Impacts of multiple refurbishment strategies on hygrothermal behaviour of basement walls

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Abstract: The refurbishment of existing buildings to provide thermal performance comparable to new design standards can be achieved using multiple design strategies. Although high structural thermal resistance is usually considered to be of high importance, hygrothermal conditions must be taken into account. They can significantly prolong the life of the building and avoid biological growth inside the structure as well as the indoor environment. In this study, three structures from different decades are compared from the point of view of thermal insulation performance, structural drying and mould growth probability, which was assessed using the Finnish mould growth model. Special interest is given to structural details that are subjected to humid conditions and details characterised by a thermal bridge, where vapour condensation can occur. The numerical computation provides a risk assessment tool for the structural elements in terms of hygrothermal performance and structural health implications.

Keywords: refurbishment; heat and mass transfer; mould; basement wall; hygrothermal conditions

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1 Introduction

The moisture safety of building envelope structures is an important part of a well-functioning building. A common structure type that has been used in both residential and public buildings is the basement wall. Basement walls separate the indoor air from the surrounding soil. The conditions in the soil are usually moist and warm, which create favourable conditions for mould growth and other moisture-related degradation phenomena, such as wood rotting and the corrosion of reinforcement bars.

The current effort towards more energy-efficient buildings in Finland is represented by Decree 4/13 from the Finnish Ministry of Environment [1]. If an existing building is retrofitted at a scale that requires an official building permit or planning permission in the case of minor construction work, then the decree requires that the building's energy efficiency be improved, assuming this is technically and economically viable. There are given multiple strategies for implementing energy-efficiency measures, one of which is the reduction of the U-value of basement walls.

The mould issue becomes an actual topic in new designs as well as in renovations of existing buildings [2]. The highest proportion of moisture and mould damage occurs in those elements that are in contact with soil [3]. A study of moisture performance assessments from a large sample indicated that repair was required for an average of 56% of walls that were in contact with soil [4]. The efficient performance of a basement wall depends greatly on the drying ability of the structure [5]. The drying speed of concrete basement walls could be increased by using vapour open insulation. However, the hygrothermal conditions are greatly influenced by indoor temperature and the thicknesses of the external and internal thermal insulation [6].

Retrofitting the basement wall from the outside is typically a more laborious and expensive solution, or it may be impossible, because of the need for excavation and/or the presence of other buildings situated near to the original structure [7]. Retrofitting from the inside automatically creates a new finish on the inside surface, which is typically done in any case during the retrofitting of basements. Inside retrofitting, however, is not typically the preferred solution from the moisture behaviour point of view because it leaves the original load-bearing structure subjected to the cold side of the thermal insulation layer, lowering its temperature and increasing relative humidity and hence increasing the risks for moisture-related problems [8]. However, if a suitable indoor retrofitting technique is provided, the structure may be assured sufficient hygrothermal performance [9]. Also, the parts of the basement wall that are above the terrain surface experience different climatic conditions on the exterior surface than those parts that are below the surface. This further complicates the combined heat and moisture behaviour of basement wall retrofitting.

Therefore, the various basement wall retrofitting options have the potential to affect the building's energy consumption, the moisture safety of the structure and potentially the indoor air quality. Although the existing literature contains results from multiple studies, there is still a need for further research to create more concrete guidelines concerning the possibilities of internal insulation and the hygrothermal behaviour of basement walls in general. The overarching goal of this article is to better understand the coupled heat and moisture behaviour of the basement wall structures with different design choices and to give recommendations for moisture-safe retrofitting methods.

2 The analysed structures and retrofitting options

2.1 The original structures and monitored points

The present study analyses three types of basement wall configuration that were used from the late 1950s to the 1990s. The three structure types appeared in Finnish construction guidelines published in the years 1959, 1963 and 1990 and were selected based on different placements of the heat and moisture barrier layers. The structures are presented in Figure 1, along with the vertical positions of the monitoring points.

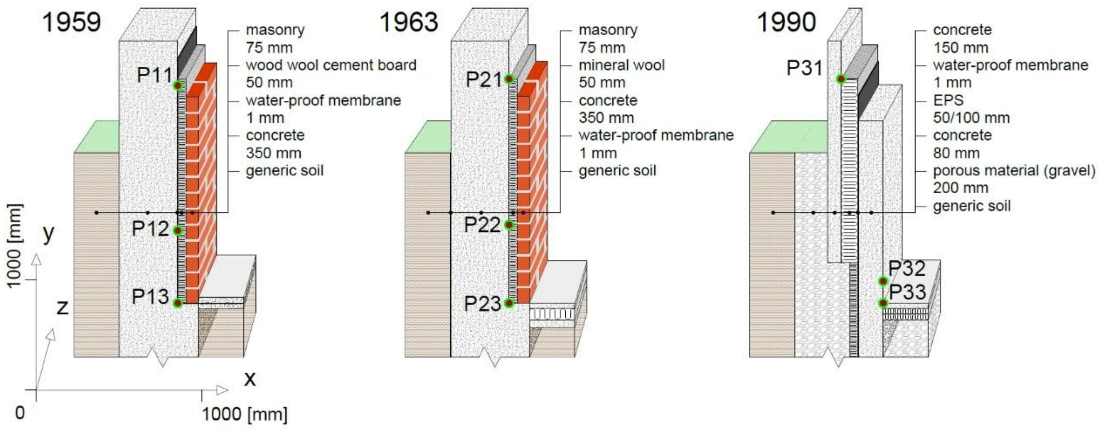

Figure 1: Original basement wall designs and the vertical position of monitoring points. The year (1959, 1963 and 1990) denotes the commonly utilized Finnish building guidelines which contained the structure type as an example.

The 1959 design of the basement wall structure had thermal and water-resistant materials installed on the interior side of the load bearing structure. The thermal insulation was typically made of 50 mm thick wood wool cement board, and it was covered by masonry from the inside. The indoor surface plasters were usually incomplete, or they were not applied at all. Therefore, the effect of interior plaster was not considered in the present study.

The 1963 design includes a moisture-proofing layer installed on the exterior side of the concrete structure. The thermal insulation was typically located between the concrete structure and the brick layer.

In the 1990 design, both the thermal and moisture insulation are placed on the exterior side of the concrete structure. In larger buildings, such as apartment buildings, the load-bearing structure was typically constructed from concrete sandwich panels. The exterior slab was extended approximately 1.2 m below the terrain, but did not touch the footing.

The first and highest vertical position of the monitoring points (P11; P21; P31) was selected to describe the above-soil conditions. The second point was placed in the middle of the wall section against the soil (P12; P22). In the 1990 design, the monitoring point was placed in the middle of the bottom part of the wall, where the exterior insulation thickness is less than that of the 1.2 m layer near the terrain surface (P32). The third monitoring point was placed at the bottom of the wall at the upper surface level of the floor slab (P13; P23; P33)

2.2 Retrofitting options

Several structural and repair alternatives were simulated for each of the structures. The study cases differ in terms of insulation material and the composition of the building elements. The reference cases consist of hygrothermal simulations of the original designs (Figure 1).

The external insulation is implemented with expanded polystyrene (EPS) and extruded polystyrene (XPS) boards. This represents a widely used method for the thermal improvement of new as well as existing buildings. A water vapour proof layer of bitumen was then placed between the exterior thermal insulation and the core structure of 1959 and 1963 designs. Condensed water between bitumen and the thermal insulation is allowed to drain from the structure through air channels. Two external elements were considered—the first leading from the footing of the basement wall up to the terrain level, and the second up to the top of the basement wall.

In the next, EPS and XPS boards were installed on the inner surface of the core structure. The exterior surface of the concrete basement wall was protected from ground moisture by the original water vapour proofing system. The inner insulation is continuous from floor to ceiling to promote the thermal efficiency of the basement. Alternate EPS thicknesses of 50 and 100 mm, and 100 mm for XPS, were considered.

Another thermal resistance improvement consisted of the original concrete core-structure and capillary-active calcium silicate (CaSi) board applied to the interior. The analyses were performed for two types of CaSi board. The first was CaSi-1, which is specified by water vapour diffusion coefficient μ=5.38 and water vapour absorption coefficient A_w=0.66 kg/(m^{2}s$^{0.5}$). The second is CaSi-2, which is specified by μ=3.85 and A_w=1.11 kg/(m^{2}s$^{0.5}$). Therefore, CaSi-2 enables easier moisture penetration because of diffusion and capillaries. Three thicknesses of board were considered: 50, 100 and 200 mm.

Besides the retrofit techniques described above, a commonly used internal insulation system is provided with capillary-active aerated concrete, which adds only a little diffusion resistance [10]. The present study applies 50 and 100 mm of aerated concrete to the inner surface of core basement walls in all of the analysed designs.

The alternatives considered in the hygrothermal simulation are summarised in Table 1 and graphically illustrated in Figure 2.

Structure	1959	1963	1990
original structure	x	x	x
exterior EPS 100 mm (up to terrain level)	x	x	
exterior EPS 100 mm (up to basement-wall top $^{+}$)	x	x	
exterior EPS 100 mm, excluding insulation indoor	x	x	

(up to terrain level)			
exterior EPS +100 mm, excluding insulation indoor (up to basement-wall top $^{+}$)	x	x	
interior EPS 50 mm	x	x	x
interior EPS 100mm	x	x	x
interior XPS 100mm		x	x
interior CaSi-1 board 50 mm	x	x	x
interior CaSi-1 board 100 mm	x	x	x
interior CaSi-1 board 200 mm	x	x	x
interior CaSi-2 board 50 mm	x	x	x
interior CaSi-2 board 100 mm	x	x	x
interior CaSi-2 board 200 mm	x	x	x
interior aerated concrete 50 mm	x	x	x
interior aerated concrete 100 mm	x	x	x
interior aerated concrete 200 mm			x

Table 1. Repair insulation techniques.

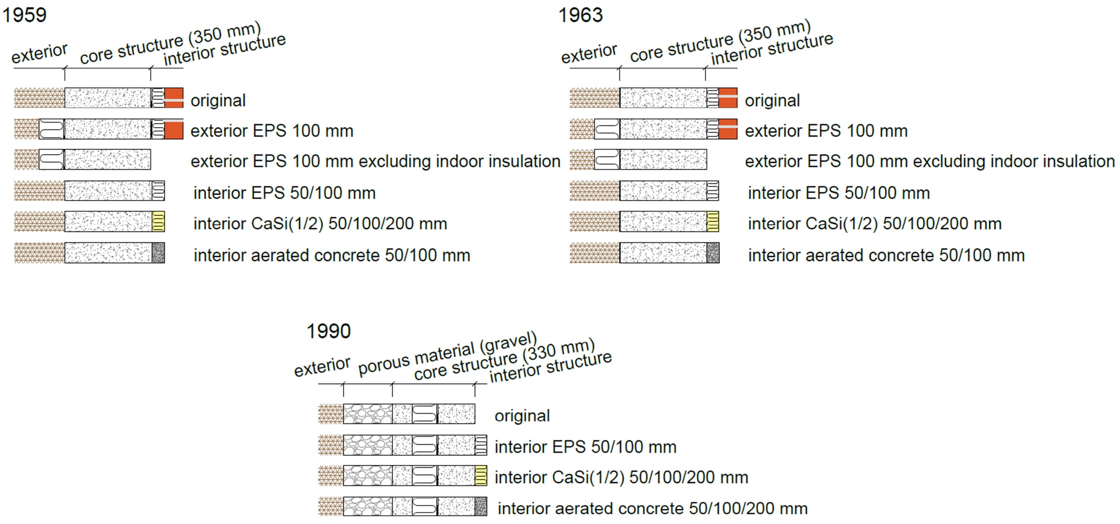

Figure 2: Retrofitting options considered in hygrothermal simulation.

3 Simulation tool and input data

3.1 Numerical simulation

Variations in the temperature and relative humidity at observed points in the structures were simulated from outdoor climate conditions using the numerical tool Delphin 5.8, which is designed for transient hygrothermal simulation of building components in one and two dimensional environment. The accuracy of the numerical modelling depends on the size and density of the elements represented by computational discretisation. The presented models apply elements of minimum size 0.5 mm, and denser mesh is focused on borders between different environments. However, the computation considerably slows down when moisture content achieves full saturation. The problematic area is usually the underground structure and soil, where humidity is mainly 100%. For this reason, the complex computational models require long computational times and often lead to unstable convergence. Therefore, each numerical model was separated into two phases. The first phase simulated temperature distribution throughout the entire geometry. The exterior boundary conditions were represented by Jokioinen 2004 weather conditions. The soil thickness was defined 3 m underneath the foundation footing, which is considered sufficient because it is significantly greater than the height of the basement walls. The basement walls were split into 9–10 sections of approximately 400 mm height, depending on the actual element distribution. The number of the sections allows similar temperature distribution along the boundary in all the analysed cases. The temperature development in time at the external basement wall surface was then stored in a batch-adjusted file. The second phase was modelled excluding the ground area, while the thermal boundary conditions were represented by the results from the first phase. The effect of moisture was defined as 100% in the boundaries that imitated a connection with the ground soil. Hence, each presented repair techniques was carried out by both phases 1 and 2, since the thermal resistance of the basement structure directly effects the ground temperature distribution. The height of the basement walls were modelled as 2.7 m with 300 mm of the wall above the ground surface. Therefore, 2.4 m of the basement wall height is in contact with the soil.

The initial humidity and temperature of the original components were defined as 97% and 7^0C. The humidity of the new components was defined as 80%.

The analysed cases assume the ground water level to be below the foundation baseline, as the gravel underneath the foundation enables only negligible capillary action. However, the effect of capillary action caused by ground water in contact with the footing of the basement wall structure was additionally analysed. The boundary condition was represented by a free water surface with constant pressure head of 0 m.

The following limitations have been identified and omitted from the simulations:

(1) Snow cover on the ground surface during winter.
(2) Freezing and thawing of the soil.
(3) Solar shading of the building itself and by its surroundings.
(4) Net movement of ground water below the building (rain and capillary transport in soil are taken into account).
(5) Dynamic values for surface transfer coefficients.

The simulation doesn't consider direct rain leakages or air convection in the analysed structures. In addition, the potential impacts to indoor air are not analysed. Therefore, it is assumed that if a mould-free situation is achieved on the interior side of the load-bearing structure, then the negative impacts from moisture-related risks are decreased substantially.

3.2 Materials

The Delphin's material database was compared to Finnish decree RIL 255-1-2014 and YM 2012 [11], based on which the concrete material properties were chosen. The material properties applied in the analysis are illustrated in Table 2 and include thermal conductivity (λ), specific heat capacity (C_p), porosity (θ_{por}), density (ρ), vapour diffusion resistance (μ), effective saturation (θ_{eff}), hygroscopic sorption at RH=80 % (θ_{80}) and water retention curve at p_C=1 atm (θ_l).

Material	λ [W/mK]	C_p [J/kgK]	θ_{por} [-]	ρ [kg/m^3]	μ [-]	θ_{eff} [m^3/m^3]	θ_{80} [m^3/m^3]	θ_l [m^3/m^3]
concrete	2.10	850	0.143	2320	110.0	0.143	0.058	0.143
wood wool cement board	0.06	1470	0.931	180	4.9	0.340	0.026	0.330
masonry	0.52	934	0.367	1677	13.3	0.344	0.005	0.343

gravel	2.10	1050	0.240	2650	7.0	0.150	0.064	0.150
EPS	0.04	1500	0.935	35	50.0	0.935	6×10^{-4}	0.935
XPS	0.03	1500	0.951	40	150.0	0.950	6×10^{-5}	0.950
CaSi-1	0.08	1064	0.887	277	5.4	0.848	0.013	0.835
CaSi-2	0.07	1158	0.910	270	3.8	0.900	0.005	0.898

Table 2. Material applied in the presented numerical approach.

3.3 Boundary conditions

The analyses were performed for a period of five years, where the first four years represent the time needed to achieve hygrothermal stability after refurbishment for further mould growth risk evaluation. Although the part of a basement wall that is covered by soil is protected from the impact of precipitation, the climate must be considered as a critical parameter. The external conditions are represented by the Jokioinen 2004 test year, which represents critical annual data for Finnish design [12]. The data is suitable for conditions where the warming and drying effects of the structure are minimal. However, the Jokioinen 2004 test year data includes temperature, humidity, wind-driven rain and short and long wave radiation. The temperature and relative humidity of the test year are illustrated in Figure 3.

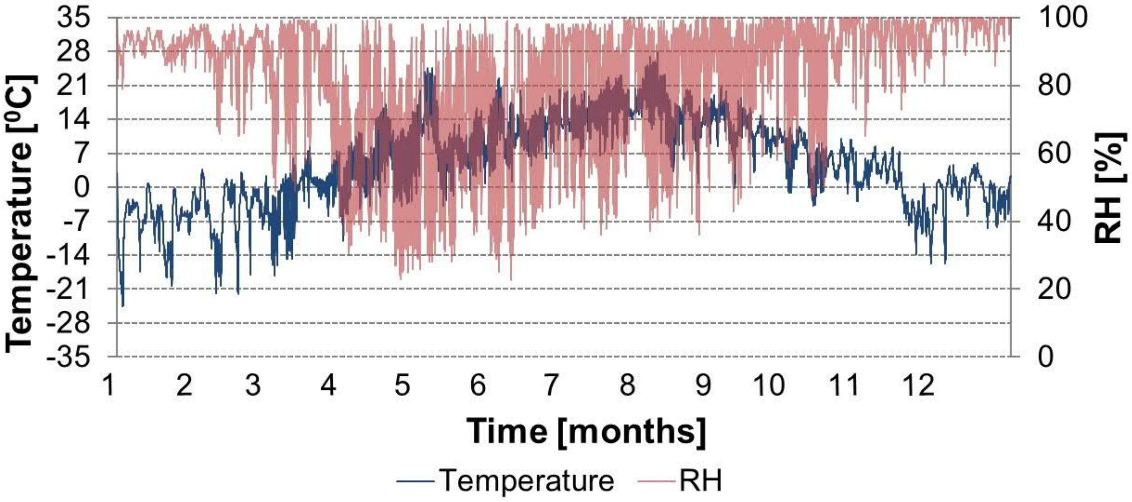

Figure 3: Exterior temperature and relative humidity.

The indoor boundary conditions are formed according to Finnish decree RIL 107-2012 [13] from outdoor conditions according to the service use of the structure. They are categorised by three individual levels of additional mass concentration of water vapour (v) in the indoor air. The presented research considers level 2 indoor environments, as the basements are assumed to be semi- or fully heated indoor environments. The indoor temperature is considered constant $\theta=21^0$C, and the additional constant mass concentration of water vapour is defined as $\Delta v=5$ g/m^3 for $\theta<5$°C and $\Delta v=2$ g/m^3 for $\theta>15$°C, which are linearly connected when $5<\theta<15$ °C.

3.4 *Interpretation of the results*

Biological growth is highly dependent on temperature, humidity, environmental sensitivity and exposure time. The Finnish mould growth model is a mathematical expression based on extensive laboratory tests and on-site measurements, including the determination of conditions suitable for mould growth, material sensitivity and quantifying the risks of mould growth [14].

The definition of the favourable conditions for mould growth initiation is represented by minimal and maximal values of temperature and relative humidity according to Equation (1). The relative humidity (RH) level separating favourable and unfavourable conditions for mould growth is defined by RH_{crit}. The graphical expression is illustrated in Figure 4.

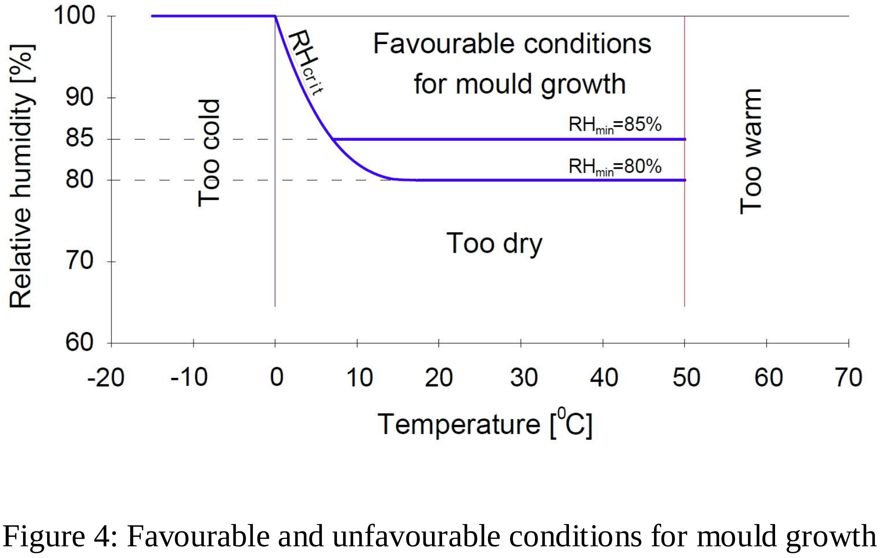

Figure 4: Favourable and unfavourable conditions for mould growth initiation.

$$RH_{crit} = \begin{cases} -0.00267T^3 + 0.160T^2 - 3.13T + 100.0, \quad when \ \ 0 \leq T \leq 20 \\ RH_{min}\%, \quad when \ \ 50 \geq T > 20 \\ no\ growth\ is\ assumed\ when\ T < 0 \text{ and } T > 50 \end{cases} \tag{1}$$

where T is the temperature in °C and the minimum relative humidity RH_{min} represents a level at which mould growth initiates according to material sensitivity. Material sensitivity plays a significant role in creating a suitable environment for the hygrothermal conditions that allow biological growth [1]. The Finnish mould growth model defines four material sensitivity classes: very sensitive (class 1), sensitive (class 2), medium resistant (class 3) and resistant (class 4). RH_{min} is defined as 80% for classes 1 and 2 and 85% for classes 3 and 4. Mould growth intensity is classified by seven levels of growth, starting from no growth (M=0) and microscopic mould species present (M=1) and ending with full visual mould coverage on the building material surface (M=6). Mould growth intensity M is expressed by Equation (2):

$$\frac{dM_{index}}{dt} = \frac{1}{24\exp(-0.68lnT - 13.9lnRH + 0.14W - 0.33SQ + 66.02)} k_1 k_2 \tag{2}$$

where t is time, k_1 and k_2 are mould-growth intensity factors for materials with different sensitivities to mould growth initiation, W is timber species and SQ is surface quality. Mould growth increases as the period over which conditions are favourable for mould growth increases. However, if the conditions change into unfavourable conditions, then growth degrades, and the potential for further mould growth decreases. The effect of the dynamic properties of mould growth intensity is expressed by Equation (3):

$$\frac{dM_{index}}{dt} = \begin{cases} -0.032, when\ t - t_1 \leq 6h \\ 0, when\ 6h \leq t - t_1 \leq 24h \\ -0.016, when\ t - t_1 > 24h \end{cases} \tag{3}$$

The wall structure is considered to function well if the M-values are less than 1. In this case, the risk of mould growth is small, and hygrothermal conditions do not affect the functionality of the structure nor pose a critical risk for health deterioration.

4 Results and discussion

4.1 1959 basement wall design

The overall mould index values (M-values) obtained from the hygrothermal analysis of the 1959 design are summarised in Table 3, which considers different repair approaches, with $^+$ denoting insulation systems applied up to the top of the basement.

Structure	Material at interface	Material sensitivity	Analysed point		
			P11	P12	P13
original design	bitumen+raw wood wool	2	5.28	0.26	0.00
exterior EPS 100mm	bitumen+raw wood wool	2	5.28	0.00	0.00
exterior EPS$^+$ 100mm	bitumen+raw wood wool	2	0.00	0.00	0.00
exterior EPS 100mm, no ins. indoor	concrete+indoor air	3	0.01	0.00	0.01
exterior EPS$^+$ 100mm, no ins. indoor	concrete+indoor air	3	0.00	0.00	0.01
interior EPS 50mm	concrete+EPS	3	2.24	2.77	3.41
interior EPS 100mm	concrete+EPS	3	1.99	2.97	3.41
interior CaSi-1 board 50mm	concrete+CaSi-1 board	3	0.30	0.00	2.82
interior CaSi-1 board 100mm	concrete+CaSi-1 board	3	0.65	0.05	2.95
interior CaSi-1 board 200mm	concrete+CaSi-1 board	3	1.22	0.95	3.00
interior CaSi-2 board 50mm	concrete+CaSi-2 board	3	0.00	0.00	0.31
interior CaSi-2 board 100mm	concrete+CaSi-2 board	3	0.00	0.00	1.55
interior CaSi-2 board 200mm	concrete+CaSi-2 board	3	0.00	0.00	2.42
interior aerated concrete 50 mm	concrete+aerated concrete	2/3	0.99	0.00	3.36
interior aerated concrete 100 mm	concrete+aerated concrete	2/3	1.60	0.13	3.45

Table 3. Mould index M-value obtained and material sensitivity considered in observed locations of 1959 basement wall design.

The original structure of the 1959 design shows a rapid increase in M-value at point P11, which is located above the terrain (Figure 5). This is caused by high relative humidity, which is above 90% for significant period of time. However, the *M*-values below the terrain remain low.

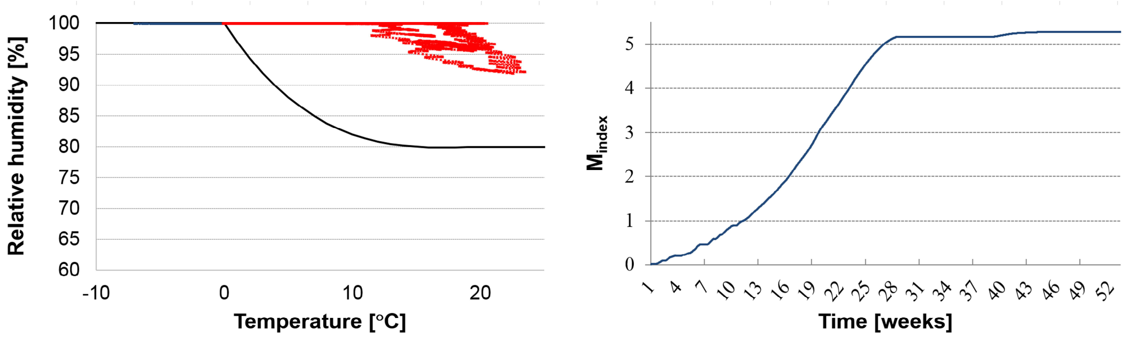

Figure 5: Graphical illustration of hygrothermal conditions (red dots indicate period of 1 hour when structure is exposed to conditions promoting mould growth initiation, while blue dots denote conditions unfavourable for mould growth) for mould growth and the mould index M development at point P11 of original structure.

Because of the thermal insulation on the interior surface of the waterproof membrane, moisture from the ground has no direct access to the insulation. Therefore, the only source of moisture entering the thermal insulation is moisture diffusion from the indoor air. However, because the load-bearing structure is exposed to ground moisture, the calcium oxide and salts may cause structural differences in the material texture, leading to unexpected water leakage in the lower parts of the basement wall. It can be assumed that the humidity below the terrain is higher than the simulation case. Hence, higher and fluctuating temperatures may cause favourable conditions for mould growth over a long period without any unfortunate accidents.

In the case where the external EPS insulation covers the structure up to the top of the basement wall, the *M*-value has negligible values at all observed points P11, P12 and P13, which indicates a small risk of biological processes. However, the results differ significantly if the original elements on the inner side are considered or left out and the external EPS insulation is only installed up to the terrain surface. When the original interior insulation is removed from the structure, the hygrothermal analyses indicate mould-free conditions on the interior concrete surface. It must be noted that rising moisture from the foundation is prohibited from drying by two thick layers of insulation on each of the concrete surfaces. If the original interior structure is left in place, the higher risk of mould growth is indicated at the top point P11.

If retrofitting is provided by installing EPS or XPS boards on the inner side of the basement wall, the concrete structure is freely open to ground water. This causes significant vapour diffusion through the concrete layer towards the indoor environment, leading to a high moisture build-up between the concrete and the EPS layer. At the lower positions (points P12 and P13), humidity increases with the thickness of the thermal insulation. Nevertheless, in both analysed cases, the *M*-value is quite high at all the observed points. The water vapour resistance factor of EPS is too high to allow moisture to dry out from the concrete; therefore, there is constant high humidity between the concrete structure and the EPS insulation, which causes potential mould growth risk. It is assumed that because the water vapour resistances of XPS and polyurethane are larger than that of the EPS, neither is a suitable solution for this case, as the humidity trapped inside the structure could increase.

CaSi-1 causes a smoother variation between extremes of RH during the analysed period together with increasing the insulation thickness. CaSi-2 follows the indoor environment's relative humidity regardless of the insulation thickness, which is a reflection of the defined water vapour diffusion and absorption coefficients. The results summarised in Table 3 indicate that by increasing the CaSi-1 thickness, the *M*-value increases. The risk of biological growth is assumed, particularly at point P13 located at the footing of the basement wall. At the upper locations (points P11 and P12), the *M*-value is within permissible limits up to a CaSi-1 thickness of 100 mm. Applying 50 mm of CaSi-2 board allows the structure to dry, and it remains dry at all observed points.

Applying aerated concrete to the indoor surface causes excessive humidity inside the basement wall footing. Increasing the thickness of the aerated concrete layer increases vapour diffusion and leads to a high moisture level inside the structure. This was particularly visible inside structures that were subjected to outdoor air, where the temperature differences are significant. Below the terrain, the humidity inside the structure is kept low because of liquid conduction and vapour diffusion followed by various driving forces. The highest humidity level is observed at the footing of the basement wall. The temperature differences between outside and inside conditions are smaller, and, therefore, the forces driving liquid transport indoors reduce the drying speed.

4.2 1963 basement wall design

The *M*-values from the 1963 basement wall design hygrothermal analysis are summarised in Table 4.

Structure	Material at interface	Material sensitivity	Analysed point		
			P21	P22	P23
original structure	concrete+mineral wool	3	1.93	1.58	3.40
exterior EPS 100mm	concrete+mineral wool	3	1.98	0.03	2.96
exterior EPS$^+$ 100mm	concrete+mineral wool	3	0.00	0.00	2.90
exterior EPS 100mm, no ins. indoor	concrete+indoor air	3	0.27	2.20	3.25
exterior EPS$^+$ 100mm, no ins. indoor	concrete+indoor air	3	0.00	0.00	0.01
interior EPS 50mm	concrete+EPS	3	1.96	2.22	3.39
interior EPS 100mm	concrete+EPS	3	1.78	1.80	3.00
interior EPS 50mm,80%RH	concrete+EPS	3	4.52	0.00	3.39
interior EPS 100mm, 80%RH	concrete+EPS	3	1.46	1.42	3.37
interior XPS 100mm, 80%RH	concrete+XPS	3	1.35	1.87	3.35
interior CaSi-1 board 50mm	concrete+CaSi-1 board	3	0.23	0.00	2.71
interior CaSi-1 board 100mm	concrete+CaSi-1 board	3	0.37	0.00	2.85
interior CaSi-1 board 200mm	concrete+CaSi-1 board	3	0.78	0.38	2.94
interior CaSi-2 board 50mm	concrete+CaSi-2 board	3	0.00	0.00	0.30
interior CaSi-2 board 100mm	concrete+CaSi-2 board	3	0.00	0.00	1.15
interior CaSi-2 board 200mm	concrete+CaSi-2 board	3	0.00	0.00	2.34

interior aerated concrete 50 mm	concrete+aerated concrete	2/3	0.58	0.00	3.37
interior aerated concrete 100 mm	concrete+aerated concrete	2/3	1.09	0.00	3.45

Table 4. Mould index M-value obtained and material sensitivity considered in observed locations of 1963 basement wall design.

The original 1963 design is assumed to have unsuitable hygrothermal performance, as the *M*-value exceeds 1 in all the observed points. This is because the thermal is installed directly onto the concrete elements. Hence, humidity trapped inside the concrete elements cannot freely dry towards the indoor environment, and excessive humidity in the interface may lead to the risk of biological growth.

Applying EPS board from the outside to cover below the terrain structures leads to significant *M*-values at points P21 and P23. However, high *M*-values are also measured at the point located in the sill of the basement wall (P23), which is located in the area where external insulation runs along the entire height of the basement wall. This is caused by a build-up of moisture through the foundation. If the external insulation covers the entire basement wall surface and the indoor surface is opened to the environment, then the *M*-value is small. Hence, in the case of repair by the implementation of external structural elements, the removal of inner elements is recommended, or they should be replaced by breathable materials that allow moisture mass transfer from the core wall. Note that exterior installation requires façade changes that must be included in the hygrothermal simulation according to the actual heritage of the building.

The results in Table 4 also illustrate that the *M*-value exceeds 1 at all observed points when both 50 and 100 mm of EPS insulation is installed on the interior side of the concrete core structure. This is caused by humid initial conditions, which were considered as 97% inside the concrete, as the EPS insulator inhibits the drying process. Hence, the water content remains high throughout the simulation period. Small humidity changes are mainly caused by temperature oscillation. To control the effect of the initial conditions, the simulation was performed for the initial humidity of the concrete to 80% *RH*. In this case, the repair would require an active drying process of the core structure before installation of the inner insulation. The initial humidity can significantly affect the long-term conditions inside the structure. In fact, the humidity rises rapidly from the beginning and achieves 97% of RH at all the analysed points by the end of the analysed period. The *M*-values presented in Table 4 show that inserting the inner EPS board causes favourable conditions for the biological process represented by mould growth. Similar results were obtained in the case where the inner insulation was represented by 100 mm of XPS. The XPS is less moisture permeable than the EPS, and, therefore, the humidity between the XPS and the core structure is associated mostly with humidity transferred from the outdoor conditions.

Similarly, if rising moisture from the ground appears, the inner calcium silicate insulation prevents the structure from drying, which leads to unsuitable conditions. Table 4 indicates that the *M*-values achieved at points P21 and P22 are within the allowed limits. However, at the low-positioned point P23, the value of *M* exceeds the limit significantly, particularly in the case of CaSi-1, which is characterised by lower water vapour permeability. CaSi-2 enables easier water vapour penetration, and the structure is therefore able to dry inward. The results indicate that applying 50 mm of permeable CaSi board could be an option for the repair of basement walls made to the 1963 design. If thicker insulation board is needed, a certain adaptation would be required, such as installing a capillary barrier between the basement wall and the foundation.

The retrofitting of the 1963 design provided by applying indoor aerated concrete leads to similar results as the 1959 design. The difference consists of the water vapour barrier protecting the outdoor basement wall. This causes slightly lower humidity on the inner core wall surface, as the structure enables drying inwards. However, the aerated concrete is more vapour resistant than CaSi board, thus causing higher humidity levels inside the structure. Therefore, increasing the aerated concrete thickness leads to greater observed humidity inside the basement wall.

4.3 1990 basement wall design

The *M*-values obtained from the hygrothermal simulation of the 1990 design, including retrofitting techniques, are summarised in Table 5.

Structure	Material at interface	Material sensitivity	Analysed point		
			P31	P32	P33
original structure, ext. concrete	concrete+bitumen	4	0.00	0.00	0.45

original structure, int. concrete	concrete+indoor air	3	0.00	0.00	0.00
interior EPS 50mm 97%	concrete+EPS	3	0.05	0.00	0.83
interior EPS 100mm 97%	concrete+EPS	3	1.38	1.14	2.03
interior EPS 50mm 80%	concrete+EPS	3	0.00	0.00	0.60
interior EPS 100mm 80%	concrete+EPS	3	0.01	0.00	1.52
interior EPS 200mm 80%	concrete+EPS	3	0.03	0.00	2.41
interior XPS 100mm 80%	concrete+XPS	3	0.00	0.00	1.94
interior CaSi-1 board 50mm	concrete+CaSi-1 board	3	0.00	0.00	0.00
interior CaSi-1 board 100mm	concrete+CaSi-1 board	3	0.00	0.00	0.00
interior CaSi-1 board 200mm	concrete+CaSi-1 board	3	0.08	0.00	0.34
interior CaSi-2 board 50mm	concrete+CaSi-2 board	3	0.00	0.00	0.00
interior CaSi-2 board 100mm	concrete+CaSi-2 board	3	0.00	0.00	0.00
interior CaSi-2 board 200mm	concrete+CaSi-2 board	3	0.00	0.00	0.00
interior aerated concrete 50 mm	concrete+aerated concrete	2/3	0.00	0.00	0.02
interior aerated concrete 100 mm	concrete+aerated concrete	2/3	0.00	0.00	0.19
interior aerated concrete 200 mm	concrete+aerated concrete	2/3	0.07	0.00	1.51

Table 5. Mould index M-value obtained and material sensitivity considered in observed locations of 1990 basement wall design.

The original design is subjected to the hygrothermal analysis, with the initial relative humidity of the concrete elements assumed to be 97%. During the five year period, the humidity at upper P31 and middle point P32 decreases to less than 80%. As the drying process has a tendency to continuously decrease, further drying is assumed, hence causing unfavourable conditions for mould growth. The moisture rises due to the capillary effect at the bottom of the basement wall. Therefore, the humidity is kept below RH_{crit} throughout the basement wall, except for the basement wall–floor junction. At point P33, the RH achieves approximately 92%. However, the *M*-values obtained are within the permissible limits at all observed points in both outer and inner concrete surfaces.

Because the previous analysis indicates a decreasing tendency of moisture inside the concrete elements, the initial humidity of concrete for further calculation is defined as 80%. Then, in the case of the inner 50 mm EPS, the RH at points P31 and P32 remains stable over the five-year period and oscillates slightly under 80%. As the thickness of the EPS increases so too does the humidity caused by diffusion resistance. In which case, using 100 mm EPS leads to higher RH inside the structure, and at the sill of the basement wall, the *M*-value exceeds the critical limit. Therefore, it is considered that applying EPS board up to 50 mm is a suitable option for improving the thermal resistance of the basement wall without causing structural health issues.

The same case was tested considering an initial relative humidity of the concrete of 97%. The 50 mm EPS board does not achieve noticeable *M*-values at any of the observed points. Since 100 mm EPS board is applied, high humidity inside the structure leads to the favourable conditions for mould growth. Therefore, EPS of up to 50 mm allows suitable permeability of the structure and leads to a significant decrease in humidity inside the basement wall. If 100 mm of XPS is installed instead, the upper part of the basement wall remains under the critical humidity limit, but the point P33 at the sill achieves an *M*-value of over 1. As the XPS is more vapour diffusion resistant than the EPS, it is not recommended for such refurbishment.

Calcium silicate insulation could be a suitable solution for the thermal improvement of the 1990 basement wall design. The *M*-values are almost zero at all observed points. The exception is 200 mm CaSi-1 insulation at the sill of the basement wall (P33), where M=0.34 was obtained. If the initial conditions of the hygrothermal simulation assume high humidity inside the structure, the CaSi-1 causes slower drying compared to CaSi-2. Nevertheless, the continuously decreasing humidity at the observed points shows sufficient efficiency, and the application of calcium silicate insulation boards is suitable.

Retrofitting via the application of indoor aerated concrete does not indicate major risks for mould growth. Three thicknesses of insulation were tested, and only point P33 at the basement wall footing exceeded the critical *M*-value. This was caused by a 200 mm thick insulation layer, which provides significant vapour diffusion resistance, thereby disabling the drying mechanism of the structure.

4.4 Discussion

Thermal transmittances U [W/m^{2}K] calculated for refurbishment with 100 mm thick thermal insulation systems are summarised in Table 6, where ‘-’ indicates the U-value for the basement wall below the surface of the ground and ‘+’ above.

Structure	1959		1963		1990	
	-	+	-	+	-	+
original structure	0.57	0.87	0.51	0.74	0.36	0.51
exterior EPS 100mm, no ins. indoor	0.24	0.33	0.23	0.32		
exterior EPS$^+$ 100mm, no ins. indoor	0.31	0.49	0.31	0.49		
interior EPS 100mm	0.31	0.38	0.31	0.38	0.19	0.23
interior CaSi-1 board 100 mm	0.41	0.55	0.41	0.55	0.24	0.29
interior aerated concrete 100 mm	0.50	0.73	0.50	0.73	0.27	0.34

Table 6. Thermal transmittance of analysed basement walls.

The presented retrofitting techniques that include ≥100 mm of thermally isolative material improve the structural thermal resistance of the original design (Table 6). However, thick elements prevent water vapour diffusion, which leads to redundant humidity inside the structure. The trapped humidity may cause favourable conditions for mould growth, further damage the structure and an unsuitable indoor environment.

To facilitate comparison, the hygrothermal performance of the different refurbishment techniques of the basement wall structural systems were presented under the same boundary conditions. It should be noted that the presented study assumes that the basement is a heated living space. Hence, the indoor conditions are assumed to be of low humidity. The hygrothermal performance of the refurbishment would be significantly affected if the indoor environment was described by high humidity. For this case, a higher water vapour resistant insulation may be more suitable, as it prevents indoor humidity from entering the structure. However, if the moisture inside the structure is caused by the capillary effect, then the inner insulation prevents evaporation, and the structure becomes humid more rapidly. For example, the performed simulation shows the unsuitability of applying water vapour resistant thermal insulation on the inner surface of the basement core structure represented by the 1963 design type. Although, the structure is protected from the exterior by a water vapour barrier, the moisture can penetrate the structure through the upper wall surface or foundation capillary effect. The inner insulation prevents the basement wall from drying inwards. Hence, the risk of mould and microbial damage is high.

With the exterior insulation system, the concrete core structure becomes warmer and drier, and the structure has potential to dry inwards. The importance of exterior insulation system consists in insulating the entire height of the basement wall. In the case where the insulation only covers the wall up to the terrain, the temperature difference between wall surfaces increases leading to water condensation and therefore high moisture levels inside the structure. Although, the exterior insulation system provides the most sustainable solution, the heritage of the building cannot be changed in many cases. Therefore, the indoor insulation retrofit is the only solution for providing a more energy-efficient building.

The indoor insulation systems causes lower temperature and higher moisture levels inside the core structure during the cold seasons. The risk of damage increases deep inside the structure, as the freezing point may affect the microstructure of the concrete elements. The polyurethane insulation systems have comparable thermal resistance to the calcium silicate systems. However, the capillary-active calcium silicate has a higher drying potential and hence keeps the humidity inside the structure low.

Special attention should be given to the footing of the basement wall, where a high humidity level is expected, and, by applying indoor insulation system, the drying potential is lower. The structure should be protected from accidental leakage from the ground and foundation via the capillary effect into the building components. Also, additional indoor cladding may inhibit the drying potential of the basement wall causing excessive humidity inside the structure and favourable conditions for biological growth. It is highly recommended that the retrofit options of a basement wall are considered in advance, as insufficient refurbishment may lead to unfavourable hygrothermal conditions and the risk of damp and damage to the structure in early years.

In the following section, a number of cases that consider the contact of ground water with the structure are presented. The goal was to evaluate the capillary effect on the hygrothermal performance of the basement walls and the importance of a capillary barrier underneath the foundation structure. The following table (Table 7) summarises the *M*-values obtained.

Design	Structure	Material sensitivity	Mould index M (with water contact)		
			P_1	P_2	P_3
1959	original design	2	5.28 (5.28)	0.44 (0.26)	0.00 (0.00)
	exterior EPS$^+$ 100mm	2	0.07 (0.00)	0.10 (0.00)	5.30 (0.00)
	interior EPS 50mm	3	2.02 (2.24)	3.16 (2.77)	3.43 (3.41)
1963	exterior EPS$^+$ 100mm, no ins. indoor	3	0.00 (0.00)	3.38 (0.00)	3.42 (0.01)
	interior EPS 100mm, 80%RH	3	1.97 (1.46)	2.97 (1.42)	3.30 (3.37)
1990	interior EPS 50mm 80%	3	0.01 (0.00)	3.24 (0.00)	3.42 (0.60)
	interior CaSi-1 board 200mm	3	0.01 (0.08)	0.01 (0.00)	2.93 (0.34)
	interior CaSi-1 board 50mm	3	0.01 (0.00)	0.01 (0.00)	2.93 (0.00)
	interior CaSi-1 board 100mm	3	0.00 (0.00)	0.01 (0.00)	2.91 (0.00)

Table 7. Mould index M-value obtained and material sensitivity in observed locations, where capillary action caused by water contact was considered (subscripts display M-values for calculation without water contact).

It can be seen that capillary action does not affect structures that are opened to the indoor area, where excessive humidity is able to dry inwards. However, if exterior thermal insulation EPS is applied, the diffusion process significantly decreases. Therefore, capillary action causes excessive humidity near the basement floor. The EPS thermal insulation installed on the interior basement wall surface does not significantly change the final evaluation, although the humidity at the lower positioned points (2 and 3) is slightly higher. The 1990 basement wall is more sensitive to the additional indoor insulation layer. The indoor 50 mm EPS already causes capillary action up to the second point located about 1 m above the basement floor, where a significantly higher *M*-value is obtained. This is explained by the air-tight structure, which disables the drying of the core basement wall structure. An improvement can be achieved by installing calcium silicate insulation to provide sufficient breathability. This enables the excessive humidity caused by capillary action to dry out. However, the width of the insulation does not play a major role in the lower positions, as the obtained risk of mould growth is similar for 20-, 50- and 100-mm wide calcium silicate thermal insulation.

5 Conclusions

The presented study analyses the hygrothermal conditions inside three common basement walls built between the late 1950s and the 1990s and considers several common retrofitting techniques. The obtained results confirm previous research that the thermal insulation of basement walls is the most robust solution; however, in many cases this is not permitted, as the heritage of the building is protected. Therefore, the study considers internal insulation cases that use various commonly used building materials. The study also illustrates method for hygrothermal simulation of fully saturated underground structure and soil in suitable computational time and stable convergence.

The obtained results suggest that more suitable refurbishment is provided by permeable indoor insulation systems. Applying inner insulation creates a colder and more humid structure, and hence the drying forces tend to be indoors. Therefore, if the inner insulation does not provide sufficient permeability, the inside structural elements become moist. The critical point is the sill of basement wall, in which water vapour diffusion from the ground is combined with capillary action from below. Thus, it is important to implement capillary resistant layers below the basement wall and provide sufficient permeability to enable the drying of the structure inwards. Using capillary-active materials to enable inward drying is a suitable and efficient solution for retrofitting. However, only a limited depth of indoor insulation will provide adequate permeability, as vapour diffusion resistance increases with building material thickness.

The refurbishment of basement walls should be analysed in detail and evaluated to clarify the goals and optimise the results. Although the main aim is usually energy efficiency, the hygrothermal performance of the structure must be taken into account, as it significantly effects the long-term behaviour and sustainability of the entire building.

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