

Hygrothermal Durability of High-Performance Concrete and Foamed Concrete Wall Systems: A Comparative Interstitial Condensation Study

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Abstract

Understanding the hygrothermal durability of insulated wall systems is essential for maintaining long-term thermal performance and preventing moisture-related deterioration. Although advanced wall assemblies have been widely developed to improve energy efficiency, their resistance to interstitial condensation remains insufficiently investigated. This study numerically evaluates the moisture transport behaviour of different wall configurations. Relative humidity distributions and water vapour fluxes were analyzed to quantify moisture migration and condensation within the wall assemblies. The results show that the FC-EPSR configuration exhibits the best hygrothermal performance, with the lowest vapour ingress ($2.8 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$), the lowest condensation ($1.0 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$), and the smallest condensation fraction (35.7%). In contrast, the HPC-Cork wall shows the highest vapour ingress and condensation, reaching a condensation fraction of 88.2%, indicating severe localized moisture accumulation despite its favorable thermal characteristics. These findings demonstrate that optimizing thermal insulation alone is insufficient for ensuring long-term durability, emphasizing the importance of integrating hygrothermal moisture transport analysis into the design of sustainable building envelopes.

1. Introduction

Improving building envelope energy efficiency is essential for reducing heat losses and operational energy consumption [1]. Consequently, wall systems are commonly evaluated using thermal indicators such as the U-value, internal surface temperature (T_{si}), and surface temperature factor (fR_{si}), which are effective for assessing thermal insulation performance and the risk of surface condensation [2-4]. However, they do not account for vapour diffusion and interstitial condensation, which affect long-term durability.

Water vapour permeability and diffusion resistance are key parameters governing the hygrothermal behaviour of building materials and are widely employed to assess the performance of insulation materials [5,6]. Recent studies have primarily focused on improving the thermal and energy performance of wall systems through advanced technologies and climate-adaptive configurations [7], while research on building renovation has mainly evaluated wall alternatives based on thermal, structural, and architectural criteria [3]. Although integrated studies have begun to consider thermal and environmental aspects of multilayer retrofit walls [2], increasing attention has also been given to moisture transfer in retrofit systems, particularly because modifications to insulation layers can alter vapour transport paths and condensation behaviour [8–10].

Nevertheless, direct comparisons of the moisture durability of different energy-efficient multilayer wall configurations for the same renovation application remain limited, particularly under consistent conditions for vapour transport and interstitial condensation risk. To address this gap, this study compares the hygrothermal durability of six previously developed and thermally evaluated retrofit wall systems using steady-state two-dimensional vapour diffusion and interstitial condensation analyses, based on relative humidity, vapour flux, vapour ingress, and condensation.

2. Materials and Methods

The six wall configurations were adopted from a previous work [3], where their thermal, environmental, and structural performance were evaluated. The investigated assemblies include the reference solid brick wall (Ref-SLCR), perforated brick with Expanded Polystyrene (PPB-EPS), hollow brick filled with perlite concrete and aerogel fibrous composite (BP-AFC), Brick filled with perlite, and EPS insulation (BP-EPS), high-performance concrete with cork insulation (HPC-Cork), and foamed concrete with recycled EPS (FC-EPSR). Their detailed geometries and material properties are reported in Ref. [3]. The Conceptual framework is presented in Figure 1.

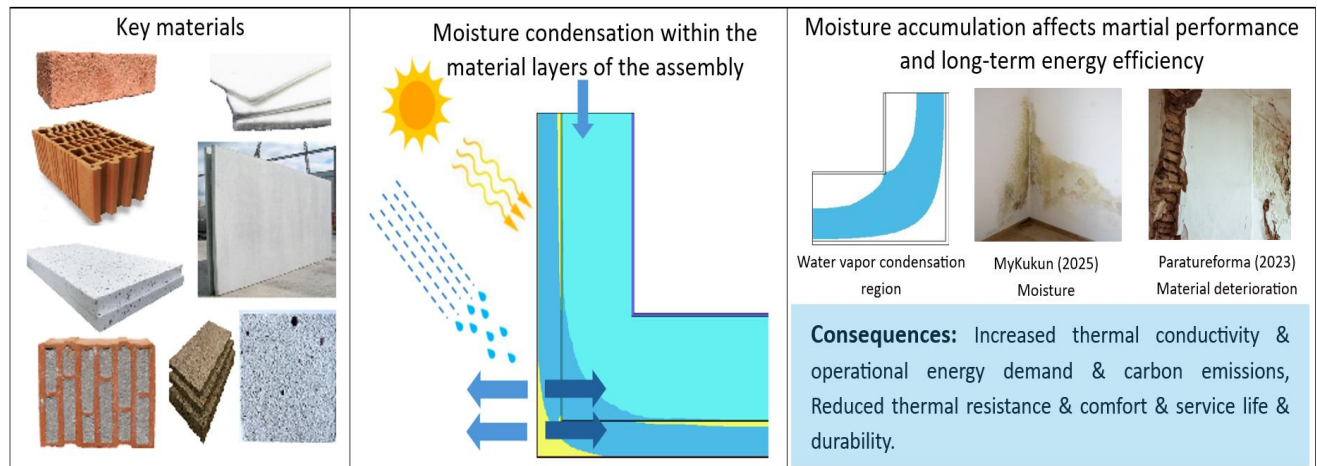


Figure 1. Conceptual framework linking wall materials, hygrothermal durability, and long-term energy performance

The hygrothermal behaviour was evaluated using the finite-element software Area, which performs two-dimensional steady-state heat conduction and water-vapour diffusion calculations according to EN-ISO-10211 and EN-ISO-13788. Heat transport is governed by the steady-state heat-conduction equation, while vapour transport is described by an analogous diffusion equation using the water-vapour diffusion coefficient. Boundary conditions account for temperature and water-vapour conditions at the wall surfaces. The governing equations were solved using the Galerkin finite-element method with triangular elements. The simulations generated two-dimensional distributions of relative humidity within each wall assembly.

Interstitial condensation was assessed by comparing the calculated vapour pressure with the corresponding saturation vapour pressure within the wall. Vapour ingress, egress, and condensation rates were determined from the calculated vapour-pressure fields and used to compare the moisture transport and condensation susceptibility of the six wall systems under consistent conditions.

3. Results and Discussion

Figure 2 illustrates the simulated relative humidity (RH) distributions within the wall junctions, while Table 1 summarizes the water vapour transport characteristics. The result demonstrates that the wall composition significantly influences moisture migration and interstitial condensation patterns.

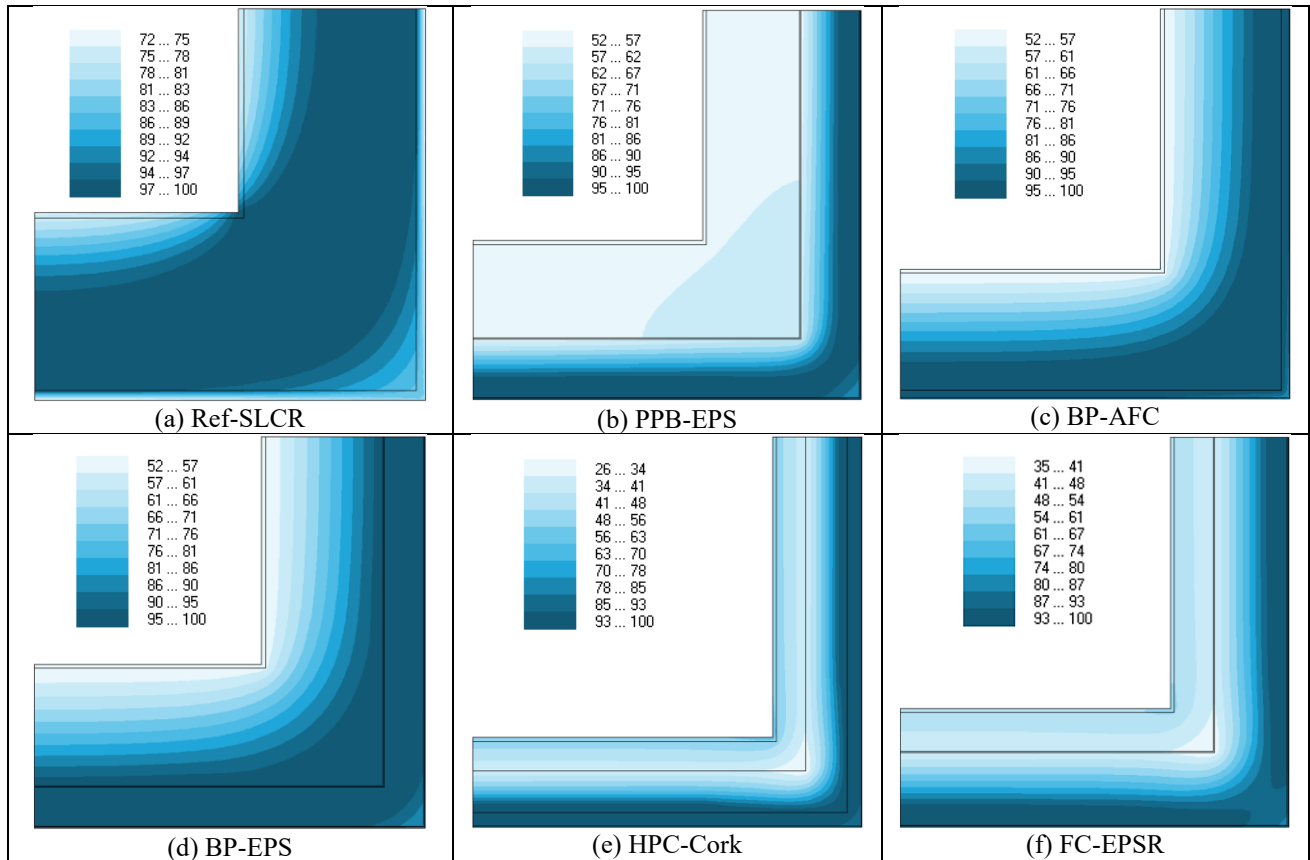


Figure 2. Simulated relative humidity (RH, %) distributions in the corner wall junctions of the six investigated wall configurations.

The reference wall (Ref-SLCR, Fig.2a) exhibits an extensive high-humidity region ($>90\%$ RH) across the corner junction, indicating relatively unrestricted vapour diffusion and moisture accumulation. This is confirmed by vapour flux results, with $7.3 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$ entering the wall and $3.6 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$ condensing within the construction. Approximately 49% of the incoming moisture is retained as condensate, indicating moderate moisture buffering capacity but a considerable risk of condensation.

The Introducing of EPS insulation substantially alters the moisture distribution. PPB-EPS (Fig.2b) and BP-EPS (Fig.2d) exhibit narrower high-humidity zones near the exterior surface, while most of the wall remains below 75% RH, demonstrating reduced vapour penetration into the wall interior. PPB-EPS demonstrates better moisture control, reducing vapour ingress to $3.4 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$ and the condensation to $1.6 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$, the second-lowest value among the investigated configurations. BP-EPS also reduces moisture transport compared with Ref-SLCR but shows higher condensation ($3.0 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$), indicating less efficient moisture management mechanism than PPB-EPS.

100 Table 1. Water vapour transport and interstitial condensation obtained from the numerical simulations.

Configuration	Incoming vapour ($\times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$)	Outgoing vapour ($\times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$)	Condensation ($\times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$)	Condensation ratio (%)
Ref-SLCR	7.3	3.7	3.6	49.3
PPB-EPS	3.4	1.7	1.6	47.1
BP-AFC	8.0	1.8	6.3	78.8
BP-EPS	4.6	1.6	3.0	65.2
HPC-Cork	17.0	2.0	15.0	88.2
FC-EPSR	2.8	1.7	1.0	35.7

101 In contrast, the BP-AFC configuration (Fig.2c) exhibits a considerably larger saturated region
 102 despite having a similar RH range to the EPS-based systems. The contour map reveals that high
 103 RH extends deeper into both the horizontal and vertical sections of the wall junction, indicating
 104 enhanced vapour accumulation. Quantitatively, BP-AFC records an incoming vapour flux of 8.0
 105 $\times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$, while $6.3 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$ condenses within the assembly. Consequently, nearly
 106 79% of the incoming moisture is converted into condensate, suggesting that the AFC configuration
 107 offers insufficient resistance to vapour transport under the investigated conditions.

108 The HPC-Cork system (Fig.2e) exhibits distinctive moisture behaviour. Although most of the wall
 109 remains dry ($\text{RH} < 60\%$), a narrow vertical zone near the exterior approaches saturation, indicating
 110 localized moisture accumulation at the material interface rather than uniform diffusion. HPC-Cork
 111 exhibits the highest vapour ingress ($1.7 \times 10^{-7} \text{ kg m}^{-1} \text{ s}^{-1}$) and the condensation amount (1.5×10^{-7}
 112 $\text{kg m}^{-1} \text{ s}^{-1}$), approximately four times higher than the reference wall. nearly 88% of the incoming
 113 moisture condenses within the assembly, indicating severe interstitial condensation despite the low
 114 bulk RH. This localized moisture concentration may increase risks of biological growth, material
 115 degradation, and reduced thermal performance.

116 Among all investigated configurations, FC-EPSR (Fig.2f) exhibits the most favourable moisture
 117 response. The contour plot indicates that regions approaching saturation are confined to a narrow
 118 zone near the exterior boundary, while the majority of the wall remains below the critical humidity
 119 threshold associated with condensation. The numerical results confirm this observation. FC-EPSR
 120 records the lowest incoming vapour flux ($2.8 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$) and the lowest condensation amount
 121 ($1.0 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$). Only 36% of the incoming vapour condenses, representing the smallest
 122 condensation ratio among all wall systems. This behaviour indicates that the FC-EPSR
 123 configuration effectively limits vapour ingress while maintaining moisture release, thereby
 124 minimizing moisture accumulation.

125 Overall, the numerical results closely correspond with the RH contour distributions in Figure 2.
 126 Wall systems exhibiting extensive saturated regions also display higher vapour ingress and greater
 127 condensation rates. Conversely, configurations with localized moisture accumulation produce
 128 lower condensation values. Considering both RH distributions and water vapour transport
 129 characteristics, FC-EPSR exhibited the highest moisture resistance, followed by PPB-EPS, BP-
 130 EPS, Ref-SLCR, BP-AFC, whereas HPC-Cork demonstrated the lowest moisture performance.
 131 The results demonstrate that selecting appropriate insulation and wall materials significantly

influences vapour diffusion behaviour and interstitial condensation, affecting the long-term hygrothermal durability of building envelopes.

Comparison with the findings of Ref. 3 demonstrates that superior thermal and environmental performance does not necessarily correspond to superior hygrothermal durability. The FC-EPSR wall maintained excellent thermal characteristics ($U = 0.195 \text{ W/m}^2\cdot\text{K}$, $T_{\text{si}} = 17.99 \text{ }^\circ\text{C}$, $f_{\text{Rsi}} = 0.943$) while also exhibiting the lowest condensation fraction, indicating the greatest resistance to interstitial moisture accumulation. In contrast, the HPC-Cork wall, although thermally efficient ($U = 0.351 \text{ W/m}^2\cdot\text{K}$, $T_{\text{si}} = 16.84 \text{ }^\circ\text{C}$, $f_{\text{Rsi}} = 0.910$), produced the highest condensation fraction among the investigated advanced wall systems. These results indicate that thermal insulation performance alone cannot reliably predict moisture durability.

4. Conclusions

The FC-EPSR system exhibited the best moisture performance, with the lowest water vapour ingress ($2.8 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$), condensation rate ($1.0 \times 10^{-8} \text{ kg m}^{-1} \text{ s}^{-1}$), and condensation fraction (35.7%). In contrast, the HPC-Cork configuration showed the highest condensation ($1.5 \times 10^{-7} \text{ kg m}^{-1} \text{ s}^{-1}$) and condensation fraction (88.2%), indicating a greater susceptibility to interstitial moisture accumulation.

The RH distributions further demonstrate that wall composition significantly influences moisture migration and the extent of high-humidity zones, with EPS-based systems providing more effective moisture control than cork- and AFC-based configurations. These findings show that thermal insulation performance alone is insufficient for predicting long-term hygrothermal durability, as moisture behavior depends on the combined effects of vapour permeability, insulation material, and layer configuration. Therefore, integrating moisture transport analysis with thermal performance assessment is essential for designing durable and energy-efficient building envelopes.

Conflict of interest

None

CRedit authorship contribution statement

Hamed: Writing-original draft preparation, Writing-review and editing, Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Software, Supervision, visualization. Hesam: Writing-original draft preparation, Writing-review and editing, Investigation, Resources, Data curation, Visualization. Ali³: Writing-review & editing, Supervision, Project administration, Investigation.

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