220	75	420	0.0001
Air and vapour control layer (S_d≤0.03 m) *	0.230	520	463	0.0001
Air and vapour control layer (0.2 m≤S_d≤5 m) *	0.230	1000	460	0.0001
Air and vapour control layer (0.3 m≤S_d≤14 m) *	0.230	1100	400	0.0001
Air and vapour control layer (0.8 m≤S_d≤35 m) *	0.400	1700	1900	0.0033

* S_d – water vapour diffusion-equivalent air layer thickness

For hygrothermal analyses and modelling, the Estonian moisture reference year (MRY) climate data (Kalamees & Vinha, 2004), indoor climate measurements from Estonian dwellings (Arumägi et al., 2015; Kalamees et al., 2011), and wind-driven rain calculation methodology (EN ISO 15927-3, 2009), were used to determine critical hygrothermal conditions. The critical indoor hygrothermal loads with indoor moisture excess Δv = 6 g/m^3 during winter (Ilomets et al., 2017) were applied.

Results

Development of prefabricated additional insulation element

The original PCLP walls of the 9-storey apartment building are to be insulated with prefabricated additional insulation elements with a total thickness of 330–380 mm (see **Fig. 4** and **Fig. 5**). After the nZEB renovation, the designed thermal transmittance U_{wall} ≤ 0.12 W/(m^2·K), U_{roof} = 0.10 W/ (m^2·K), U_{window} ≤ 0.80 W/(m^2·K). The additional insulation element was designed for the highly insulated building to fulfil the requirements of a nZEB with primary energy consumption after the renovation <105 kWh/(m^2·y) (RT I, 05.06.2015, 2015).

The prefabricated additional insulation element (see **Fig. 4** and **Fig. 5**) is based on timber frames (c/c 600 mm) with glass wool or rock wool (GW, RW) insulation or cellulose blown wool where the air and vapour tightness from the inner side is guaranteed with an air and vapour control layer and covered with a wind barrier layer from the external side. The ventilated air gap with vertical timber battens 28×70 mm contributes to the drying of built-in moisture, and the facade boarding with horizontal sills ensures the weather-proof protection of the envelope structures. To minimize convection between structures and to fill the gap between the uneven original wall surface and the prefabricated element, a light mineral wool buffer layer (GW, ρ = 22 kg/m^3) is anticipated on the warm side of the prefabricated element. The thickness of the buffering layer may vary up to 120 mm and its thickness depends on the concrete frames, stepping out around each PCLP on the external surface about 105 mm (see **Fig. 5** right). A buffering layer fixed in the factory in a zigzag pattern with strings that are released after the element is installed or by using adhesives. The elements will be mounted to the original walls with steel brackets, allowing adjustment and levelling of elements in all 3 directions during installation. To save space in living premises, the ventilation ductwork (125–160 mm) will be embedded in the factory in the main insulation and buffer layer of the elements.

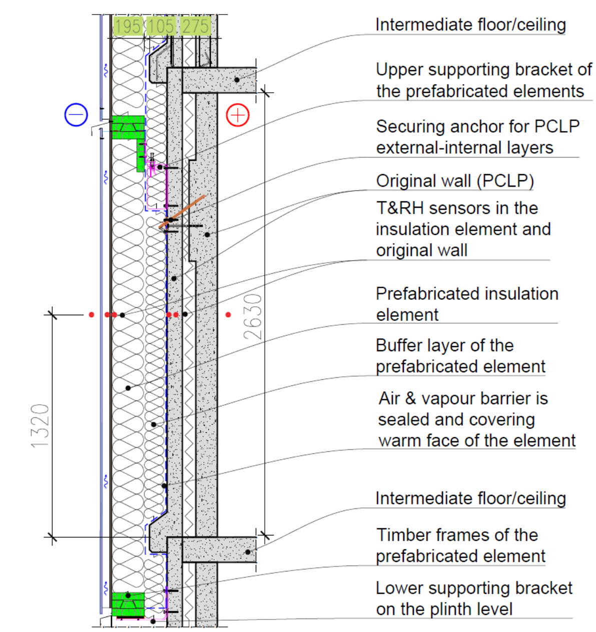


Fig. 4

Vertical cross-section of the prefabricated additional insulation element developed on the existing PCLP wall

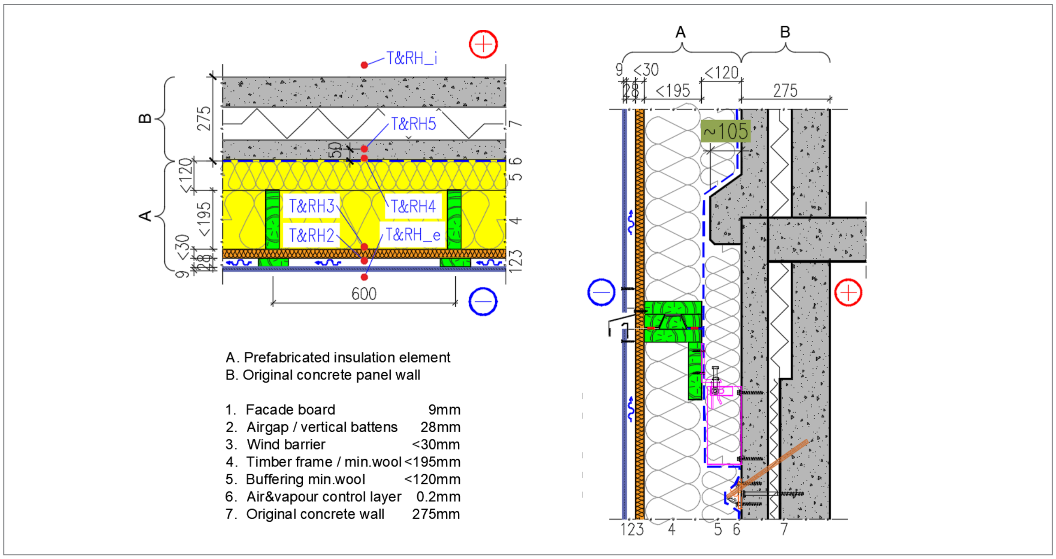


Fig. 5

Horizontal cross-section with marks of critical points measured and analysed (left) and vertical cross-section (right) of the prefabricated additional insulation element on the original PCLP wall

Three types of test elements, equipped with sensors and loggers to measure the temperatures, relative humidity and heat flux, and examine the hygrothermal performance of the structure of the envelope and moisture dry-out-related behaviour, were developed and prototypes installed in February 2023 (see **Fig. 2**, **Fig. 3**, **Fig. 4**, and **Fig. 5**):

- Type A: element with insulation layer 195 mm (+ buffer layer) and with air and vapour control layer between the original wall and the installed prefabricated element (with water vapour diffusion-equivalent air layer thickness 0.3 m<S_d<14 m) and 30 mm GW wind barrier board with windtight facing;
- Type B: element with insulation layer 195 mm (+ buffer layer), and with air and vapour control layer (S_d<0.03 m) and 13 mm RW wind barrier board with windtight facing;
- Type C: element with insulation layer 145 mm (+ buffer layer), and with air and vapour control layer (0.8 m<S_d<35 m) and 9 mm fibre cement wind barrier board.

Results of the measurements

Relative humidity and temperature were measured with installed wall test elements from February 2023 to January 2024. The results are represented in **Fig. 6**, **Fig. 7**, **Fig. 8**, and **Fig. 9**.

Results of the measurements of relative humidity and temperatures in the apartment (see **Fig. 7**) show a correlation with outdoor climate, as with lower outdoor temperatures in living rooms temperature drop is also noticeable. In **Fig. 8** (left), the indoor moisture excess, and in **Fig. 8** (right) relative humidity values are close or slightly above the limit for the rooms with high occupancy, while in that particular apartment lives only a pair of elderly people. These results are explained by the need for more efficient and adjustable ventilation and heating systems.

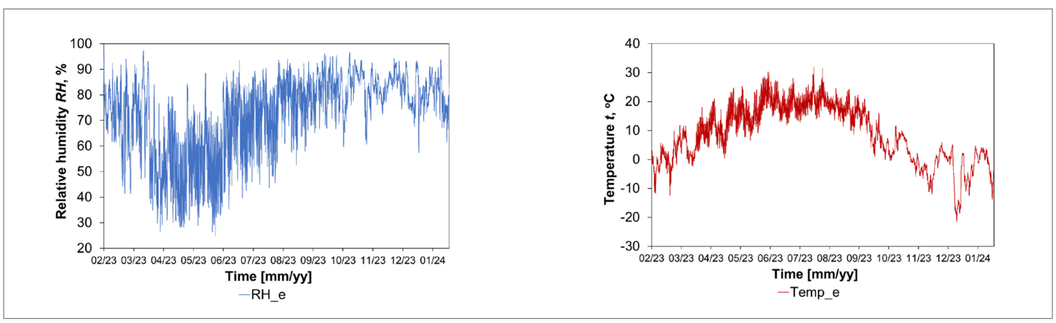


Fig. 6

Outdoor relative humidity (left) and temperature (right) measured in Feb 2023 – Jan 2024

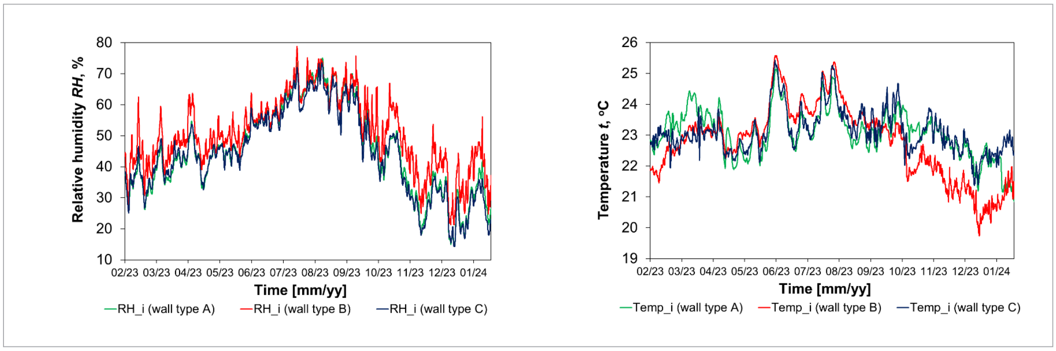


Fig. 7

Indoor relative humidity (left) and temperatures (right) measured in Feb 2023 – Jan 2024 with wall test element types A, B, and C

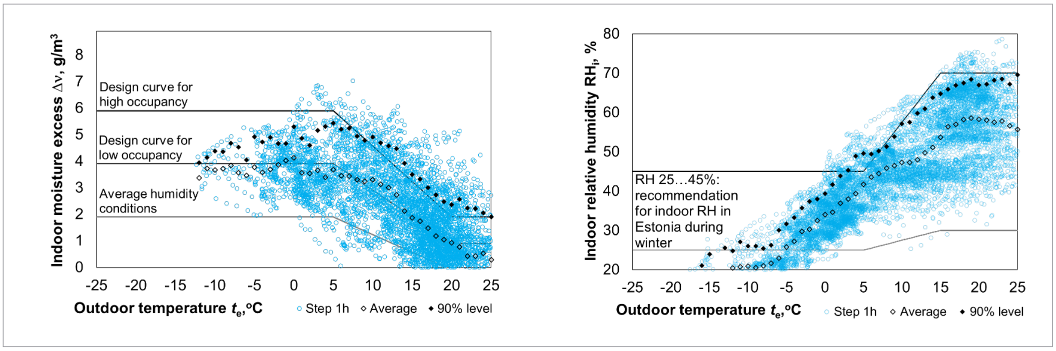


Fig. 8

Indoor moisture excess (left) and indoor relative humidity (right) depending on outdoor temperature measured in Feb 2023 – Jan 2024 with wall test element types A, B, and C

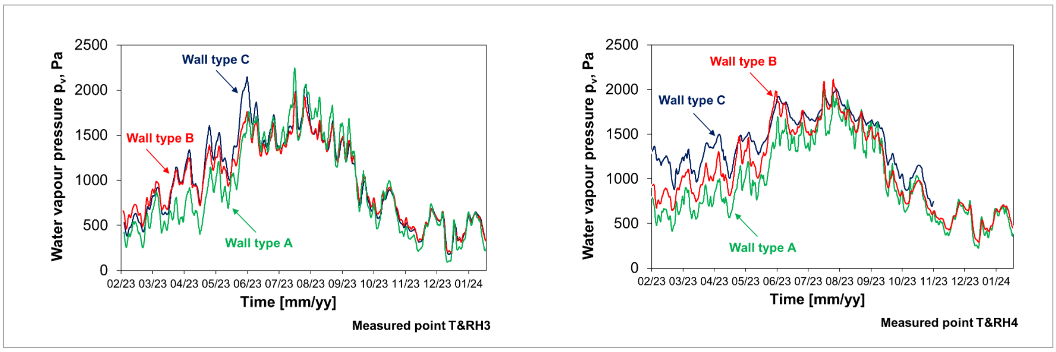


Fig. 9

Moisture level behind the wind barrier board (left), and behind the air and vapour control layer (right) measured in Feb 2023 – Jan 2024 with wall test element types A, B, and C. See points T&RH3 and T&RH4 in Fig. 5

Results of the measurements in the different spots of the installed test element (see Fig. 9) show the variance of the moisture level, both behind the air and vapour control layer (see point T&RH4) and behind the wind barrier (see point T&RH3). The drying out from the PCLP moisture volume is higher in point T&RH4 if there is a vapour control layer with lower water vapour permeability properties. A lower water vapour permeability of the wind barrier layer at point T&RH3 will lead to increased water vapour levels behind the wind barrier board. Conversely, the higher water vapour permeability of the vapour control layer will promote greater moisture flow through the insulated structure, creating a higher moisture volume behind the wind barrier board. This situation could potentially lead to moisture damage and mould growth in that specific area.

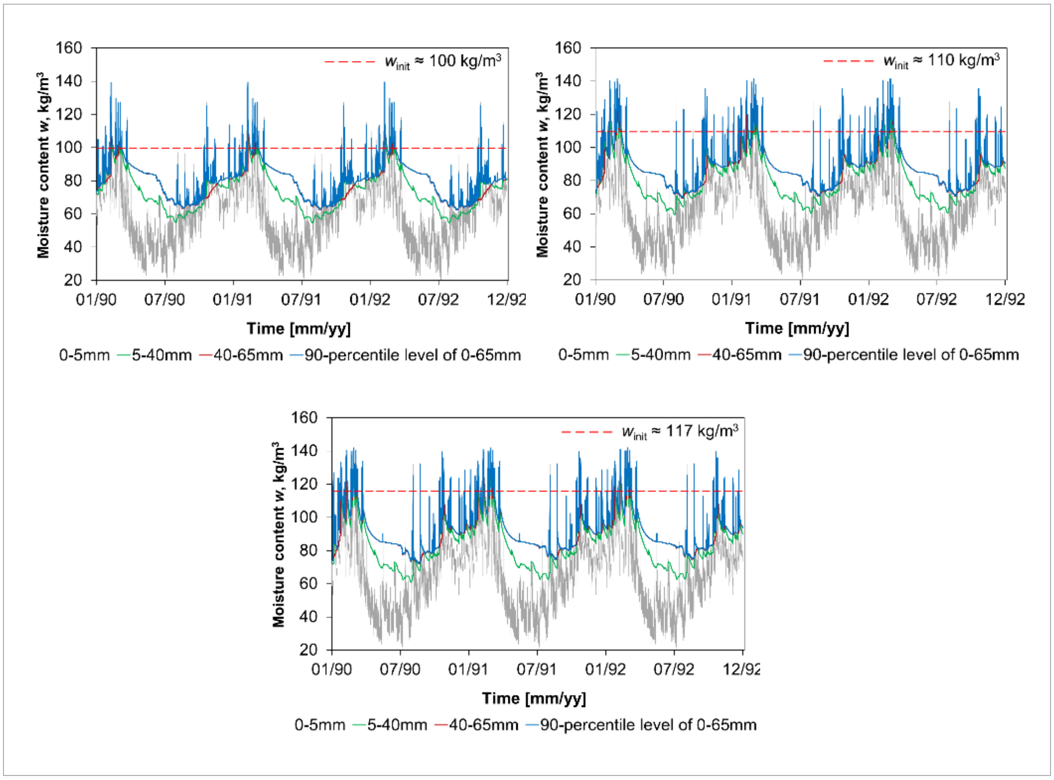
For the measurements of the wall test element types A, B, and C, different air and vapour control layers (membranes) were installed to compare their performance simultaneously. Between the air and vapour control layer and the original PCLP wall is quite thick (<120 mm) buffering light mineral wool layer (see Fig. 5, pos.5), and there are no separating seals between different element types installed. Therefore, we can see in the results, that drying out from PCLP moisture levels are equalising behind the air and vapour control layer over all tested wall area (see Fig. 9 right) and no big differences can be detected, despite that the vapour control layers have different properties of water vapour permeability and therefore should perform differently. Thus, to obtain the results with materials with different properties, separating sealing between those materials is needed. On the other hand, this result confirms that moisture redistribution is taking place even in such conditions and structures. That type of installation could be a lifeline in real cases where accidental or unanticipated moisture overload may occur.

Results of the simulations

The study analysed the initial moisture content (IMC) and moisture redistribution in the PCLP (before installing prefabricated elements and without additional external insulation) using local MRY data, indoor climate data, and information on wind-driven rain. In Fig. 10 the moisture content is shown at various depths and heights of the 65 mm thick external PCLP slab, highlighting the 90th percentile of results (indicating 10% of results with higher moisture content). The data reveals significant variations in moisture content across different depths of the PCLP and seasons. Moisture levels in the external slab at the 9th and 16th stories are notably higher than at the 5th storey due to increased exposure to wind-driven rain. Based on the results, the critical IMC of the PCLP at the height of the 9th storey, oriented to the SW, is w = 110 kg/m^3 and at the height of the 16th storey is w = 117 kg/m^3 which is considered as a base initial value for the hygrothermal design of such projects in the Estonian climate.

Fig. 10

Differences of the moisture content in the external 65 mm PCLP slab in different depths and 90-percentile level, without prefabricated insulation elements at the height of the 5th storey (top left), 9th storey (top right), and 16th storey (bottom center) of the external wall, oriented to the SW



The analyses were continued with the PCLP wall of the 9-storey building, as 16-storey buildings are less studied and require a more thorough assessment of their condition and structures. Simulations with installed prefabricated insulation elements and with the IMC of the PCLP at the height of the 9th storey (w = 110 kg/m^3) were carried out for the structure shown in Fig. 5 with the sets of the materials used for the wall test element types A, B, and C. Results of the moisture dry-out and mould index calculated in the most critical points (T&RH3, T&RH4) are shown in Fig. 11, Fig. 12, and Fig. 13.

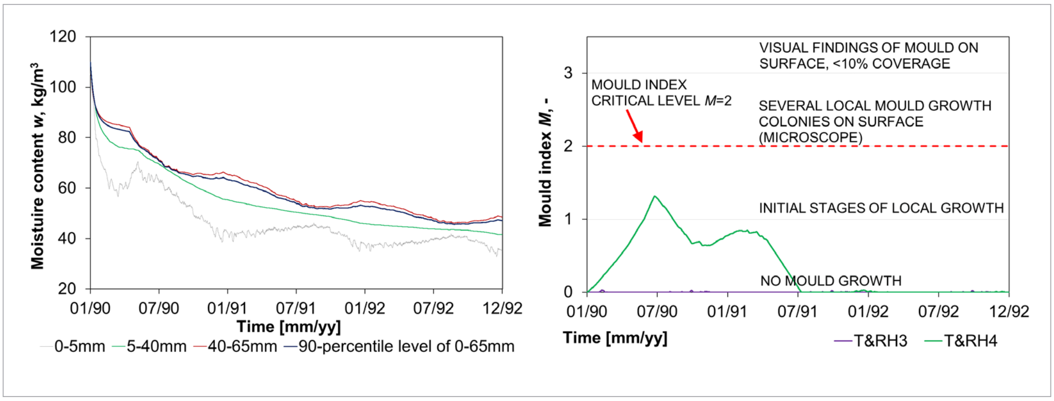


Fig. 11

Moisture dry-out of the PCLP at different depths (left) with the installed element type A, with a 30 mm GW wind barrier board and an air and vapour control layer with varying S_d-value (0.3 m<S_d<14 m). Mould index in points T&RH3 and T&RH4 of the wall type A (right). See Fig. 5 for the locations of the points analysed

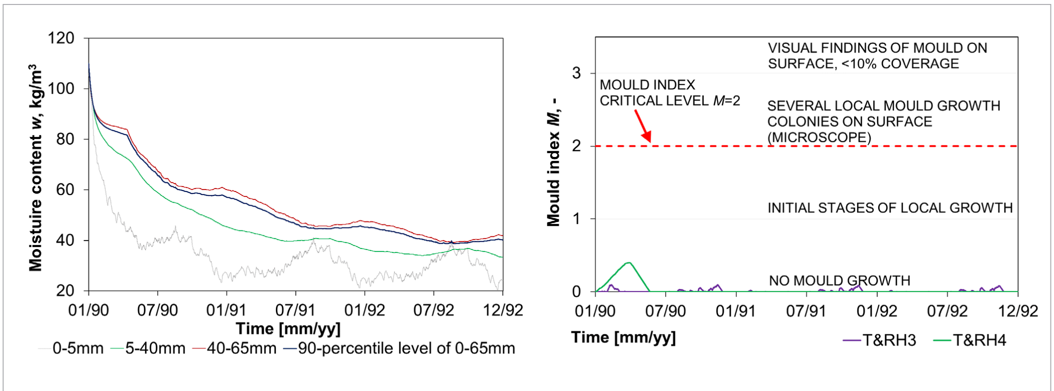


Fig. 12

Moisture dry-out of the PCLP at different depths (left) with the installed element type B, with a 13 mm RW wind barrier board and an air and vapour control layer (S_d<0.03 m). Mould index in points T&RH3 and T&RH4 of the wall type B (right). See Fig. 5 for the locations of the points analysed

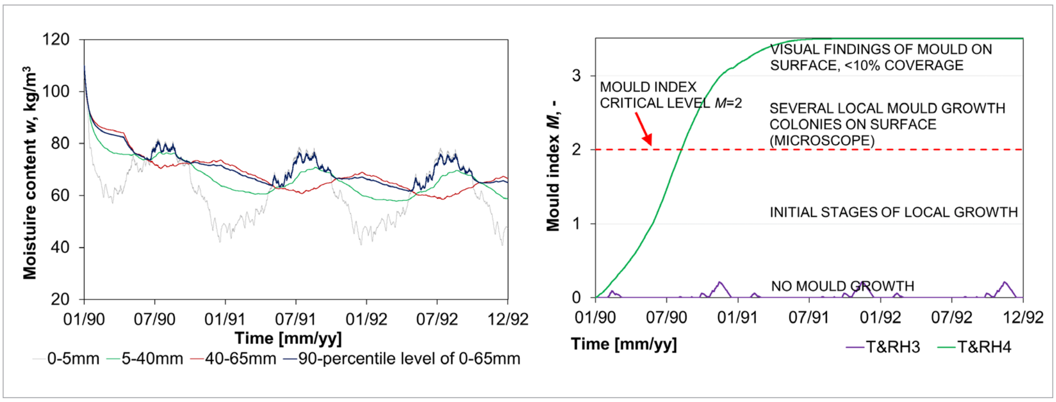


Fig. 13

Moisture dry-out of the PCLP at different depths (left) with the installed element type C, with a 9 mm fibre cement wind barrier board and an air and vapour control layer (0.8 m<S_d<35 m). Mould index in points T&RH3 and T&RH4 of the wall type C (right). See Fig. 5 for the locations of the points analysed

In addition to the analyses of test wall elements, the performance of different wind barrier products available on the market, and the range of air and vapour control layers were analysed based on the mould growth risk as a criterion. The aggregated results of the hygrothermal performance analysis are presented in the form of a mould growth risks assessment in Table 4. In columns (no. 2–9) are different air and vapour control layers listed with their water vapour diffusion-equivalent air layer thickness (S_d). In rows, critical points T&RH3 and T&RH4 for each analysed set, and mould indexes presented in coloured cells with the 5 most common types of wind barriers on the local market. In all sets presented, the mineral wool insulation (RW or GW) is used in the installed prefabricated elements and the IMC of the PCLP wall w = 110 kg/m^3. It is assumed that sets with high mould growth risk are not applicable for high-rise buildings in the Estonian climate (see sets in Table 4 where red colour in cells is present, i.e., mould growth risk is high, since mould index M ≥ 2).

Table 4

The risk of mould growth (mould index M) of an externally insulated with prefabricated elements (with RW or GW insulation in thickness 195–340 mm) PCLP wall with different air and vapour control layers, and wind barrier layers (with its thermal resistance (R, m2·K/W) in critical points T&RH3 and T&RH4. See **Fig. 5** for the locations of the points analysed and **Table 3** for the properties of the materials

1	2	3	4	5	6	7	8	9
See **Fig. 5** for the locations of the critical points analysed	Air and vapour control layer and its S_d-value (m)							
	0.03	0.2 – 5	0.3 – 14	0.5 – 25	0.8 – 35	0.1	0.2	2.0
	Air and vapour control layer	Air and vapour control layer with varying water vapour resistance				Gypsum board without paper	Fiber cement board	OSB
	Membrane, thickness 0.2–0.3 mm					9 mm	12 mm	12 mm
Critical point	Wind barrier – sheathing membrane ~0.2 mm (R ≈ 0.00 m^2·K/W)							
T&RH4	Yellow	Yellow	Yellow	Red	Red	Yellow	Yellow	Red
T&RH3	Green	Green	Green	Green	Green	Green	Green	Green
	Wind barrier – fibre cement board 9 mm (R ≥ 0.03 m^2·K/W)							
T&RH4	Green	Green	Yellow	Yellow	Red	Green	Green	Red
T&RH3	Green	Green	Green	Green	Green	Green	Green	Green
	Wind barrier – gypsum board without paper 9 mm (R ≥ 0.05 m^2·K/W)							
T&RH4	Green	Green	Yellow	Yellow	Red	Green	Green	Red
T&RH3	Green	Green	Green	Green	Green	Green	Green	Green
	Wind barrier – RW/GW board with windtight facing ≥ 13 mm (R ≥ 0.40 m^2·K/W)							
T&RH4	Green	Green	Yellow	Yellow	Red	Green	Green	Red
T&RH3	Green	Green	Green	Green	Green	Green	Green	Green
	Wind barrier – wood fibreboard ≥ 22 mm (R ≥ 0.45 m^2·K/W)							
T&RH4	Green	Green	Yellow	Yellow	Red	Green	Green	Red
T&RH3	Yellow	Yellow	Green	Green	Green	Green	Green	Green

The risk of mould formation, shown in **Table 4**, is categorized by colours:

_ Green – no mould growth risk, M < 1;

_ Yellow – minor mould growth risk, 1 ≤ M < 2;

_ Red – high mould growth risk, M ≥ 2

A moisture dry-out analysis and mould index calculations show that the risk of mould growth rises as the vapour resistance of the air and vapour control layer of the elements increases and as the thermal resistance and vapour permeability of the wind barrier layer decrease. Thermal resistance of the wind barrier layer has somewhat less impact on hygrothermal performance than water vapour resistance and its sensitivity to mould growth. Wooden-based wind barrier fibreboard with higher thermal resistance has a higher mould growth risk than MW wind barrier board with lower thermal resistance. The IMC of the original PCLP wall (w≤110 kg/m^3; u≤4.7%) is drying to the equilibrium level (w≤40 kg/m^3; u≤2.1%) over a quite long time. The built-in moisture dry-out can last for more than 3 years when the air and vapour control layer's 0.3 m<S_d<0.8 m (at RH>85%) and approximately 2 years with a mineral wool wind barrier layer and when the air and vapour control layer's S_d<0.3 m (at RH>85%). With the air and vapour control layer's higher value than S_d<0.8 m (at RH>85%), the hygrothermal performance and moisture dry out of studied hereinbefore structures are not completely assured, as lower water vapour permeability may cause in critical conditions accumulation of the water vapour or even condensate for a long period in the inner parts of structures insulated.

Discussion

The research aimed to identify material combinations and conditions that best meet the requirements for renovating high-rise buildings, considering potential hygrothermal risks. Previous studies (Colinart et al., 2019; Geving, 2017; Vinha, 2007) have shown that the optimal solution for renovating existing building envelopes involves the use of insulation with low water vapour resistance, for both the insulation and wind barrier layers. Additionally, a vapour control layer with varying vapour resistance capability is recommended. Solutions that have higher vapour resistance in the outer layer and lower thermal resistance (such as sheathing membrane, strand board, or gypsum board) compared to MW may lead to excessive humidity buildup, potentially increasing the risk of mould growth and envelope degradation.

High thermal resistance and water vapour permeability of the wind barrier layer, and materials' sensitivity to mould growth are crucial for an effective and moisture-safe building envelope. Research shows that the risk of mould growth increases with a higher vapour resistance in the outer layer of building elements (such as sheathing membrane vs. MW board) and thicker insulation (resulting in lower temperatures and higher relative humidity in the external layers). In some cases, cement fibreboard performed better than wood fibreboard as a wind barrier, despite having lower water vapour permeability and thermal resistance, due to its increased resistance (i.e. lower sensitivity) to mould. Therefore, fibre cement board and gypsum wind barrier board could also be suitable options, but their vapour permeability must be assessed carefully each time, as there might be similar but more vapour-tight alternatives available in the market.

In the process of the renovation of older buildings with prefabricated additional insulation elements, it is crucial to consider the negative implications of using a vapour barrier layer with higher vapour resistance, such as a PE foil. Research indicates that drying-out moisture can accumulate between the original wall and the vapour-tight layer of the insulation element, leading to persistent condensation for an extended period, even up to 4–5 years (Pihelo et al., 2016). Conversely, opting not to use a vapour control layer between the original wall and the installed insulation elements may result in mould growth issues and degradation, especially if the original wall's moisture content is close to saturation levels. For instance, during rainy periods in late summer or autumn, the external layer of the original wall may become very wet, reaching RH = 100% due to wind-driven rain. Additionally, if the water vapour resistance of an element's outer layer, such as a wind barrier, is too high, it may hinder the drying out of built-in moisture, impacting the overall hygrothermal performance of the system. Other authors have shown similar results(Mundt-Petersen, 2015).

Our findings indicate that preventing mould growth is possible, with MW board, wood fibreboard, or cement fibreboard being the recommended materials for wind protection. Regarding production, using a rigid wind barrier such as wood fibreboard or cement fibreboard is preferred due to faster installation processes. However, these wind barriers may not be suitable for facades with high moisture content. Therefore, it is advisable to incorporate a safety margin into the insulation element. The MW wind barrier board is the optimal choice due to its high thermal resistance and water vapour permeability.

When deep energy renovations are being done on high-rise buildings, it's important to consider not just fire safety and structural strength, but also the hygrothermal performance. This means considering how moisture moves through the building envelope. Adding prefabricated insulation elements on the outside can impact this by creating a barrier that can trap moisture, potentially leading to issues if levels become too high. To prevent this, it's recommended to use an air and vapour control layer with moderate and variable water vapour resistance. This approach has proven effective for 3-storey buildings (Bumanis & Pugovics, 2019; Pihelo & Kalamees, 2023) and 5-storey buildings as well (Pihelo et al., 2020).

Conclusions

The analyses found that external walls with the ventilated facade solution containing a wind barrier layer with low thermal resistance and water vapour permeability are more prone to mould growth. The results highlight that, in terms of the hygrothermal performance of the solutions studied, the most effective solution is a wind barrier with high thermal resistance and vapour permeability, and materials with medium or low sensitivity to mould growth. The increased water vapour permeability of the wind barrier and the air and vapour control layer helps to efficiently dry out moisture from the insulated wall structures. Higher thermal resistance leads to higher temperatures between the wind barrier and the insulation, reducing relative humidity, and with that, also moisture-related risks. Variations in the hygrothermal properties of air and vapour control layers underscore the importance of adhering closely to planned solutions. Therefore, meticulous planning is necessary when designing the renovation of the building envelope of highly insulated high-rise structures in cold and humid climates, considering materials' hygrothermal characteristics to ensure proper moisture removal and prevent mould formation, and taking into consideration the critical moisture content of the original wall (w = 110 kg/m^3 for the PCLP walls at the height of the 9th storey, and w = 117 kg/m^3 at the height of the 16th storey).

Many older buildings suffer from low thermal efficiency and inadequate indoor climate. To address this issue, prefabricated insulation elements can be added after a comprehensive hygrothermal analysis, followed by a moisture safety protocol (ByggaF, 2013; Wallenten & Mjörnell, 2019) and integrated design (Rovers et al., 2018).

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