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Report on Properties and Position of Materials in the Building Envelope for Housing and Small Buildings

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REPORT ON PROPERTIES AND POSITION OF MATERIALS IN THE BUILDING ENVELOPE FOR HOUSING AND SMALL BUILDINGS

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Executive Summary

The National Research Council of Canada (NRC) has undertaken computer modelling to investigate the change in risk of condensation in wall assemblies associated with increasing the thermal resistance (R-value) of cavity insulation for various scenarios of exterior insulation products. The project was requested by the *Task Group (TG) on Properties and Position of Materials in the Building Envelope,* acting on behalf of the Standing Committee on Housing and Small Buildings (SCHSB). The work originated from a Code Change Request (CCR) CCR-802 in which it was suggested that the application of the Water Vapour Permeance (WVP) limit as provided in the requirement be raised from 60 to 300 ng/(Pa•s•m²) whilst leaving the application limit for air leakage characteristic of building envelope materials unchanged at 0.1 L/(s•m²) at 75 Pa.

The CCR-802 refers to a study that suggests that an increased risk of condensation in wall assemblies could be associated with materials having WVP values ranging between 60 to 300 ng/(Pa•s•m²), when installed on the outboard portion of the wall assembly of Canadian homes, and such materials are currently exempt from having to comply with the thermal resistance ratios set out in Table 9.25.5.2 of the National Building Code of Canada (NBCC). It further suggests that this change would ensure an additional margin of safety to the formation of condensation in the wall assembly for the prescriptive requirements to minimize condensation and thereby better guarantee the long term performance of wall assemblies. The scientific validity of the WVP of 60 ng/(Pa•s•m²) limit was also questioned in the CCR-802.

In response to the CCR-802, NRC undertook a parametric study, under the direction of the TG members, and investigated a range of values of WVP from 2 to 1800 ng/(Pa•s•m²). The parametric study did not include values of WVP specific to product brands; rather, it used a generic approach that covers the values for WVP of most products currently available in the market. The construction details common to all wall assemblies to be modelled were also selected and specified in the report. The hygrothermal performances of all selected walls were compared to NBCC's prescribed reference wall, labelled in this study as "REF". The hygrothermal performance was expressed using the mould index criteria, which allowed sufficient resolution to assess the risk of moisture condensation and related risk of mould growth in the wall assemblies. Also, the respective mould index criteria were selected so that those cases where assemblies comply with information provided in Table 9.25.5.2. of NBCC 2010 would fall into an acceptable performance.

Two main wall configurations were selected in a three storey building, namely:

1. Wall configurations without structural sheathing and having cavity insulation of R-19 and R-24 and,
2. Wall configurations with structural sheathing and having cavity insulation of R-19 and R-24.

The R-values of the outboard insulation investigated were R-4, R-5 and R-6, and the investigated range of WVP for these insulation levels had values of: 2, 45, 60, 90, 200, 300 and 1800 ng/(Pa•s•m²). The WVP of the exterior insulation was taken to be constant and the WVP of the OSB sheathing was taken as a function of its relative humidity, as recommend based on the literature review by Glass [58]. All wall assemblies were subjected to different climatic conditions of Canada as represented by selecting a set of cities that included: Vancouver (BC), St John's (NL), Ottawa (ON) and Edmonton (AB).

For each climatic location, the weather data was analyzed so as to identify the orientation of the wall assembly with highest exfiltration rate. Note that the higher the exfiltration rate, the greater the risk to the formation of condensation and mould growth within the wall. As such, for each climatic condition, all numerical simulations were conducted for the wall assemblies that face the highest predominant exfiltration rates. Furthermore, the walls in the third storey are subjected to highest exfiltration rate compared to the walls in lower stories. Thus, all wall assemblies that were investigated in this study are the wall assemblies of the third storey of low-rise buildings, which are assumed to represent the worst case scenario.

A sensitivity analysis was conducted to investigate the effect of different air leakage rates (10%, 25%, 50%, 75% and 100% of the total value) on the hygrothermal performance of the wall assembly and to determine the locations within the wall assembly that are most at risk due to air leakage. Results showed a 75% and 100% (i.e. 0.1 L/(s•m²) at 75 Pa) of the air leakage rate would result in a risk of mould growth. However, an air leakage rate of 50% (i.e. 0.05 L/(s•m²) at 75 Pa) of the total value or less resulted in no risk of mould growth in the wall assembly.

After conducting the numerical simulations for all wall assemblies with and without structural sheathing, and based on the air leakage path that was considered in this study, the different wall locations at risk for the formation of condensation and mould growth were identified and for which the corresponding value for mould index was calculated. It is important to point out that the wall locations at risk of mould growth would change by considering different air leakage paths within the wall assembly.

The simulation results were summarized in a simple form using the following two parameters:

- Overall average mould index, and
- Overall maximum mould index.

The two parameters above are determined within the period of the simulation of two years (average year followed by a wet year, selected from long-term meteorological data for each location).

The main observations for this study are summarized as follows:

- The simulation results showed that the critical locations inside the wall assembly at risk of mould growth are the top portion and bottom portion of the wall assembly, for the selected air leakage path.
- The hygrothermal performance of a wall system greatly depends on the "combined effect" of the three main environmental parameters, namely, Heating Degree Days (HDD), Moisture Index (MI) and wind speed (e.g. lower HDD without considering the effect of other environmental parameters does not necessarily result in better hygrothermal performance).
- For all wall systems (with and without structural sheathing), incorporating outboard insulation of an R-4 or higher, with a WVP ranging from 2 to 1800 ng/(Pa•s•m²) resulted in lower mould index than the reference walls (i.e. without outboard insulation).

- For the wall systems investigated in this study, and for the range of assumptions made, St. John's appears to have the most severe combination of climate parameters in comparison to the other three locations investigated (Vancouver, Ottawa and Edmonton); the greatest values for the overall average and maximum mould index of the wall configurations amongst the four locations occurred in this location.

- The study confirmed that the values for the overall average and maximum mould index of walls with stud cavity insulation of R-19 are lower than that of walls with stud cavity insulation of R-24 as the interface with the exterior sheathing tend to be colder.

- The study confirmed that the values for the overall average and maximum mould index of walls configured with structural OSB sheathing are lower than that for walls configured without structural OSB sheathing, for the same outboard insulation value. This is due to higher moisture storage capacity of the OSB layer (in walls with structural sheathing) compared to that of a plastic insulation layer (in walls without structural sheathing).

- For outboard insulation of R-0.62 (i.e. same R-value as the OSB layer of 11 mm thick) in wall assemblies without structural sheathing, the value of the average and maximum mould index decreases with increasing WVP of the outboard insulation for four climate conditions investigated.

- For a given type of outboard insulation of R-4, R-5, R-6, the change in the values of average and maximum mould index in relation to the WVP of the outboard insulation differed depending on the location:

    - For the coldest and driest climate (i.e. Edmonton), the average and maximum mould index value of walls with structural sheathing insignificantly changed with the value of the WVP of the outboard insulation. Whereas the average and maximum mould index value of walls without structural sheathing decreases with increasing of the WVP of the outboard insulation.

    - For cold and dry climate (i.e. Ottawa), the average and maximum mould index value insignificantly changed with the value of the WVP of the outboard insulation for both walls with and without structural sheathing.

    - For the milder and more humid coastal climates (i.e. Vancouver and St John's), the average and maximum mould index value increases with increasing the WVP of the outboard insulation for both walls with and without structural sheathing.

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REPORT ON PROPERTIES AND POSITION OF MATERIALS IN THE BUILDING ENVELOPE FOR HOUSING AND SMALL BUILDINGS

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Introduction

A brief review of literature is provided specifically on the use of hygrothermal models to further understanding of the moisture performance of the building envelope of housing and small buildings in a cold climate. In particular, the review focuses on a selected set of publications [1-5] that were the basis for the provision in the 1995 National Building Code of Canada (NBCC) [6] on the use and placement of low-permeance materials applied to the outside of walls. From these publications the importance of air and vapour control in minimizing the effects of air movement through, and subsequent moisture accumulation in the wall assembly could be qualified from the results of hygrothermal simulation. Hence an exhaustive study of heat, air and moisture control in walls of Canadian homes is not provided although a very useful overview on this topic and in which is described the historic basis for current practices, is given by Bomberg and Onysko [7].

Ojanen and Kumaran [1]

In 1990, the Canadian Standards Association Committee responsible for the Standard on Residential Mechanical Ventilation Systems (CAN/CSAF326-M91) approached the National Research Council of Canada (NRC) to determine what the effect of over pressurization of residential houses on the moisture performance of the building envelope. A related question was whether the 10 Pa over pressurization limit was acceptable for homes located across Canada. A numerical simulation study by Ojanen and Kumaran [1], one of the first of its kind, addressed the issue and reached the following conclusions:

a. At most of the locations studied (nine cities in Canada[1]), the warmest of which was Vancouver (approximately 2800 Heating Degree Days (HDD) below 18°C), an appreciable amount of moisture accumulated within the wall cavity during the heating season (1 October to 1 May). However, at most locations with the exception of the coldest (Resolute Bay) during the drying period the cavity dried out, though certain portions of the cavity took longer than others.
b. Moisture accumulation in walls of buildings in cold climates occurs through the exfiltration of indoor air to the outdoors, the amount that accumulates being dependent not only on the rate of exfiltration through the assembly, but more importantly, on outdoor climate conditions and more specifically, the temperature and vapor pressure of the air on either side of the wall.

[1] Vancouver, Windsor, Toronto, Fredericton, Montreal, Ottawa, Edmonton, Winnipeg, Resolute Bay

c. From a practical perspective, however, if indoor and outdoor conditions allow moisture accumulation, even small rates of exfiltration could produce high levels of moisture content in material layers of the wall.
d. Modelling uniform airflow through the walls produced an earlier onset of wetting and faster drying out than the non-uniform airflow case that was modelled.
e. The non-uniform airflow case (i.e. entry at interior and top of wall; exit at base of wall), however, presented more risk of moisture related damage to wall components than the uniform airflow case.

Karagiozis and Kumaran [2]

The next significant study to address the moisture performance of residential walls in a cold climate was undertaken by Karagiozis and Kumaran [2]. The objective of the study was to examine, through use of a two-dimensional hygrothermal model, the moisture content of components and total moisture accumulation in walls of six different vapour retarders incorporated in a typical Canadian residential wall and subjected to a range of climate as might occur across Canada. No airflow was considered in this study. Three cities were used: Vancouver (2800 HDD), Ottawa (4500 HDD), and Winnipeg (5600 HDD). Six different vapour control strategies were modelled: no vapour control (plain gypsum), and vapour barriers having values for permeance of 400, 200, 100, 60 ng/(Pa•s•m²) (Type II vapour retarder), and 15 ng/(Pa•s•m²) (Type I vapour retarder).

One conclusion was that steady state exterior boundary conditions inadequately capture the moisture performance and that transient conditions (i.e. real weather data) were needed to properly capture performance. This study [2] concluded that vapour control of the building envelope was important for buildings located in cold climates and in general, moisture accumulates in the wall during the heating season but dries out in the summer. The amount of vapour control necessary was dependent on the on exterior climate and indoor conditions. Buildings in Vancouver, for example, required a minimum of vapour control whereas buildings in Winnipeg a Type II (60 ng/(Pa•s•m²)) vapour retarder would be sufficient. In this study [2], as in the study by Ojanen and Kumaran [1], there were low-permeance materials placed on the exterior of the sheathing panel (OSB). The OSB was allowed to dry to the exterior. Note that OSB was assumed to have a vapour permeance ranging from ~60 to 300 ng/(Pa•s•m²) depending on its moisture content.

Ojanen and Kumaran [3]

A subsequent study by Ojanen and Kumaran [3] further investigated the effect of air-leakage on the moisture accumulation in typical walls of cold climates. In this study [3], the moisture accumulation of different air leakage paths was examined as well as the effect of varying indoor relative humidity and the placement of insulation outboard of the exterior sheathing panel. Two paths that allow for air flow along the interior of the sheathing surface were determined to be the worst in terms of moisture accumulation in the wall assembly. The worst case scenario was determined by a path where air entered the wall cavity from the interior at the top of the wall and exited at the bottom. The next least performing case with respect to the potential for moisture accumulation in the wall was closely followed by the scenario whereby air entered the cavity from the bottom and exited from the top of the cavity. The study showed that the accumulation of moisture did not monotonically increase with air leakage but rather there was a leakage rate at which the moisture accumulation peaked, and following which, the rate of moisture accumulation in the cavity decreased. This seemingly counterintuitive result was explained by the fact that, at high air exfiltration rates, a sufficient amount of heat was transferred to raise the temperature of the surrounds so that the risk of formation of condensation within the cavity was reduced.

The critical air flow rate at which a maximum of moisture accumulation occurred in the wall cavity was 1 L/(s•m^2) at 75 Pa. Indoor relative humidity was also treated but not in a systematic fashion. Specifically, the effects on the accumulation of moisture in the cavity were considered at constant Relative Humidity (RH) levels of 35% and 48% and results showed that there was a significant difference in moisture accumulation between the two cases at a constant rate of air exfiltration. The authors acknowledged that a proper treatment of indoor conditions was needed to better understand the consequences of both lower and higher values of indoor RH on moisture accumulation in the wall. Moisture accumulation, expressed as an index to enable relative comparisons, was shown to be positively correlated with the values of the HDD of a given location. It was shown that the amount of moisture accumulation in the wall cavity increased sharply with HDDs. This study forms the basis for the vapour control measures provided in the National Building Coode of Canada (NBCC) as of 1995 [7].

The study by Ojanen and Kumaran [3] was the first to look at the effect of increased thermal resistance exterior to the sheathing or using sheathing with an increased thermal resistance (i.e. thermal resistance increased as compared to OSB). Not surprisingly, the results of the simulation showed that increasing the temperature of the interior surface of the sheathing significantly reduced the amount of moisture accumulation and this in turn lead to higher tolerances for indoor RH and air leakage of the wall assembly. Some of the main observations were that for a constant rate of air permeance across the assembly, the moisture accumulation within the assembly decreased in relation to corresponding increases in the vapour permeance of the exterior surface. Also, the interior moisture load is more significant with respect to moisture accumulation in the cavity as compared to the exfiltration rate, and added exterior insulation is beneficial to reducing the risk to the formation of condensation. It should be noted that in all cases the vapour permeance of the materials exterior to the cavity was at least 60 ng/(Pa•s•m^2) and as high as 1500 ng/(Pa•s•m^2).

Kumaran and Haysom [4]

Kumaran and Haysom [4] discuss the approach to wall design described in the 1995 National Building Code of Canada (NBCC). In the 1995 NBCC, restrictions on the use of low-permeance materials applied to the outside of walls as provided in the 1990 NBCC [8] were relaxed. Previous to the 1995 code change, a concern had developed with the recognition that air barriers and vapour retarders could be separate components within a wall. This raised the possibility that an air-barrier having a low water vapour permeance could be placed on the exterior side of the sheathing panel such that it was possible for moisture to condense on the interior surface of the panel. Consequently a restriction had been placed on low vapour permeance air barriers such that the interior surface of the panel be above the dew point temperature when the outdoor temperature was 10°C above the January design temperature. This restriction, as provided in the 1990 NBCC [8], was relaxed in the 1995 NBCC [6]. However concerns were then raised about low permeance materials other than air barrier components, that could be applied towards the exterior and that were not intended for use as an air barrier.

Energy considerations had driven designers to consider adding thermal resistance to the wall as a means of reducing energy usage in homes. As such, given a stud cavity of nominal size, either 89 mm or 140 mm, there are two options for adding insulation. The first is to add insulation at the interior surface. This case is well understood and it is relatively easy to produce successful designs. The drawback however is that the added wall thickness reduces the interior living space. Adding insulation to the exterior offers another solution. As was shown in the previous study, adding exterior insulation can improve the thermal performance of a wall provided that the added insulation does not decrease the vapour permeability towards the exterior; i.e. interfere with the ability of the wall to dissipate moisture to the exterior.

As was described earlier, the study by Ojanen and Kumaran [3] examined the effect of adding low-permeance insulated sheathing to the exterior of a typical wall. The concern was that a modest amount of air exfiltration could potentially contribute to condensation on the cold surface of the low permeance material. Three basic walls were considered: a perfect wall with air leakage, a wall with diffuse air leakage and a wall with diffuse air leakage and an added layer of low-permeance insulated exterior sheathing. Simulations were completed for various Canadian locations and the minimum ratios of outboard to inboard thermal resistance for various HDD were determined. The study results were included in the 1995 NBCC in Table 9.25.1.2. Low permeance, for the purposes of Table 9.25.1.2, was defined as below 60 ng/(Pa•s•m²) [6].

Chown and Mukhopadhyaya [5]

Chown and Mukhopadhyaya [5] established the context for the changes that were included in the NBCC 2005 [9] with respect to Part 9 applications of low air and vapour permeance materials. The paper traces the historical development of Article 9.25.1.2 and Table 9.25.1.2. The authors point out the following assumptions used to develop the table that were not stated in the NBCC. Specifically:

a. Air exfiltration was based on Shaw's 1987 NRC airtightness study [10 and 11];
b. Interior relative humidity was assumed to be 36% during the heating period; and
c. The vapour permeance of the interior vapour retarder was 60 ng/(Pa•s•m²).

The proposed changes were intended to address the situation where the interior RH was maintained above 35% or in locations that were mild and where the RH was regularly over 35% during the heating season, such as might be expected in coastal climates as found in the lower mainland of British Colombia (BC). The proposed change was to limit the use of Table 9.25.1.2 to locations where the RH during the heating season was below 35%. This study [5] used the information provided from a more recent work on air leakage from which the air leakage was calculated using a normalized leakage area of 1.44 cm^2/m^2 of wall [12]. Measurement data for the Vancouver/Seattle area showed that the indoor RH was consistently above 35% in some cases above 40%. A change to the assumed RH levels for non-coastal climates was not considered. The study was limited to locations below 4000 HDDs. Three walls were modelled, a base case wall, a wall with a Type II vapour barrier, and a "tight" wall with a Type I vapour barrier (15 ng/(Pa•s•m²)). Exterior insulation was provided using 12.5 mm of foil-faced polyisocyanurate insulation. Only Vancouver was modelled and the results showed that the 35% RH need not apply and by extrapolation that Table 9.25.1.2 could be applied as a minimum requirement. Locations of particular concern were colder than Vancouver but nonetheless considered mild coastal climates. A Mild Climate Indictor (MCI) was proposed based on an empirical formula derived from anecdotal evidence to discriminate between locations that have mild climates and high moistures loads where the interior RH is consistently above 35%. A threshold limit of 6300 MCI was set based on anecdotal evidence (see Article 9.25.1.2 of the 2005 NBCC). It was suggested that:

a. Further work be conducted to verify the findings, and
b. Further studies should be conducted where indoor conditions above 35% RH are being maintained in the heating season for colder climates.

Summary of NRC Research in Support of Table 9.25.1.2

Chown and Mukhopadhyaya [5] provide a brief history of the development of air and vapour barrier provisions in the NBCC since the first Canadian Building Code was published in 1941 to the most recent changes made in 2005. The key change in 1990 was that it was permissible to separate the functions of air barrier and vapour retarder thus allowing for the possibility of placing low permeance materials exterior to the main thermal resistance of the wall. The study reported by Kumaran and Haysom [4] provided the basis for placement of low permeance materials within building envelopes in cold climates. The key assumption in this study [4] was that diffuse air leakage occurred across the assembly up to the allowable Code limit of 0.1 L/s•m^2. The following study by Chown and Mukhopadhyaya [5], was undertaken to investigate the effect indoor conditions on the placement of low permeance materials, did not use diffuse leakage but rather an air-path through postulated openings in the air barrier and the vapour retarder as was done for the studies undertaken by Ojanen and Kumaran [1 and 3]. The study by Chown and Mukhopadhyaya [5] further refined the basis for placement of low-permeance materials for mild and humid climates where the expectation is that indoor RH would likely exceed 34%. The difference in modelling approaches needs to be resolved from a comparative perspective and from a perspective of Code interpretation. A discontinuous air barrier, while being realistic, does not constitute a Code compliant wall whereas the diffuse case scenario is perhaps unrealistic for modern constructions, but does comply.

Overview of Current Project

Within the National Building Code of Canada (NBCC) there are technical requirements given in Section 9.25. [13] that address the properties and position of materials serving as a vapour barrier and having a Water Vapour Permeance (WVP) lower than 60 ng/(Pa•s•m^2). To comply with the requirements, such materials need to be placed either on the warm face of the wall assembly, outside of a vented air space, or the ratio of total thermal resistance outboard to inboard of the material's inner surface has to be within 0.2 to 0.75, with the specific value being determined by the number of annual Heating Degree Days (HDD) to which the assembly would be subjected (see Table 9.25.5.2. [13]).

This requirement ensures that the installation of low-permeance materials in the assembly will minimize the formation of condensation in the wall assembly. In practical terms, this implies that the colder the location, the more external insulation would be required to maintain the necessary temperature in the wall cavity to control moisture accumulation. However, this requirement does not apply to any building envelope material with WVP values higher than 60 ng/(Pa•s•m²), which leaves the installation of medium permeance building envelope materials (above 60 ng/(Pa•s•m²)) unregulated.

Project Scope

The Canadian Codes Centre received a code change request (CCR-802) in which it was suggested that the application of the WVP limit as provided in the requirement be raised from 60 to 300 ng/(Pa•s•m²) whilst leaving the application limit for air barrier properties of building envelope materials unchanged at 0.1 L/(s•m²) at75 Pa. The code change request refers to a study that suggests that an increased risk of condensation is associated with materials of WVP between 60 and 300 ng/(Pa•s•m²) that are installed outboard of the insulated wall cavity, and these materials are currently exempt from having to comply with the thermal resistance outboard to inboard ratios set out in Table 9.25.5.2 [13]. It further suggests that this change would ensure an additional margin of safety to the formation of condensation in the wall assembly for the prescriptive requirements to minimize condensation and thereby better guarantee the long term performance of wall assemblies. The scientific validity of the WVP of 60 ng/(Pa•s•m²) limit associated with the application of the table to outboard low permeance insulation was also questioned in the CCR-802.

During the development of the recently published energy efficiency requirements in Part 9 of the NBCC, the Standing Committee on Housing and Small Buildings (SCHSB) of the Canadian Commission on Building and Fire Codes (CCBFC) discussed higher levels of insulation for walls. The SCHSB was concerned about the risk of formation of condensation in the wall assembly if more thermal resistance were added to the stud cavity as well as requiring exterior insulating sheathing to meet minimum thermal resistance (R-value) requirements in some climate zones. Prompted by that discussion and the issues raised in the CCR-802, the SCHSB had interest in investigating whether these circumstances could increase the risk of forming condensation within the wall assembly if a minimum R-value of exterior insulating sheathing is not specified for materials having a WVP of between 60 and 300 ng/(Pa•s•m²).

Both, the discussions undertaken within the SCHSB and the issues raised in CCR-802 suggest that leaving the requirements as they are may have a substantial economic impact considering: (a) the possible heightened risk of building envelope failures, and (b) an unfair market advantage for some companies over others, based on a value for the WVP application limit for low-permeance materials that may not have sufficient scientific justification.

In order to investigate the risk of condensation in wall assemblies introduced by increased cavity insulation and exterior insulating products that have WVP that fall outside the scope of NBCC 2010 Table 9.25.5.2 [13], the clients of this project contacted the NRC-Construction to conduct a parametric investigation using hygrothermal simulations to model a number of different wall assemblies of interest to the SCHSB. This investigation included a review of a broad collection of different types of generic wall assemblies and incorporated a wide range of values of WVP of products without referring to specific products.

In this project, the *Task Group (TG) on Properties and Position of Materials in the Building Envelope* acted on behalf of the SCHSB to provide feedback on technical details for the modeling and the modeling results. The TG is mandated to report to the SCHSB and to make a recommendation based on the findings of the investigation. It is intended that the information provided in this report would permit deciding whether it is necessary to change the application limit as given in Table 9.25.5.2 of the 2010 NBCC [13]. The NRC's hygrothermal model called "hygIRC-C" was used to conduct the numerical simulations for different wall assemblies, subjected to different climatic conditions of Canada. A description of this model is discussed next.

Description of Numerical Simulation model – hygIRC-C

The NRC's hygrothermal model, hygIRC-C was used in this project to predict the risk of condensation and mould growth in wall assemblies with and without structural sheathing (see Table 2 and Table 3) when these walls are subjected to different air leakage rates and different climatic conditions in Canada. This model has been validated and used in a number of projects to assess the thermal and hygrothermal performance of different components of building envelopes (roofing, wall and fenestration systems). It is important to emphasize that the predictions by such a model for the airflow, temperature, and moisture (or relative humidity) distributions within a wall assembly, when subjected to a pressure differential (and resulting air leakage rate) across the assembly, are necessary to accurately determine the mould index in different layers of the wall assembly.

The hygIRC-C model simultaneously solves the highly nonlinear two-dimensional and three-dimensional Heat, Air and Moisture (HAM) equations that define values of heat, air and moisture transfer across building components. The HAM equations were discretized using the Finite Element Method (FEM). The hygIRC-C model has been extensively benchmarked in a number of other projects and has been used in several related studies to assess the thermal and hygrothermal performance of wall and roofing systems [14-44].

Record of Benchmarking hygIRC-C Model

In a previous project called "Wall Energy Rating (WER)", the three-dimensional version of this model was used to conduct numerical simulations for different full-scale 2 x 6 wall assemblies incorporating, or not, penetrations representative of a window installation, such that the effective thermal resistance (R-value) of the assemblies could be predicted, taking into consideration air leakage across the assembly. The stud cavity of these walls incorporated open cell polyurethane foam, closed cell spray polyurethane foam or glass fibre insulation. The predicted R-values for these walls were in good agreement (within ± 5% which is the same as the uncertainty of test data, see [16-19]) with the measured R-values that were obtained from testing in the NRC's Guarded Hot Box (GHB) according to the ASTM C-1363 standard test method [45].

The present model was also benchmarked against GHB test results according to the ASTM C-1363 standard test method [45] and heat flow meter according to the ASTM C-518 standard test method [46], and then used to conduct numerical simulations to investigate the effect of foil emissivity on the effective thermal resistance of different wall systems with foil bonded to different types of thermal insulations placed in furred assemblies, in which the foil was adjacent to the airspace [22, 25, 26, and 28-31]. The accurate calculations of the airflow and temperature distributions within the test specimens resulted in that the predictions of the present model for the R-values were in good agreements with the measured R-values (within the uncertainties of the experimental data, see [26, 29, 30, 31] for more details). Furthermore, the model was used to determine the reductions in the R-values of the specimens as a result of increasing the foil emissivity due to water vapour condensation and/or dust accumulation on the surface of the foil.

In a number of previous studies by Saber [37-41], the model was used to conduct numerical simulations to predict the airflow and temperature distributions as well as the R-values of vertical, horizontal and inclined enclosed airspaces, subjected to different directions of heat flow. The predicted R-values were compared with the R-values for enclosed airspaces of different thicknesses and operating conditions as provided in the ASHRAE handbook of fundamentals [47]. In these same studies the dependence of the R-value on a wide range of the airspace aspect ratio (i.e. ratio of the length or height of the airspace to its thickness) of the enclosed airspace was also investigated. Additionally, practical correlations were developed for determining the R-values of enclosed airspaces of different thicknesses, and for a wide range of values for various parameters, namely, aspect ratio, temperature differential, average temperature, and emissivity of the different surfaces of the airspaces [37-41]. These correlations are ready to be implemented in energy simulations models such as Energy Plus, ESP-r and DOE.

Also, the present model was benchmarked and thereafter used to assess the effect of thermal mass on the thermal performance of Insulated Concrete Form (ICF) wall systems when placed in NRC-Construction’s Field Exposure of Walls Facility (FEWF) and subjected to yearly periods of local Canadian climate [23-24, 34-35]. Results showed that the predictions of the present model for the temperature and heat flux distributions within the ICF wall systems were in good agreements with the test data. Recently, the present model was benchmarked against field data obtained in the NRC’s FEWF of highly insulated residential wood-frame construction in which Vacuum Insulation Panels (VIPs) were used as the primary insulation components; the results from this work showed that the model predictions were in good agreement with the test data [42-44].

More recently, the hygIRC-C model was benchmarked against test results of a number of samples of Exterior Insulation and Finishing Systems (EIFS) [48]. The test results were obtained using the NRC’s Guarded-Hot-Plate (GHP) apparatus in accordance of the ASTM C-177 standard test method [49]. The accurate calculations of the airflow and temperature distribution within the test specimens had resulted that the model predictions for the R-values of different samples were in good agreements with the test results (within ±5%). Thereafter, the present model was used to investigate the effect of air leakage due to infiltration and exfiltration on the effective R-values of different EIFS assemblies, subjected to different climatic conditions. The results of this study will be published at a later date. These studies focused on predicting the thermal performance of different types of walls [14-18, 22-23, 24-26, 28-35, 37-44]; however, no account was made for moisture transport across the wall assemblies.

In instances where the model has been used to account for moisture transport across wall assemblies, the present model predicted the drying rate of a number of wall assemblies subjected to different outdoor and indoor boundary conditions [21] in which there was a significant vapor drive across the wall assemblies. The results showed that there was overall agreement between the results derived from the present model and the hygIRC-2D model, a model that had previously been developed and benchmarked at NRC-Construction [36]. As well, model predictions were in good agreement with the experimental measurements of the drying and drying rate of the assembly with respect to the shape of the drying curve and the length of time predicted for drying. Additionally, the predicted average moisture content of the different wall assemblies over the test periods were in good agreement, all being within ±5% of those measured experimentally [21].

Additionally, with respect to the prediction of the hygrothermal performance of roofing systems, the present model was used to investigate the moisture accumulation and energy performance of reflective (white coloured) and non-reflective (black coloured) roofing systems that were subjected to different climatic conditions of North America [32, 33]. The results of these studies showed that the climatic conditions of St John's and Saskatoon resulted in a high risk of long-term moisture accumulation in the white roofing systems. In case of climatic conditions in which white roofing systems have no risk of moisture accumulation, however, the results of these studies provided the amount of energy saving due to using white roofing systems compared to using black roofing systems (see [32, 33] for more details).

Having previously benchmarked the hygIRC-C model to several tests undertaken in field and controlled laboratory conditions, this model was used with confidence in this study to investigate the risk of condensation and mould growth in different wall assemblies with and without structural sheathing when these walls were subjected different Canadian climatic conditions. The description of the wall assemblies and simulation parameters are provided next.

Wall Assembly Configurations and Simulation Parameters

Hygrothermal simulations of wall assemblies were conducted using the hygIRC-C model and using the construction details common to all wall assemblies to be modelled as listed in Table 1. For each of the materials or components specified, the rationale for the selection of specific materials was also given.

The numerical simulations were conducted in two phases:

1. Phase 1 was the first priority of the modeling cases. The simulation parameters and the rationale of these parameters of Phase 1 are provided in Table 2. In this phase, two reference wall assemblies were considered each having no exterior insulation but for which insulation in the wall stud cavity provided R-19; specifically: REF1 for a wall with structural sheathing and REF3 for wall without structural sheathing. For wall assemblies with no exterior insulation and having a higher R-value of R-24 in the stud cavity, another two reference wall assemblies were considered: REF2 and REF4 for walls with and without structural sheathing, respectively. In instances where the reference wall assemblies did not include structural sheathing, a generic polystyrene (i.e. EPS or XPS) layer was assumed to have a nominal R-value of 0.62 ft^2•hr•^oF/BTU (same as OSB layer of 7/16 inch thick in walls with structural sheathing) and WVP value of 60 ng/(Pa•s•m^2).
2. Phase 2 represented modeling cases of secondary priority. The purpose of this phase was to investigate the hygrothermal performance of wall assemblies (with and without structural sheathing, see Table 3) incorporating exterior insulations products covering a wide range of WVP values and varying from 45 ng/(Pa•s•m^2) to 1800 ng/(Pa•s•m^2). As well, the corresponding specifications for cavity insulation, OSB sheathing and exterior insulation for these walls are provided in Table 3.

Table 1. Construction details common to all wall assemblies to be modelled

Material selection	Rationale
An exterior finish consisting of vinyl cladding installed on 19 mm strapping	To minimize the impact of exterior water ingress and lack of drying
A weather-resistive barrier (WRB) with a WVP of 1400 ng/(Pa•s•m^2) such as spun bonded polyolefin membrane	Common construction and highly permeable so as not to affect the goals of the project
2 x 6 Wood-frame construction using framing members at 16 in on center	Most common construction for housing
A vapour barrier with a WVP of 60 ng/(Pa•s•m^2)	NBCC 2010 minimum requirement 9.25.4.2. (see reference [13])
An interior finish consisting of 12.5 mm gypsum board	Most common construction

Table 2. Phase 1 – First Priority Modeling Cases (160 Cases)

Wall Assembly	# of runs	Cavity Insulation R –value (ft^2•hr•°F/BTU)	(Structural) Sheathing	Exterior Insulation R-value (ft^2•hr•°F/BTU)	Exterior Insulation WVP (ng/Pa•s•m^2)	Actual R_{out} / R_{in} Ratio	Comments/Rationale
RER3	4	19	EPS/XPS	0.62	60	N/A	Benchmark case without insulation value but with similar product than insulated cases (mould index criteria 2)
REF1	4	19	7/16" OSB	None	N/A	N/A	Benchmark case with OSB but without insulation (mould index criteria 1)
REF4	4	24	EPS/XPS	0.62	60	N/A	Benchmark case without exterior insulation, high R cavity insulation (future requirement in Edmonton)
REF2	4	24	7/16" OSB	None	N/A	N/A	Benchmark case with OSB, without exterior insulation, high R cavity insulation (future requirement in Edmonton)
Wall 101	4	19	None	4	2	0.23	Requirements apply, material properties are most severe
Wall 102	4	19	7/16" OSB	4	2	0.26	Requirements apply, material properties are most severe, impact of OSB
Wall 103	4	19	None	4	60	0.23	Limit to requirements, base case
Wall 104	4	19	7/16" OSB	4	60	0.26	Limit to requirements, base case, impact of OSB
Wall 105	4	19	None	4	90	0.23	Requirements don't apply, ratio too low for Edmonton
Wall 106	4	19	7/16" OSB	4	90	0.26	Requirements don't apply, ratio too low for Edmonton, impact of OSB
Wall 107	4	19	None	5	2	0.27	Requirements apply, material properties are most severe
Wall 108	4	19	7/16" OSB	5	2	0.30	Requirements apply, material properties are most severe, impact of OSB
Wall 109	4	19	None	5	60	0.27	Limit to requirements, base case
Wall 110	4	19	7/16" OSB	5	60	0.30	Limit to requirements, base case, impact of OSB
Wall 111	4	19	None	5	90	0.27	Requirements don't apply, ratio too low for Edmonton
Wall 112	4	19	7/16" OSB	5	90	0.30	Requirements don't apply, ratio too low for Edmonton, impact of OSB
Wall 113	4	19	None	6	2	0.32	Requirements apply, material properties are most severe
Wall 114	4	19	7/16" OSB	6	2	0.35	Requirements apply, material properties are most severe, impact of OSB
Wall 115	4	19	None	6	60	0.32	Limit to requirements, base case
Wall 116	4	19	7/16" OSB	6	60	0.35	Limit to requirements, base case, impact of OSB
Wall 117	4	19	None	6	90	0.32	Requirements don't apply, ratio acceptable for Edmonton
Wall 118	4	19	7/16" OSB	6	90	0.35	Requirements don't apply, ratio acceptable for Edmonton, impact of OSB

Wall Assembly	# of runs	Cavity Insulation R –value (ft^2•hr•^{o}F/BTU)	(Structural) Sheathing	Exterior Insulation R-value (ft^2•hr•^{o}F/BTU)	Exterior Insulation WVP (ng/Pa•s•m^2)	Actual R_{out} / R_{in} Ratio	Comments/Rationale
Wall 119	4	24	None	4	2	0.20	Requirements apply, material properties are most severe, increased risk through high R cavity insulation
Wall 120	4	24	7/16" OSB	4	2	0.22	Requirements apply, material properties are most severe, increased risk through high R cavity insulation, impact of OSB
Wall 121	4	24	None	4	60	0.20	Limit to requirements, base case, high R cavity insulation
Wall 122	4	24	7/16" OSB	4	60	0.22	Limit to requirements, base case, high R cavity insulation, impact of OSB
Wall 123	4	24	None	4	90	0.20	Requirements don't apply, ratio too low for Edmonton
Wall 124	4	24	7/16" OSB	4	90	0.22	Requirements don't apply, ratio too low for Edmonton, impact of OSB
Wall 125	4	24	None	5	2	0.24	Requirements apply, material properties are most severe, increased risk through high R cavity insulation
Wall 126	4	24	7/16" OSB	5	2	0.26	Requirements apply, material properties are most severe, increased risk through high R cavity insulation, impact of OSB
Wall 127	4	24	None	5	60	0.24	Limit to requirements, base case, high R cavity insulation
Wall 128	4	24	7/16" OSB	5	60	0.26	Limit to requirements, base case, high R cavity insulation, impact of OSB
Wall 129	4	24	None	5	90	0.24	Requirements don't apply, ratio too low for Edmonton
Wall 130	4	24	7/16" OSB	5	90	0.26	Requirements don't apply, ratio too low for Edmonton, impact of OSB
Wall 131	4	24	None	6	2	0.28	Requirements apply, material properties are most severe, increased risk through high R cavity insulation
Wall 132	4	24	7/16" OSB	6	2	0.29	Requirements apply, material properties are most severe, increased risk through high R cavity insulation, impact of OSB
Wall 133	4	24	None	6	60	0.28	Limit to requirements, base case, high R cavity insulation
Wall 134	4	24	7/16" OSB	6	60	0.29	Limit to requirements, base case, high R cavity insulation, impact of OSB
Wall 135	4	24	None	6	90	0.28	Requirements don't apply, ratio too low for Edmonton
Wall 136	4	24	7/16" OSB	6	90	0.29	Requirements don't apply, ratio too low for Edmonton, impact of OSB

Table 3. Phase 2 – Other Modeling Cases (192 Cases)

Wall Assembly	# of runs	Cavity Insulation R-Value (ft^2•hr•°F/BTU)	(Structural) Sheathing	Exterior Insulation R-Value (ft^2•hr•°F/BTU)	Exterior Insulation WVP (ng/Pa•s•m^2)	Actual R_{out} / R_{in} Ratio	Comments/Rationale
Wall 201	4	19	None	4	300	0.21	
Wall 202	4	19	None	5	300	0.26	
Wall 203	4	19	None	6	300	0.32	
Wall 204	4	24	None	4	300	0.17	
Wall 205	4	24	None	5	300	0.21	
Wall 206	4	24	None	6	300	0.25	
Wall 207	4	19	7/16" OSB	4	300	0.21	
Wall 208	4	19	7/16" OSB	5	300	0.26	
Wall 209	4	19	7/16" OSB	6	300	0.32	
Wall 210	4	24	7/16" OSB	4	300	0.17	
Wall 211	4	24	7/16" OSB	5	300	0.21	
Wall 212	4	24	7/16" OSB	6	300	0.25	
Wall 213	4	19	None	4	45	0.21	
Wall 214	4	19	None	5	45	0.26	
Wall 215	4	19	None	6	45	0.32	
Wall 216	4	24	None	4	45	0.17	
Wall 217	4	24	None	5	45	0.21	
Wall 218	4	24	None	6	45	0.25	
Wall 219	4	19	7/16" OSB	4	45	0.21	
Wall 220	4	19	7/16" OSB	5	45	0.26	
Wall 221	4	19	7/16" OSB	6	45	0.32	
Wall 222	4	24	7/16" OSB	4	45	0.17	
Wall 223	4	24	7/16" OSB	5	45	0.21	

Wall Assembly	# of runs	Cavity Insulation R-Value (ft^2•hr•^{o}F/BTU)	(Structural) Sheathing	Exterior Insulation R-Value (ft^2•hr•^{o}F/BTU)	Exterior Insulation WVP (ng/Pa•s•m^2)	Actual R_{out} / R_{in} Ratio	Comments/Rationale
Wall 224	4	24	7/16" OSB	6	45	0.25	
Wall 225	4	19	None	4	200	0.21	
Wall 226	4	19	None	5	200	0.26	
Wall 227	4	19	None	6	200	0.32	
Wall 228	4	24	None	4	200	0.17	
Wall 229	4	24	None	5	200	0.21	
Wall 230	4	24	None	6	200	0.25	
Wall 231	4	19	7/16" OSB	4	200	0.21	
Wall 232	4	19	7/16" OSB	5	200	0.26	
Wall 233	4	19	7/16" OSB	6	200	0.32	
Wall 234	4	24	7/16" OSB	4	200	0.17	
Wall 235	4	24	7/16" OSB	5	200	0.21	
Wall 236	4	24	7/16" OSB	6	200	0.25	
Wall 237	4	19	None	4	1800	0.21	
Wall 238	4	19	None	5	1800	0.26	
Wall 239	4	19	None	6	1800	0.32	
Wall 240	4	24	None	4	1800	0.17	
Wall 241	4	24	None	5	1800	0.21	
Wall 242	4	24	None	6	1800	0.25	
Wall 243	4	19	7/16" OSB	4	1800	0.21	
Wall 244	4	19	7/16" OSB	5	1800	0.26	
Wall 245	4	19	7/16" OSB	6	1800	0.32	
Wall 246	4	24	7/16" OSB	4	1800	0.17	
Wall 247	4	24	7/16" OSB	5	1800	0.21	
Wall 248	4	24	7/16" OSB	6	1800	0.25	

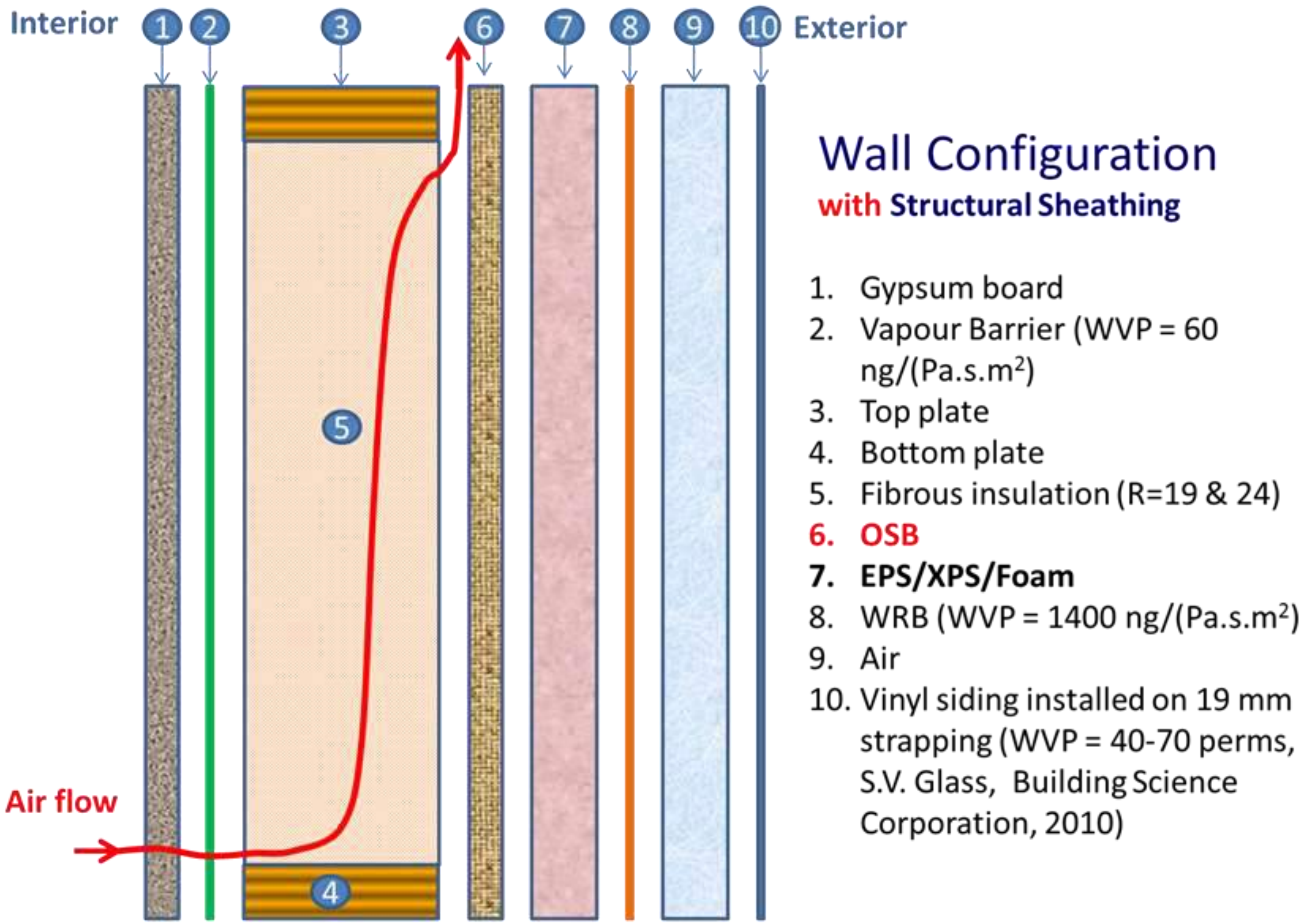


Figure 1. Schematic of wall assembly configuration showing different component layers and assumed path of air flow through assembly; wall assembly includes structural sheathing

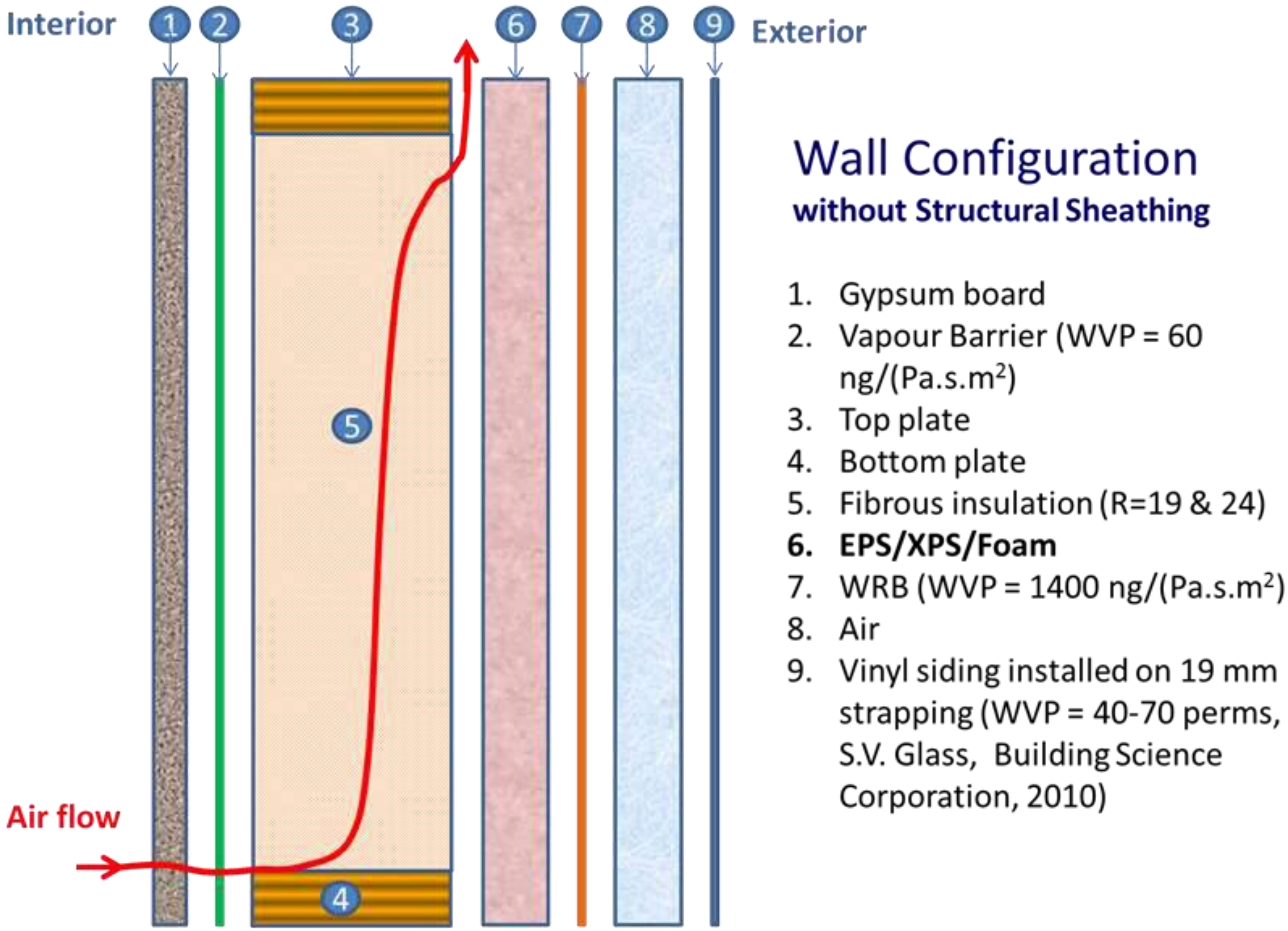


Figure 2. Schematic of wall assembly configuration showing different component layers and assumed path of air flow through assembly; wall assembly does not include structural sheathing

Figure 1 shows a schematic a wall assembly with structural sheathing. Also, Figure 2 shows schematic a wall assembly without structural sheathing. As will be explained later, the locations in these wall assemblies (see also Table 2 and Table 3) at risk of condensation and mould are listed in Table 4. Whereas the simulated results of moisture contents and temperatures are produced for every location within the wall system at every time step, an analysis of results was performed to establish which locations in the wall showed the greatest susceptibility to risk of condensation for the assemblies studied, in order to rationalize the presentation of results. Post-processing of simulation results and reporting thus focussed on the locations reported in Table 4.

Table 4. Locations in wall assembly at risk of condensation and mould growth

Location	Depths and heights (mm; inches)
Top plate layer	51 and 63 mm (2 and 2.5 inches)
Insulation at top plate	10 mm by 51 and 63 mm (2 and 2.5 inches)
Interface between top plate and insulation	2.5 inches
Insulation at base of wall assembly	10 mm deep by heights of 152, 305, 457 mm (6, 12 and 18 inches)
Interface between sheathing panel and insulation	152 and 305 mm (6 and 12 inches)

Simulation Conditions

In this section, the different simulation conditions that were used to conduct the numerical simulations for all wall assemblies listed in Table 2 and Table 3 are discussed.

Vapour Barrier Conditions

As provided in Subsection 9.25.4 of the NBCC [13], the current maximum allowable WVP value for vapour barriers is 60 ng/(Pa•s•m^2). While it is recognized that there are product choices with much lower values of WVP, the selection of materials having this value for WVP for this parametric study is expected to maximize inward and outward vapour drive.

Air Leakage Conditions

All cases were modeled with some air flow introduced through openings into the assembly, as this is a likely scenario given the imperfections of the air barrier system of wall assemblies. Additionally, completing the investigation without considering the effects of air leakage would not create useful results in terms of assessing the risk to the formation of condensation in wall assemblies given that air leakage of indoor air to the wall assembly (i.e. exfiltration) is the primary cause for the formation of condensation in the assembly itself.

The modeling assumed that the path for air movement is initiated at the interior and is introduced at the bottom of the wall and thereafter moisture is deposited along the interior face of the sheathing panel and exits through the top of the wall. This air leakage path was one of the scenarios used in the study by Ojanen and Kumaran [50] in which it was assumed that air would move through imperfections that existed at the wall top plate and the joint between the interior face of the exterior sheathing and the exterior of the top plate.

The air leakage rate for all cases in all locations was set to 0.1 L/(s•m²) at 75 Pa, which was an assumption used in at least one previous study (see e.g. [50]). The impact of this assumption on the hygrothermal performance was investigated in a sensitivity analysis, by modeling a wall assembly with different air leakage rates from which would be derived the least performing and most vulnerable wall assembly with respect to the formation of condensation and the risk to the formation of mould within the assembly. The results of that sensitivity study supported the selection of 0.1 L/(s•m²) at 75 Pa as a means of challenging the wall system with a large amount of moisture ingress.

Approach to Simulation of Air Leakage

In the present study, the air leakage rate (Q) as a function of the total pressure differential across the wall assemblies (ΔP_{tot}) is given as:

$$Q = a\,\Delta P_{tot}^{n} \qquad (1)$$

In a previous NRC project "Wall Energy Rating, WER [15, 16, 17, 18 and 19]), the air leakage rates were measured for a number of 2 x 6 in wood-frame wall systems having different types of thermal insulation in the wall cavities (e.g. open cell spray foam, closed cell spray foam, and glass fibre). For the full-scale wall systems with and without penetrations and having glass fibre insulation, the average value of the exponent '*n*' in Eq. (1) was 0.7; this value was used in the current project. The value of the coefficient '*a*' in Eq. (1) was determined to satisfy the condition at which the air leakage rate is 0.1 L/(s•m²) at ΔP_{tot} = 75 Pa when the exponent n = 0.7. As such, the value of the coefficient *'a'* is equal 0.00487 L/(s•m²•Pa$^{0.7}$) where Q in L/(s•m²) and ΔP_{tot} in Pa.

The total pressure across the building envelope is given as:

$$\Delta P_{tot} = \Delta P_{wind} + \Delta P_{st} + \Delta P_{ven} \qquad (2)$$

Where:

ΔP_{wind} is pressure differential due to wind,

ΔP_{st} is pressure differential due to stack effect, and

ΔP_{ven} is pressure differential due to mechanical ventilation system (i.e. pressurization or depressurization due to heating and cooling conditions); ΔP_{ven} was neglected in this study and thus $\Delta P_{ven} = 0$.

Stack Pressure Differential

The stack pressure differential is calculated as:

$$\Delta P_{st} = z\left(\rho_{outd} - \rho_{ind}\right) g \tag{3}$$

Where ρ_{outd} and ρ_{ind} are the outdoor and indoor air densities, respectively, g is the gravitation acceleration (9.81 m^2/s). In Eq. (3) z is the height which is measured from the location of the neutral plane (NPL) as shown in Figure 3. A low-rise building with three stories was considered in this study. The location of the neutral plane is assumed at the mid height of the building (see Figure 4). It is recognized that some localized positive pressure may occur, but that this effect would be less than the overall stack effect, which can be expected to be around 10 Pa. The stack pressure was calculated at different heights of a three storey building, and subjected to climatic conditions of Ottawa, Edmonton, Vancouver and St John's. For the climatic conditions of Ottawa, Figure 5a & b and c show the stack pressure at the top of the third storey, top of the second storey and bottom of the first storey, respectively. As shown in this figure, the location at the top of the third storey is subjected to highest exfiltration rate (Figure 5a) whereas the location at the bottom of the first storey is subjected to highest infiltration rate (Figure 5b). Since the location of the NPL is located at the mid height of the building, the location at the top of the second storey is subjected to lower infiltration and exfiltration rates (Figure 5b). Assuming that the greater the exfiltration rate the higher of risk of condensation and mould growth, the wall assembly in the third storey would thus represent the worst case scenario for the risk of condensation and mould growth within the wall cavity. As such, all wall assemblies shown in Figure 1 and Figure 2 (see also Table 2 and Table 3) that were investigated in this project represent wall assemblies of the third storey of low-rise buildings.

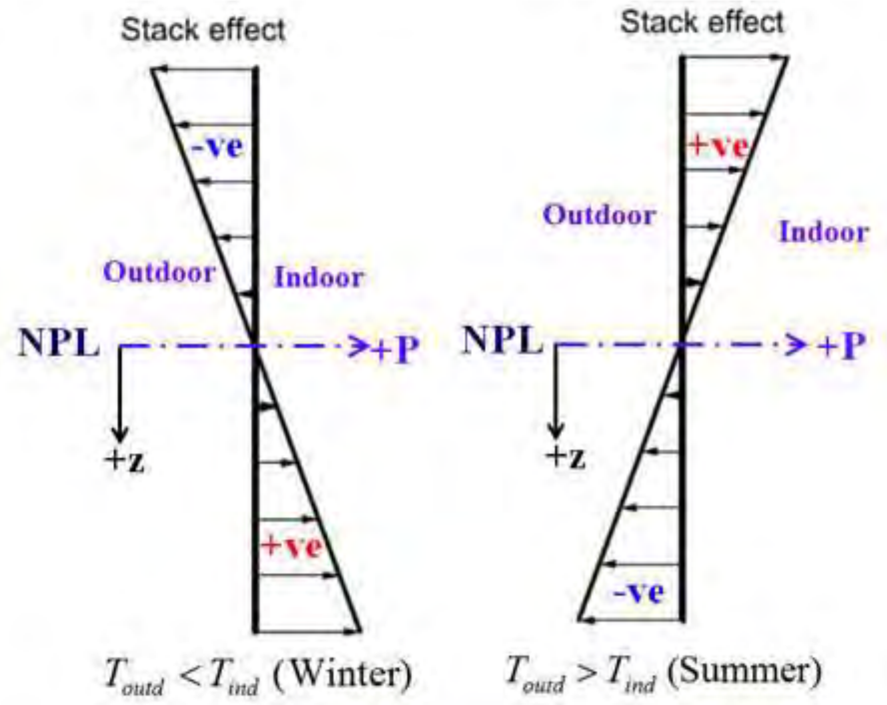


Figure 3. Stack pressure distribution in winter and summer conditions

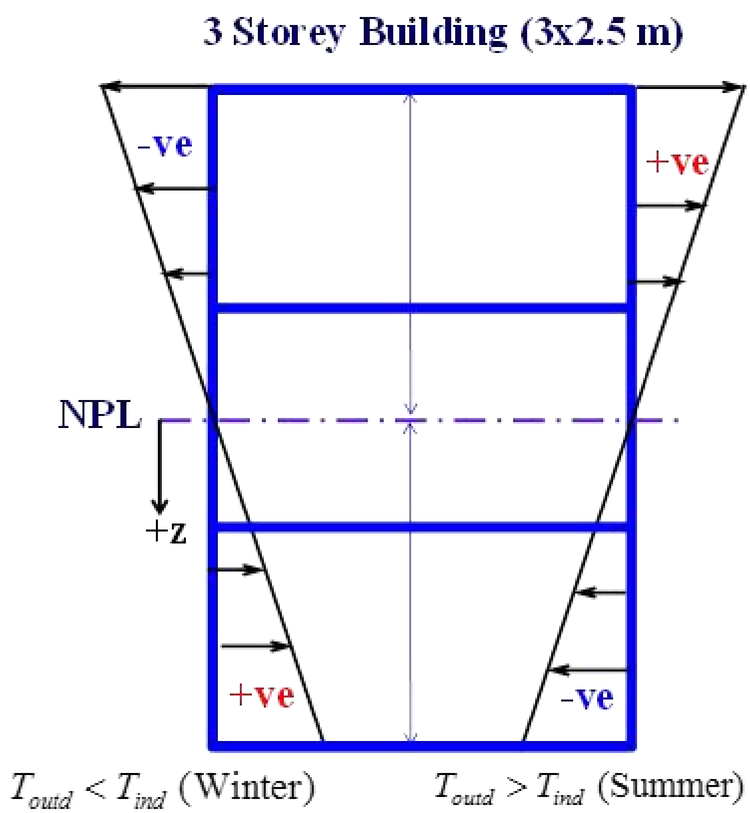


Figure 4. Location of the neutral plane (NPL) at the mid height of three storey building

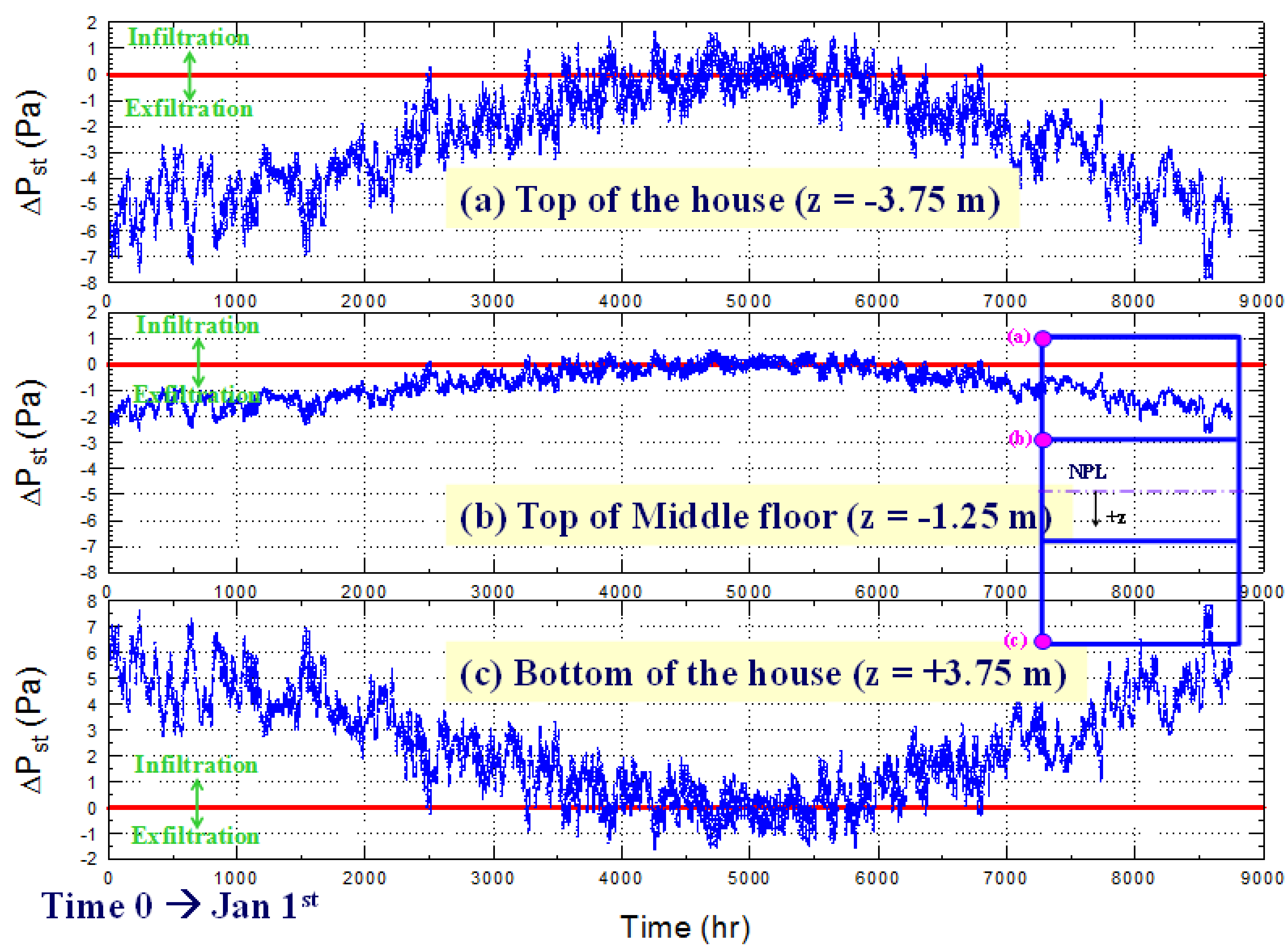


Figure 5. Stack pressure at different locations of three storey building located in Ottawa

Wind Pressure Differential on Building Envelopes

It is important to determine the wind pressure on building façades in order to solve the coupled HAM equations and account for both energy and moisture transport through building envelopes due to infiltration (introduction of outside air through the envelope into a building) and exfiltration. Essentially, the turbulence or gustiness of the approaching wind to the building envelope as well as the unsteady character of airflow around the building causes the pressure at the building's exterior surface to fluctuate. For a given height (z) at which the wind speed is $V(Z)$, the wind pressure on building façade, ΔP_w, is given as [51]:

$$\Delta P_{wind} = C_{wp} P_{dyn}, \text{ where } P_{dyn} = \frac{1}{2}\rho_a V^2(Z) \tag{4}$$

The wind speed in Eq. (4) is calculated using a power law given as [52]:

$$V(Z) = \left(\frac{Z}{Z_{ref}}\right)^{0.22} V_{ref}, \tag{5}$$

where Z_{ref} is a reference height above the ground at which the reference wind speed, V_{ref}, is measured in m/s. The weather data for a given location provides a value for V_{ref}, which is usually measured at $Z_{ref} = 10\text{ m}$.

In Eq. (4), ρ_a is the outdoor air density and C_{wp} is the surface pressure coefficient of the wind, for which the pressure coefficient depends on the height of the building and building shape, wind direction, and influence of nearby buildings, vegetation, and topographic features upstream of the building.

For low-rise buildings having three stories or less in height, Walker and Wilson [54] developed a harmonic trigonometric correlation to determine the surface average pressure coefficients on a wall as function of wind direction. Figure 6 shows a comparison between the calculated value of C_{wp} using their correlation [54] and the measurements of surface pressure coefficients by Akins et al. [55]. The measurements of pressure coefficients provided by Akins et al. [55] were used to develop another correlation for C_{wp}. Based on the angle of incidence, θ, of the wind impinging on the building and ranging between 0^o – 90^o and between 270^o – 360^o, the present correlation for the C_{wp} is given as:

$$C_{wp} = \frac{3}{40}\left(C_{wp}(1)+C_{wp}(2)-C_{wp}(3)-C_{wp}(4)\right)\begin{Bmatrix}\cos(\beta)+\left(\cos(\beta)\right)^2+\left(\cos(\beta)\right)^3\\ +\left(\cos(\beta)\right)^4+\left(\cos(\beta)\right)^5\end{Bmatrix}$$
$$-\left(C_{wp}(1)+C_{wp}(2)+C_{wp}(3)+C_{wp}(4)\right)\begin{Bmatrix}a_1\sin(\beta)+b_1\left(\sin(\beta)\right)^2\\ +c_1\cos(\beta)\sin(\beta)\\ +d_1\cos(\beta)\left(\sin(\beta)\right)^2\end{Bmatrix} \quad (6)$$
$$\text{with}\quad \beta=\begin{cases}\theta & \text{for } 0^o\le\theta\le 90^o\\ 360^o-\theta & \text{for } 270^o\le\theta\le 360^o\end{cases}$$

Where: a_1 = 4.496, b_1 = -5.1459, c_1 = -4.2831, and d_1 = 4.605,

$C_{wp}(1)$ = pressure coefficient when wind is at 0^o (+0.60),

$C_{wp}(2)$ = pressure coefficient when wind is at 180^o (-0.30),

$C_{wp}(3)$ = pressure coefficient when wind is at 90^o (-0.65), and

$C_{wp}(4)$ = pressure coefficient when wind is at 270^o (-0.65).

For incidence angle $90^o < \theta < 270^o$, the obtained C_{wp} correlation is:

$$C_{wp} = C_{wp}(2)-\left(C_{wp}(1)+C_{wp}(2)+C_{wp}(3)+C_{wp}(4)\right)\begin{Bmatrix}a_2\sin(\theta)+b_2\left(\sin(\theta)\right)^2\\ +c_2\cos(\theta)\sin(\theta)\\ +d_2\cos(\theta)\left(\sin(\theta)\right)^2\end{Bmatrix} \quad (7)$$

Where: a_2 = 3.057E-3, b_2 = -3.3762E-1, c_2 = -8.2012E-3, and d_2 = 1.4803E-2.

The calculated values of the pressure coefficients using the present correlation (Eq. (6) and Eq. (7)) and that obtained using Walker and Wilson [54, 56] are compared with measurements by Akins et al. [55] in Figure 6 and Figure 7. As shown in Figure 7, the calculated values of C_{wp} using Walker and Wilson [54] are within +5% and -10%, and within +10% and -20% of the measured values of C_{wp} by Akins et al. [55] for the cases of infiltration and exfiltration, respectively. However, the calculated values of C_{wp} using the present correlation are in good agreement with the measured values of C_{wp} by Akins et al. [55] to within $\pm$ 5% for both infiltration and exfiltration cases. The present correlation for C_{wp} was used in this project.

As indicated earlier, the higher the exfiltration rate, the greater the risk of condensation and subsequent mould growth. For each climatic location, the weather data was analyzed to identify the orientation of the wall assembly yielding the highest exfiltration rate. An example of these analyses is shown in Figure 8 for a wall assembly subjected to climatic conditions of Ottawa. As shown in this figure, a wall system facing south has the highest exfiltration rate. The corresponding hourly wind pressure of that wall is shown in Figure 9. For each climatic condition, all numerical simulations were conducted for the wall assemblies listed in Table 2 and Table 3 that face the direction yielding highest exfiltration rate and which is assumed represents the worst case scenario.

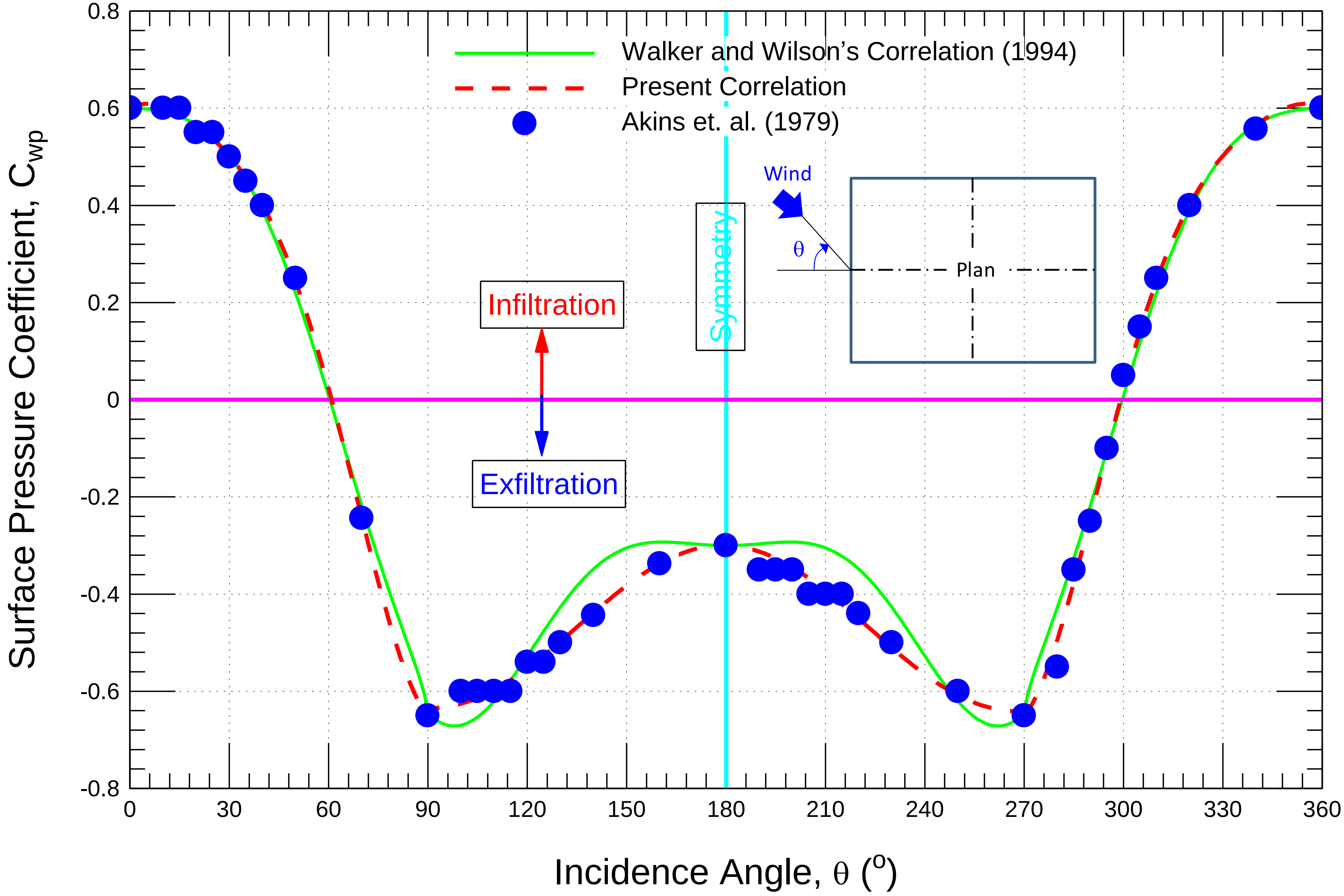


Figure 6. Comparison of calculated pressure coefficients using present correlation and Walker and Wilson correlation [54] with the measurements [55].

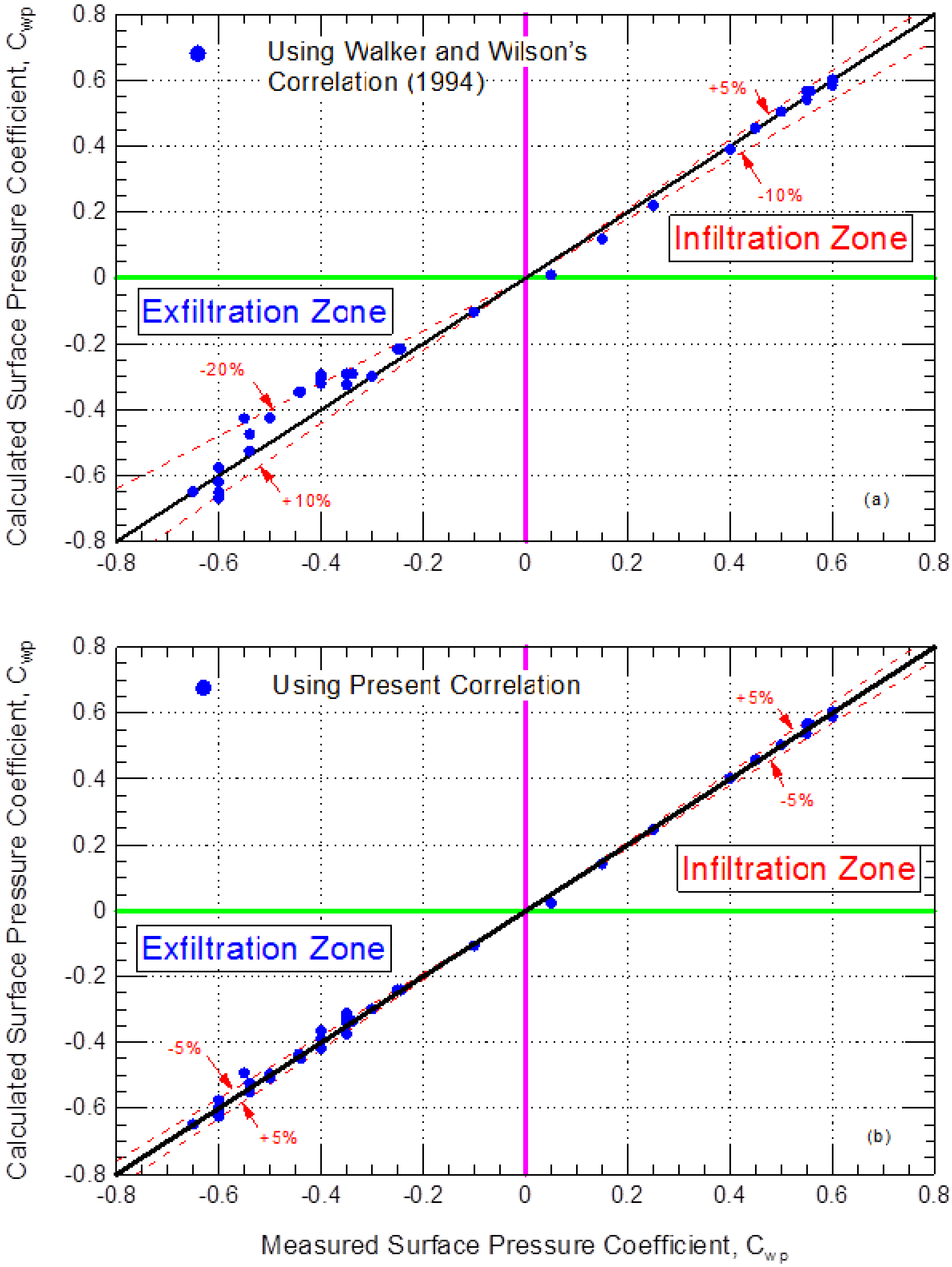


Figure 7. Comparison of measured [55] and calculated pressure coefficients using: (a) Walker Wilson correlation [54], and (b) present correlation.

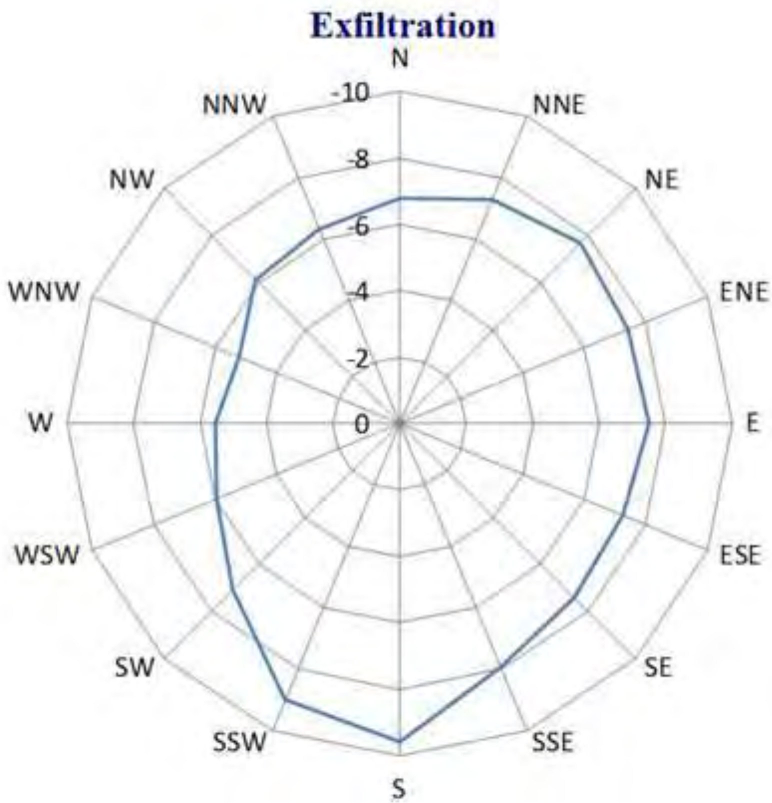


Figure 8. Exfiltration: Average yearly negative wind pressure in Pa (Ottawa weather)

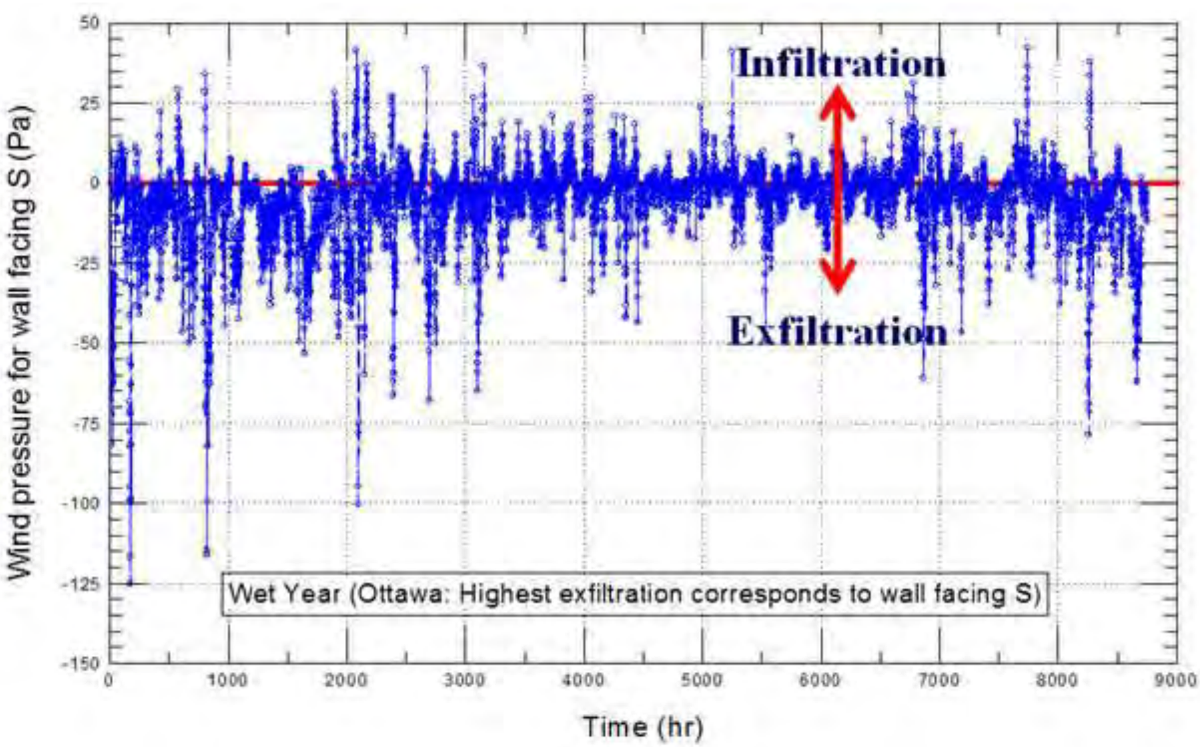


Figure 9. Hourly wind pressure of wall facing south (Ottawa weather)

Climatic Conditions

The wall assemblies shown in Figure 1 (with structural sheathing) and Figure 2 (without structural sheathing) and listed in Table 2 and Table 3 are subjected to different climate conditions of four different locations across Canada and having differing values of Heating Degree Days (HDD) and Moisture Index (MI), namely:

- **Vancouver, BC** (mild, wet, HDD18 = from 2600 to 3100, MI = 1.44),
- **St John's, NL** (cold, wet, HDD18 = 4800, MI = 1.41),
- **Ottawa, ON** (cold, dry, HDD18 = 4440 - 4500, MI = 0.84), and
- **Edmonton, AB** (cold, dry, HDD18 = 5120, MI = 0.48).

These locations were selected for the following reasons:

- To represent climatic conditions that might pose a significant risk to moisture accumulation in a wall assembly.
- The availability of field data with respect to wall assemblies (Vancouver and Ottawa).
- To represent a climate zone, where energy efficiency requirements can be satisfied with an interior R-24 insulation product or with traditional R-19 batts and exterior insulation in a sufficiently cold climate to cause potential risk to the formation of condensation in the wall assembly (Edmonton).

Wall assemblies of the third storey of low-rise buildings were modeled in the orientation showing the highest average annual exfiltration rate. Walls were assumed to be shaded to minimize the impact of solar-driven moisture ingress into the assembly and to minimize the solar drying effect on the wall. However, diffuse radiation was taken into consideration.

Weather Data

Hygrothermal simulations were conducted for a period of two years where the first year corresponded to an average year (conditioning year, where equal drying and wetting potential exists (MI)) and the second year corresponded to a wet year. The weather data of the different locations were obtained from the NRC's weather database.

Indoor Conditions

Regarding to the indoor moisture load, it was proposed as per the statement of work (SoW) that the water vapour pressure differential across the wall assembly (from indoor to outdoor) correspond to a moisture load of 5.2 g/m³, which is consistent with previous studies, in which a moisture load of 7.1 L/day was chosen for a 1 storey, 80 m² house, with indoor temperature 21°C, water vapour pressure differential close to 700 Pa, and 0.3 ACH by mechanical ventilation. In this case, $\Delta P_v = P_{v,indoor} – P_{v,outdoor}$ = 700 Pa, which is referred to Option-A. Given the climatic conditions of Ottawa, as an example, the indoor relative humidity (RH_{ind}) of Option-A is shown in Figure 10. As shown in this figure, the Option-A resulted in a quite high RH_{ind}, which at times exceeded 100%. As such, discussions took place with clients and the Task Group (TG) on Low Permeance Materials to explore other options for the indoor relative humidity, namely:

- Option-B. This option was based on the method given in ASHRAE 160.
- Option-C. This option was similar to Option-A (i.e. ΔP_v = 700 Pa) but the value of RH_{ind} was capped at 70%.
- Option-D. This option was based on a modified ASHRAE 160 by reducing the interior RH with increasingly cold temperatures in the wintertime.

The indoor relative humidity profile within a period of one year is compared for the four options above in Figure 10. Further discussions with the clients and the TG resulted in recommending Option-C for the indoor relative humidity when conducting all numerical simulations of different wall assemblies that are listed in Table 2 and Table 3.

Regarding to the indoor temperature, cooling was to be used when the interior temperature reached 25°C to minimize summer condensation scenarios; such scenarios have not been fully addressed in the building envelope requirements of Part 9 of the NBCC 2010 [13].

Other indoor conditions were set according to that provided in the ASHRAE Standard 160 [57] with respect to recommendations for conditioned space.

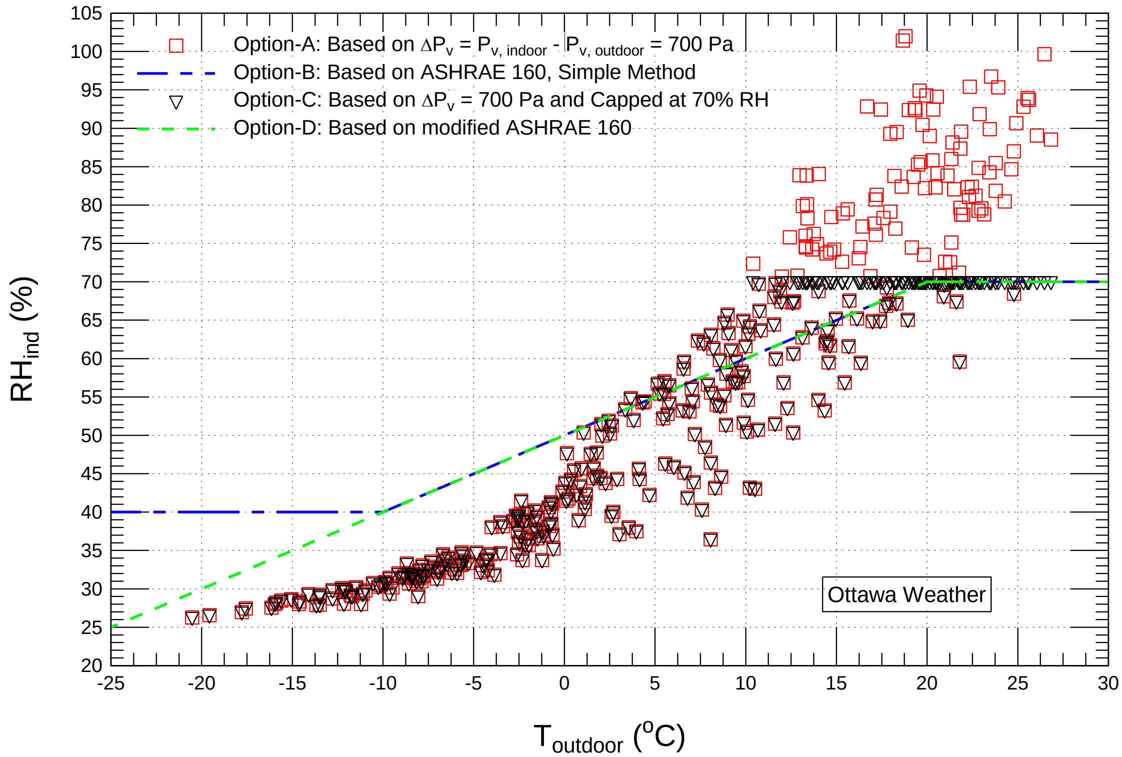


Figure 10. Different options for indoor relative humidity (Ottawa weather)

Initial Conditions

The initial temperature in all layers of the wall assemblies were taken equal to 21°C and the initial moisture content of all material layers corresponded to a relative humidity of 50%.

Material Properties

The hygrothermal properties of all material layers were obtained from the NRC's material database. However, the hygrothermal simulations were conducted using the constant R-value and constant Water Vapour Permeance (WVP) for the exterior insulation as indicated in Table 2 and Table 3. The thickness of the exterior insulation for the different values of thermal resistance (R-value) and WVP were taken as 1 inch. These values may not correspond with existing building products currently available on the market, but are instead selected to develop the necessary data in the region of interest (high inboard R-value, low outboard R-value, and medium permeance) from which to discern any trends as regards to the potential for the formation of condensation in the wall assembly.

A sheathing panel made of 7/16 inch (11 mm) thick OSB was considered for all wall assemblies with structural sheathing that are listed in Table 2 and Table 3. Glass [58] compiled the available data for the WVP of OSB (11 mm thick), which is shown in Figure 11. The recommended values of WVP of OSB as a function of relative humidity that were used in the numerical simulations are shown by the solid curve in this figure. A curve fit of these data is also provided in Figure 12.

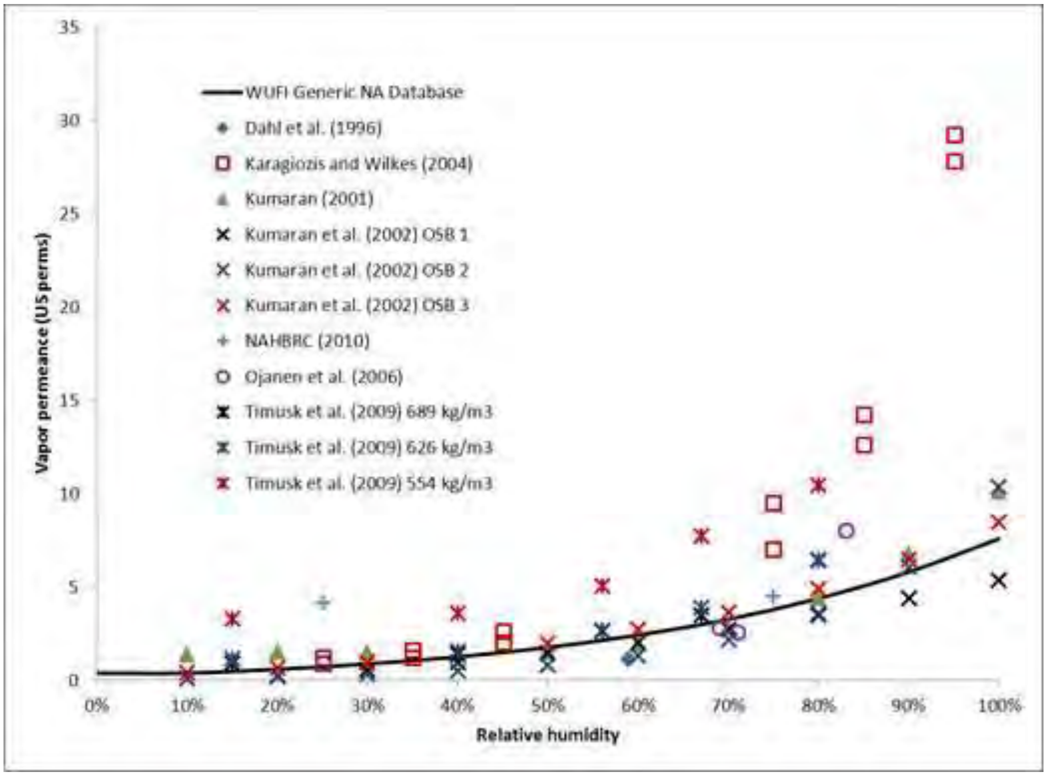


Figure 11. Dependence of water vapor permeance (WVP) of OSB of 11 mm thick on the relative humidity. Compilation of literature data by Glass [58].

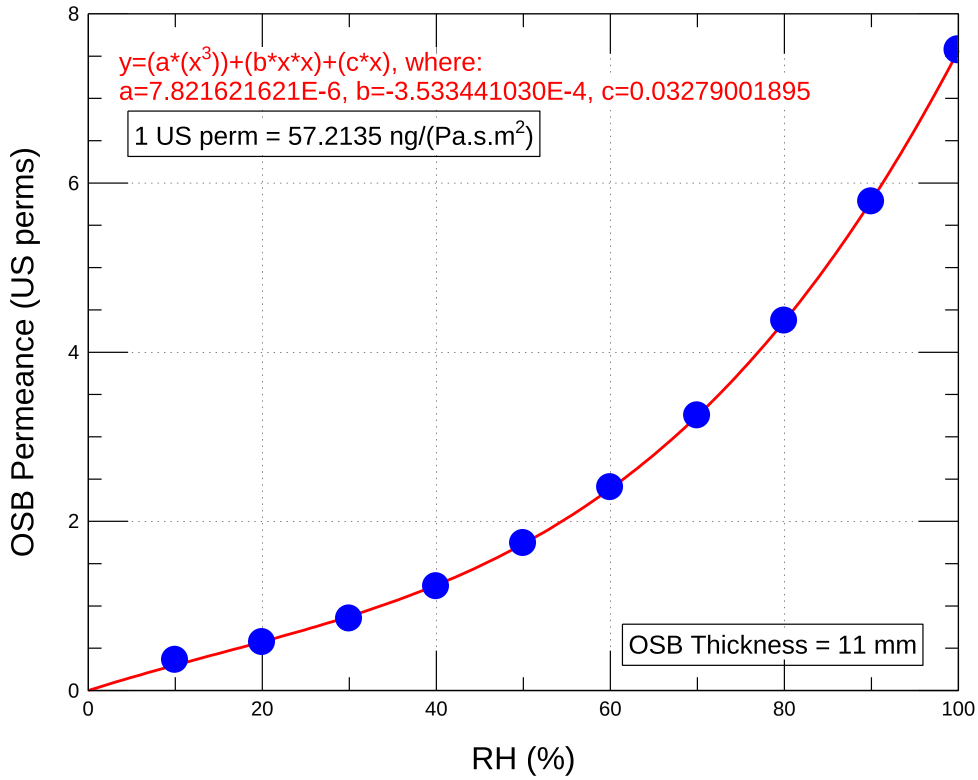


Figure 12. WVP of OSB of 11 mm thick that used in numerical simulations

Acceptable Performance

The modeling results for each case were expressed using the mould index (M) criteria developed by Hukka and Viitanen [59], Viitanen and Ojanen [60], and Ojanen et al. [61]. The selected mould index criteria allowed sufficient resolution to assess the risk of moisture condensation in those cases where the modeled assembly currently does not have to comply with the information provided in Table 9.25.5.2 of the NBCC 2010 [13] or where the modeled assembly does not comply, but the requirements apply. The descriptions of the mould index levels are provided in Table 5.

The most recent mould model by Ojanen et al. [61] was used in this project to determine the mould index of different materials of the wall assemblies listed in Table 2 and Table 3. In that model [61], the sensitivity of different construction materials for mould growth was classified in four sensitivity classes, namely, very sensitive, sensitive, medium resistant and resistant (see Table 6). Table 7 provides the assumed correspondence of sensitivity class for materials located within the wall assembly modelled in this study. More specifically, the sensitivity class for the top and bottom plates, OSB layer and foam layer was considered “Sensitive”, whereas the sensitivity class of the materials for cavity insulation (fiber-based), drywall and membranes was considered “Medium Resistant”.

Table 5. Description of Mould Index (M) levels [59, 60, 61]

M	Mould Index (M) Description of Growth Rate
0	No growth
1	Small amounts of mould on surface (microscope), initial stages of local growth
2	Several local mould growth colonies on surface (microscope)
3	Visual findings of mould on surface, < 10% coverage, or < 50% coverage of mould (microscope)
4	Visual findings of mould on surface, 10%–50% coverage, or > 50% coverage of mould (microscope)
5	Plenty of growth on surface, > 50% coverage (visual)
6	Heavy and tight growth, coverage about 100%

Table 6. Mould growth sensitivity classes and some corresponding materials [61]

Sensitivity Class	Materials	RH_{min} (%)#
Very Sensitive	Pine sapwood	80
Sensitive	Glued wooden boards, PUR with paper surface, spruce	80
Medium Resistant	Concrete, aerated and cellular concrete, glass wool, polyester wool	85
Resistant	PUR with polished surface	85

Minimum relative humidity needed for mould growth

Table 7. Mould growth sensitivity classes for different materials of wall assemblies listed in Table 2 and Table 3

Sensitivity Class	Material Layers of Wall Assemblies	RH_{min} (%)#
Very Sensitive		80
Sensitive	Top plate, bottom plate, OSB, foam	80
Medium Resistant	Fibre, gypsum, membranes	85
Resistant		85

Minimum relative humidity needed for mould growth

Sensitivity analyses on the Effect of Air Leakage Rate on the Hygrothermal Performance

A parametric study was conducted to investigate the effect of the air leakage rate on the hygrothermal performance of wall assemblies with and without structural sheathing. This parametric study was conducted to investigate the risk of mould growth in a wall assembly and permit identifying within the assembly the locations of likely mould growth given the different air leakage rates to which was subjected. In these analyses, the full amount of the air leakage rate is given by Eq. (1) and different percentages of that value, ξ, (i.e. ξ = 10%, 25%, 50% and 75%) were considered.

An example of these analyses is given for a wall assembly (Wall 104) with structural sheathing as shown in Figure 13. The contour shown in Figure 13b is a snapshot for the relative humidity within the different layers of the wall assembly when subjected to the climate of Ottawa over a period of two years and for the case of ξ = 100% (i.e. full amount of air leakage rate). Figure 13b shows the locations within the wall assembly at risk for the formation of condensation; these are predicted to occur at the top portion and bottom portion of the wall assembly in proximity, respectively, to the exit and entry points for air exfiltration across the assembly.

A series of figures illustrating the variation in average value of relative humidity of specific sections of Wall 104 as a function of air leakage rate when subjected to a period of two years of Ottawa climate[2] are provided in Figure 14 through Figure 21. These include average RH profiles for the:

- Entire OSB layer (Figure 14);
- 45 cm high portion at the bottom of the OSB layer (Figure 15);
- Interface between OSB and fibre-based cavity insulation (Figure 16);
- 45 cm high at the bottom portion of OSB – fibre interface (Figure 17);
- Entire bottom plate (Figure 18);
- Interface between top plate and fibre-based cavity insulation (Figure 19);
- Interface between OSB and exterior insulation (Figure 20); and
- 45 cm high at the bottom portion of the OSB – exterior insulation interface (Figure 21).

[2] Time = 0 in these figures corresponds to January 1st at 0.00 am.

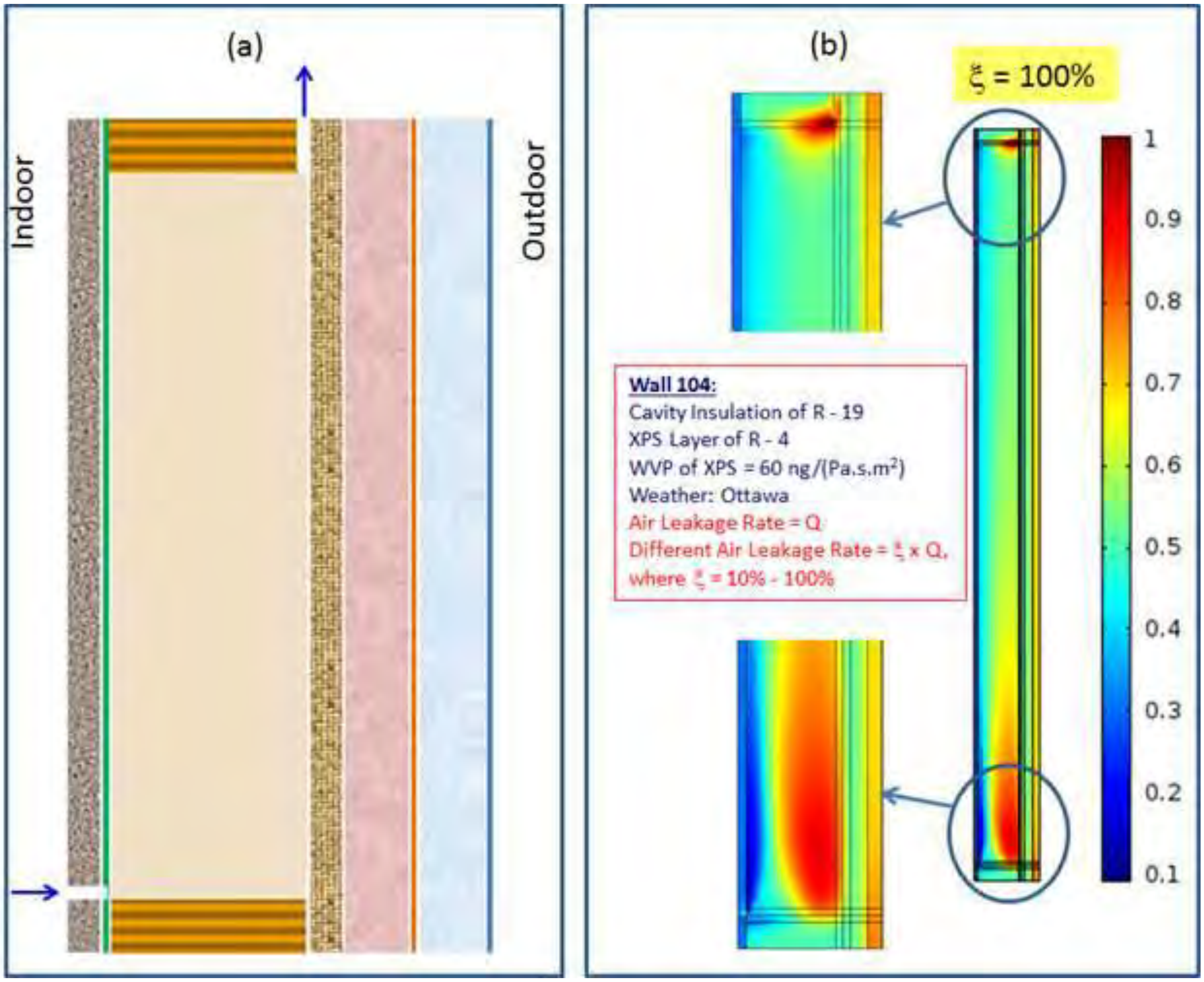


Figure 13. Schematic of Wall 104 and contours of the relative humidity showing the locations at high risk of condensation.

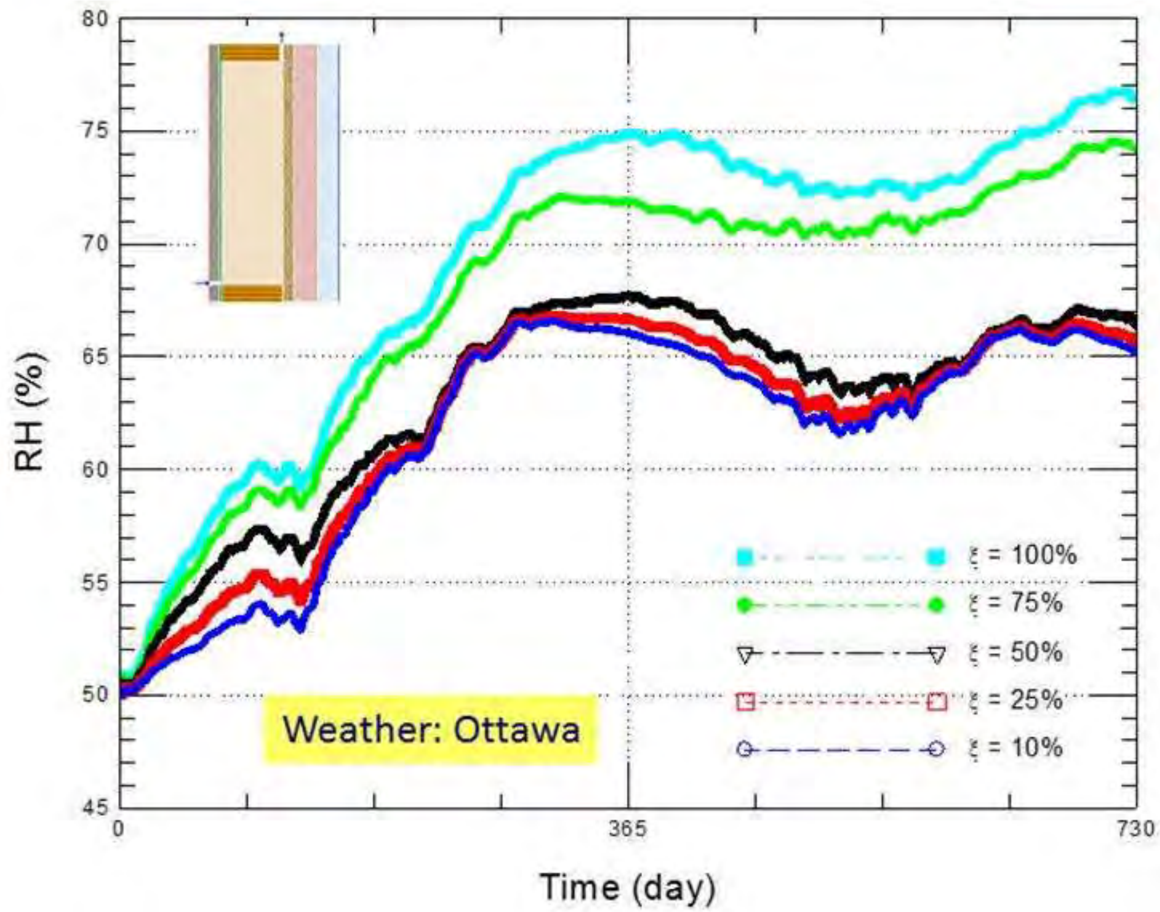


Figure 14. Average RH in the entire OSB layer of Wall 104 for different air leakage rates and subjected to Ottawa climate conditions over 2 years

The minimum relative humidity (RH_{min}) at which mould would grow depends on the sensitivity class of the material. Table 6 shows that the RH_{min} is 80% for very sensitive and sensitive materials, and 85% for medium resistant and resistant materials [61].

Figure 14 shows the dependence of the average RH for the entire OSB layer (7/16 inch thick and 8 ft high) during a period of two years where the first year corresponds to an average year and the second year corresponds to a wet year. As shown in this figure, decreasing the air leakage rate (from ξ = 100% (i.e. 0.1 L/(s•m²) at 75 Pa) to 10%) resulted in a decrease in the average RH of the OSB layer. By considering the average RH for the entire OSB layer, an air leakage rate of 0.1 L/(s•m²) at 75 Pa (i.e. ξ = 100%) or less results in a lower average RH of the OSB and at which no risk to mould growth would arise (see Table 7; average RH < 80%). As indicated earlier, however, the high risk of mould growth would occur in the bottom and top portions of the wall assembly (e.g. see Figure 13b).

Figure 15 shows the average RH in a 45 cm high portion at the bottom of the OSB at different air leakage rates. As shown in this figure, an air leakage rate of 50% of 0.1 L/(s•m²) at 75 Pa or less resulted in a lower average RH in the OSB and at which no risk of mould growth would arise (average RH < 80%). However, for air leakage rates of ξ = 75% and ξ = 100%, the highest average value of RH is 82% and 86%, respectively, resulting in a risk of mould growth in the bottom portion of the OSB layer.

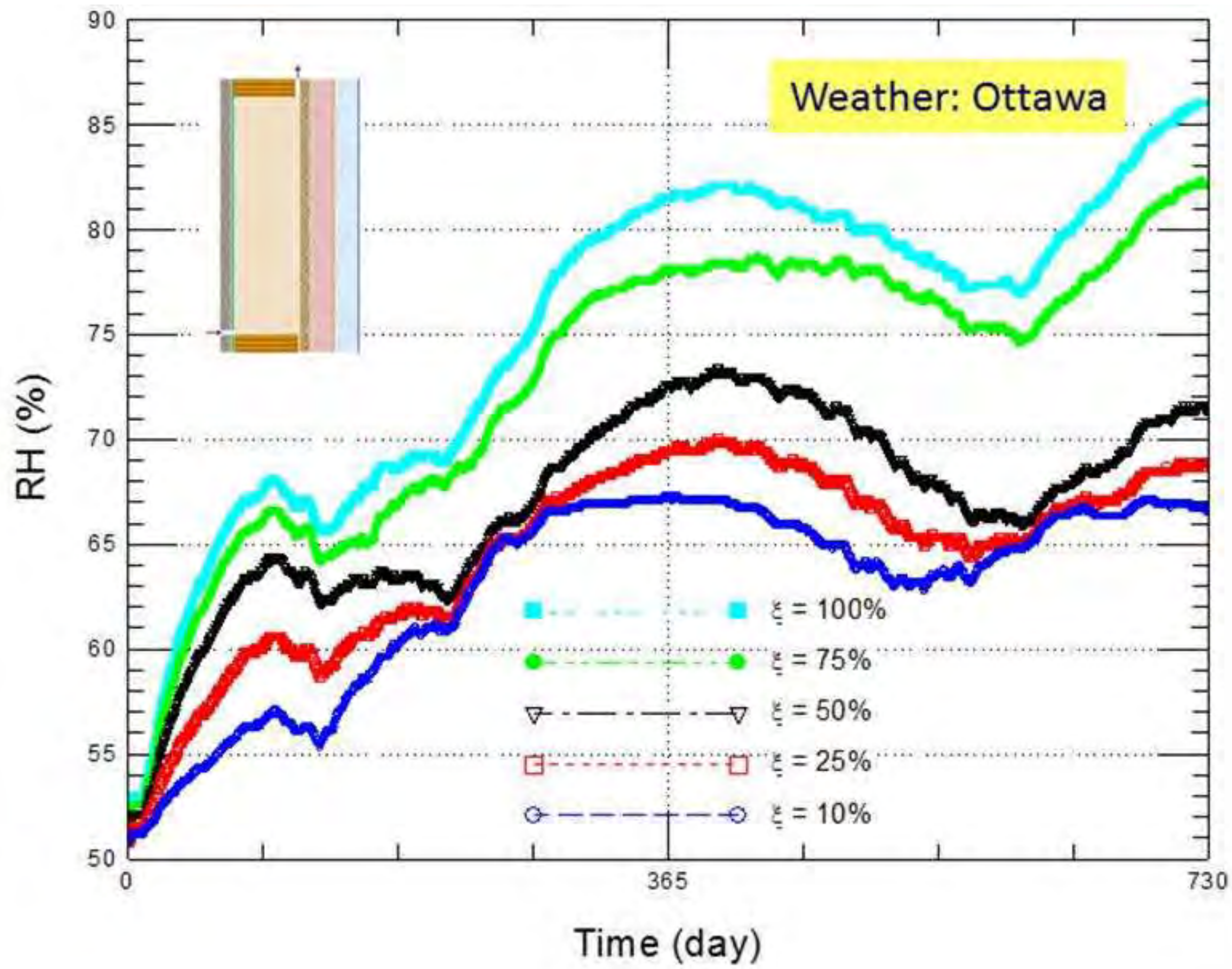


Figure 15. Average RH in the bottom portion of OSB layer of 45 cm high for different air leakage rates (Wall 104)

Examination the entire interface along the OSB and the fibre-based cavity insulation, as given in Figure 16, shows that the highest average RH of the OSB at different air leakage rates, is less than 80% and thus at no risk to mould growth. However, focusing on a 45 cm high portion at the bottom of the OSB along the interface with the fibre-based insulation, as seen in Figure 17, an air leakage rate 50% or less resulted in no risk of mould growth. Whereas there is a risk to mould growth in this portion at air leakage rates of 75% and 100% of 0.1 L/(s•m²) at 75 Pa given that the average RH increases to above 80% (highest average RH = 85% and 93%, for air leakage rates of 75% and 100%, respectively).

In Figure 18, it is seen that the bottom plate has no risk for mould growth as the RH is lower than 80% for the different air leakage rates.

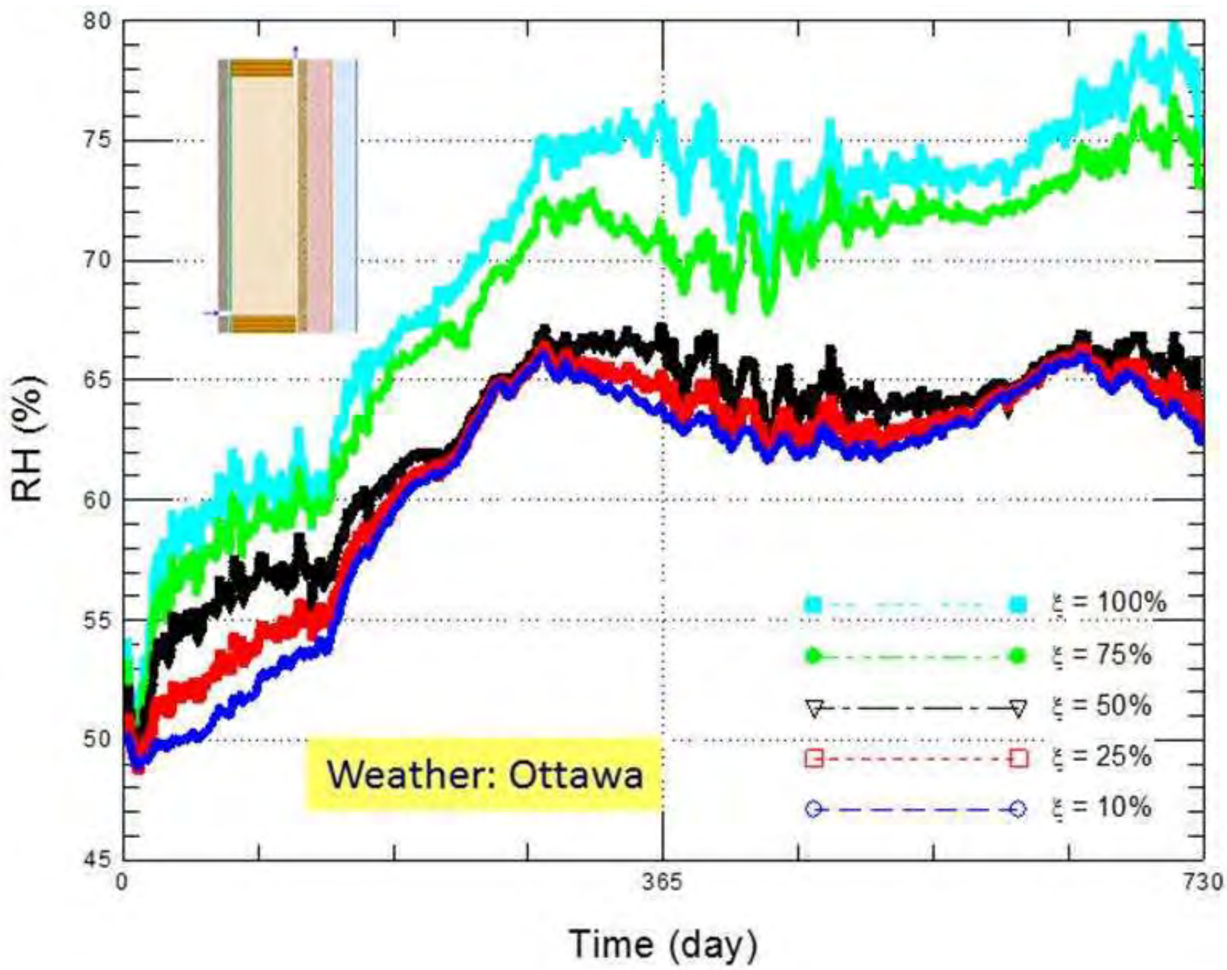


Figure 16. Average RH at whole OSB – fibre interface for different air leakage rates (Wall 104)

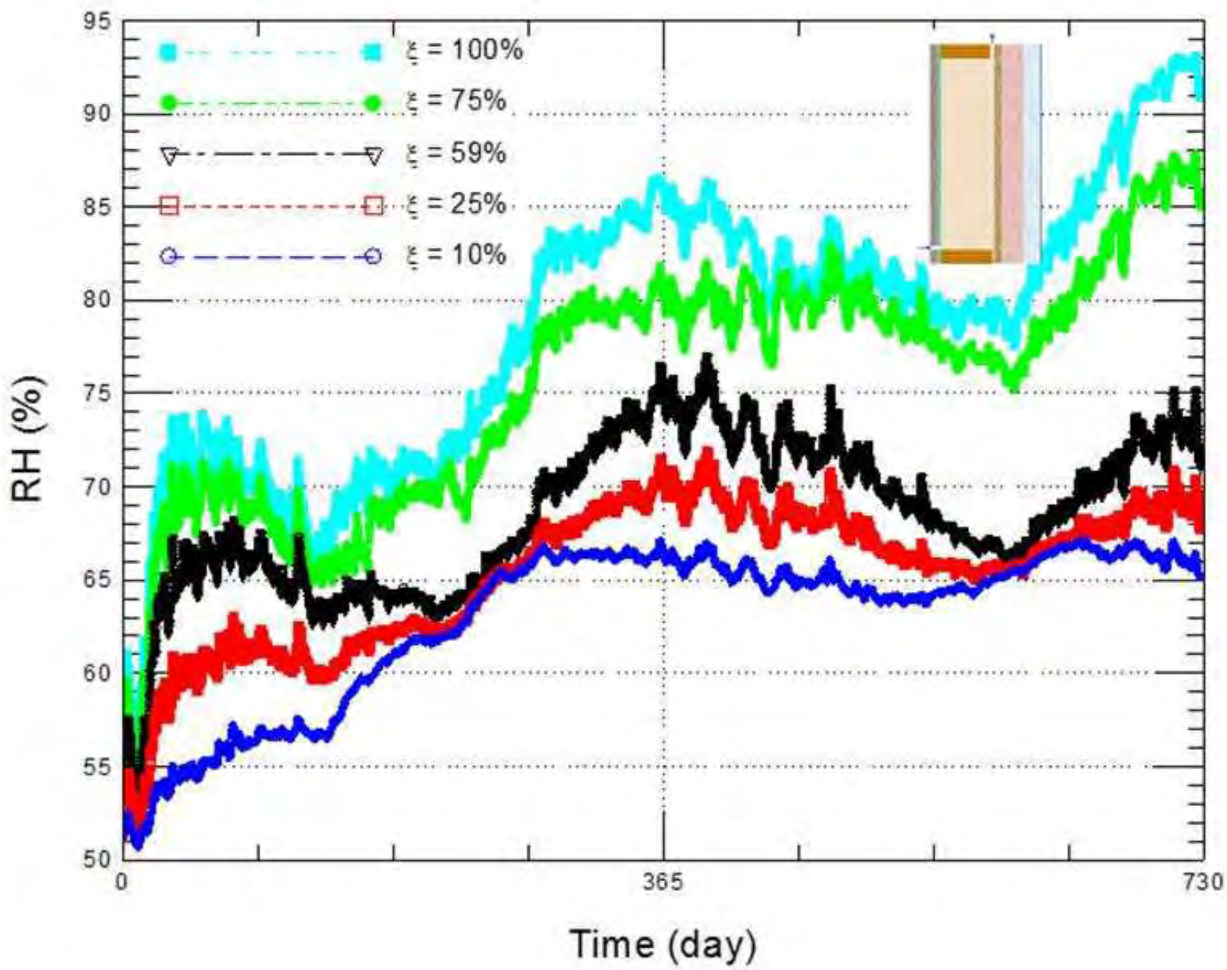


Figure 17. Average RH at the bottom portion of OSB – fibre interface of 45 cm high for different air leakage rates (Wall 104)

The average RH at the interface between the top plate and the fibre-based cavity insulation is shown in Figure 19. As shown in this figure, no risk for the occurrence of mould growth is evident in instances where the air leakage rate is 50% of 0.1 L/(s•m²) at 75 Pa or less, whereas there is a risk for mould growth at air leakage rates of 75% and 100% given that the average RH at the top plate – fibre interface is above 80% (highest average value of RH = 86% and 90%, for air leakage rate of 75% and 100%, respectively).

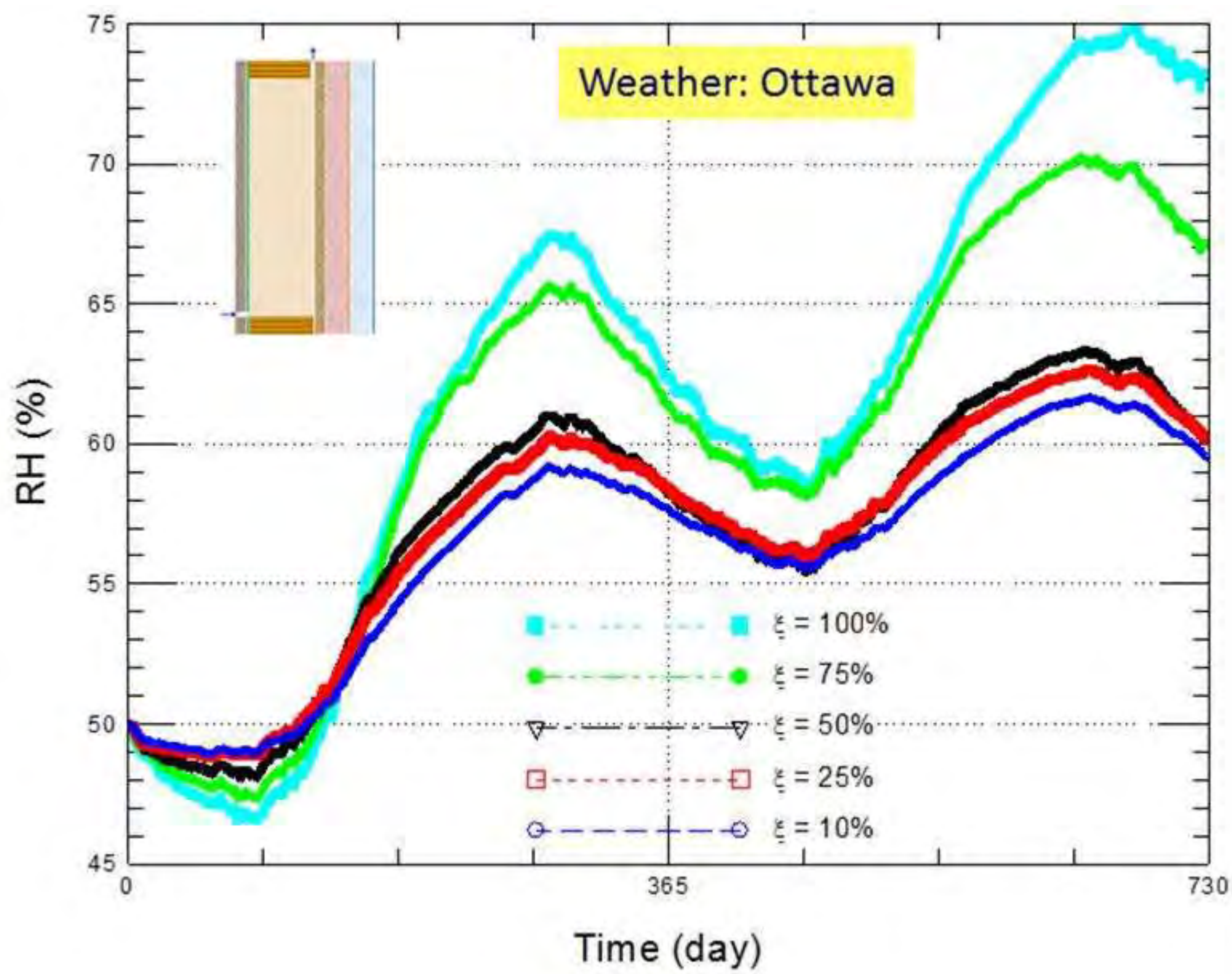


Figure 18. Average RH in the whole bottom plate for different air leakage rates (Wall 104)

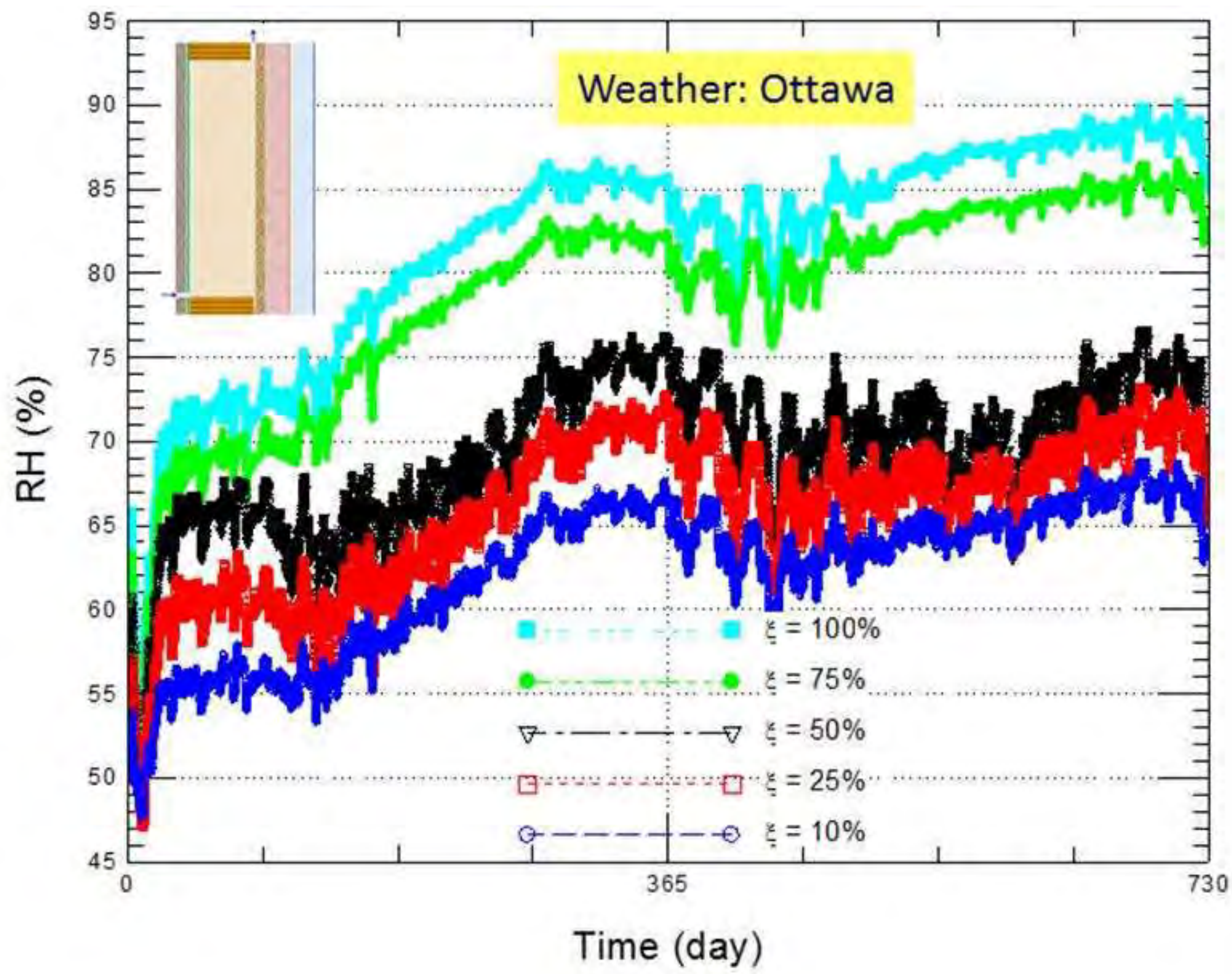


Figure 19. Average RH at top plate – fibre interface for different air leakage rates (Wall 104)

Looking at the interface along the entire height of the OSB and the exterior insulation, the highest average RH, as shown in Figure 20, is less than 80% at the different air leakage rates; as such there is no risk of mould growth along this interface.

As shown in Figure 21, for the 45 cm high portion at the bottom of the OSB – along the interface with the exterior insulation, there is no risk for mould growth at an air leakage rate of 50% or less whereas at air leakage rate of 75% and 100% there is a risk for mould growth given the higher value for the average RH in this location (i.e. highest average RH = 81% and 84%, for the cases of 75% and 100% of air leakage rate, respectively).

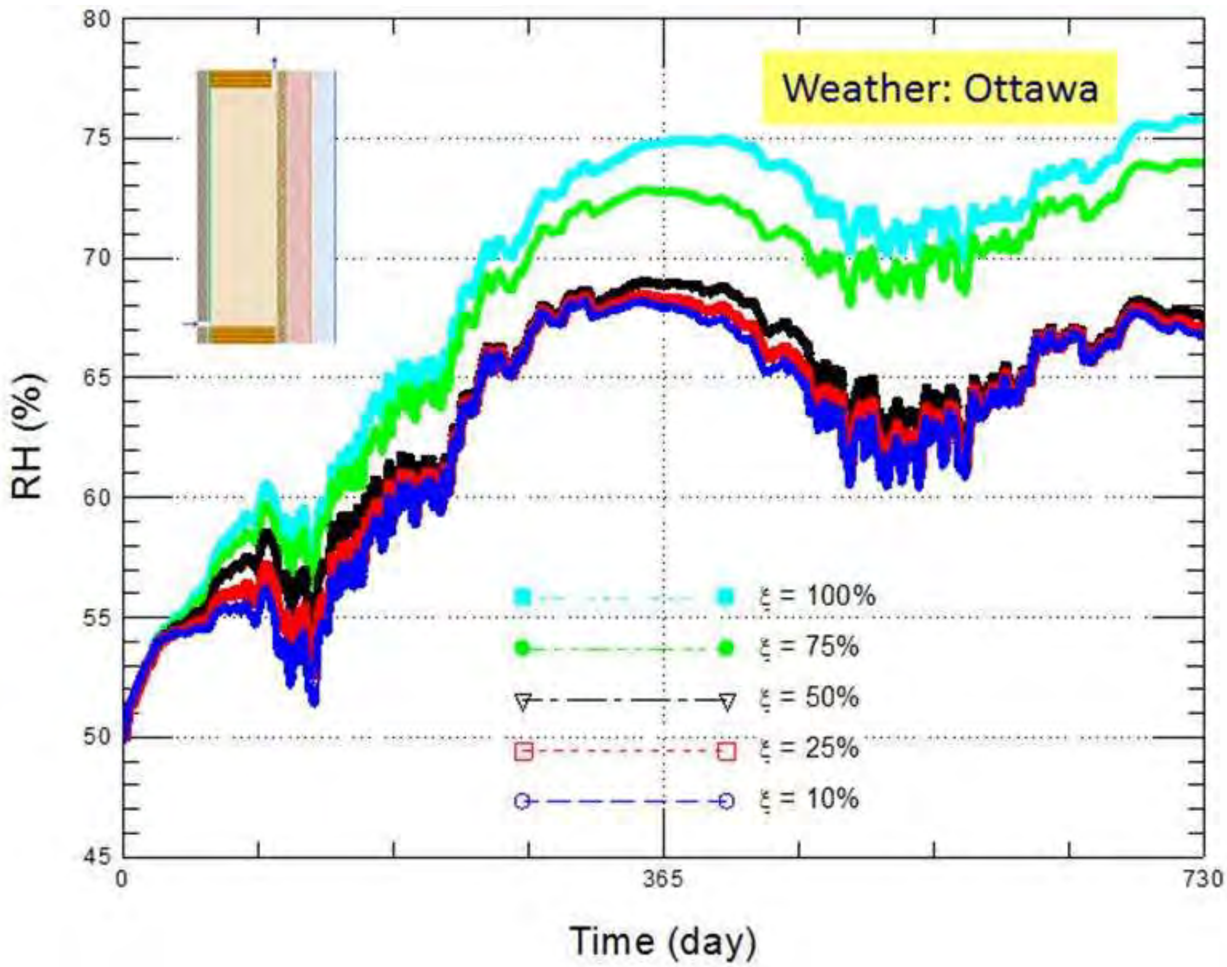


Figure 20. Average RH at OSB – exterior insulation interface for different air leakage rates (Wall 104)

In summary, a parametric study was conducted to investigate the effect of the air leakage rate on the risk of mould growth in a wall assembly and to help identifying locations in the cavity that were at risk to mould growth, hence critical locations in the assembly. An example was presented in this section for the Wall 104 (includes structural sheathing panel), subjected to climatic conditions of Ottawa over a period of two years. Results showed that at air leakage rates of 75% and 100% of 0.1 L/(s•m²) at 75 Pa there was a risk for mould growth in the wall assembly. However, at air leakage rates of 50% or less no risk of mould growth was evident given that the components in the wall assembly did not reach a threshold value of RH at which mould would likely grow. Note that at a pressure differential of 75 Pa, an air leakage rate of 50% corresponds to an air leakage of 0.05 L/(s•m²) where 100% corresponds to 0.1 L/(s•m²).

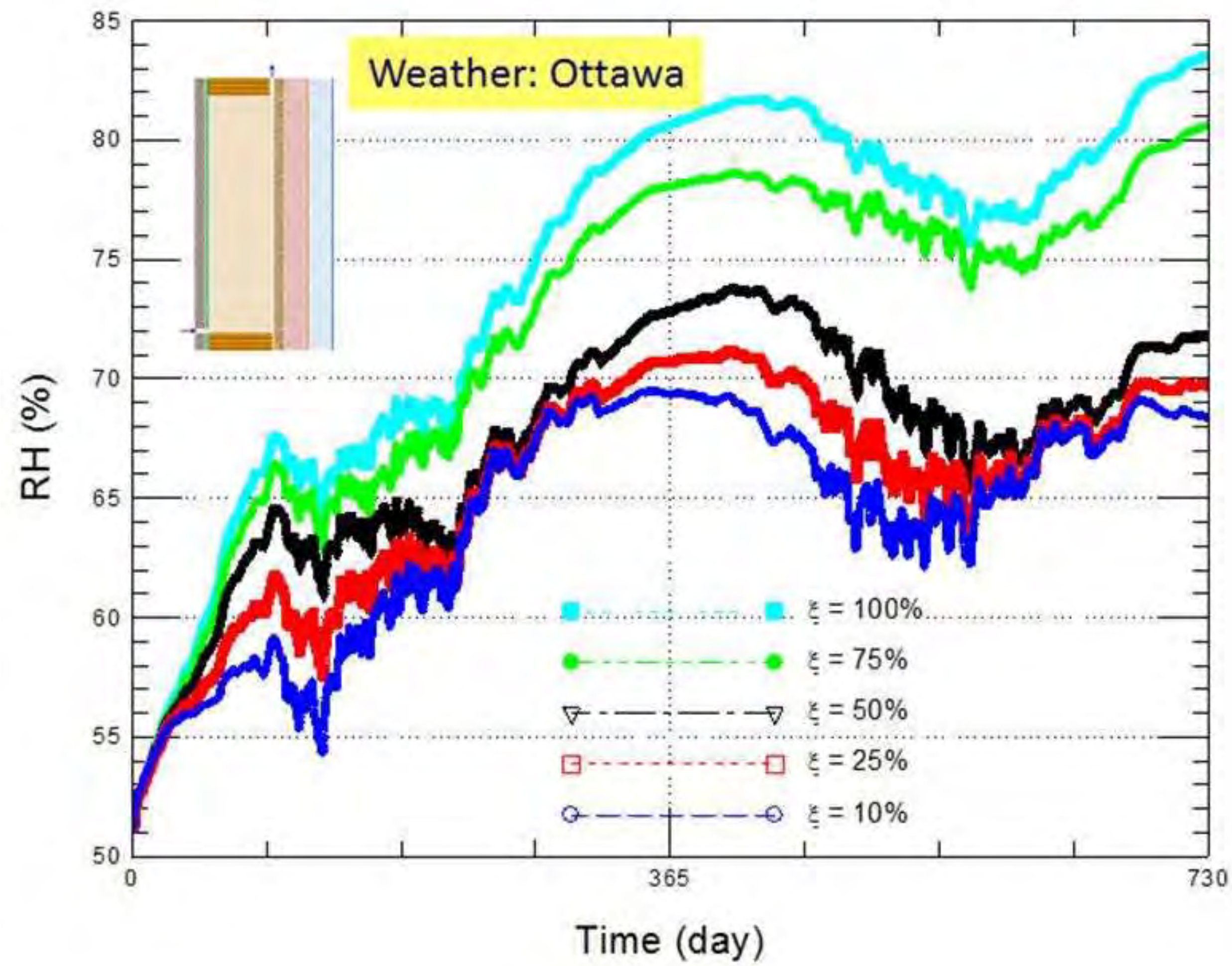


Figure 21. Average RH at the bottom portion of the OSB – exterior insulation interface of 45 cm high for different air leakage rates (Wall 104)

A summary of simulated conditions that were used in the numerical modeling for all wall assemblies is provided in Table 8. The critical locations inside the wall assembly at risk of mould growth were identified and in general these locations are the top portion and bottom portion of the wall assembly (see Figure 22). However, after conducting the numerical simulations for all wall assemblies with and without structural sheathing (see Table 2 and Table 3), the different locations at risk for the formation of condensation and mould growth are listed in Table 9. At these locations, the Mould Index (M) was calculated for the different wall assemblies on the basis of the mould sensitivity classes of the different materials layers within the wall assembly as provided in Table 7.

It is important to point out that the locations within the wall assemblies at risk of condensation and mould growth (listed in Table 9 and shown in Figure 22) are based on the air leakage path that is considered in this study and shown in Figure 1 and Figure 2. Considering a different air leakage path, however, would result in different locations within the wall assemblies at risk of condensation and mould growth.

Table 8. Summary of simulated conditions

Criteria	Assumptions/Conditions
Pressure exponent	0.7
Predominant wall orientation	Facing the highest exfiltration rate
∆P for stack effect	Top storey of a 3-storey building to maximize the effect of exfiltration
∆P for ventilation	Assume depressurization/pressurization from ventilation source is negligible
Air leakage rate	Corresponds to 0.1 L/(s•m^2) at 75 Pa
Interior moisture load	Constant water vapour pressure differential, ΔP_v = 700 Pa and capped at 70% RH
Water vapour permeance of OSB	Function of the relative humidity ranging from 0-100% as recommended by Glass [58]
Modeling period	Two years – Jan to Dec: one average year followed by one wet year
Geographical locations	Ottawa, Edmonton, Vancouver and St John's

Table 9. List of locations at risk of condensation at which the mould index are evaluated

(a) Wall with Structural Sheathing	(b) Wall without Structural Sheathing
Top Plate Layer	Top Plate Layer
Top Plate – Fiber Interface	Top Plate – Fiber Interface
Fiber (1 cm thick & 18" high)	Fiber (1 cm thick & 18" high)
Fiber (1 cm thick & 12" high)	Fiber (1 cm thick & 12" high)
OSB-Fiber Interface (12" high)	Foam-Fiber Interface (12" high)
Fiber (1 cm thick & 6" high)	Fiber (1 cm thick & 6" high)
OSB-Fiber Interface (6" high)	Foam – Fiber Interface (6" high)
Top Plate Layer (2" long)	Top Plate Layer (2" long)
Top Fiber of 1 cm high (2" long)	Top Fiber of 1 cm high (2" long)
Top Fiber of 1 cm high - Fiber interface (2" long)	Top Fiber of 1 cm high - Fiber interface (2" long)
Top Plate – Fiber Interface (2" long)	Top Plate – Fiber Interface (2" long)
Top Plate Layer (2.5" long)	Top Plate Layer (2.5" long)
Top Fiber of 1 cm high (2.5" long)	Top Fiber of 1 cm high (2.5" long)
Top Plate – Fiber Interface (2.5" long)	Top Plate – Fiber Interface (2.5" long)
Top Fiber of 1 cm high – Fiber interface (2.5" long)	Top Fiber of 1 cm high – Fiber interface (2.5" long)

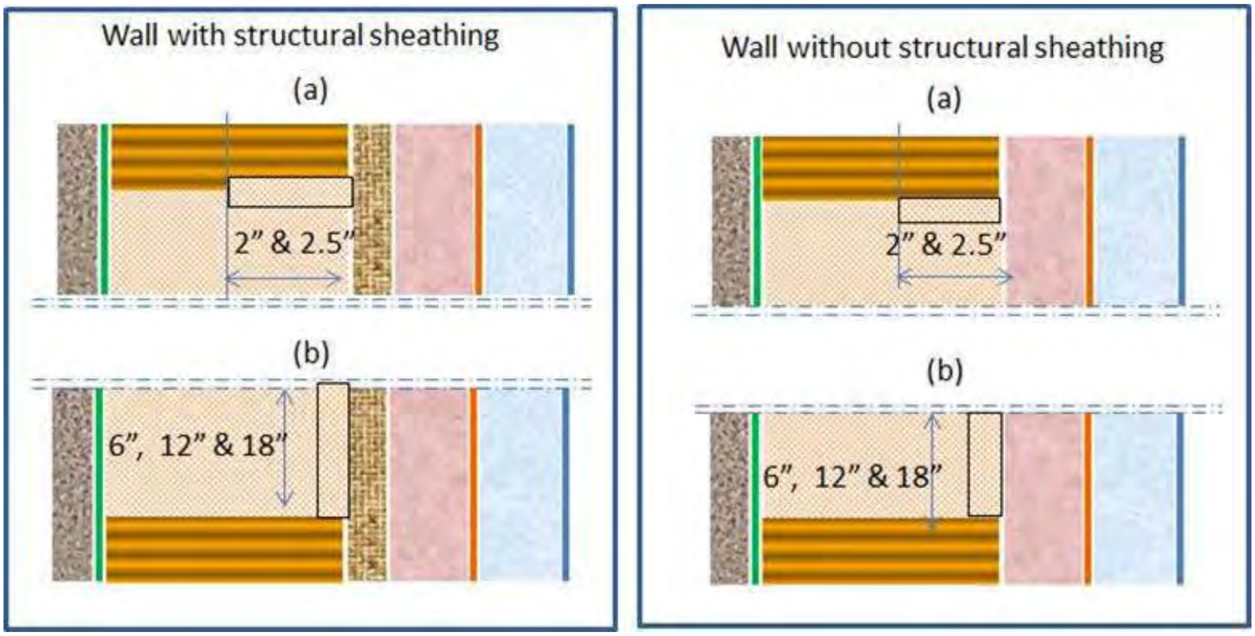


Figure 22. Locations in wall assembly at risk of formation of condensation and mould growth: (a) Location at top plate and in the top plate, the insulation, and along interface between top plate and insulation layers; (b) at base plate of wall assembly in insulation and along interface between sheathing panel and insulation

Results and Discussion

In this section, the effects of different parameters that affect the hygrothermal performance of wall assemblies are discussed. The list of wall assemblies with structural sheathing is provided in Table 10, and the list of wall assemblies without structural sheathing is provided in Table 11. In this report, in instances where the units for Water Vapour Permeance (WVP) and R-value are not reported, the units for each of these parameters are respectively, as ng/(Pa•s•m²) and ft^2•h•°F/BTU.

The different parameters affecting the hygrothermal performance of wall assemblies and discussed in this section include the effect of:

- Geographical locations;
- Water Vapour Permeance of the exterior insulation; and
- R-value of exterior insulation.

Effect of geographical locations on hygrothermal performance

The hygrothermal performance for different wall assemblies listed in Table 10 and Table 11 were obtained when these walls were subjected to the climate of four cities each differing in geographical location and that included: Ottawa, Edmonton, Vancouver and St. John's. The primary environmental parameters that greatly affect the hygrothermal performance are:

i. The outdoor temperature (can be represented by the Heating Degree Days, HDD). The greater the number of HDD the higher the risk for mould growth in a wall assembly. Among other geographical locations, Edmonton has the highest HDD (HDD = 5120), followed by St John's (HDD = 4800).

ii. The outdoor relative humidity, as represented by the Moisture Index (MI). The higher the value of MI, the smaller the drying potential of a wall assembly and hence, the higher the risk of mould growth. Among other geographical locations, Vancouver has the highest MI (MI = 1.44), followed by St John's (MI = 1.41).

iii. The wind speed. The higher the wind speed, the greater the air leakage rate across the wall assembly, and hence, the higher the risk for mould growth within the wall assembly (see section "Sensitivity analyses on the Effect of Air Leakage Rate on the Hygrothermal Performance"). The air leakage rates of the different geographical locations are shown in Figure 23 through Figure 26. As shown in these figures, among other geographical locations, St John's has the highest air leakage rate.

Table 10. Wall assemblies with structural sheathing

Walls with Structural Sheathing			
Cavity Insulation		Exterior Insulation	
R-19	R-24	R (ft^2.h.^{o}F/BTU)	WVP (ng/Pa•s•m^2)
REF1	REF2	None	None
Wall 102	Wall 120	4	2
Wall 219	Wall 222	4	45
Wall 104	Wall 122	4	60
Wall 106	Wall 124	4	90
Wall 231	Wall 234	4	200
Wall 207	Wall 210	4	300
Wall 243	Wall 246	4	1800
Wall 108	Wall 126	5	2
Wall 220	Wall 223	5	45
Wall 110	Wall 128	5	60
Wall 112	Wall 130	5	90
Wall 232	Wall 235	5	200
Wall 208	Wall 211	5	300
Wall 244	Wall 247	5	1800
Wall 114	Wall 132	6	2
Wall 221	Wall 224	6	45
Wall 116	Wall 134	6	60
Wall 118	Wall 136	6	90
Wall 233	Wall 236	6	200
Wall 209	Wall 212	6	300
Wall 245	Wall 248	6	1800

Table 11. Wall assemblies without structural sheathing

Walls without Structural Sheathing			
Cavity Insulation		Exterior Insulation	
R-19	R-24	R (ft^2.h.^{o}F/BTU)	WVP (ng/Pa•s•m^2)
REF3	REF4	0.62	60
REF3-N1	REF4-N1	0.62	2
REF3-N2	REF4-N2	0.62	90
REF3-N3	REF4-N3	0.62	300
Wall 101	Wall 119	4	2
Wall 213	Wall 216	4	45
Wall 103	Wall 121	4	60
Wall 105	Wall 123	4	90
Wall 225	Wall 228	4	200
Wall 201	Wall 204	4	300
Wall 237	Wall 240	4	1800
Wall 107	Wall 125	5	2
Wall 214	Wall 217	5	45
Wall 109	Wall 127	5	60
Wall 111	Wall 129	5	90
Wall 226	Wall 229	5	200
Wall 202	Wall 205	5	300
Wall 238	Wall 241	5	1800
Wall 113	Wall 131	6	2
Wall 215	Wall 218	6	45
Wall 115	Wall 133	6	60
Wall 117	Wall 135	6	90
Wall 227	Wall 230	6	200
Wall 203	Wall 206	6	300
Wall 239	Wall 242	6	1800

Figure 27a & b show comparisons of the mould index (M) at the bottom portion of the wall assembly at:

a. OSB-fibre interface of 12" high, and
b. fibre of 1 cm thick and 12 inch high (adjacent to OSB layer) for the reference wall with structural sheathing (REF1) that is subjected to the climatic conditions of Ottawa, Edmonton, Vancouver and St John's.

Also, Figure 28a & b show a comparison of values for the mould index at the top portion of the wall assembly, specifically at:

a. top plate – fibre interface and
b. top plate layer of 2.5 inch long (adjacent to OSB layer) for same wall assembly (REF1).

Similar comparisons of the mould index for the reference wall without structural sheathing (REF3), subjected to the climatic conditions of different geographical locations are shown in Figure 29 and Figure 30.

As shown in this figures, the combined effects of the three environmental parameters, provided above, have brought about, in the case of walls subjected to the climatic conditions of Ottawa, the lowest value of mould index, whereas the highest value of mould index can be found for walls subjected to the climatic conditions of St John's.

For example, the maximum mould index during the simulation period (2 years) at the OSB-fibre interface of 12" high for wall REF1 (with structural sheathing) are 1.79, 3.61, 3.79 and 3.07 for the climatic conditions of Ottawa, Edmonton, St John's and Vancouver, respectively (see Figure 27a and Table 12), and the corresponding average value of mould index over the period of two years are 0.43, 1.20, 3.09 and 1.91 (Table 12). For the wall referred to as REF3 (without structural sheathing), the maximum value of mould index at the interface between the exterior insulation and foam-fibre of 12" high are 4.88, 5.30, 5.29 and 4.59 for the climatic conditions of Ottawa, Edmonton, St John's and Vancouver, respectively (see Figure 29a and Table 13), and the corresponding average values of mould index are 2.70, 3.25, 4.84 and 3.56 (Table 13).

Note that the maximum value of mould index as shown in Figure 27a and Table 12 at the interface between the OSB and the fibre-based cavity insulation (12" high) of the wall REF1 for the case of Edmonton (M_{max} = 3.61) is higher than that for the case of Vancouver (M_{max} = 3.07). Furthermore, the maximum value of mould index for the case of Edmonton occurs during a shorter period of time than that for the case of Vancouver. On the other hand, the average value of mould index in the case of Edmonton (M_{avg} = 1.20) is lower than that for the case Vancouver (M_{avg} = 1.91). For the wall REF3 (see Figure 29a and Table 13), the maximum value of mould index at the foam-fibre interface (12" high) for the case of Ottawa (M_{max} = 4.88, occurs during shorter period of time) is higher than that for the case of Vancouver (M_{max} = 4.59, occurs during longer period of time), but the average mould index in the case of Ottawa (M_{avg} = 2.70) is much lower than that for the case of Vancouver (M_{avg} = 3.56).

Because the maximum value of mould index may occur during a short period of time, the values of average mould index would be more representative for the overall hygrothermal performance of the wall assembly as compared to the values for the maximum mould index. Nevertheless, the results presented in this report will be given in terms of both the average and maximum mould index. For the wall REF1 and the wall REF3, and subjected to different climatic conditions, the average mould index (M_{avg}) and maximum mould index (M_{max}) during the simulation period (2 years) at different locations inside the wall assembly (see Table 9) are given in Table 12 and Table 13, respectively.

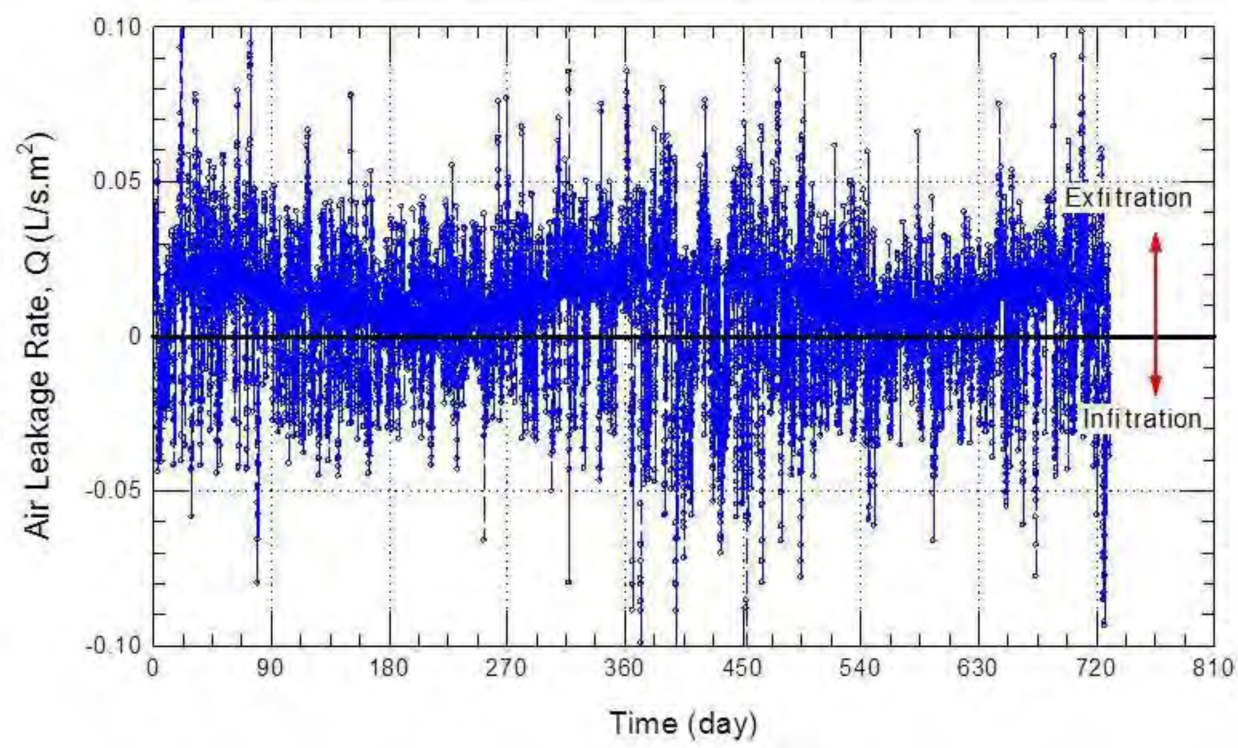


Figure 23. Air leakage rate for wall systems subjected to climatic condition of Ottawa

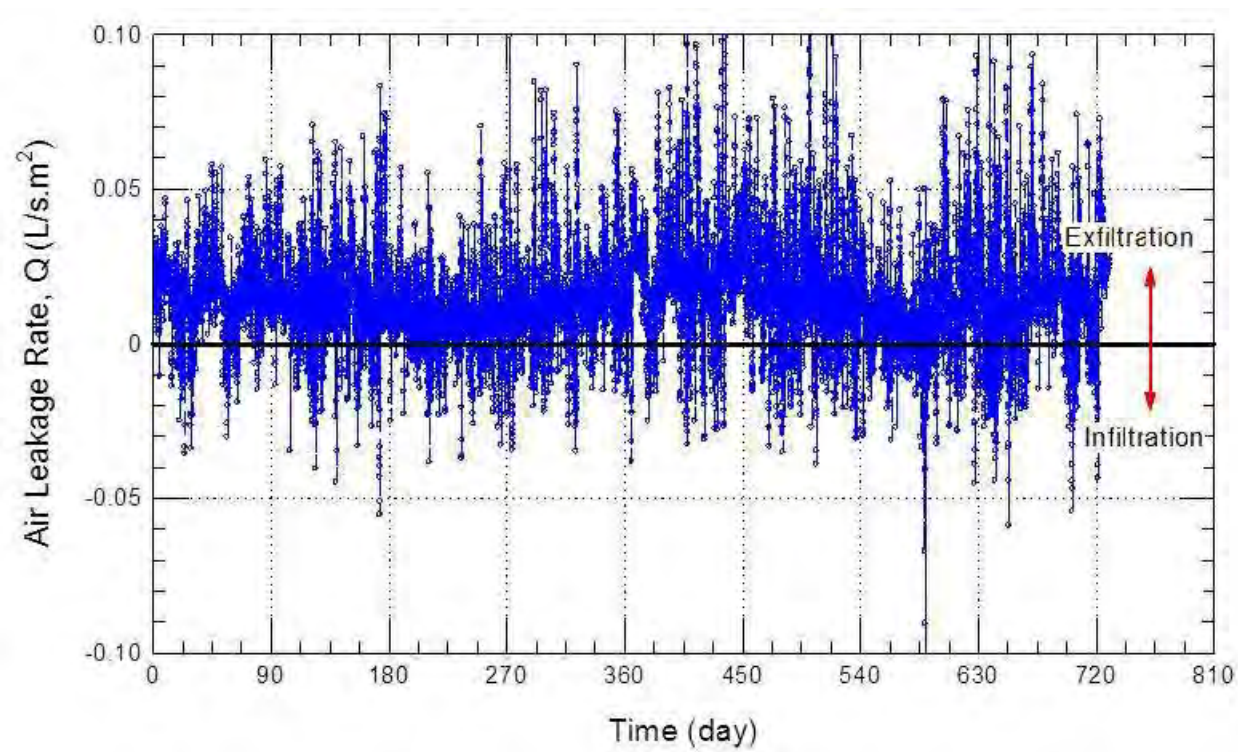


Figure 24. Air leakage rate for wall systems subjected to climatic condition of Edmonton

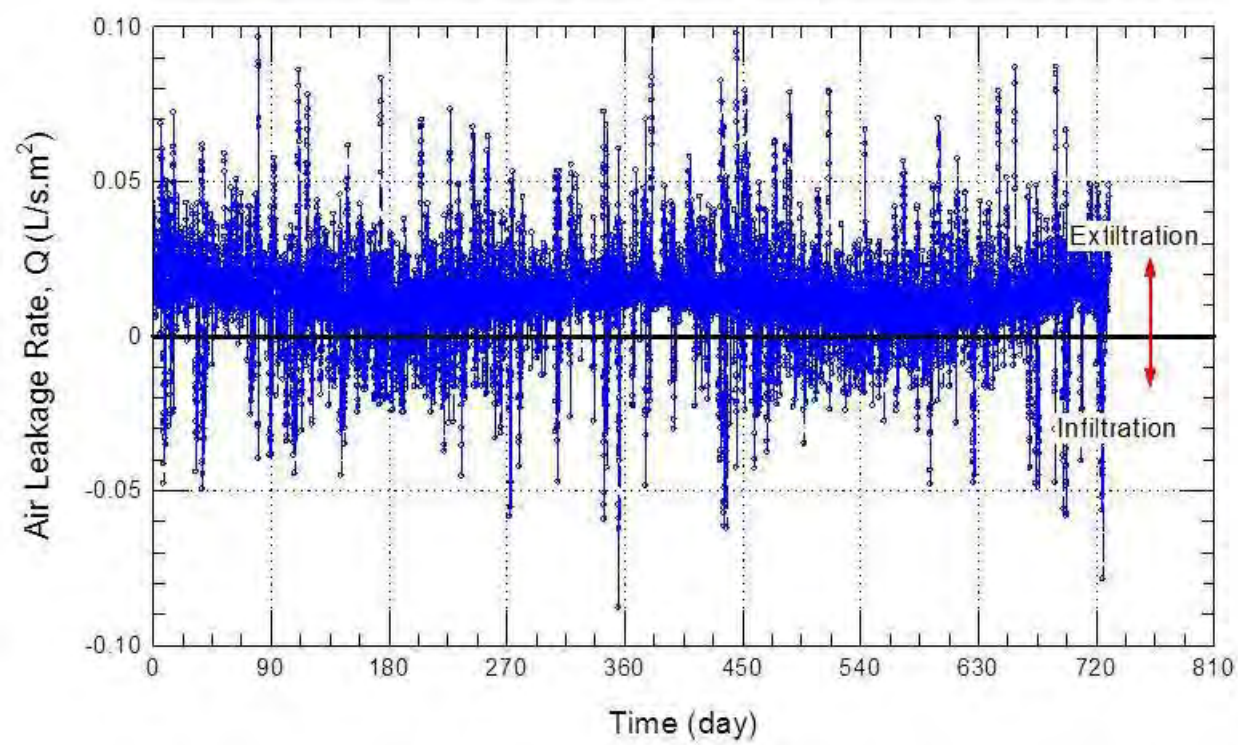


Figure 25. Air leakage rate for wall systems subjected to climatic condition of Vancouver

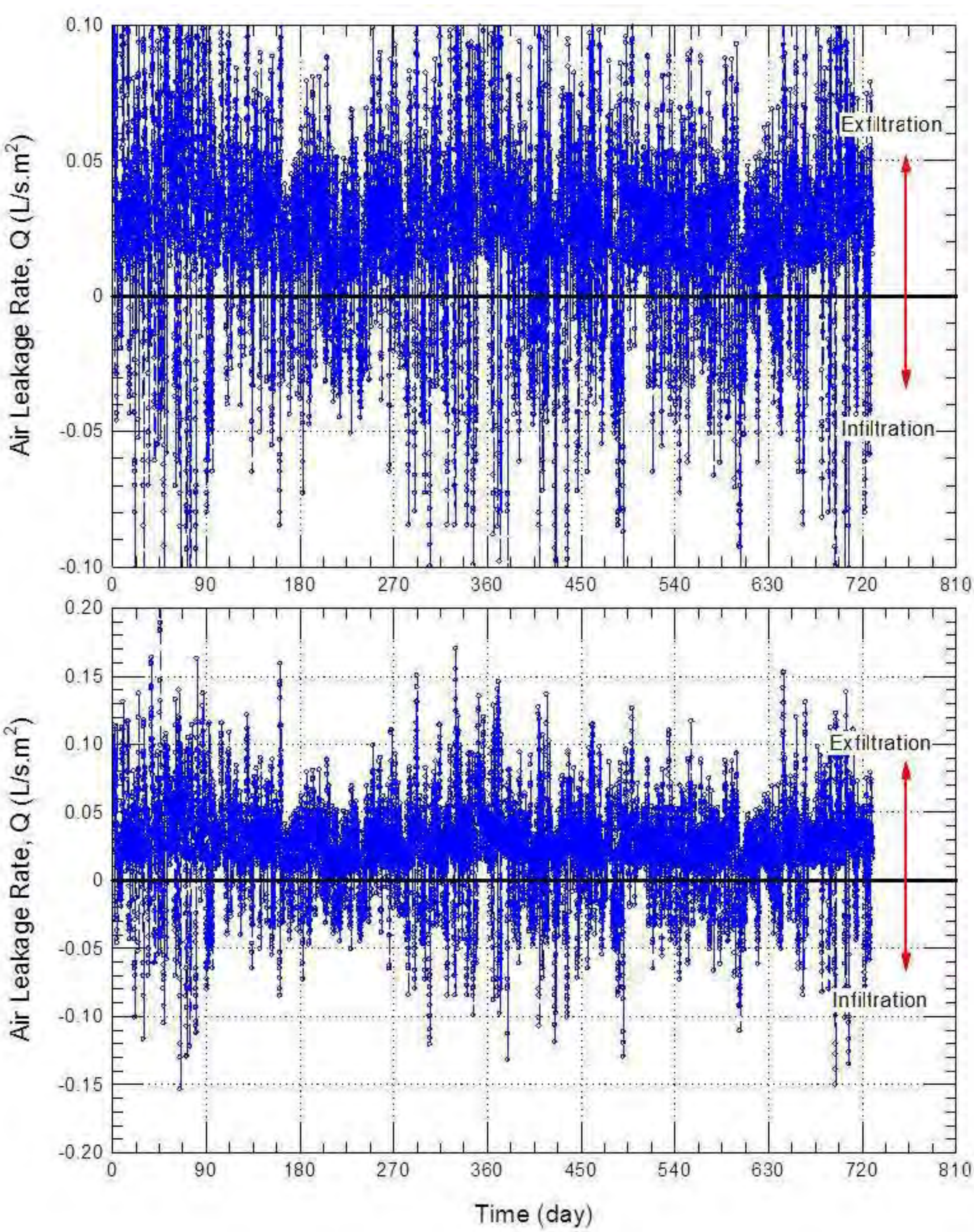


Figure 26. Air leakage rate for wall systems subjected to climatic condition of St John's

Table 12. Effect of geographical locations on the average and maximum mould index at different locations inside a reference wall assembly with structural sheathing (Wall: REF1)

Location	Wall	Top Plate Layer	Top Plate - Fiber interf.	Fiber (1 cm thick & 18" high)	Fiber (1 cm thick & 12" high)	OSB-Fiber interf. (12" high)	Fiber (1 cm thick & 6" high)	OSB-Fiber interf. (6" high)	Top Plate Layer (2" long)	Top Fiber of 1 cm high (2" long)	Top Fiber of 1 cm high - Fiber interf. (2" long)	Top Plate - Fiber interf. (2" long)	Top Plate Layer (2.5" long)	Top Fiber of 1 cm high (2.5" long)	Top Plate - Fiber interf. (2.5" long)	Top Fiber of 1 cm high - Fiber interf. (2.5" long)	R-Foam	WVP	Overall Avg.
Average Mould Index (M_{avg})																			
Ottawa	REF1	0.00	0.25	0.00	0.03	0.43	0.37	1.15	1.03	2.22	1.58	4.17	0.48	1.24	2.85	0.63	NA	NA	1.09
Edmonton	REF1	0.70	1.40	0.00	0.23	1.20	0.85	2.01	2.31	2.93	2.47	4.66	1.66	2.34	3.92	1.63	NA	NA	1.89
St John's	REF1	1.75	2.47	0.35	1.98	3.09	2.19	3.31	3.79	3.35	3.15	5.18	3.21	3.17	4.76	2.79	NA	NA	2.97
Vancouver	REF1	1.34	2.17	0.15	0.87	1.91	1.16	2.42	2.79	3.09	2.69	4.74	2.29	2.67	4.00	2.27	NA	NA	2.30
Maximum Mould Index (M_{max})																			
Ottawa	REF1	0.00	1.01	0.00	0.25	1.79	1.60	3.16	2.63	3.49	3.43	5.07	1.93	3.01	4.11	2.32	NA	NA	2.25
Edmonton	REF1	2.06	2.77	0.04	1.60	3.61	2.84	4.59	3.96	3.50	3.49	5.30	3.46	3.46	5.16	3.21	NA	NA	3.27
St John's	REF1	3.22	3.75	1.34	2.73	3.79	2.97	4.06	4.99	3.50	3.50	5.30	4.50	3.50	5.30	3.48	NA	NA	3.73
Vancouver	REF1	2.81	3.56	0.76	2.22	3.07	2.57	3.60	4.03	3.50	3.50	5.30	3.63	3.45	4.84	3.32	NA	NA	3.34

Table 13. Effect of geographical locations on the average and maximum mould index at different locations inside a reference wall assembly without structural sheathing (Wall: REF3)

Location	Wall	Top Plate Layer	Top Plate - Fiber interf.	Fiber (1 cm thick & 18" high)	Fiber (1 cm thick & 12" high)	Foam-Fiber interf. (12" high)	Fiber (1 cm thick & 6" high)	Foam-Fiber interf. (6" high)	Top Plate Layer (2" long)	Top Fiber of 1 cm high (2" long)	Top Fiber of 1 cm high - Fiber interf. (2" long)	Top Plate - Fiber interf. (2" long)	Top Plate Layer (2.5" long)	Top Fiber of 1 cm high (2.5" long)	Top Plate - Fiber interf. (2.5" long)	Top Fiber of 1 cm high - Fiber interf. (2.5" long)	R-Foam	WVP	Overall Avg.
Average Mould Index (M_{avg})																			
Ottawa	REF3	0.00	0.28	0.00	0.73	2.70	1.37	3.61	1.14	2.43	1.86	4.32	0.48	1.40	3.06	0.70	0.62	60	1.60
Edmonton	REF3	0.80	1.62	0.02	1.32	3.25	1.90	4.32	2.55	3.08	2.77	4.80	1.90	2.54	4.15	2.00	0.62	60	2.47
St John's	REF3	1.84	2.58	0.89	2.94	4.84	2.99	4.90	3.91	3.39	3.26	5.21	3.33	3.27	4.90	3.00	0.62	60	3.42
Vancouver	REF3	1.35	2.25	0.46	1.67	3.56	1.93	4.02	2.91	3.20	2.89	4.85	2.39	2.79	4.12	2.44	0.62	60	2.72
Maximum Mould Index (M_{max})																			
Ottawa	REF3	0.00	1.16	0.07	2.45	4.88	3.28	5.28	2.62	3.49	3.44	5.10	1.91	3.09	4.15	2.41	0.62	60	2.89
Edmonton	REF3	2.25	2.96	0.24	3.33	5.30	3.49	5.30	4.08	3.50	3.50	5.30	3.59	3.49	5.24	3.36	0.62	60	3.66
St John's	REF3	3.26	3.79	2.26	3.39	5.29	3.48	5.30	5.01	3.50	3.50	5.30	4.53	3.50	5.30	3.48	0.62	60	4.06
Vancouver	REF3	2.77	3.55	1.50	2.97	4.59	3.28	4.97	4.02	3.50	3.50	5.30	3.61	3.44	4.83	3.30	0.62	60	3.67

Table 14. Effect of WVP of exterior insulation of R-4 on the average and maximum mould index at different locations inside wall assemblies with structural sheathing (Weather: Edmonton)

Wall	Top Plate Layer	Top Plate - Fiber interf.	Fiber (1 cm thick & 18" high)	Fiber (1 cm thick & 12" high)	OSB-Fiber interf. (12" high)	Fiber (1 cm thick & 6" high)	OSB-Fiber interf. (6" high)	Top Plate Layer (2" long)	Top Fiber of 1 cm high (2" long)	Top Fiber of 1 cm high - Fiber interf. (2" long)	Top Plate - Fiber interf. (2" long)	Top Plate Layer (2.5" long)	Top Fiber of 1 cm high (2.5" long)	Top Plate - Fiber interf. (2.5" long)	Top Fiber of 1 cm high - Fiber interf. (2.5" long)	R-Foam	WVP	Overall Avg.
Average Mould Index (M_{avg})																		
REF1	**0.70**	**1.40**	**0.00**	**0.23**	**1.20**	**0.85**	**2.01**	**2.31**	**2.93**	**2.47**	**4.66**	**1.66**	**2.34**	**3.92**	**1.63**	**NA**	**NA**	**1.89**
102	0.18	0.58	0.00	0.01	0.25	0.07	0.44	1.41	2.22	1.30	4.09	0.96	1.29	2.94	0.52	4	2	1.08
104	0.18	0.58	0.00	0.01	0.24	0.07	0.43	1.43	2.23	1.31	4.10	0.97	1.31	2.94	0.53	4	60	1.09
106	0.18	0.58	0.00	0.01	0.24	0.07	0.44	1.43	2.24	1.32	4.10	0.97	1.32	2.95	0.54	4	90	1.09
207	0.18	0.59	0.00	0.01	0.24	0.08	0.45	1.45	2.25	1.34	4.11	0.98	1.35	2.96	0.56	4	300	1.10
Maximum Mould Index (M_{max})																		
REF1	**2.06**	**2.77**	**0.04**	**1.60**	**3.61**	**2.84**	**4.59**	**3.96**	**3.50**	**3.49**	**5.30**	**3.46**	**3.46**	**5.16**	**3.21**	**NA**	**NA**	**3.27**
102	0.78	1.74	0.00	0.21	1.40	0.55	2.07	2.97	3.50	3.07	5.17	2.39	2.52	4.19	1.45	**4**	**2**	**2.13**
104	0.78	1.73	0.00	0.20	1.36	0.56	2.08	2.99	3.50	3.10	5.17	2.41	2.55	4.20	1.42	**4**	**60**	**2.14**
106	0.78	1.73	0.00	0.20	1.36	0.56	2.09	3.00	3.50	3.11	5.17	2.41	2.56	4.20	1.41	**4**	**90**	**2.14**
207	0.79	1.73	0.00	0.21	1.37	0.60	2.12	3.01	3.50	3.15	5.18	2.42	2.59	4.22	1.43	**4**	**300**	**2.15**

Table 15. Effect of WVP of exterior insulation of R-4 on the average and maximum mould index at different locations inside wall assemblies without structural sheathing (Weather: Edmonton)

Wall	Top Plate Layer	Top Plate - Fiber interf.	Fiber (1 cm thick & 18" high)	Fiber (1 cm thick & 12" high)	Foam-Fiber interf. (12" high)	Fiber (1 cm thick & 6" high)	Foam-Fiber interf. (6" high)	Top Plate Layer (2" long)	Top Fiber of 1 cm high (2" long)	Top Fiber of 1 cm high - Fiber interf. (2" long)	Top Plate - Fiber interf. (2" long)	Top Plate Layer (2.5" long)	Top Fiber of 1 cm high (2.5" long)	Top Plate - Fiber interf. (2.5" long)	Top Fiber of 1 cm high - Fiber interf. (2.5" long)	R-Foam	WVP	Overall Avg.
Average Mould Index (Mavg)																		
REF3	**0.80**	**1.62**	**0.02**	**1.32**	**3.25**	**1.90**	**4.32**	**2.55**	**3.08**	**2.77**	**4.80**	**1.90**	**2.54**	**4.15**	**2.00**	**0.62**	**60**	**2.47**
101	0.33	0.87	0.00	0.39	2.70	1.10	3.27	1.82	2.67	1.72	4.44	1.17	1.87	3.41	0.88	4	2	**1.78**
103	0.30	0.81	0.00	0.29	1.98	0.91	2.65	1.74	2.61	1.63	4.40	1.13	1.76	3.35	0.87	4	60	**1.63**
105	0.30	0.81	0.00	0.25	1.83	0.84	2.52	1.73	2.60	1.63	4.39	1.12	1.75	3.34	0.88	4	90	**1.60**
201	0.29	0.82	0.00	0.13	1.32	0.57	2.04	1.71	2.59	1.64	4.37	1.12	1.72	3.32	0.93	4	300	**1.51**
Maximum Mould Index (M_{max})																		
REF3	**2.25**	**2.96**	**0.24**	**3.33**	**5.30**	**3.49**	**5.30**	**4.08**	**3.50**	**3.50**	**5.30**	**3.59**	**3.49**	**5.24**	**3.36**	**0.62**	**60**	**3.66**
101	1.16	2.09	0.15	1.72	5.24	3.18	5.30	3.26	3.50	3.46	5.30	2.71	3.17	4.54	2.11	4	2	**3.13**
103	1.10	2.05	0.10	1.51	4.84	2.94	5.29	3.24	3.50	3.45	5.30	2.64	3.12	4.51	2.08	4	60	**3.04**
105	1.09	2.05	0.09	1.38	4.64	2.84	5.26	3.24	3.50	3.45	5.30	2.64	3.12	4.50	2.08	4	90	**3.01**
201	1.09	2.07	0.07	0.84	3.72	2.30	4.89	3.24	3.50	3.44	5.30	2.63	3.10	4.48	2.13	4	300	**2.85**

Table 16. Effect of thermal resistance (R-value) of exterior insulation of WVP of 60 on the average and maximum mould index at different locations inside wall assemblies with structural sheathing (Weather: Ottawa)

Wall	Top Plate Layer	Top Plate - Fiber interf.	Fiber (1 cm thick & 18" high)	Fiber (1 cm thick & 12" high)	OSB-Fiber interf. (12" high)	Fiber (1 cm thick & 6" high)	OSB-Fiber interf. (6" high)	Top Plate Layer (2" long)	Top Fiber of 1 cm high (2" long)	Top Fiber of 1 cm high - Fiber interf. (2" long)	Top Plate - Fiber interf. (2" long)	Top Plate Layer (2.5" long)	Top Fiber of 1 cm high (2.5" long)	Top Plate - Fiber interf. (2.5" long)	Top Fiber of 1 cm high - Fiber interf. (2.5" long)	R-Foam	WVP	Overall Avg.
Average Mould Index (M_{avg})																		
REF1	**0.00**	**0.25**	**0.00**	**0.03**	**0.43**	**0.37**	**1.15**	**1.03**	**2.22**	**1.58**	**4.17**	**0.48**	**1.24**	**2.85**	**0.63**	**NA**	**NA**	**1.09**
104	0.00	0.00	0.00	0.00	0.01	0.00	0.09	0.28	0.84	0.06	3.08	0.01	0.19	1.63	0.00	**4**	**60**	**0.41**
110	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.19	0.65	0.02	2.84	0.00	0.11	1.43	0.00	**5**	**60**	**0.35**
116	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.49	0.00	2.62	0.00	0.06	1.25	0.00	**6**	**60**	**0.30**
Maximum Mould Index (M_{max})																		
REF1	**0.00**	**1.01**	**0.00**	**0.25**	**1.79**	**1.60**	**3.16**	**2.63**	**3.49**	**3.43**	**5.07**	**1.93**	**3.01**	**4.11**	**2.32**	**NA**	**NA**	**2.25**
104	0.00	0.00	0.00	0.03	0.32	0.10	0.87	1.24	2.48	0.64	4.21	0.25	0.97	3.00	0.03	**4**	**60**	**0.94**
110	0.00	0.00	0.00	0.01	0.10	0.04	0.30	1.04	2.18	0.35	4.03	0.00	0.71	2.81	0.02	**5**	**60**	**0.77**
116	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.84	1.87	0.15	3.87	0.00	0.52	2.65	0.01	**6**	**60**	**0.66**

Table 17. Effect of thermal resistance (R-value) of exterior insulation of WVP of 60 on the average and maximum mould index at different locations inside wall assemblies without structural sheathing (Weather: Ottawa)

Wall	Top Plate Layer	Top Plate - Fiber interf.	Fiber (1 cm thick & 18" high)	Fiber (1 cm thick & 12" high)	Foam-Fiber interf. (12" high)	Fiber (1 cm thick & 6" high)	Foam-Fiber interf. (6" high)	Top Plate Layer (2" long)	Top Fiber of 1 cm high (2" long)	Top Fiber of 1 cm high - Fiber interf. (2" long)	Top Plate - Fiber interf. (2" long)	Top Plate Layer (2.5" long)	Top Fiber of 1 cm high (2.5" long)	Top Plate - Fiber interf. (2.5" long)	Top Fiber of 1 cm high - Fiber interf. (2.5" long)	R-Foam	WVP	Overall Avg.
Average Mould Index (M_{avg})																		
REF3	**0.00**	**0.28**	**0.00**	**0.73**	**2.70**	**1.37**	**3.61**	**1.14**	**2.43**	**1.86**	**4.32**	**0.48**	**1.40**	**3.06**	**0.70**	**0.62**	**60**	**1.60**
103	0.00	0.01	0.00	0.07	0.84	0.17	1.13	0.40	1.21	0.25	3.40	0.06	0.36	1.98	0.01	4	60	**0.66**
109	0.00	0.00	0.00	0.02	0.51	0.05	0.67	0.28	0.91	0.07	3.15	0.01	0.22	1.72	0.00	5	60	**0.51**
115	0.00	0.00	0.00	0.01	0.28	0.01	0.37	0.19	0.70	0.02	2.90	0.00	0.13	1.49	0.00	6	60	**0.41**
Maximum Mould Index (M_{max})																		
REF3	**0.00**	**1.16**	**0.07**	**2.45**	**4.88**	**3.28**	**5.28**	**2.62**	**3.49**	**3.44**	**5.10**	**1.91**	**3.09**	**4.15**	**2.41**	**0.62**	**60**	**2.89**
103	0.00	0.33	0.03	0.51	2.43	1.03	2.83	1.52	2.84	1.27	4.43	0.57	1.55	3.29	0.21	4	60	**1.52**
109	0.00	0.11	0.02	0.22	1.73	0.48	2.09	1.28	2.56	0.67	4.24	0.18	1.12	3.08	0.07	5	60	**1.19**
115	0.00	0.01	0.01	0.17	1.29	0.21	1.50	1.05	2.25	0.38	4.07	0.00	0.81	2.89	0.04	6	60	**0.98**

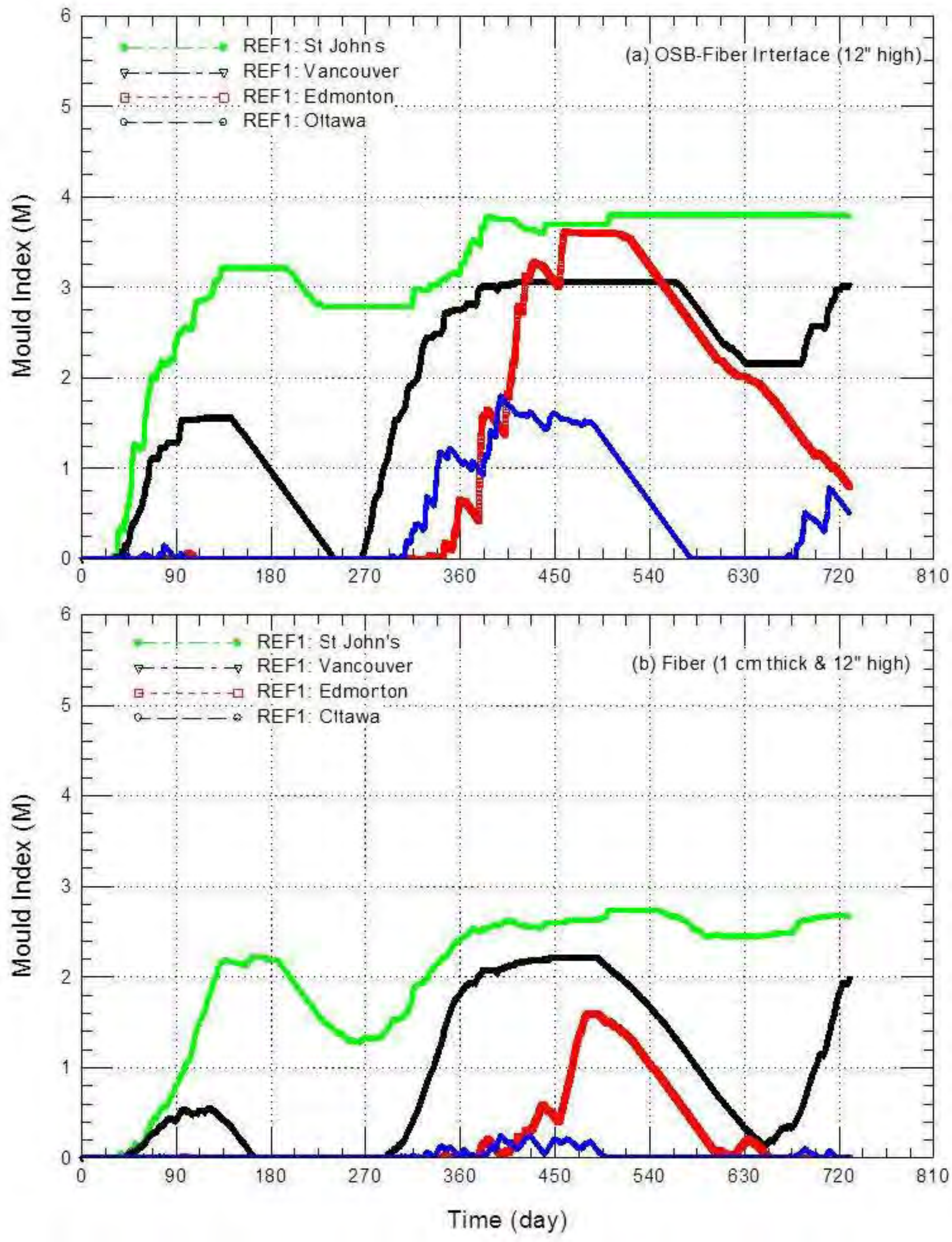


Figure 27. Effect of geographical locations on the mould index at the bottom portion of wall assembly with structural sheathing: (a) OSB-fiber interface (12" high) and (b) fiber (1 cm thick & 12" high) (Wall: REF1)

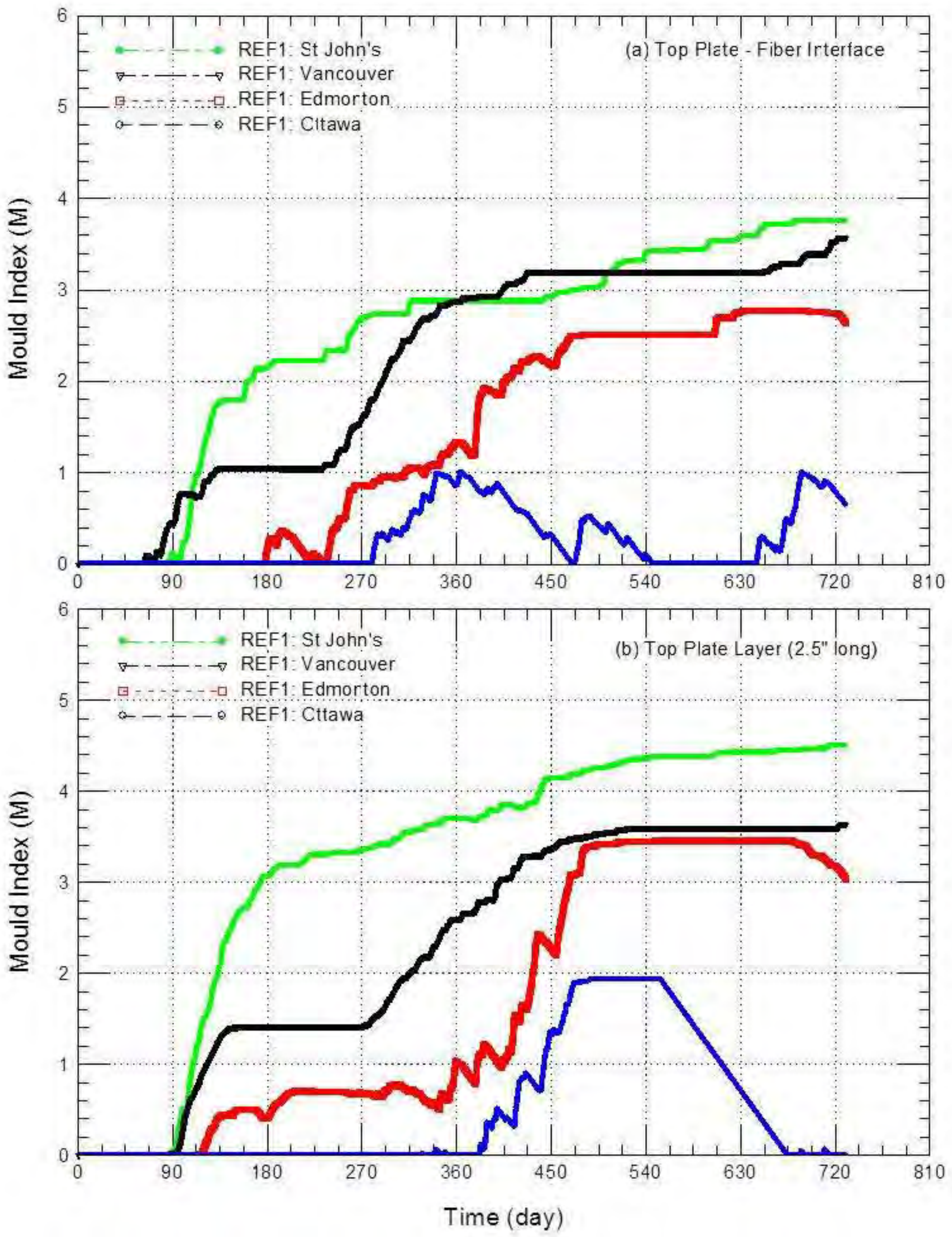


Figure 28. Effect of geographical locations on the mould index at the top portion of wall assembly with structural sheathing: (a) top plate - fiber interface and (b) top plate layer (2.5" long) (Wall: REF1)

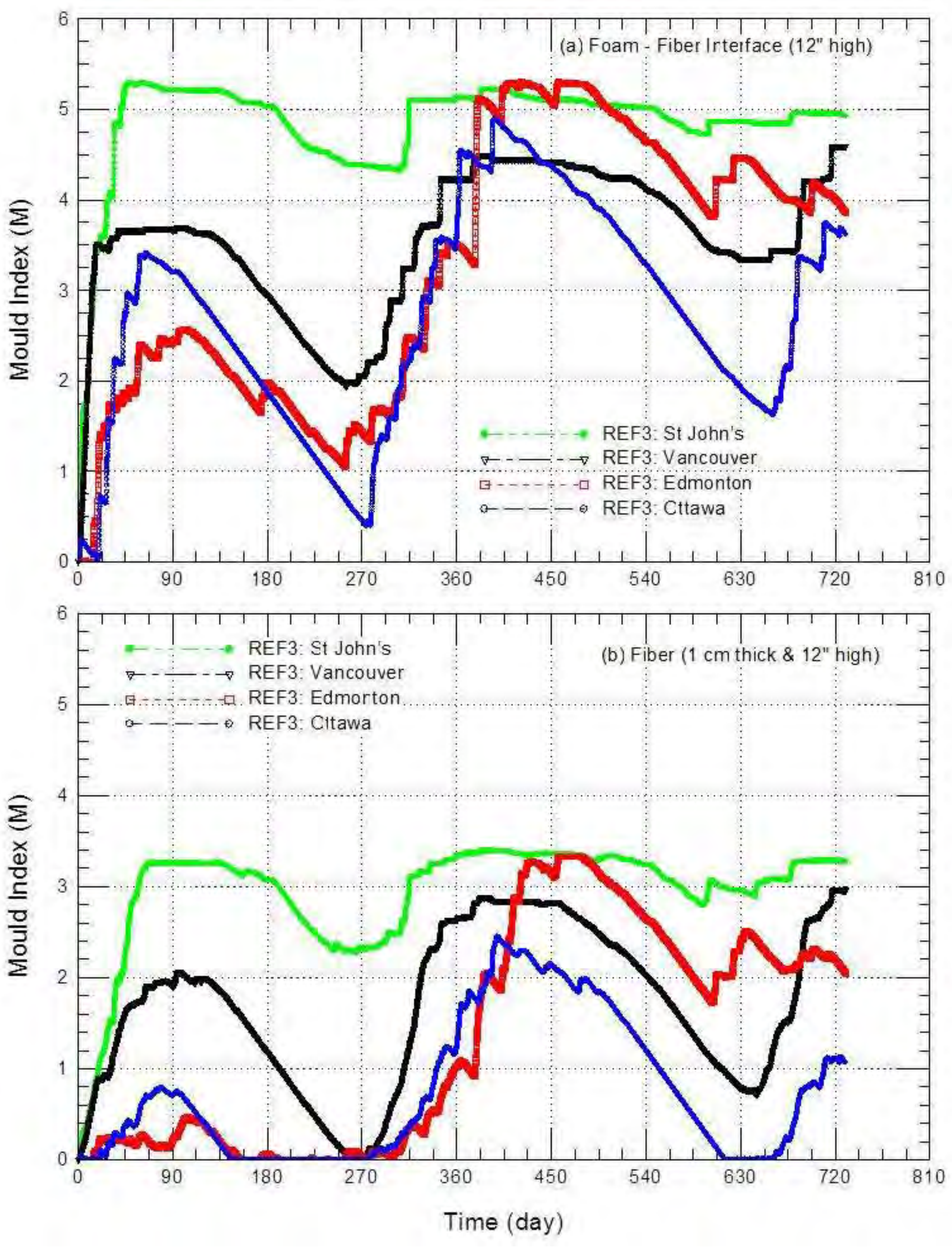


Figure 29. Effect of geographical locations on the mould index at the bottom portion of wall assembly without structural sheathing: (a) foam-fiber interface (12" high) and (b) fiber (1 cm thick & 12" high) (Wall: REF3)

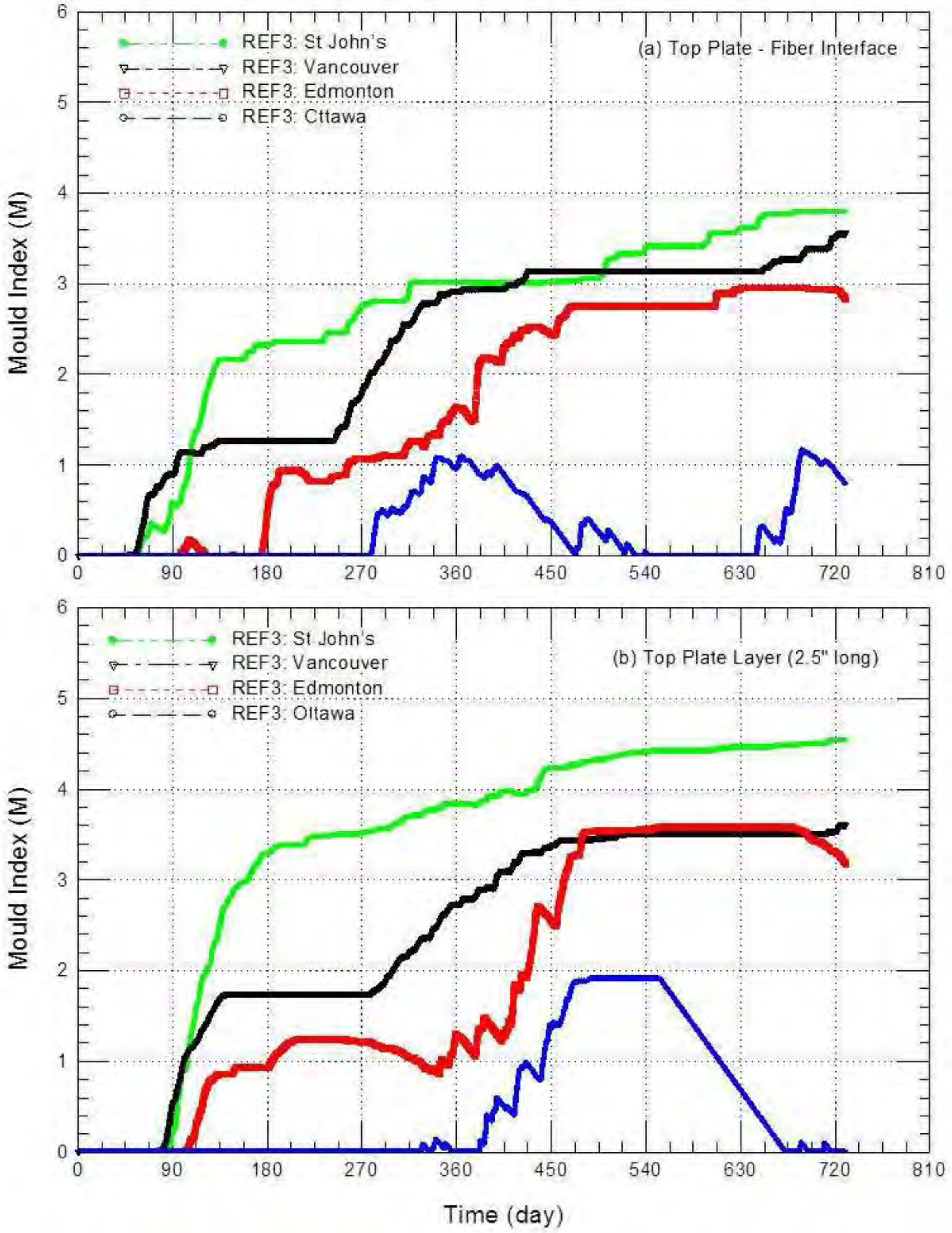


Figure 30. Effect of geographical locations on the mould index at the top portion of wall assembly without structural sheathing: (a) top plate - fiber interface and (b) top plate layer (2.5" long) (Wall: REF3)

Effect of Water Vapour Permeance (WVP) of the exterior insulation on hygrothermal performance

For wall assemblies with structural sheathing, Figure 31a & b show comparisons of the mould index at the bottom portion of the wall assembly at:

a. OSB-fibre interface (12” high), and
b. fibre of 1 cm thick (12” high) for the reference wall REF1 and other four walls with exterior insulation of R = 4 but with different WVP of 2 (wall 102), 60 (wall 104), 90 (wall 106), and 300 (wall 207) when these wall were subjected to the climatic conditions of Edmonton.

Also, Figure 32a & b show comparisons of the mould index at the top portion of these wall assemblies at:

a. top plate – fibre interface, and
b. top plate layer of 2.5 inch long for same wall assemblies.

The exterior insulation of R-4 helped to maintain the wall cavity warmer than the case of no exterior insulation, as would be expected. As such, the mould index in the walls 102, 104, 106 and 207, as shown in Figure 31 and Figure 32, and Table 14, is lower than that in reference wall REF1 (no exterior insulation).

On a side note, Figure 12 shows that the WVP of the OSB sheathing increases by increasing its Relative Humidity (RH). For example, the WVP of the OSB increases from 4.37 US perm (250 ng/(Pa•s•m²)) to 7.57 US perm (433 ng/(Pa•s•m²)) as its RH increases from 80% to 100%. In addition to the high moisture storage capacity of the OBS compared to other construction materials (e.g. EPS, XPS, fibre), at high RH of the OSB that would cause mould growth (i.e. above 80%, [59, 60, 61]), the rate of moisture flux inside the OSB increases as its RH increases. In other words, moisture moves inside the OSB with lower resistance at higher RH levels.

In case of adding exterior insulation in the walls 102, 104, 106 and 207, its WVP played an insignificant role in moisture transport. As shown in Figure 31 and Figure 32, increasing the WVP of the exterior insulation from 2 to 300 resulted in an insignificant change in the mould index.

Table 14 provided the average mould index and maximum mould index during the simulation period (2 years) at different locations inside these wall assemblies at risk of mould growth (see Table 9). This table clearly shows that both average and maximum mould indexes are lower for walls with exterior insulation than that for the reference wall REF1. Also, this table shows that the value of the WVP of the exterior insulation has an insignificant effect on both average and maximum mould indexes.

For wall assemblies without structural sheathing, Figure 33a & b show comparisons of the mould index at the bottom portion of the wall assembly at:

a. foam-fibre interface (12” high), and
b. fibre of 1 cm thick (12” high) for the reference wall REF3 (foam insulation of R = 0.62 and WVP = 60) and other four walls with foam insulation of R = 4 but

with different WVP of 2 (wall 101), 60 (wall 103), 90 (wall 105), and 300 (wall 201) when these wall were subjected to the climatic conditions of Edmonton.

Also, Figure 34a & b show comparisons of the mould index at the top portion of these wall assemblies at:

a. top plate – fibre interface, and
b. top plate layer of 2.5 inch long for same wall assemblies.

As shown in these figures, for the same value of WVP of the foam insulation (WVP = 60 for walls REF3 and 103), the foam insulation of R = 4 resulted in lower mould index than that in the reference wall REF3 (foam insulation of R = 0.62) due to warmer wall cavity in the former than in the latter. For example, within the simulation period of 2 years, the maximum mould indexes at the foam-fibre interface (12" high) and fibre of 1 cm thick (12" high) for wall 103 are, respectively, 4.84 and 1.51 compared to 5.30 and 3.33 for wall REF3 (see Figure 33a & b and Table 15). Furthermore, the corresponding average mould indexes for wall 103 are, respectively, 1.98 and 0.29 compared to 3.25 and 1.32 for wall REF3. At top plate – fibre interface and top plate layer of 2.5 inch long, the maximum mould indexes for wall 103 are, respectively, 2.05 and 2.64 compared to 2.96 and 3.59 for wall REF3 (see Figure 34a & b and Table 15), and the corresponding average mould indexes for wall 103 are, respectively, 0.81 and 1.13 compared to 1.62 and 1.90 for wall REF3.

For the same R-value of the foam insulation (R = 4), Figure 33a & b show that the foam with lower WVP resulted in higher mould index. For example, the maximum mould indexes at foam-fibre interface (12" high) in wall 101 (WVP = 2), wall 103 (WVP = 60), wall 105 (WVP = 90) and wall 201 (WVP = 300) are 5.24, 4.84, 4.64 and 3.72, respectively, and the corresponding average mould indexes are 2.70, 1.98, 1.83 and 1.32 (Table 15).

At the location of interest within the batt insulation, i.e., the outer fibre layer of 1 cm thick (12" high), the maximum mould indexes in these wall assemblies are 1.72, 1.51, 1.38 and 0.84, respectively, and the corresponding average mould indexes are 0.39, 0.29, 0.25 and 0.13. Table 15 provided the average mould index and maximum mould index during the simulation period (2 years) at different locations inside these wall assemblies at risk of mould growth shown in Table 9.

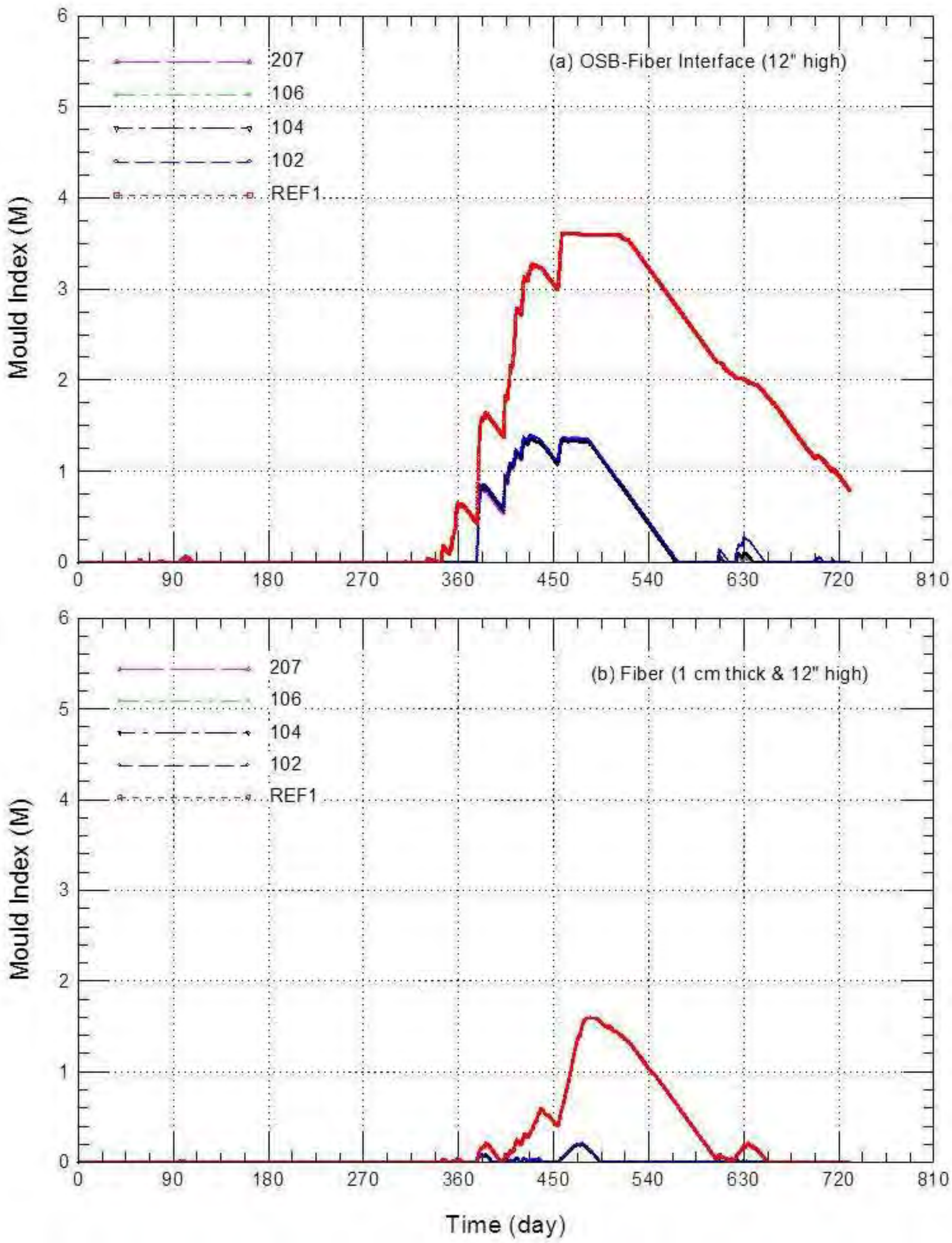


Figure 31. Effect of WVP of exterior insulation of R-4 on the mould index at the bottom portion of the wall assemblies with structural sheathing: (a) OSB-fiber interface (12" high), and (b) fiber (1 cm thick & 12" high) (Weather: Edmonton)

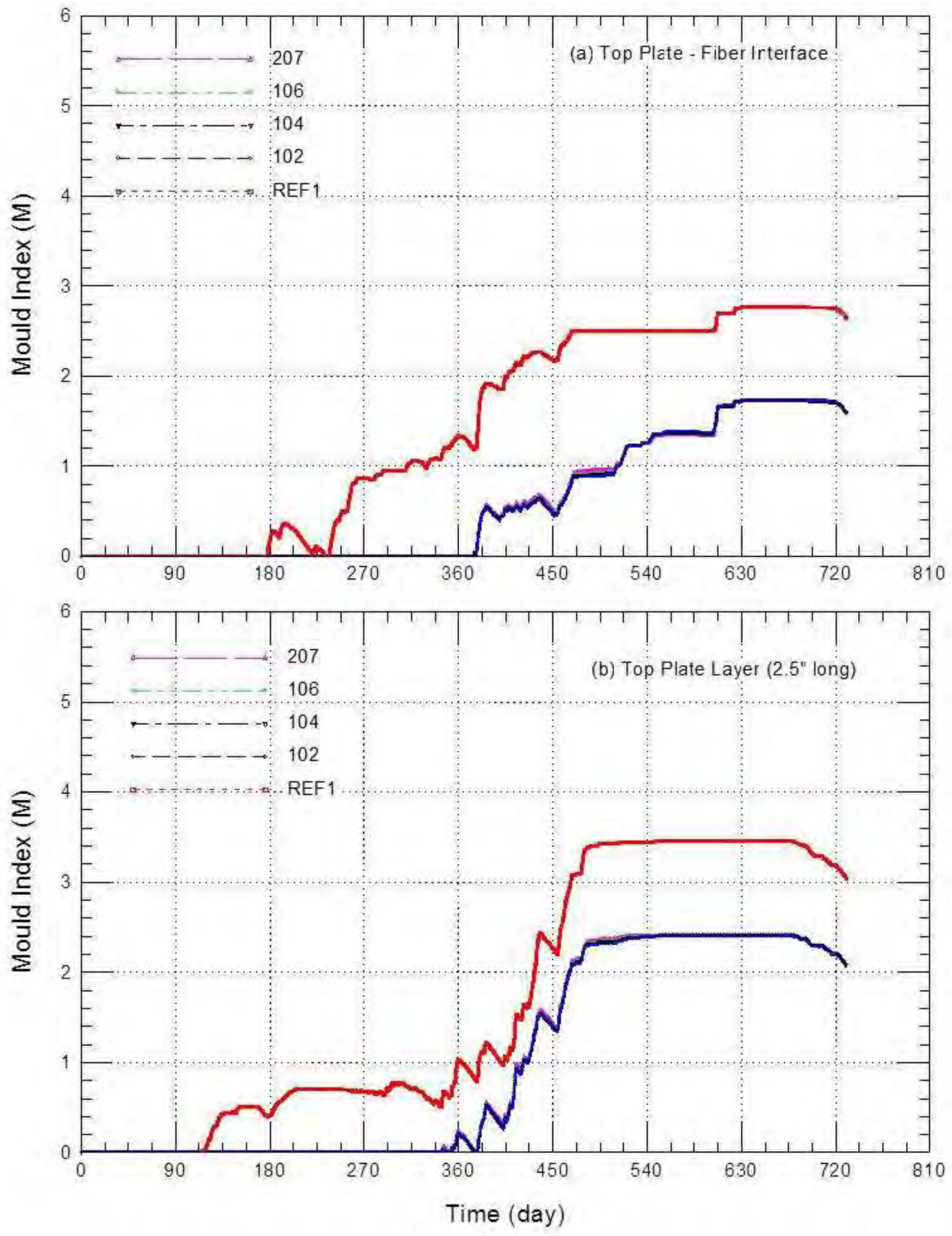


Figure 32. Effect of WVP of exterior insulation of R-4 on the mould index at the top portion of the wall assemblies with structural sheathing: (a) top plate - fiber interface, and (b) top plate layer (2.5" long) (Weather: Edmonton)

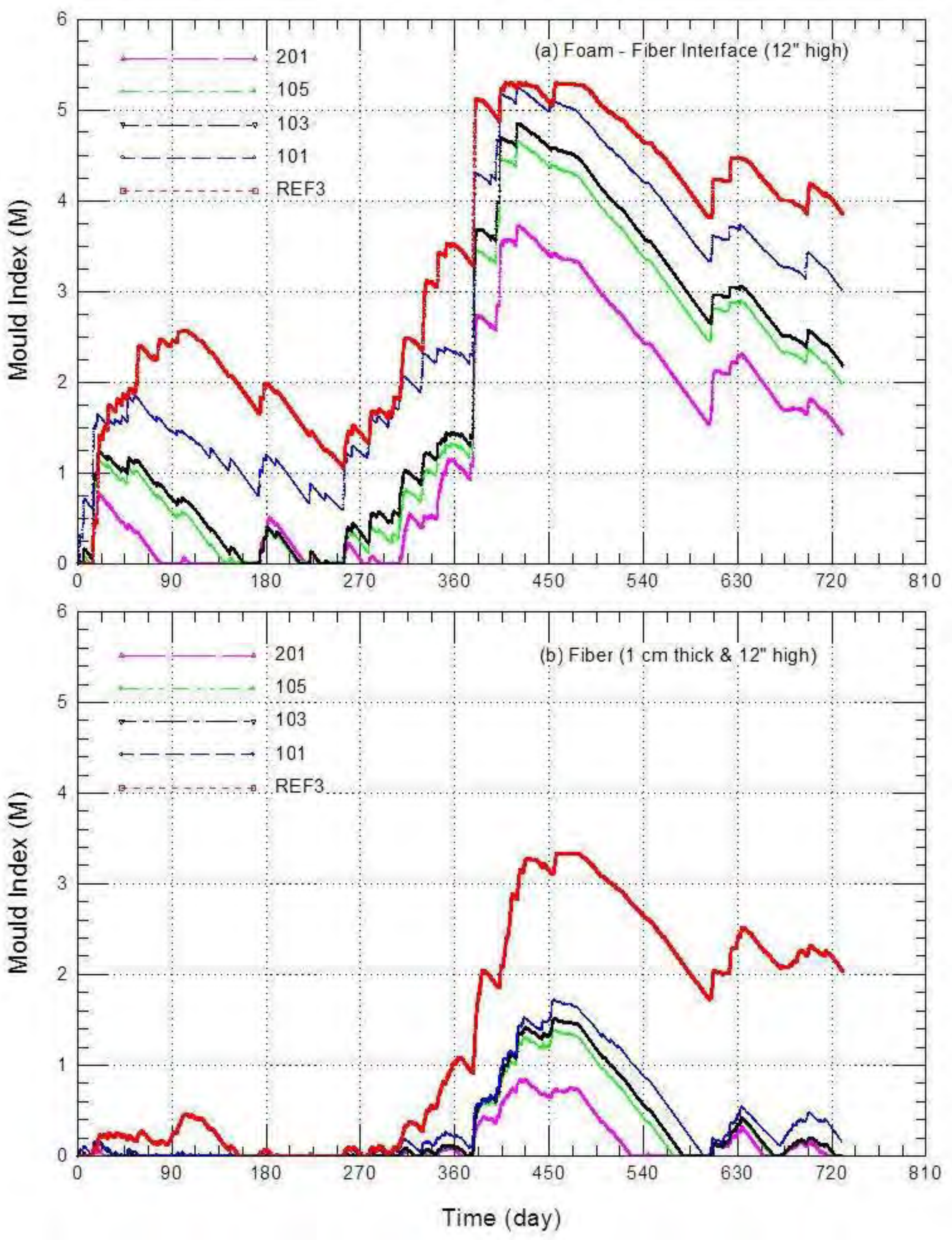


Figure 33. Effect of WVP of exterior insulation of R-4 on the mould index at the bottom portion of the wall assemblies without structural sheathing: (a) foam-fiber interface (12" high), and (b) fiber (1 cm thick & 12" high) (Weather: Edmonton)

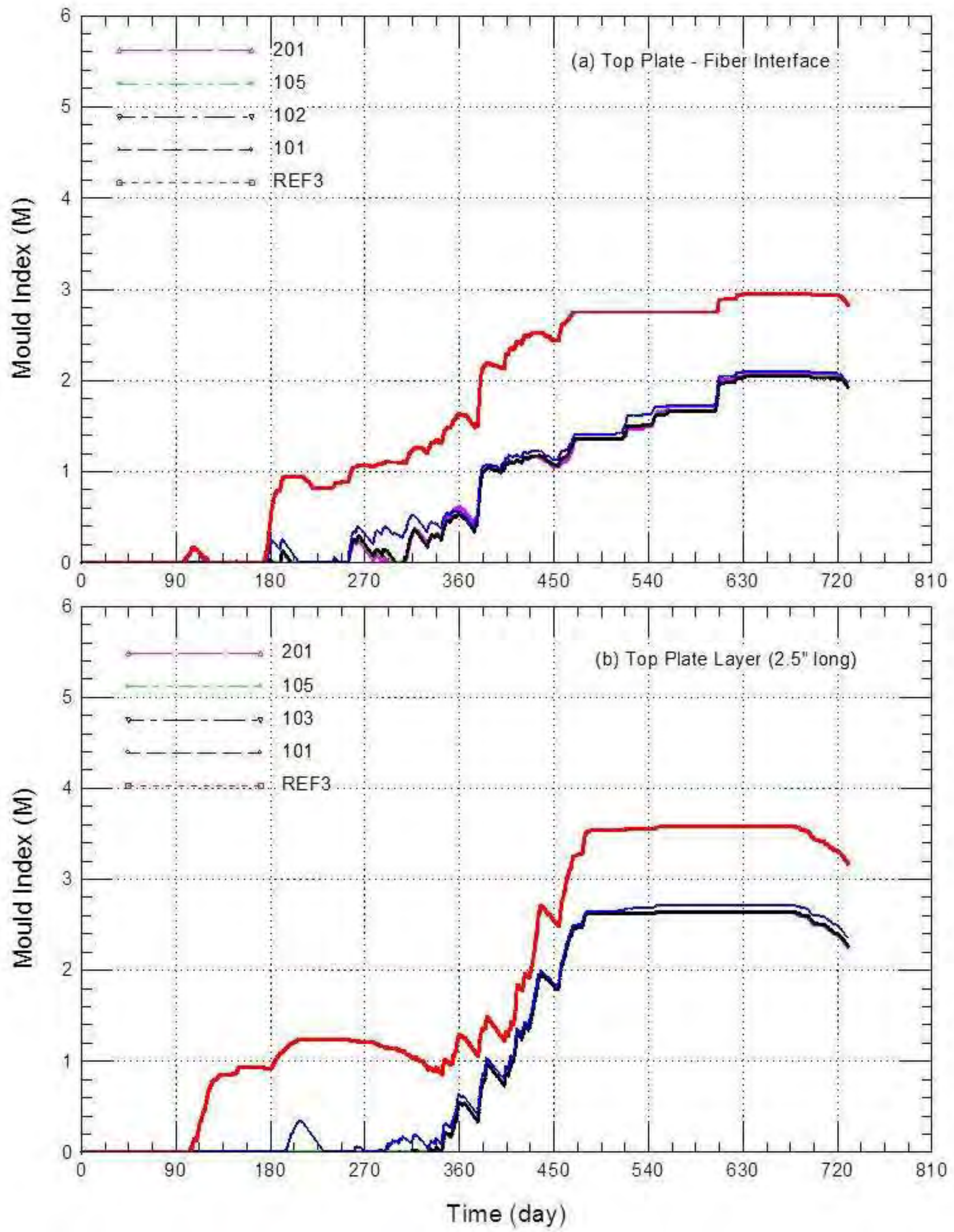


Figure 34. Effect of WVP of exterior insulation of R-4 on the mould index at the top portion of the wall assemblies without structural sheathing: (a) top plate - fiber interface, and (b) top plate layer (2.5" long) (Weather: Edmonton)

Effect of exterior insulation R-value on hygrothermal performance

For wall assemblies with structural sheathing, Figure 35a & b show comparisons of the mould index at the bottom portion of the wall assembly at:

a. OSB-fibre interface (12" high), and
b. fibre of 1 cm thick (12" high) for the reference wall REF1 and other four walls with exterior insulation of WVP = 60 but with different R-values of 4 (wall 104), 5 (wall 110) and 6 (wall 116) when these wall were subjected to the climatic conditions of Ottawa.

Also, Figure 36a & b show comparisons of the mould index at the top portion of these wall assemblies at:

a. top plate – fibre interface, and

b. top plate layer of 2.5 inch long for same wall assemblies.

As shown in these figures, the higher the R-value of the exterior insulation is the warmer wall cavity, and consequently there is less interstitial condensation occurring during the cold periods and hence the lower mould index. For example, the maximum mould index at OSB-fibre interface (12" high) for wall 104 with R-4, wall 110 with R-5 and wall 116 with R-6 are 0.32, 0.10 and 0.02, respectively, which are much lower than the maximum mould index for the reference wall REF1 with no exterior insulation (M_{max} = 1.79, see Table 16). At the top plate layer of 2.5 inch long, Figure 36b shows that the maximum mould index for walls 104, 110 and 116 are 0.25, 0.00, and 0.00, respectively, compared to 1.93 for reference wall REF1 (Table 16).

At the same WVP of the exterior insulation of 60 for wall assemblies without structural sheathing, Figure 37a & b show comparisons of the mould index at the bottom portion of the wall assembly at:

a. foam-fibre interface (12" high), and

b. fibre of 1 cm thick (12" high) for the reference wall REF3 (foam insulation of R = 0.62) and other three walls with different R-values of foam insulation: wall 103 (R = 4), wall 109 (R = 5), and wall 115 (R = 6) when these wall were subjected to the climatic conditions of Ottawa.

Also, Figure 38a & b show comparisons of the mould index at the top portion of these wall assemblies at:

a. top plate – fibre interface and

b. top plate layer of 2.5 inch long for same wall assemblies.

Similar to walls with structural sheathing, these figures shows that mould index decreases by increasing the R-value of the exterior insulation. For example, the maximum mould index at the foam-fibre interface (12" high) for walls REF3, 103, 109, and 115 are, respectively, 4.88, 2.43, 1.73 and 1.29 (see Figure 37a and Table 17). Additionally, the corresponding average mould indexes for these walls are 2.70, 0.84, 0.51 and 0.28, respectively (Table 17). At fibre of 1 cm thick (12" high), the maximum mould index for walls REF3, 103, 109, and 115 are 2.45, 0.51, 0.22 and 0.17, respectively (see Figure 37b and Table 17), and the corresponding average mould index are 0.73, 0.07, 0.02 and 0.01, respectively. At the top plate layer of 2.5 inch long, Figure 38b shows that the maximum mould index for these walls are 1.91, 0.57, 0.18 and 0.00, respectively, and the corresponding average mould index are 0.48, 0.06, 0.01 and 0.00, respectively (Table 17).

The average mould index and maximum mould index during the simulation period (2 years) at different locations inside the wall assembly (see Table 9) are provided in Table 16 for walls with structural sheathing (REF1, 104, 110 and 116) and in Table 17 for walls without structural sheathing (REF3, 103, 109, and 115).

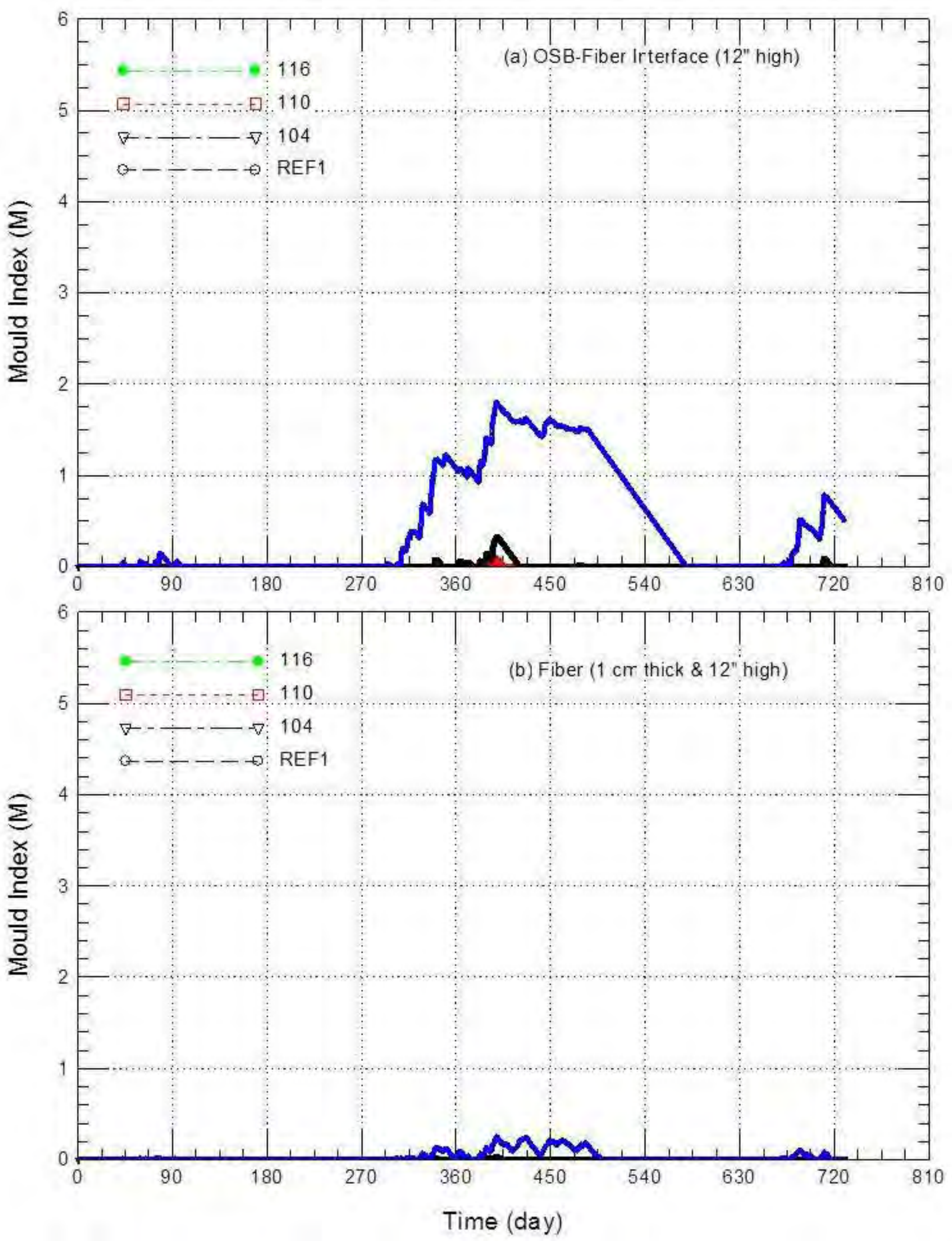


Figure 35. Effect of thermal resistance (R-value) of exterior insulation of WVP of 60 on the mould index at the bottom portion of the wall assemblies with structural sheathing: (a) OSB-fiber interface (12" high), and (b) fiber (1 cm thick & 12" high) (Weather: Ottawa)

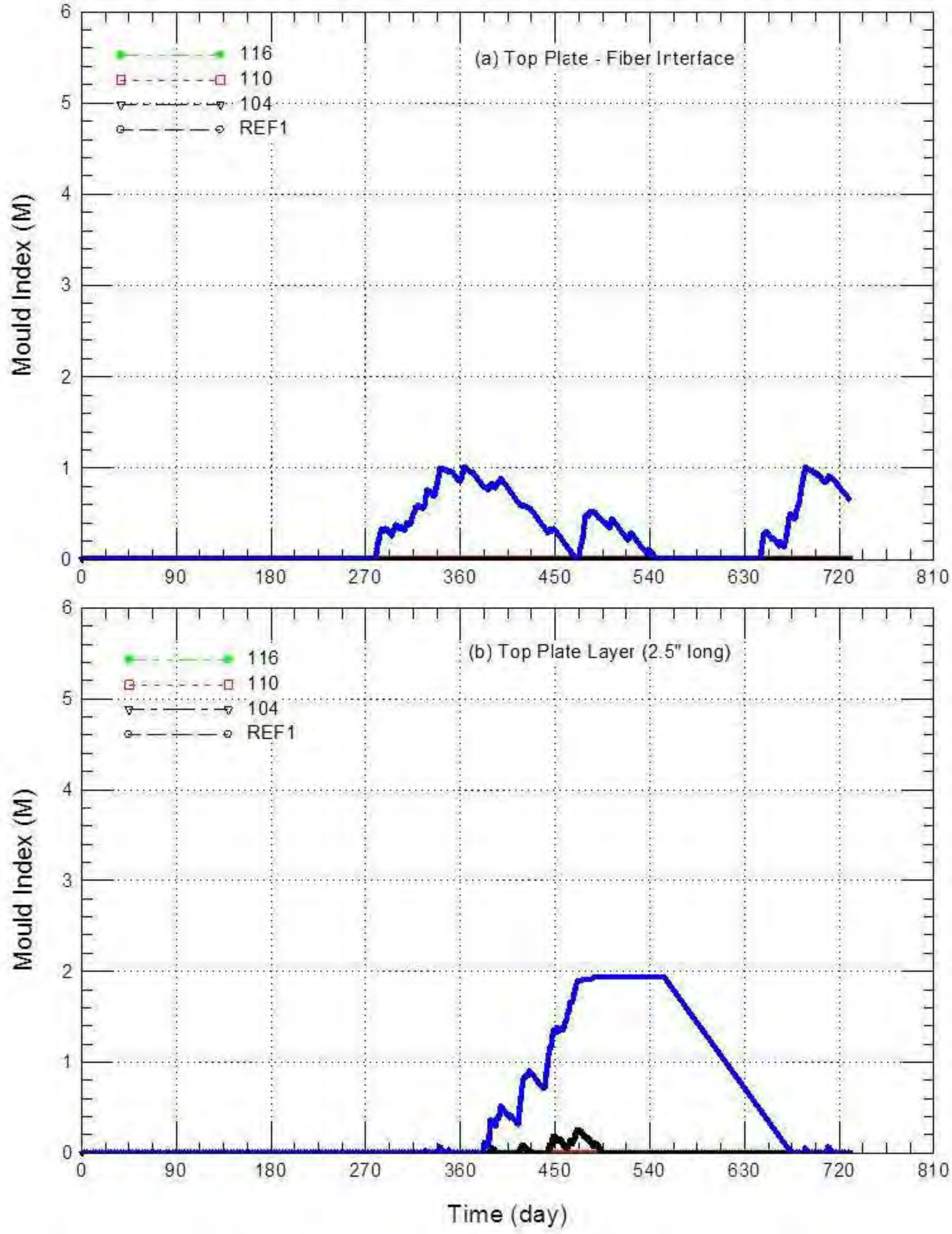


Figure 36. Effect of thermal resistance (R-value) of exterior insulation of WVP of 60 on the mould index at the top portion of the wall assemblies with structural sheathing: (a) top plate - fiber interface, and (b) top plate layer (2.5" long) (Weather: Ottawa)

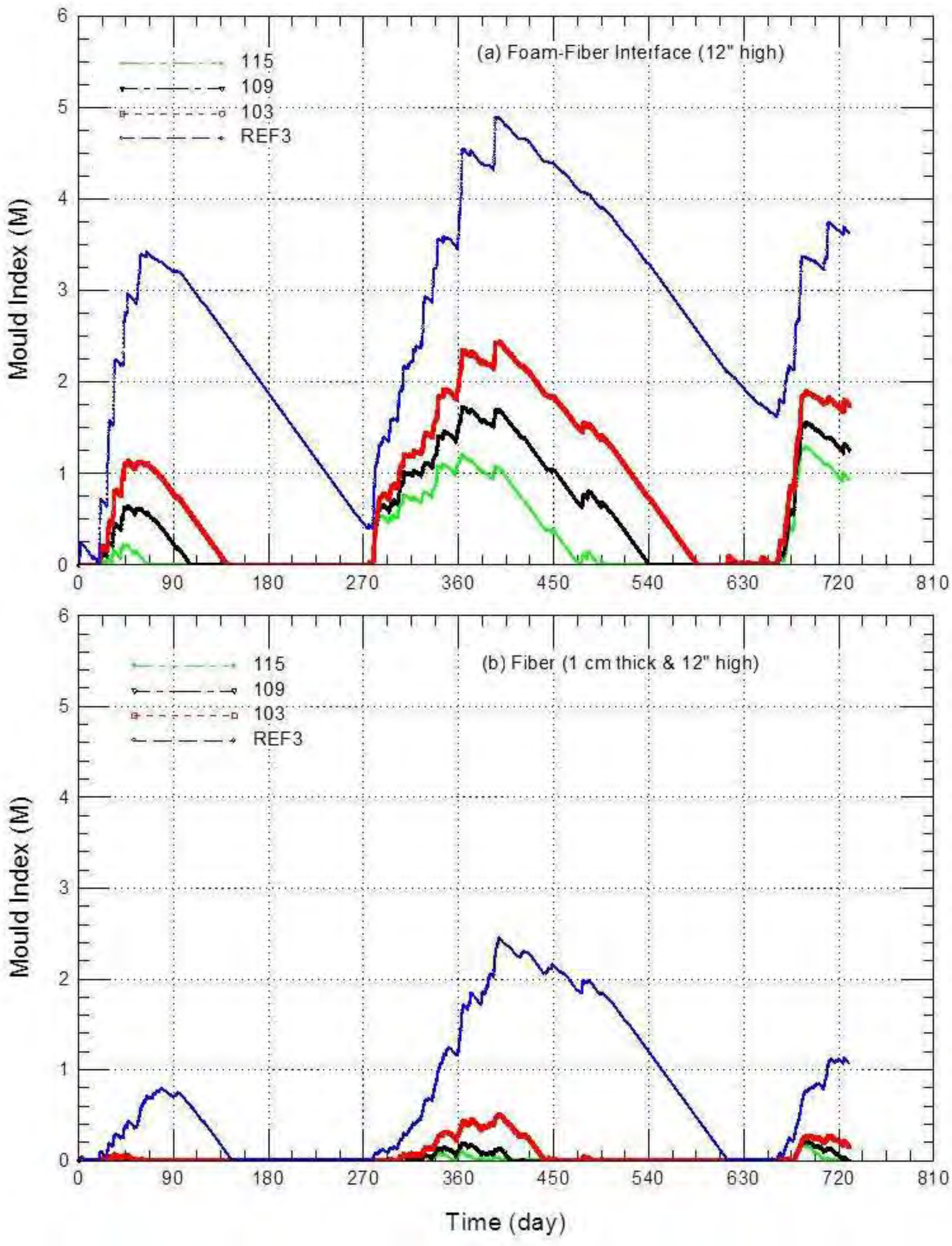


Figure 37. Effect of thermal resistance (R-value) of exterior insulation of WVP of 60 on the mould index at the bottom portion of the wall assemblies without structural sheathing: (a) foam-fiber interface (12" high), and (b) fiber (1 cm thick & 12" high) (Weather: Ottawa)

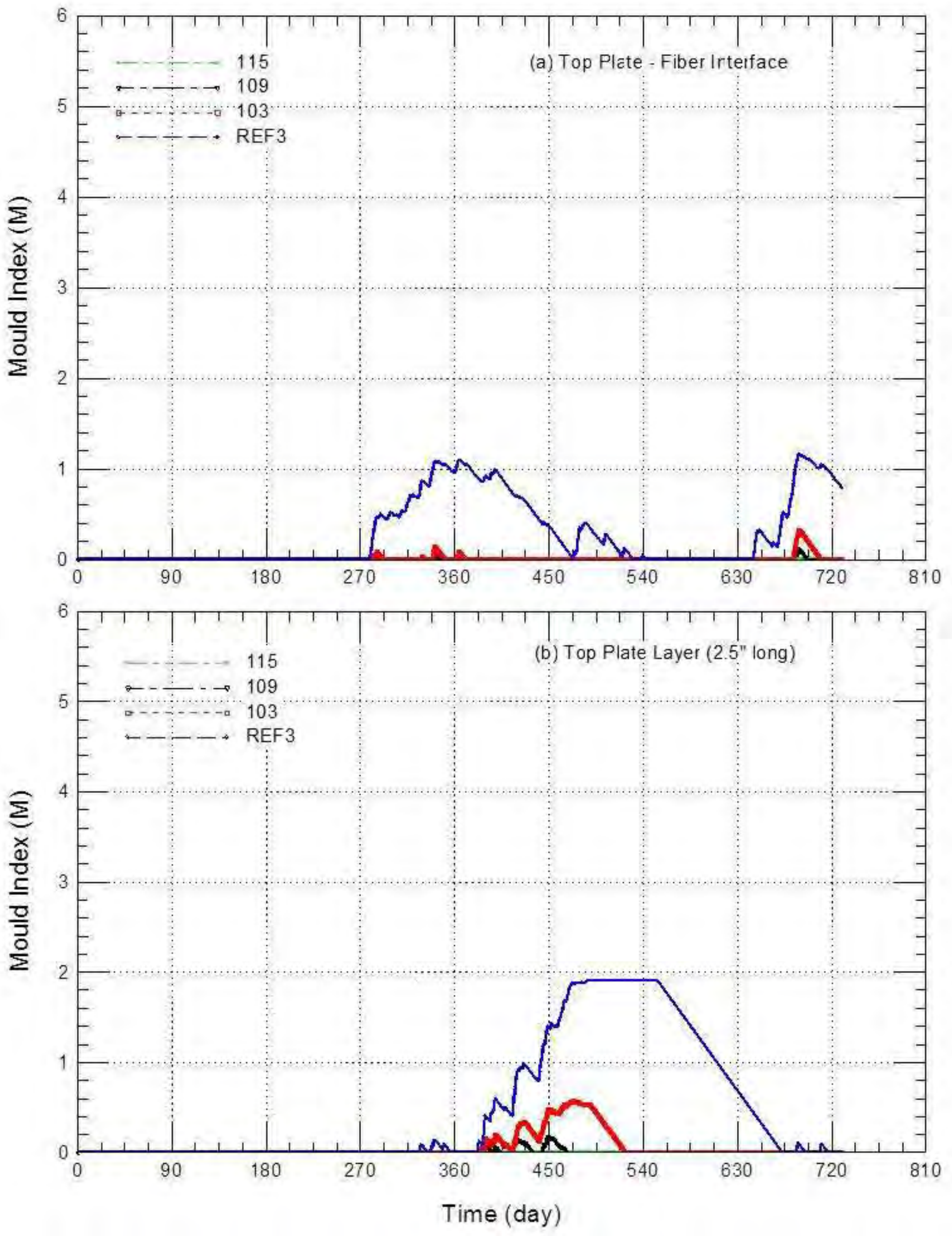


Figure 38. Effect of thermal resistance (R-value) of exterior insulation of WVP of 60 on the mould index at the top portion of the wall assemblies without structural sheathing: (a) top plate - fiber interface, and (b) top plate layer (2.5" long) (Weather: Ottawa)

Approach for Assessing the Overall Performance

A summary of the simulation results derived for Edmonton, Ottawa, Vancouver, and St John's are given in the adjoining tables and figures. The results are presented on basis of a simple form using the following two parameters:

- Overall average mould index (M_{AVG}) at different locations in the wall at which mould may grow. These locations are listed in Table 9 for walls with and without structural sheathing.
- Overall maximum mould index (M_{MAX}) at different locations in the wall at which mould may grow.

The two parameters above were determined based on a simulation period of two years, i.e., simulation of the average year followed by a wet year for the location of interest. The overall average mould index is the average value obtained from the average mould index at all locations within the assembly (see Table 9). Whereas the overall maximum mould index is given by the average value of the maximum mould index values at all locations within the assembly (see Table 9).

Both these values are provided for each of the different wall configurations having nominal insulation in the stud cavity (referred to as inboard insulation) of either R-19 or R-24, as well as for each of the exterior insulation (referred to as outboard insulation) conditions that may vary from R-0 or R-0.62, depending on whether the wall incorporates a structural sheathing, to values of R-4, R-5, and R-6. The list of wall assemblies with structural sheathing is given in Table 10 and that without structural sheathing is given in Table 11. These tables provide information as regards the values of thermal resistance (R-value) in $ft^2 \cdot h \cdot {}^oF/BTU$ and water vapour permeance in $ng/Pa \cdot s \cdot m^2$ of the outboard insulation of different wall configurations incorporating or not, structural sheathing.

Simulation Results for different Wall Assemblies

The results are presented in Figure 39 through Figure 48 in the following order: Edmonton, Ottawa, Vancouver and St John's, and where:

- Figure 39 through Figure 42 for Edmonton, AB (cold, dry climate with HDD18 = 5120, MI = 0.48),
- Figure 43 and Figure 44 for Ottawa, ON (cold, dry climate with HDD18 = 4440 to 4500, MI = 0.84),
- Figure 45 through Figure 46 for Vancouver, BC (mild, wet climate with HDD18=2600 to 3100, MI = 1.44), and
- Figure 47 and Figure 48 for St John's, NL (mild, wet climate with HDD18 = 4800, MI = 1.41).

(1) Edmonton, AB

In all instances, the values derived for both the overall average mould index (M_{AVG}) and maximum mould index (M_{MAX}) for walls with and without structural sheathing and having either R-19 or R-24 stud cavity insulation, are less than those for the reference walls. The values for M_{AVG} for these sets of walls with structural sheathing range from 1.89 to 0.80 for the case of R-19 stud cavity insulation (Figure 39a) and from 1.98 to 0.86 for the case of R-24 stud cavity insulation (Figure 39b). The corresponding values for M_{MAX} for these sets of walls with structural sheathing range from 3.27 to 1.57 (Figure 40a) and from 3.36 to 1.70 (Figure 40b) for the case of R-19 and R-24 stud cavity insulation, respectively.

The values for M_{AVG} for the walls without structural sheathing range from 2.63 to 1.10 for the case of R-19 stud cavity insulation (Figure 41a) and from 2.72 to 1.19 for the case of R-24 stud cavity insulation (Figure 41b). The corresponding values for M_{MAX} for these sets of walls range from 3.70 to 2.10 (Figure 42a) and from 3.74 to 2.23 (Figure 42b) for the case of R-19 and R-24 stud cavity insulation, respectively.

As might be expected, increasing the R-value of the outboard insulation decreases the value of both the overall M_{AVG} and M_{MAX} for both walls with and without structural sheathing.

As indicated earlier, the structural sheathing (i.e. OSB) has not only high moisture storage capacity but also high Water Vapour Permeance (WVP) at high relative humidity (see Figure 12). For a given R-value of the outboard insulation, its WVP ranging from 2 to 1800 resulted in insignificant change in the value of both M_{AVG} and M_{MAX} for walls with structural sheathing (Figure 39 and Figure 40). For example, for the R-19 stud cavity insulation, having outboard insulation of R-4, values for M_{AVG} and M_{MAX}, respectively, are estimated to be 1.10 and 2.15 over the range of values for the WVP of this outboard insulation of 2 to 1800; the M_{AVG} and M_{MAX}, respectively, values diminishes to 0.95 and 1.86 for configurations having outboard insulation of R-5, and 0.82 and 1.59 for configurations having outboard insulation of R-6. Thus when structural panels are used in walls, these walls remain insensitive to variations in values of WVP of the outboard insulation, as regards the values of M_{AVG} and M_{MAX} of the wall.

However, for the walls without structural sheathing, both M_{AVG} and M_{MAX} decreases as the value for WVP increases; hence increasing the potential for moisture dissipation of the outboard insulation reduces the risk to the formation of mould (Figure 41 and Figure 42). For example, for the R-19 stud cavity insulation, having outboard insulation of R-0.62, the value for M_{AVG} decreases from 2.72 and 2.36 as the value for the WVP of this outboard insulation increases from 2 to 300. Furthermore, as the value of WVP of the outboard insulation increases from 2 to 1800, the M_{AVG} value decreases from 1.89 to 1.49 for configurations having outboard insulation of R-4; and M_{AVG} value decreases from 1.61 to 1.33 and from 1.34 to 1.20 for configurations having outboard insulation of R-5 and R-6, respectively.

As regards comparison between walls incorporating or not a structural sheathing panel, the overall values for M_{AVG} and M_{MAX} were greater for wall configurations not incorporating the structural sheathing panel. As well, for these same wall configurations, the overall values of M_{AVG} and M_{MAX} were greater for the case of R-24 stud cavity insulation than that for the case of case R-19 stud cavity insulation.

(2) Ottawa, ON

As was the case for Edmonton, in all instances, the values derived for the overall average mould index (M_{AVG}) for walls with and without structural sheathing and having either R-19 or

R-24 stud cavity insulation, are less than those for the reference walls. The values of M_{AVG} for the reference walls with structural sheathing in the case of R-19 and R-24 stud cavity insulation are 1.09 and 1.18, respectively (Figure 43). For walls without structural sheathing, the values of M_{AVG} for the reference walls decreases from 1.68 to 1.50 (R-19 stud cavity insulation) and decreases from 1.78 to 1.61 (R-24 stud cavity insulation) as the WVP of the outboard insulation of R-0.62 increases from 2 to 300 (Figure 44).

As compared to the results obtained for Edmonton, however, the values for M_{AVG} for these sets of walls are lower. For example, the values of M_{AVG} of walls with structural sheathing range from a low of 0.28 to 1.09 (R-19 stud cavity insulation) and from a low of 0.31 to 1.18 (R-24 stud cavity insulation) for Ottawa, whereas for Edmonton these ranged from a low of 0.80 to 1.89 (R-19 stud cavity insulation) and from a low of 0.86 to 1.98 (R-24 stud cavity insulation). Additionally, the values of M_{AVG} of walls without structural sheathing range from a low of 0.40 to 1.68 (R-19 stud cavity insulation) and from a low of 0.45 to 1.78 (R-24 stud cavity insulation) for Ottawa, whereas for Edmonton these ranged from a low of 1.10 to 2.63 (R-19 stud cavity insulation) and from a low of 1.19 to 2.72 (R-24 stud cavity insulation).

Walls configured with a structural sheathing panel have values of M_{AVG} that are, in general, lower than values of M_{AVG} for walls configured without a structural sheathing panel for a given type of outboard insulation (i.e. R-4, R-5, R-6). Values of M_{AVG} diminish as the R-value of the outboard insulation increases. Hence, values of M_{AVG} for walls having outboard insulation of R-6 are less than those of outboard insulation of R-4; there is little difference in values of M_{AVG} for walls having inboard/cavity insulation of R-19 as compared to walls having R-24. The values of the overall maximum mould index (M_{MAX}) for wall assemblies with and without structural sheathing are provided in Figure A - 1 and Figure A - 2, respectively.

(3) Vancouver, BC

Values of M_{AVG} for walls subjected to a Vancouver climate are comparatively greater than that of Ottawa, and slightly greater than those of Edmonton.

As was the case for Edmonton and Ottawa, walls configured with a structural sheathing panel have values of M_{AVG} that are, in general, lower than values of M_{AVG} for walls configured without a structural sheathing panel for a given type of outboard insulation (i.e. R-4, R-5, R-6). For a given value of WVP of the outboard insulation, values for M_{AVG} diminish as the R-value of the outboard insulation increases. Note that the Moisture Index (MI) of Vancouver climate is the highest (MI = 1.44) among other geographical locations. This would result in less drying potential of wall assembly compared to dry climates (e.g. Edmonton, MI = 0.48).

Interestingly however, for a given R-value of the outboard insulation, values of M_{AVG} increase with a corresponding increase in the WVP of the insulation. This is evident for each of the three outboard insulation types (i.e. R-4, R-5, R-6) for both the R-19 and R-24 stud cavity insulation, and for walls configured with or without a structural sheathing panel. For example, for outboard insulation of R-4, the value of M_{AVG} of wall with structural sheathing increases from 1.28 to 1.63 (R-19 stud cavity insulation) and from 1.37 to 1.73 (R-24 stud cavity insulation) as the WVP of the outboard insulation increases from 2 to 1800. Also, for outboard insulation of R-4, the value of M_{AVG} of wall without structural sheathing increases from 1.83 to 2.15 (R-19 stud cavity insulation) and from 1.94 to 2.26 (R-24 stud cavity insulation) as the WVP of the outboard insulation increases from 2 to 1800.

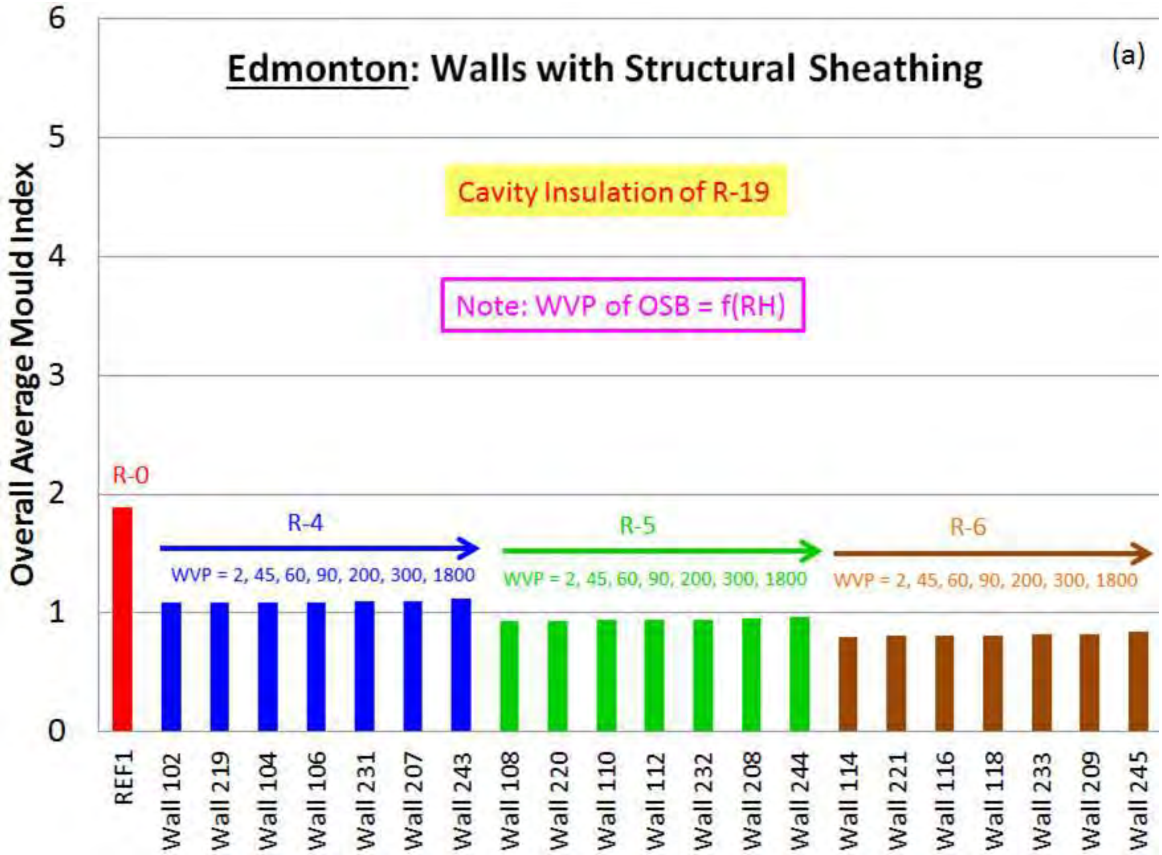
The values of the overall maximum mould index (M_{MAX}) for wall assemblies with and without structural sheathing are provided Figure A - 3 and Figure A - 4, respectively.

(4) St John's, NL

The greatest values for the overall M_{AVG} of the wall configurations with and without structural sheathing occur in St John's as compared to the other cities investigated. This is because: (a) the St John's climate has the highest air leakage rate compared to the other geographical locations investigated, and (b) the St John's climate is a wet climate with moisture index (MI = 1.41) slightly lower than that of Vancouver climate (MI = 1.44). The trends that were previously described for Vancouver likewise apply to St John's; specifically:

- Walls configured with a structural sheathing panel have values of M_{AVG} that are, in general, lower than values of M_{AVG} for walls configured without a structural sheathing panel for a given type of outboard insulation (i.e. R-4, R-5, R-6);
- For a given value of WVP of the outboard insulation, values for M_{AVG} diminish as the R-value of the outboard insulation increases; and
- For a given R-value of the outboard insulation, values of M_{AVG} increase with a corresponding increase in the WVP of the board insulation.

The values of the overall maximum mould index (M_{MAX}) for wall assemblies with and without structural sheathing are provided Figure A - 5 and Figure A - 6, respectively.



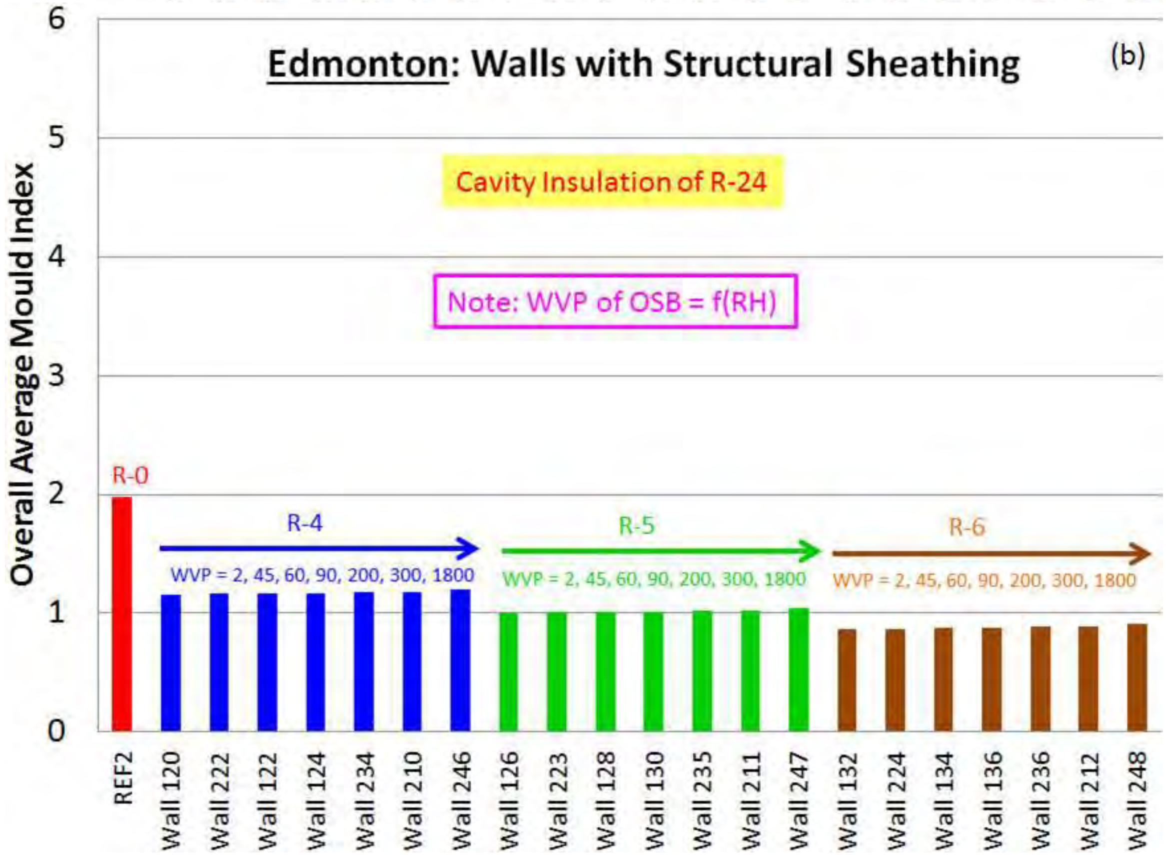


Figure 39. Simulation results for Edmonton - Values of overall average mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

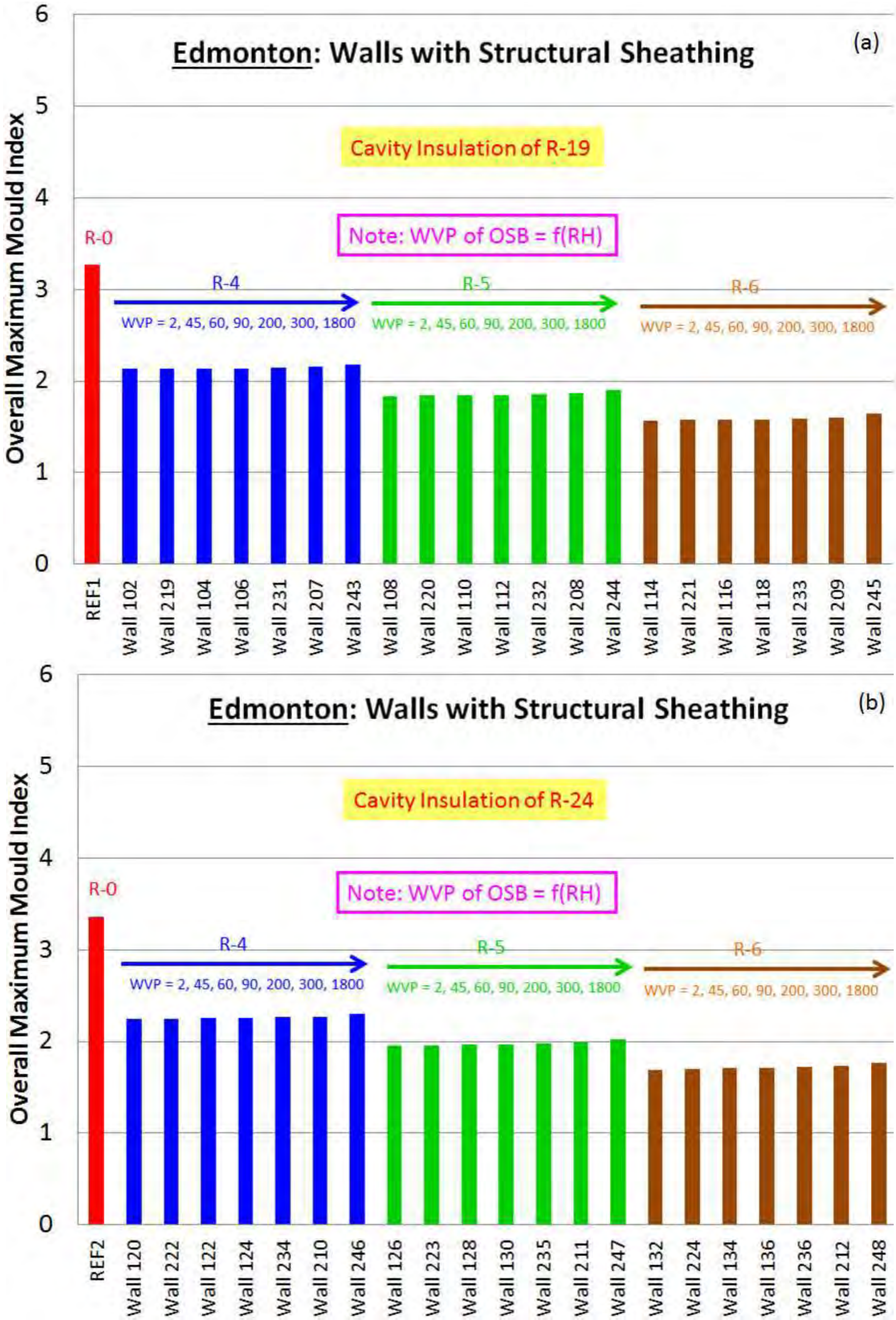


Figure 40. Simulation results for Edmonton - Values of overall maximum mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

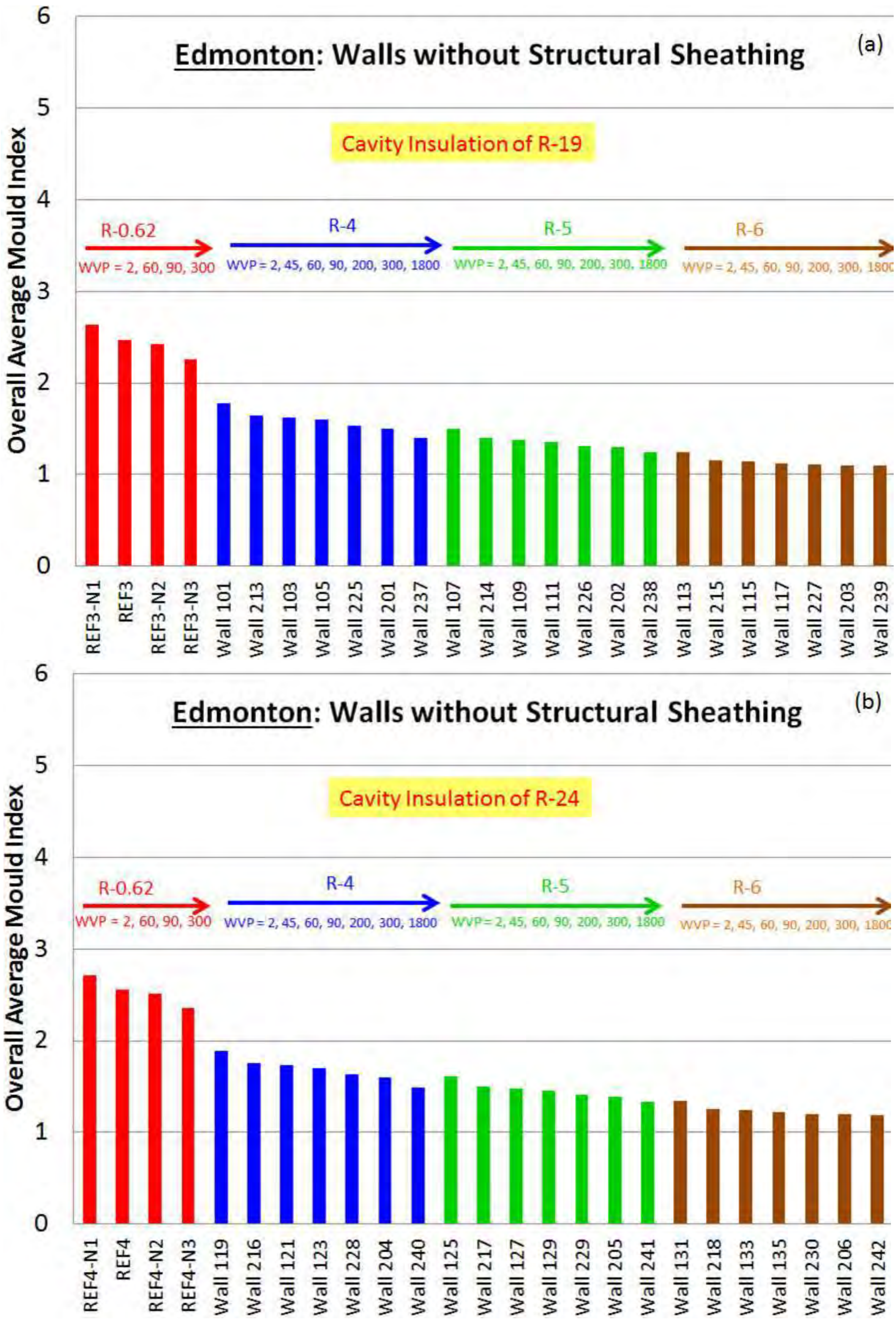


Figure 41. Simulation results for Edmonton - Values of overall average mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

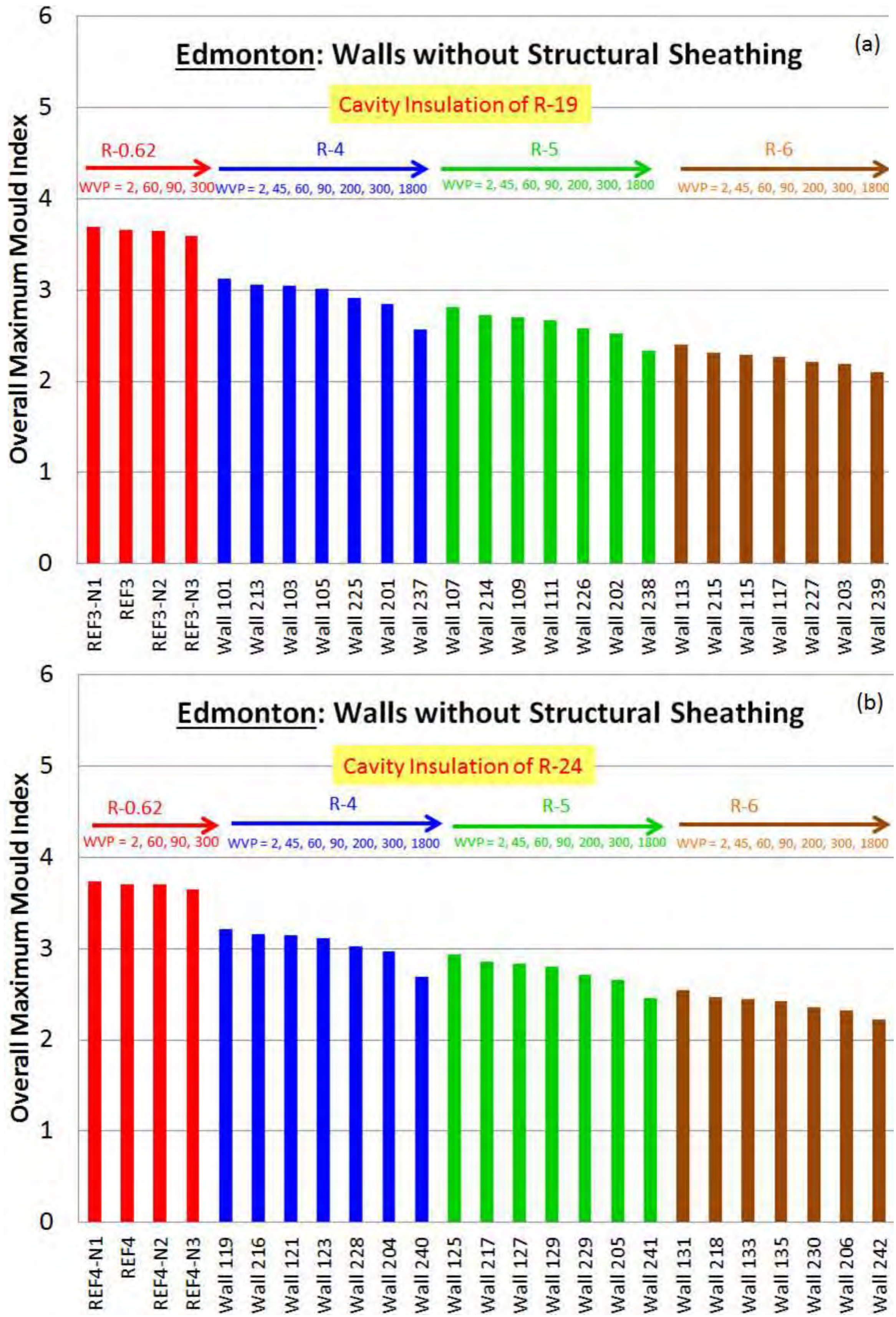


Figure 42. Simulation results for Edmonton - Values of overall maximum mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

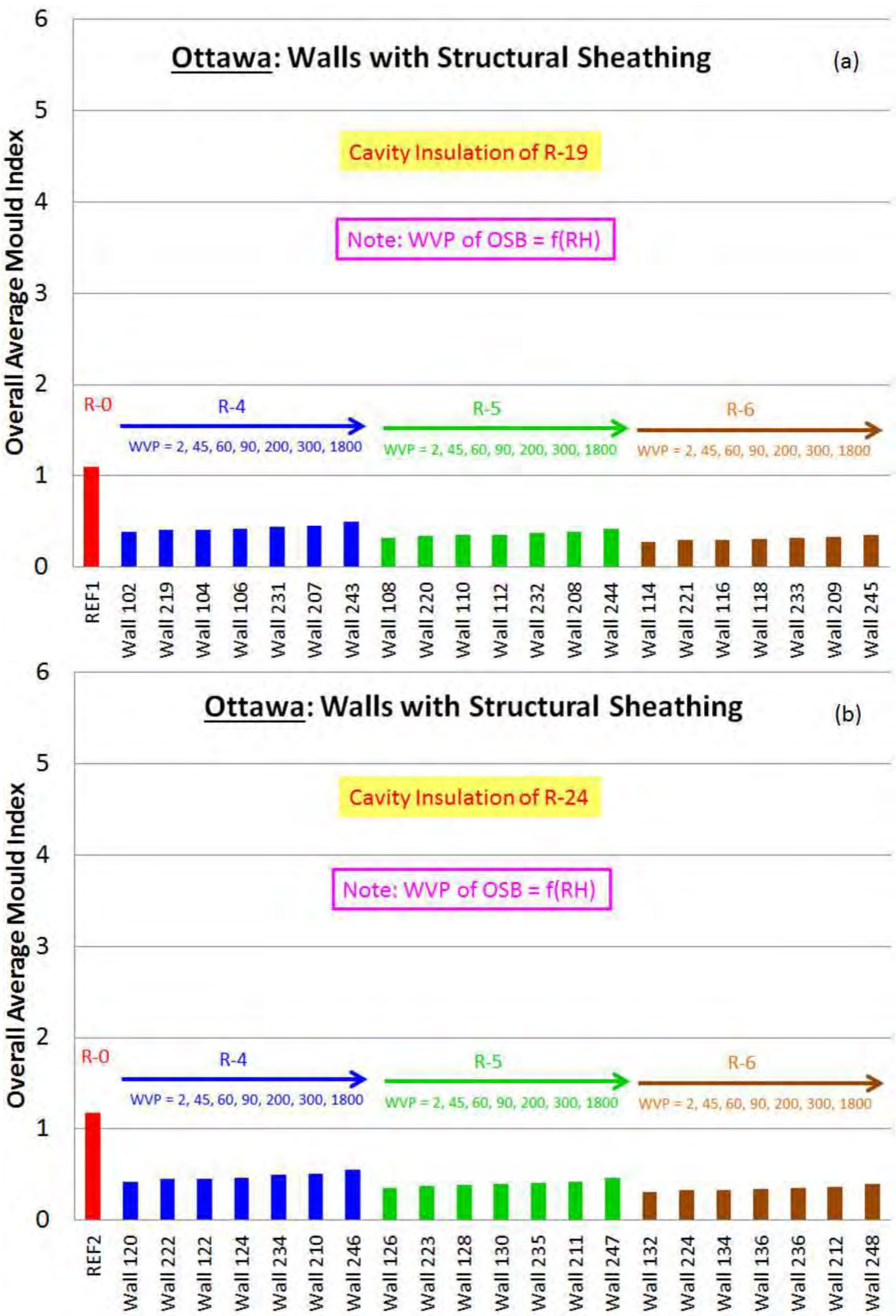


Figure 43. Simulation results for Ottawa - Values of overall average mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

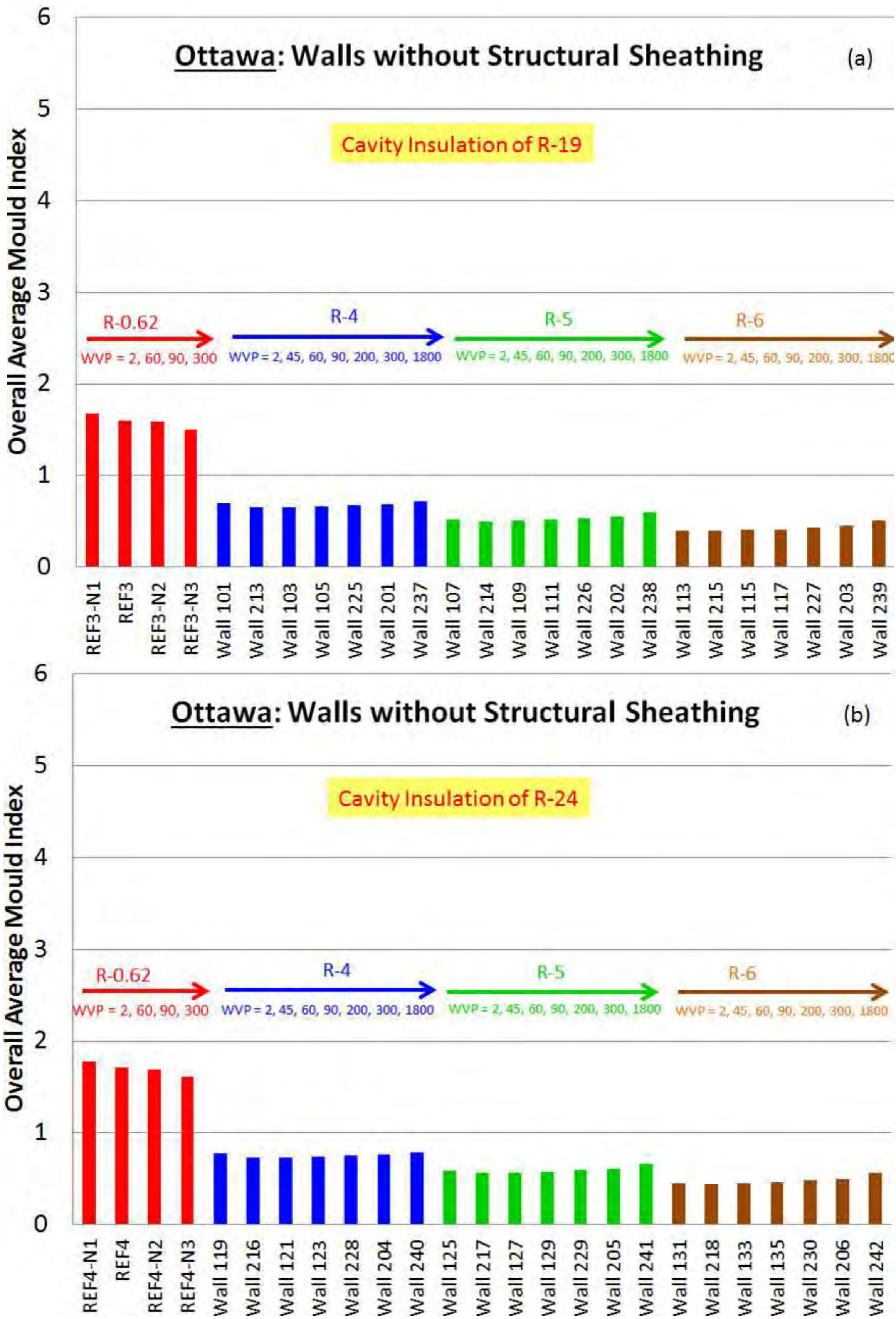


Figure 44. Simulation results for Ottawa - Values of overall average mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

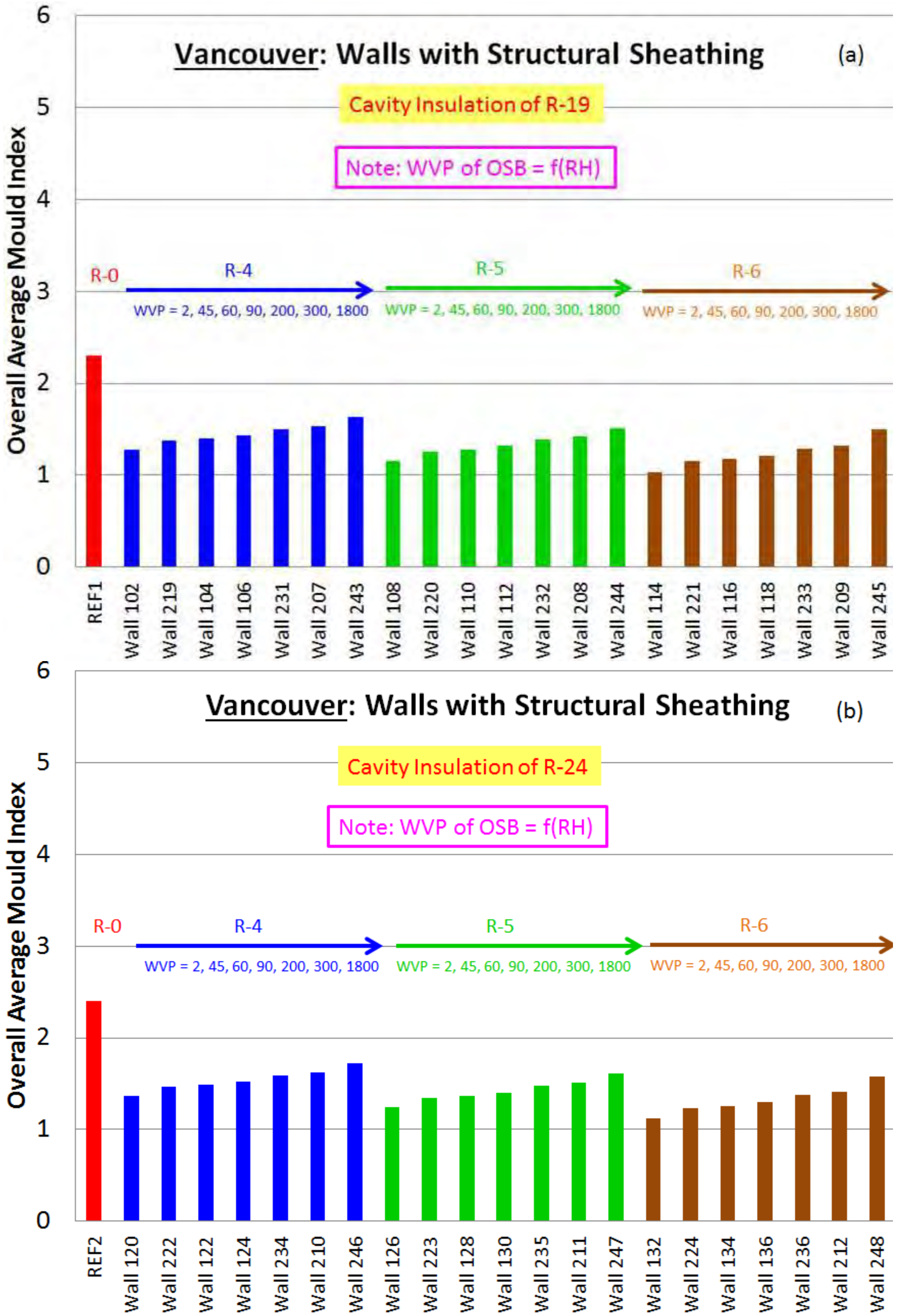
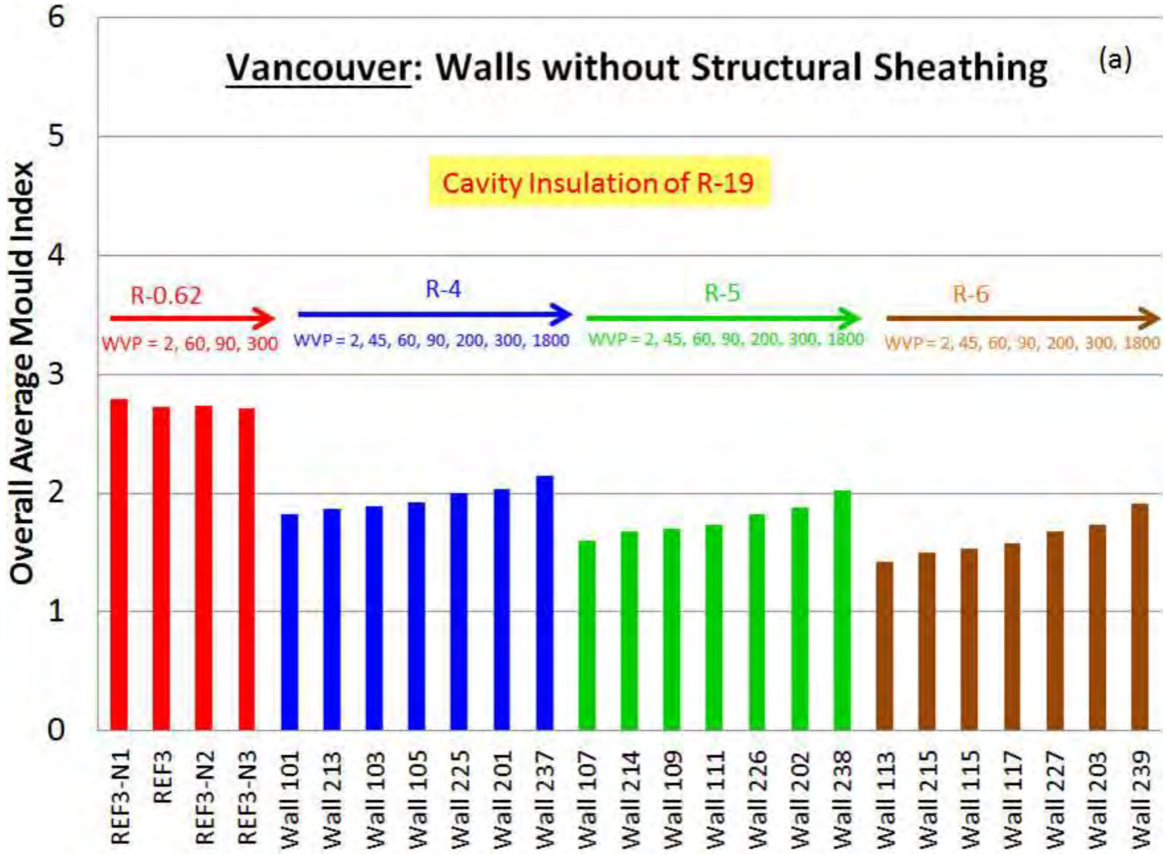


Figure 45. Simulation results for Vancouver - Values of overall average mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24



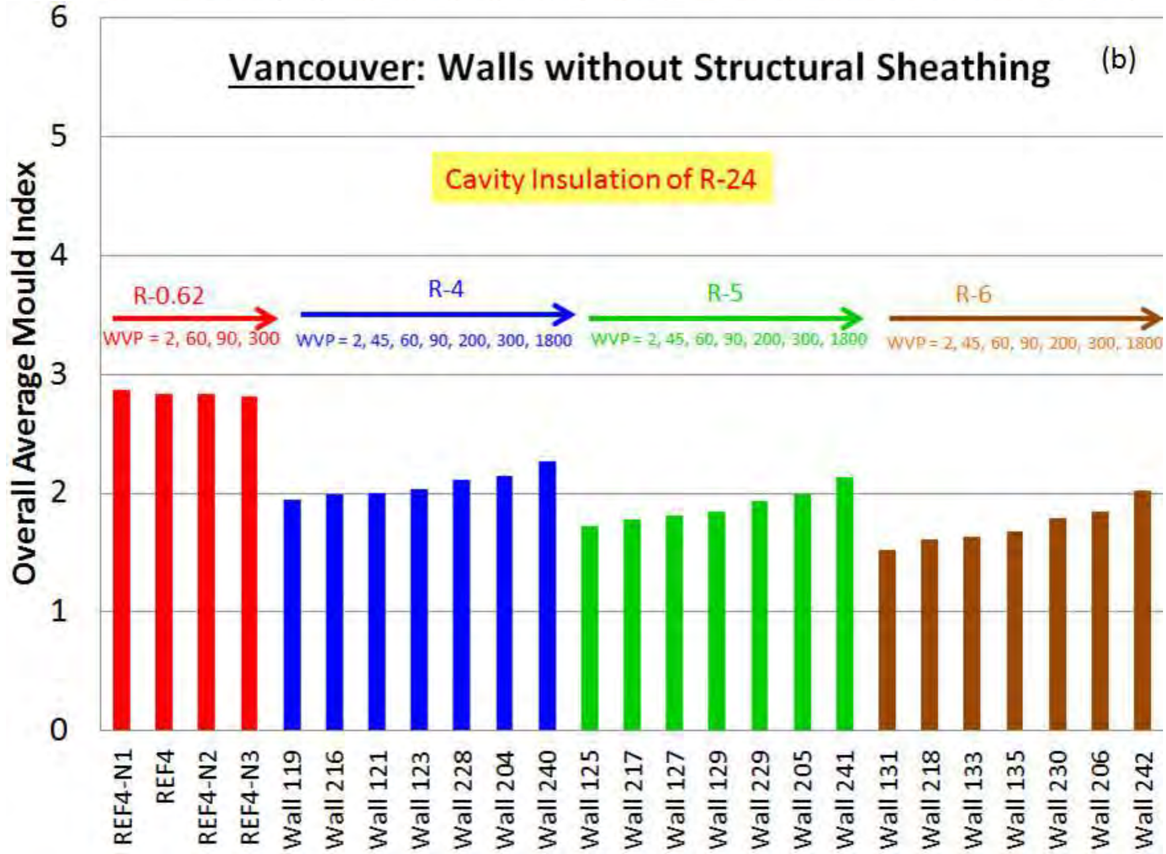


Figure 46. Simulation results for Vancouver - Values of overall average mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

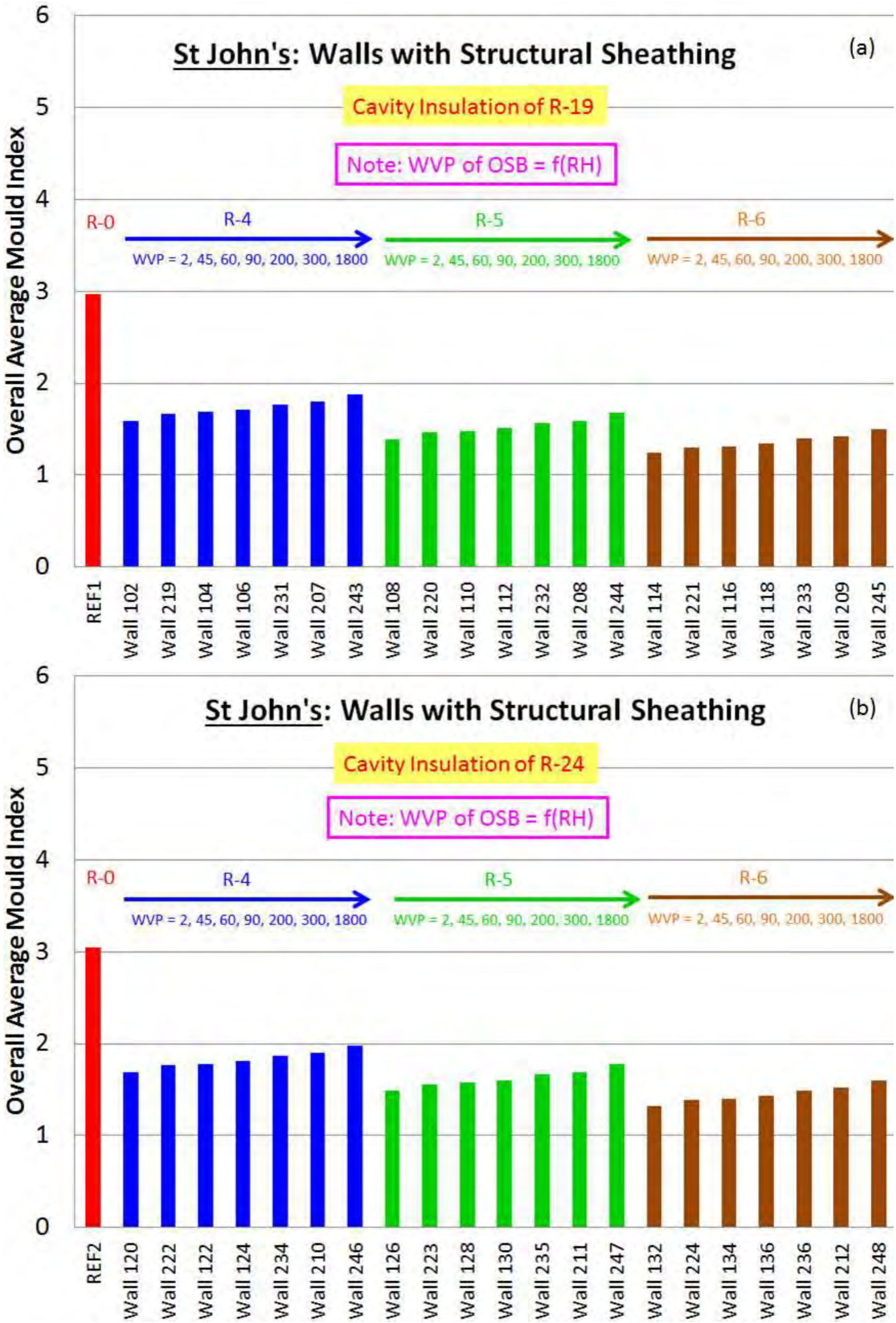


Figure 47. Simulation results for St John's - Values of overall average mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

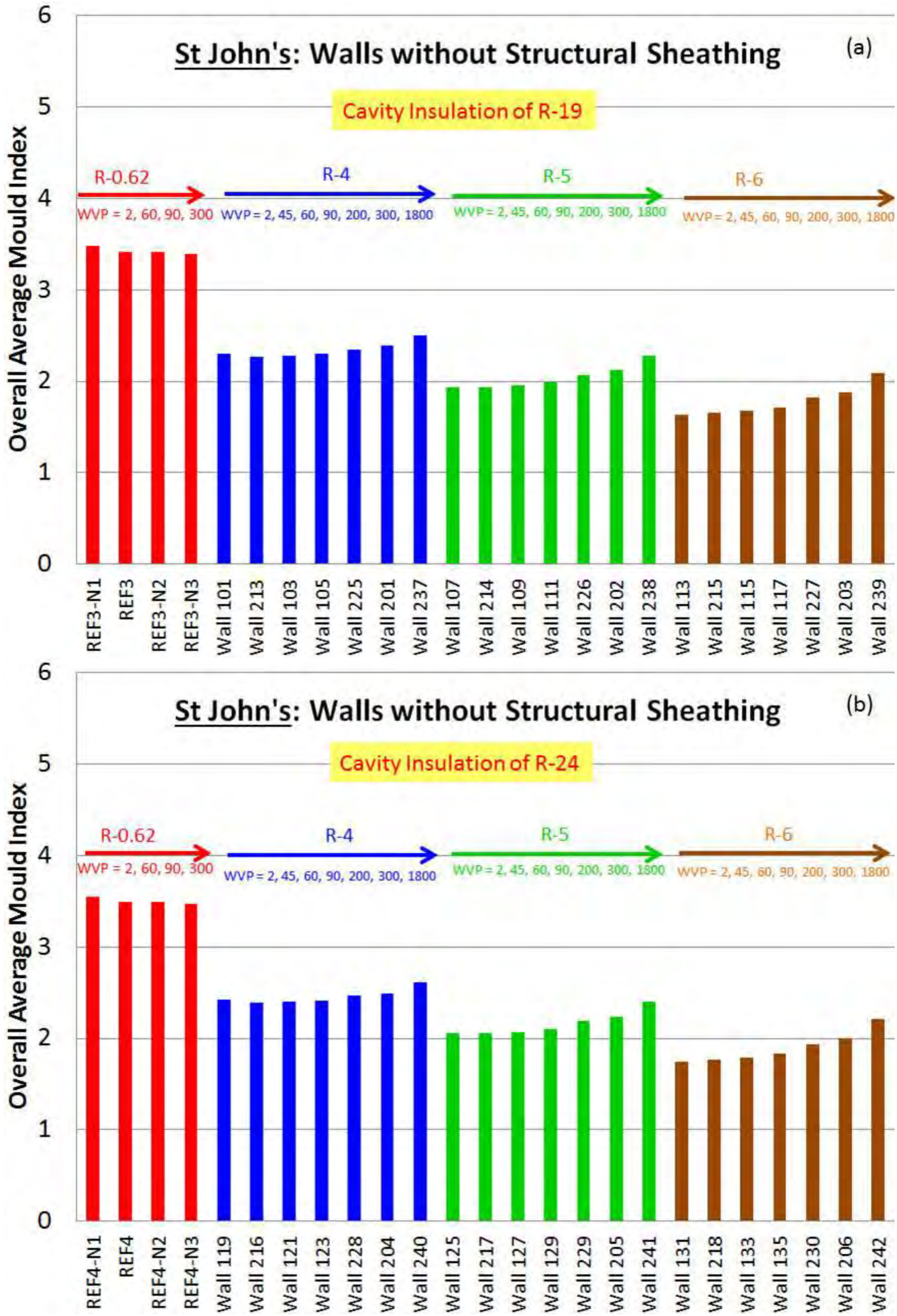


Figure 48. Simulation results for St John's - Values of overall average mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

Summary and Conclusions

- A sensitivity analysis was conducted to investigate the effect of different air leakage rate of 10%, 25%, 50%, 75% and 100% on the hygrothermal performance of wall assemblies. Results showed that a 75% and 100% (i.e. 0.1 L/(s•m²) at 75 Pa) of the air leakage rate would result in a risk of mould growth. However, an air leakage rate of 50% (i.e. 0.05 L/(s•m²) at 75 Pa) or less resulted in no risk of mould growth in the wall assembly.
- The modeling results for different wall assemblies were expressed using the mould index criteria. The most recent model by Ojanen et al. [61] was used to determine the expected value of mould index of different materials within the wall assemblies.
- Based on the air leakage path that is considered in this study, the simulation results showed that the critical locations inside the wall assembly at risk of mould growth are the top and bottom portions of the wall assembly. Considering a different air leakage path, however, could result in different locations within the wall assemblies at risk of condensation and mould growth.
- The simulation results were presented on the basis of a simple form using the following two parameters:
    - The overall average value of mould index (M_{AVG}) which is the average value of mould index at all locations within the assembly.
    - The overall maximum value of mould index which is the average value of the maximum mould index values at all locations within the assembly.
- St John's appears to have the most severe climate in comparison to the other three locations investigated (Vancouver, Ottawa and Edmonton); the greatest values of the overall average mould index (M_{AVG}) of the wall configurations amongst the four locations occurred in this location.
- The values for the overall average mould index of walls with insulation in the stud cavity of R-19 are lower than that of walls with R-24 insulation in the stud cavity.
- Values for the overall average mould index of walls configured with structural sheathing are lower than that of walls configured without structural sheathing.
- For a thermal resistance of the outboard insulation of R-0.62 (i.e. same value as OSB of 11 mm thick) in wall assemblies without structural sheathing, the M_{AVG} value decreases with increasing the WVP of the outboard insulation for different climate conditions.
- For a given type of outboard insulation of R-4, R-5, R-6, the change in M_{AVG} values in relation to the WVP of the outboard insulation differed depending on the location:
    - For the coldest and driest climate (i.e. Edmonton), the M_{AVG} value of walls with structural sheathing insignificantly changed with the WVP of the outboard insulations. Whereas the M_{AVG} value of walls without structural sheathing decreases with increasing value for the WVP of the outboard insulation.
    - For cold and dry climates (i.e. Ottawa), the M_{AVG} value insignificantly changed with the WVP of the outboard insulation for walls with and without structural sheathing.

- For the milder coastal climates (i.e. Vancouver and St John's), the M_{AVG} value increases with increasing the WVP of the outboard insulations for walls with and without structural sheathing.

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Appendix – A: Overall average and maximum mould index for different geographical locations

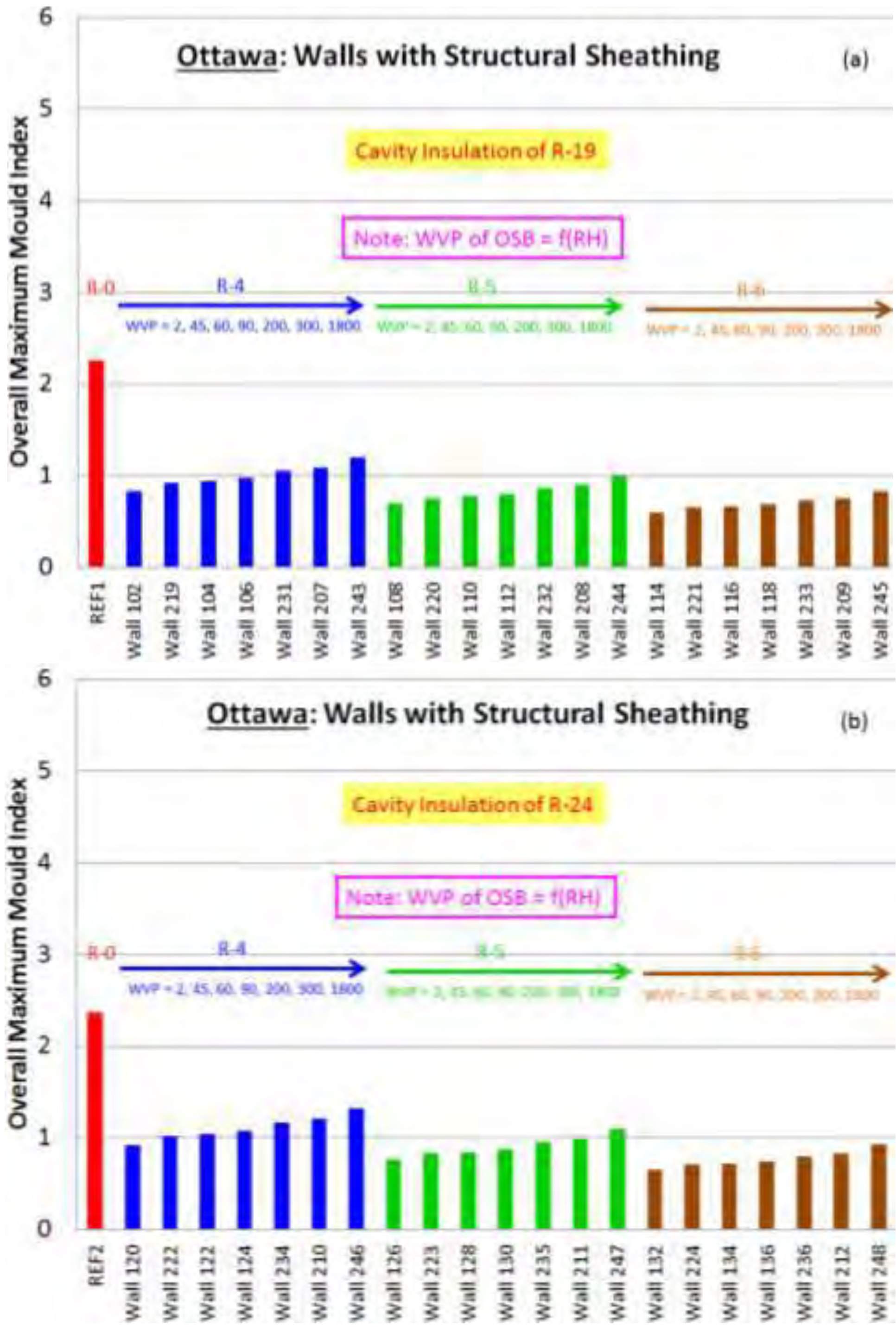

Figure A - 1 Simulation results for Ottawa - Values of overall maximum mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

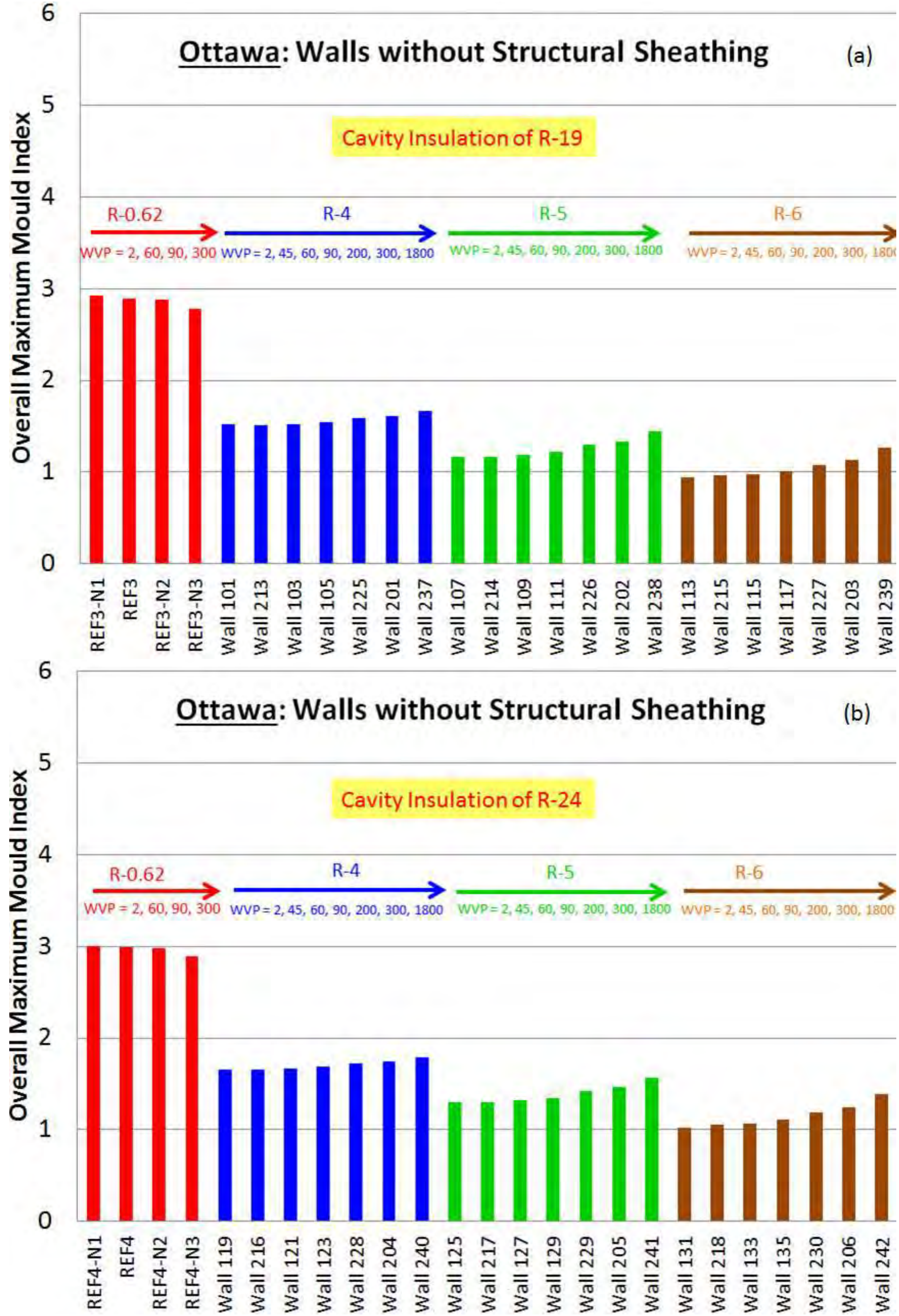

Figure A - 2. Simulation results for Ottawa - Values of overall maximum mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

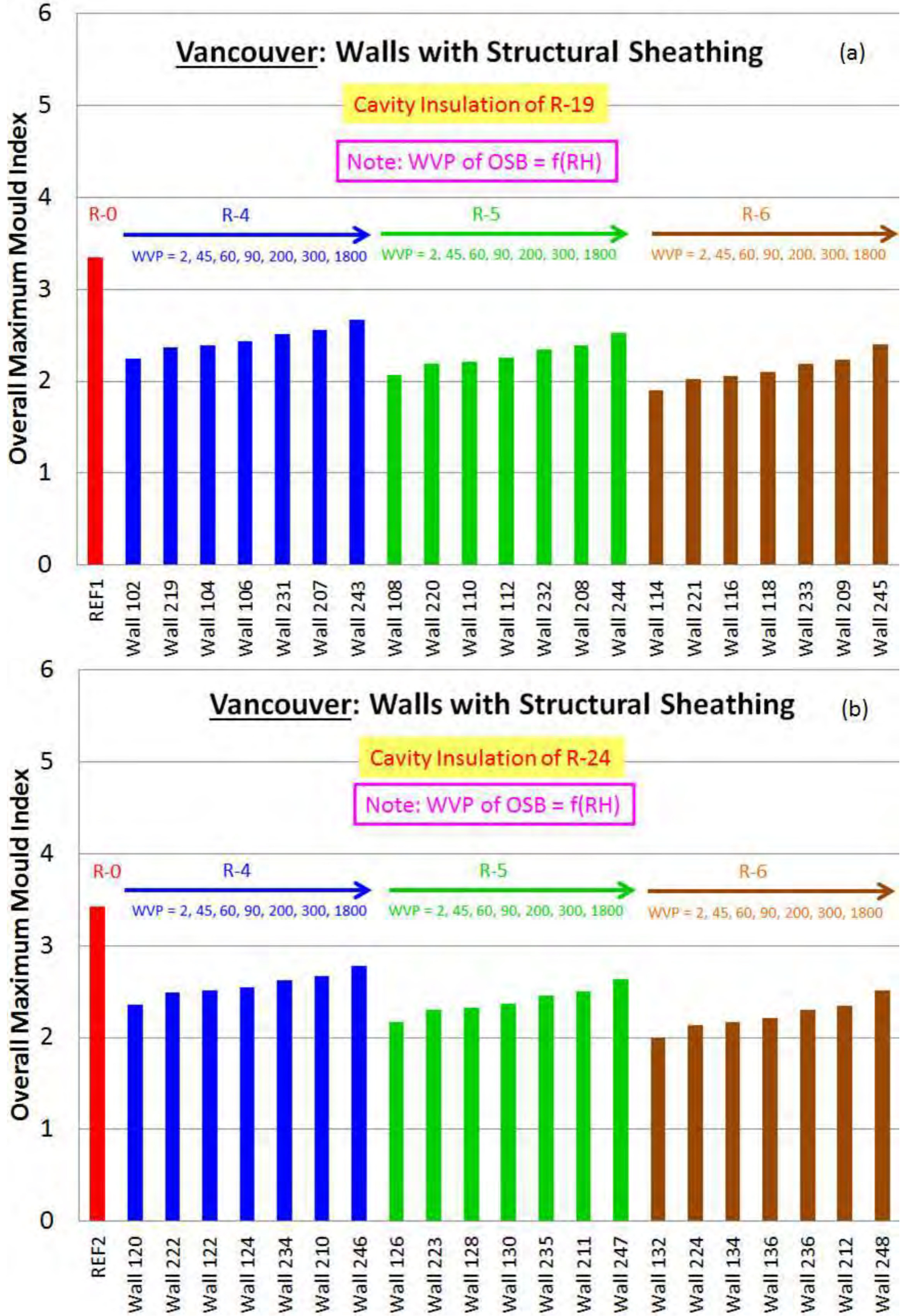

Figure A - 3. Simulation results for Vancouver - Values of overall maximum mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

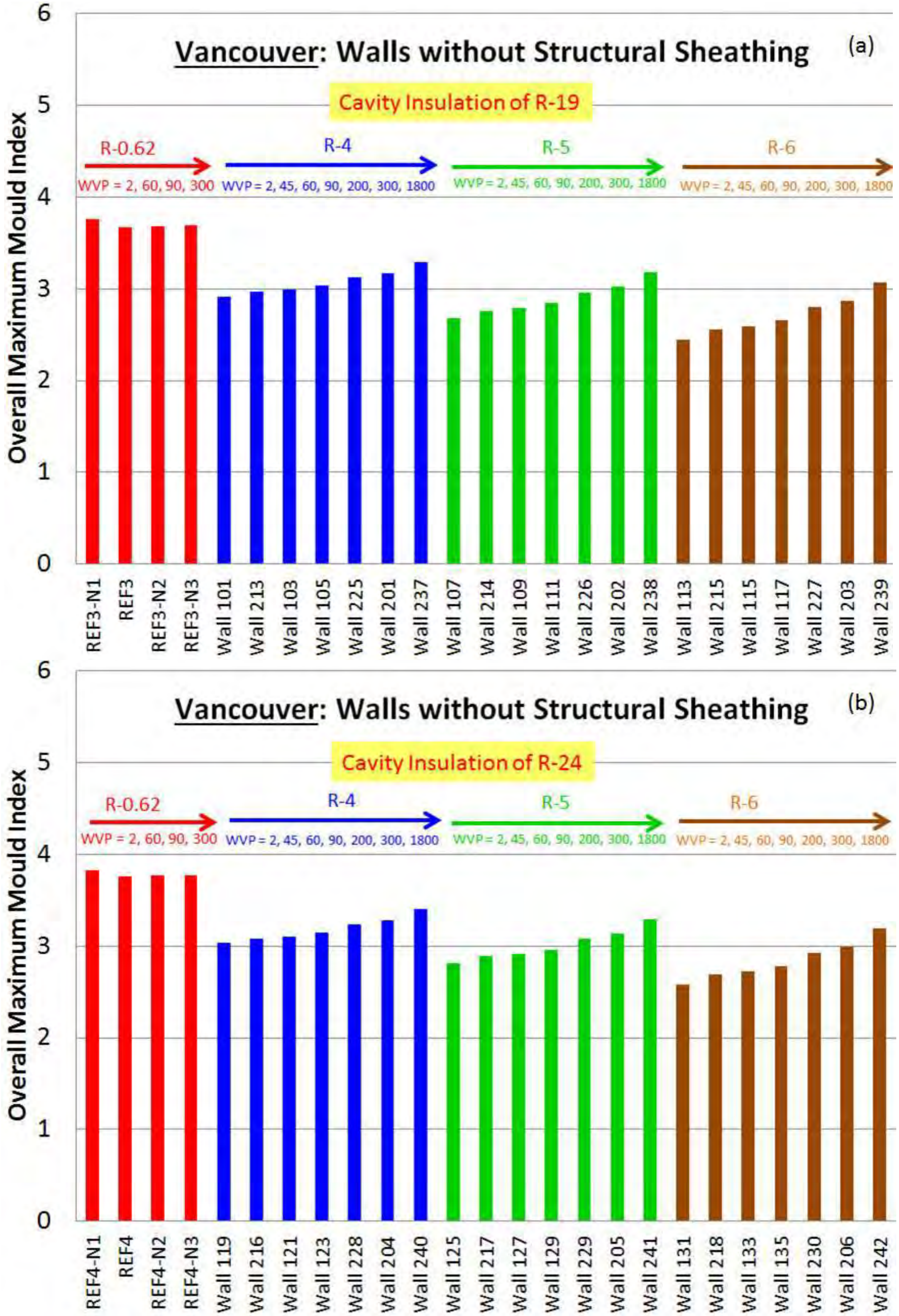

Figure A - 4. Simulation results for Vancouver - Values of overall maximum mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

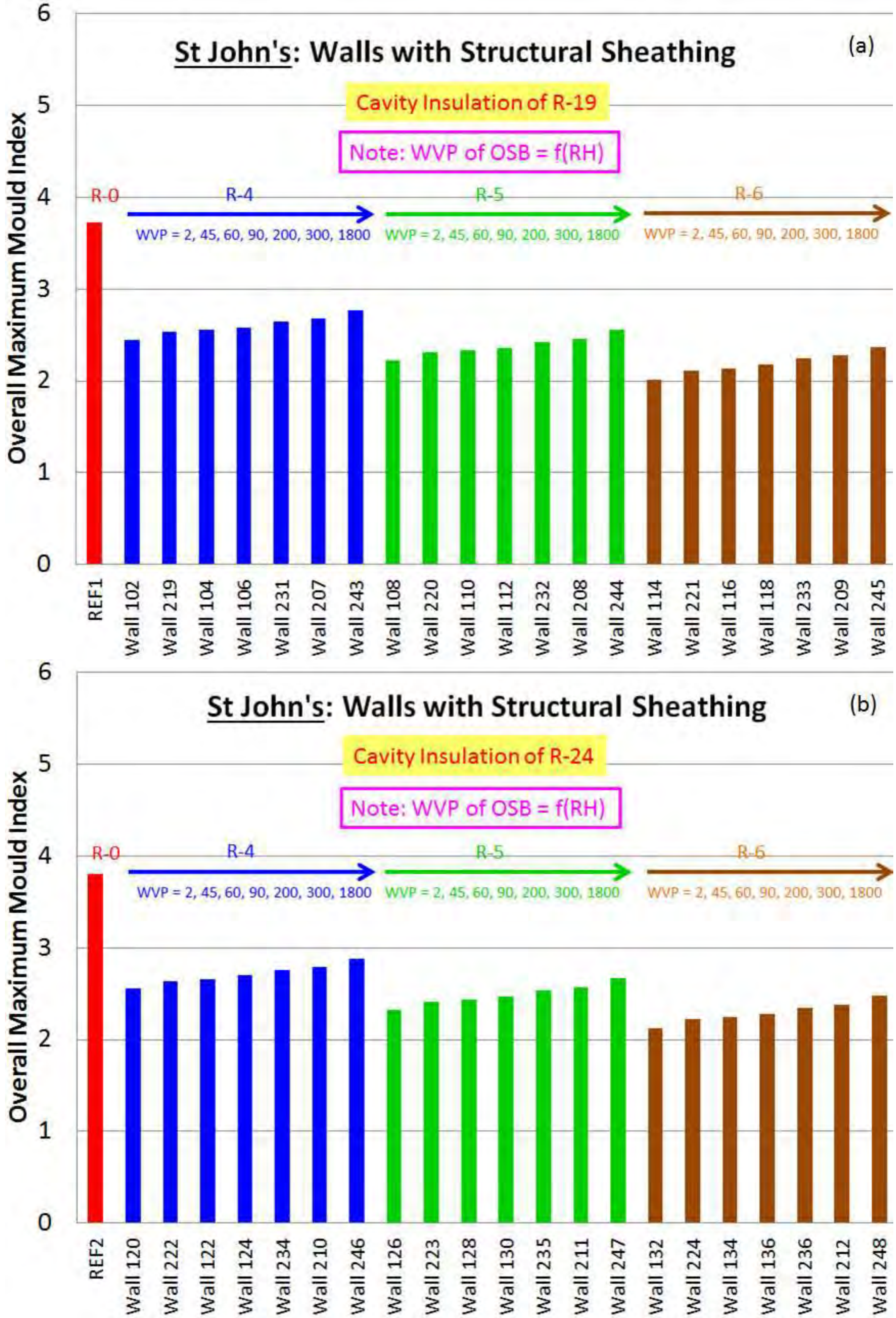

Figure A - 5. Simulation results for St John's - Values of overall maximum mould index for walls with structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

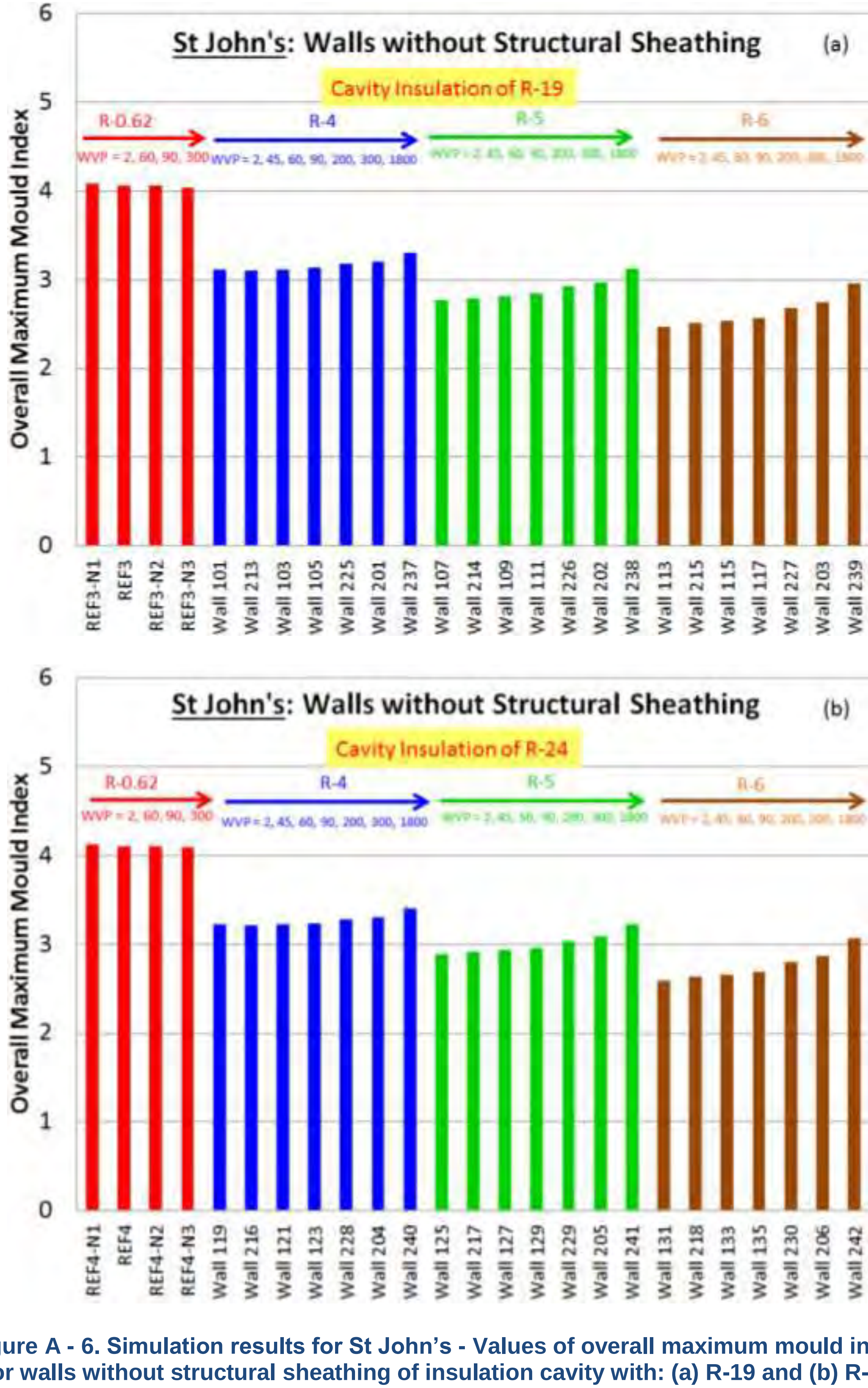

Figure A - 6. Simulation results for St John's - Values of overall maximum mould index for walls without structural sheathing of insulation cavity with: (a) R-19 and (b) R-24

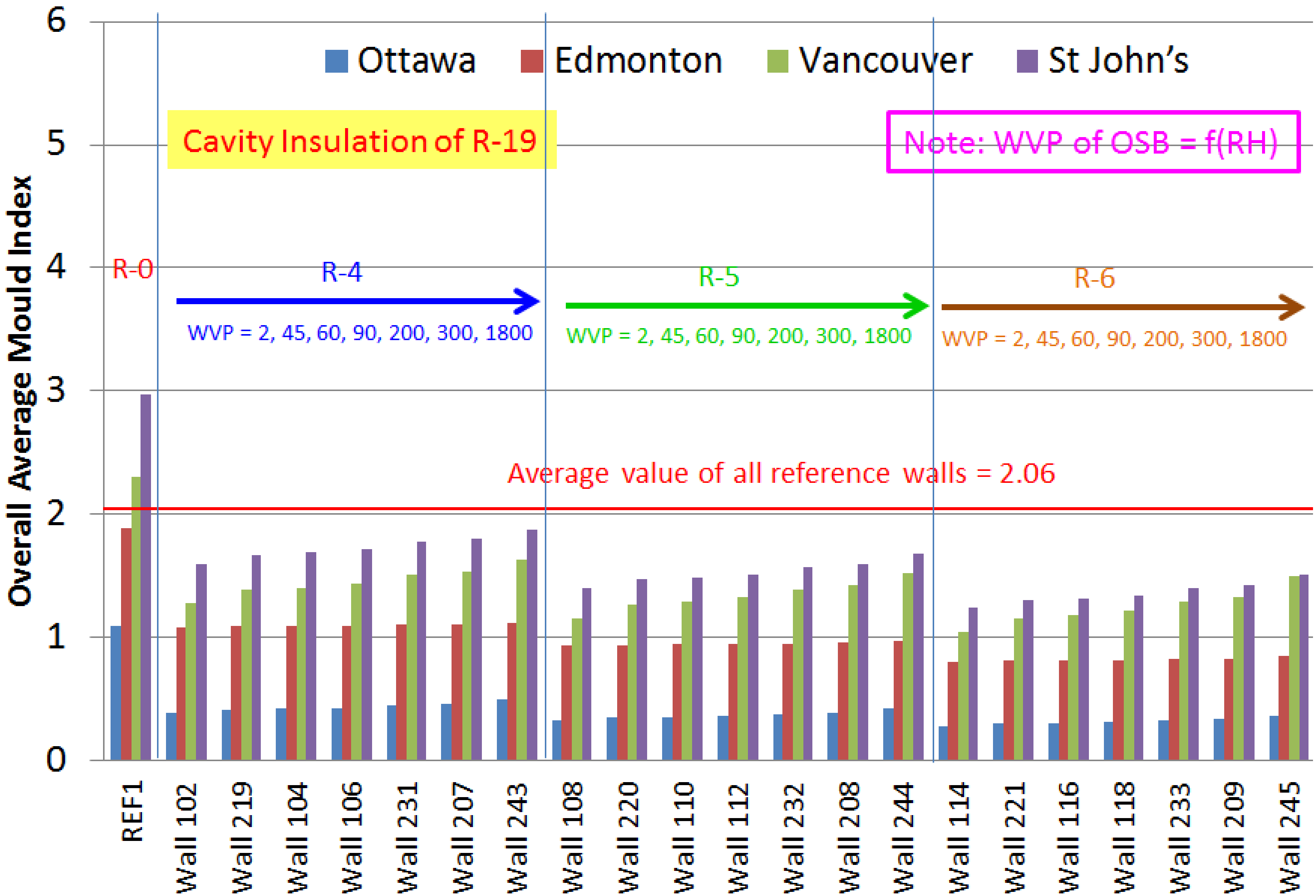

Figure A - 7. Comparison of the overall average mould index for walls with structural sheathing (insulation cavity of R-19)

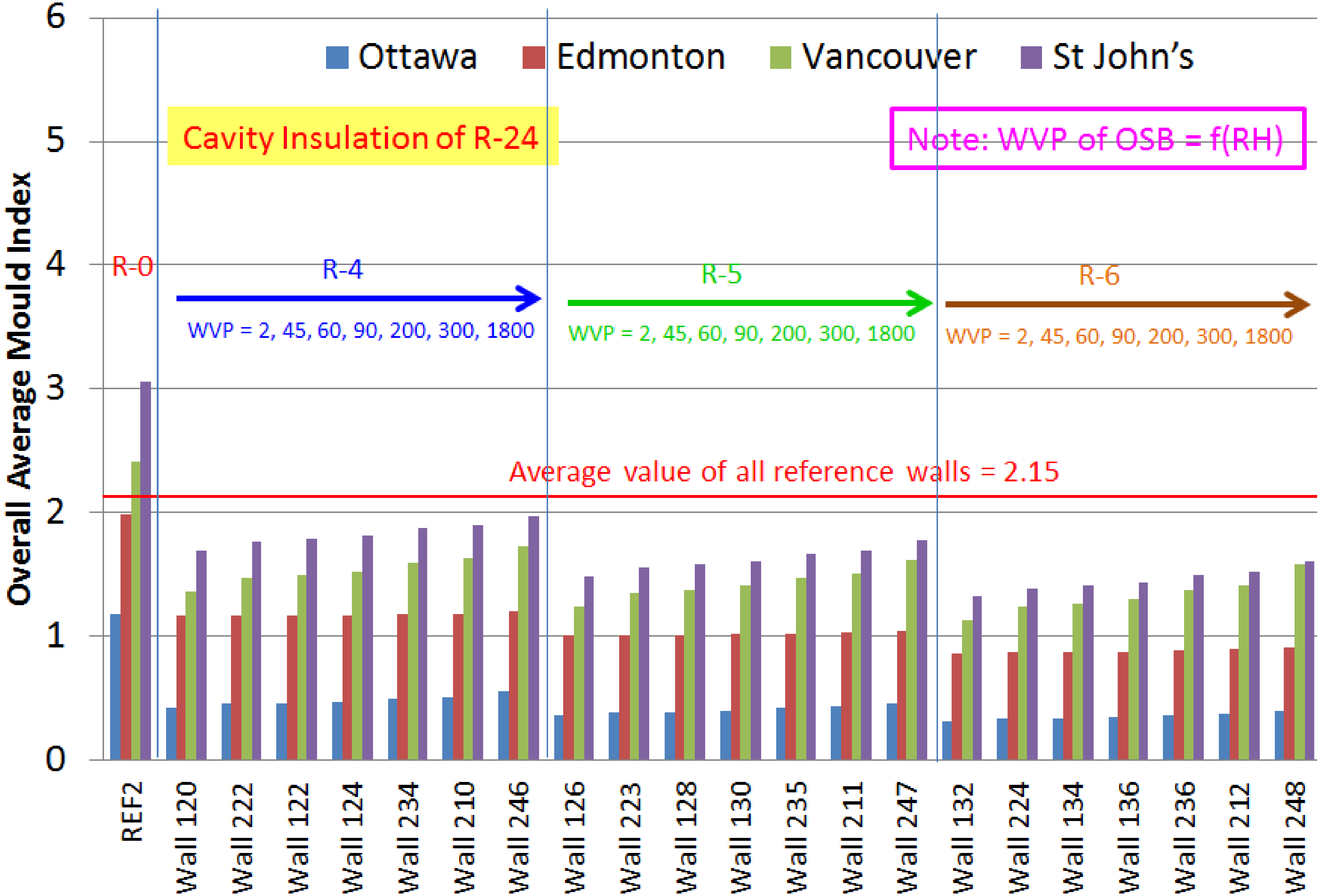

Figure A - 8. Comparison of the overall average mould index for walls with structural sheathing (insulation cavity of R-24)

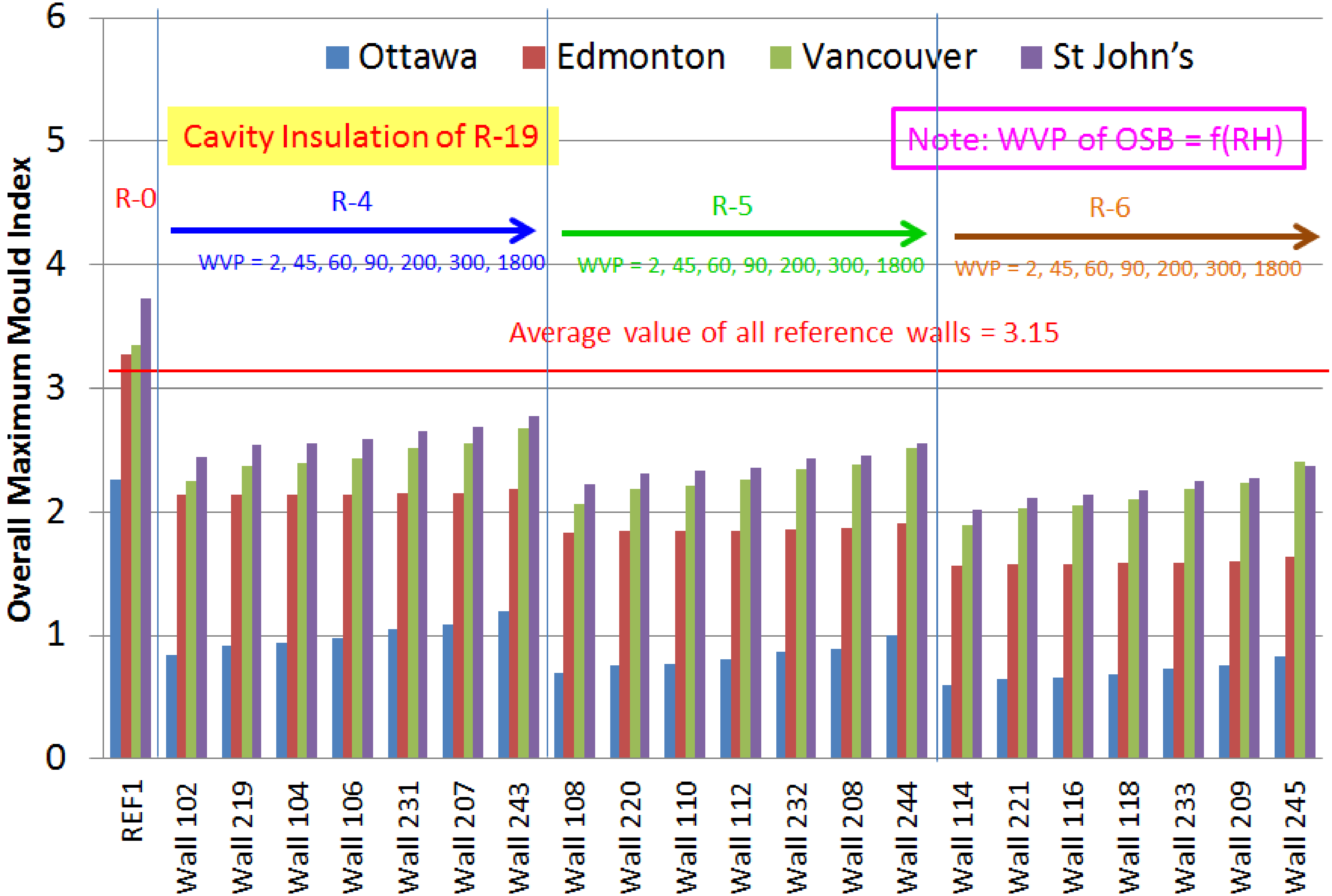

Figure A - 9. Comparison of the overall maximum mould index for walls with structural sheathing (insulation cavity of R-19)

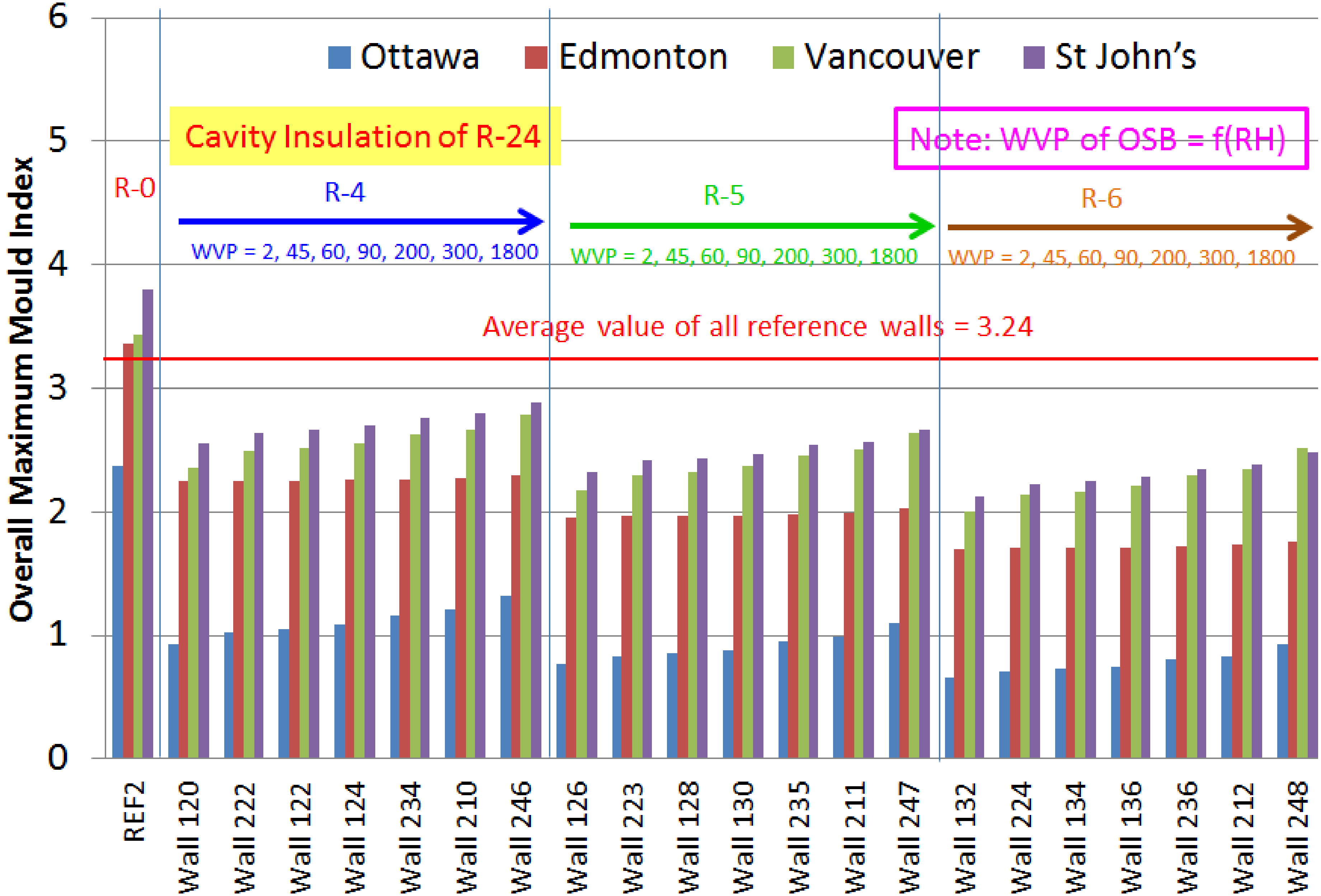

Figure A - 10. Comparison of the overall maximum mould index for walls with structural sheathing (insulation cavity of R-24)

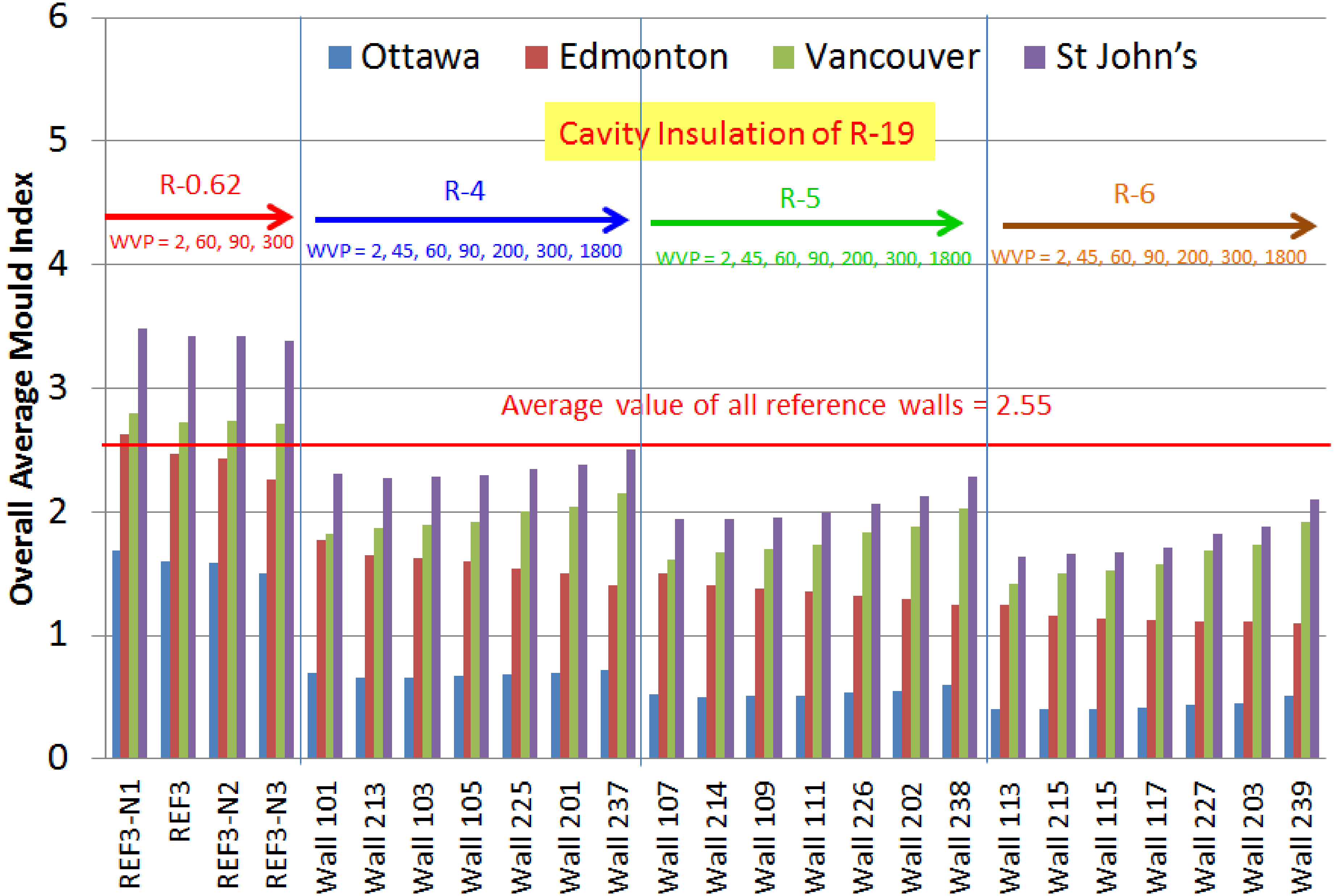

Figure A - 11. Comparison of the overall average mould index for walls without structural sheathing (insulation cavity of R-19)

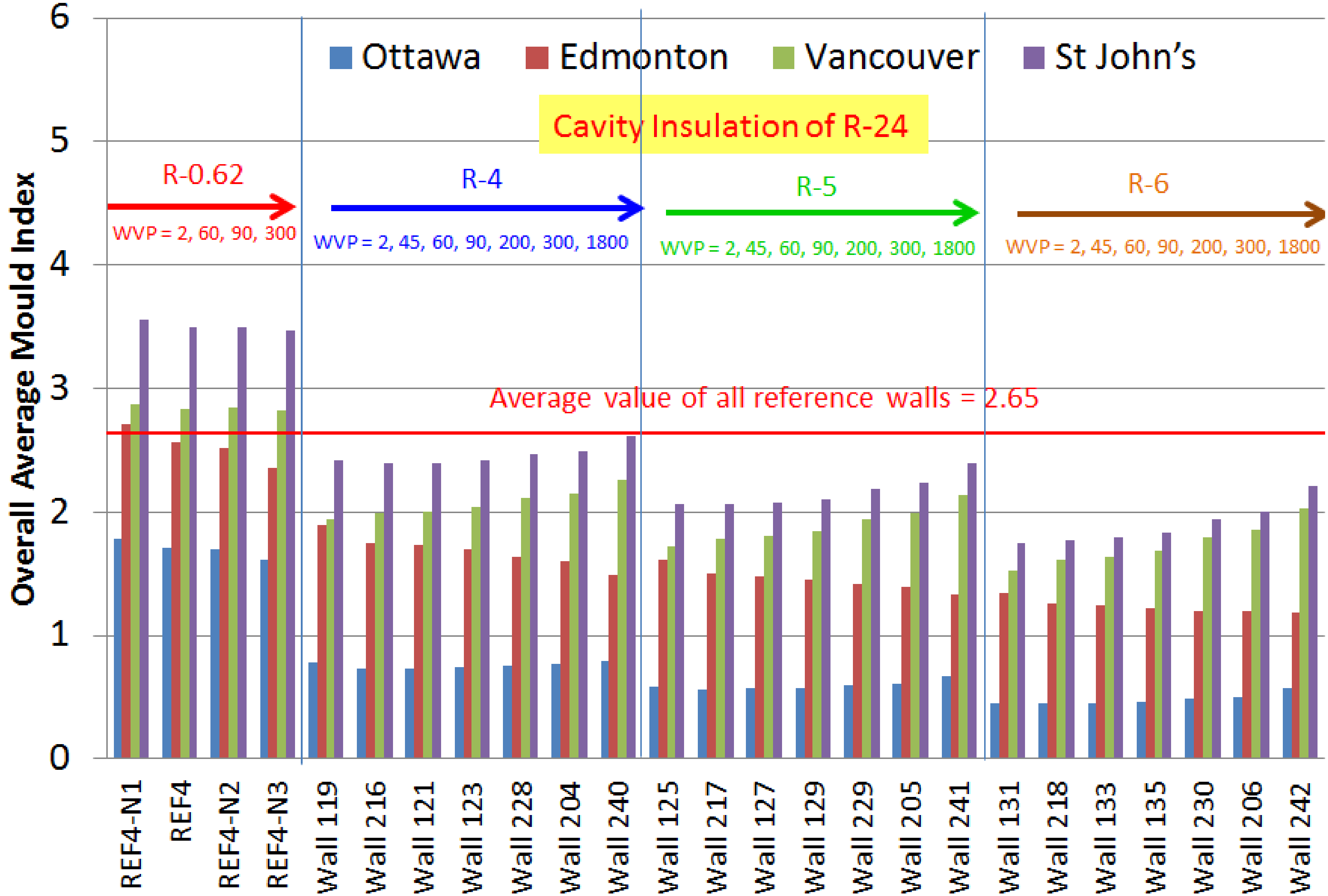

Figure A - 12. Comparison of the overall average mould index for walls without structural sheathing (insulation cavity of R-24)

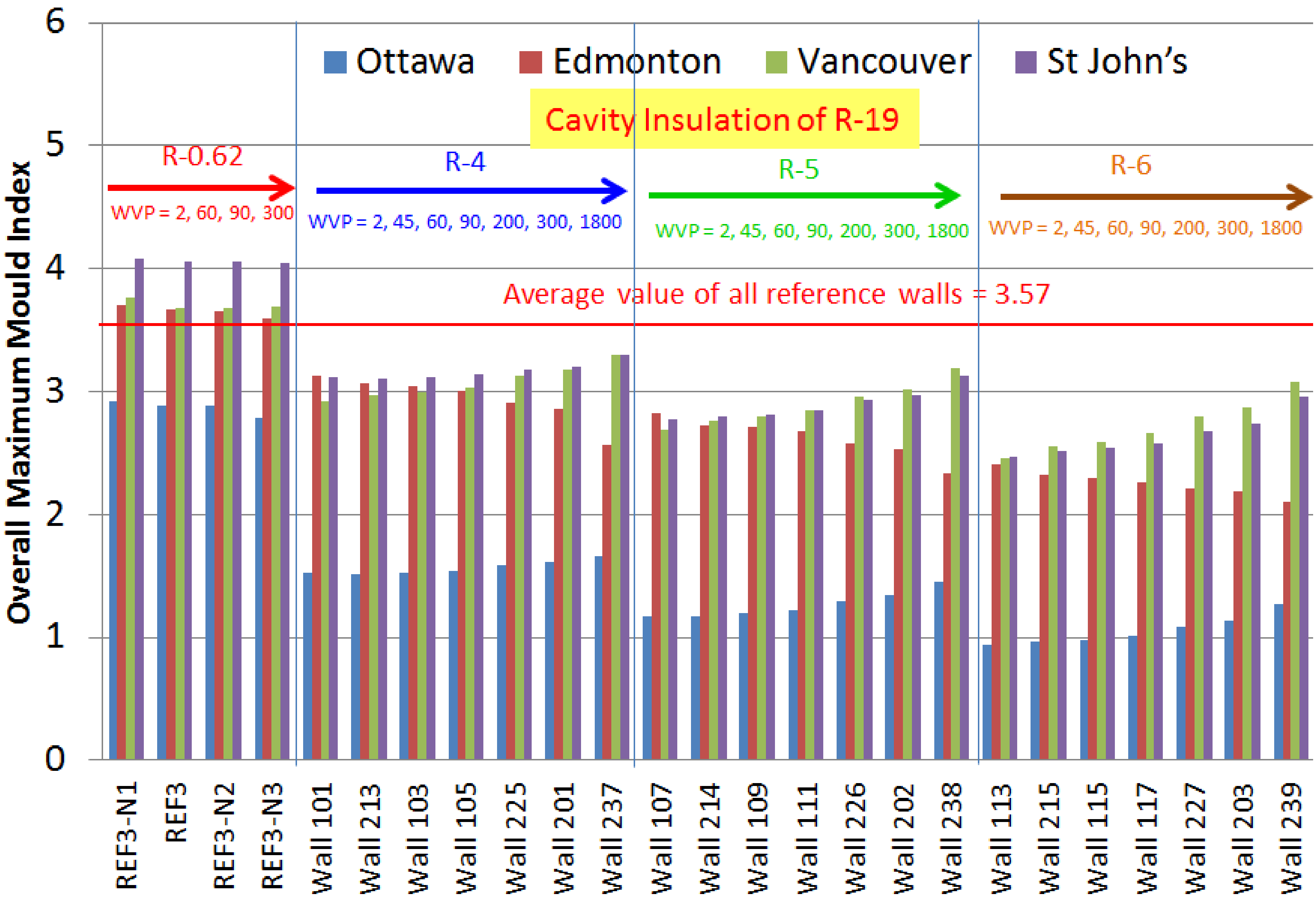

Figure A - 13. Comparison of the overall maximum mould index for walls without structural sheathing (insulation cavity of R-19)

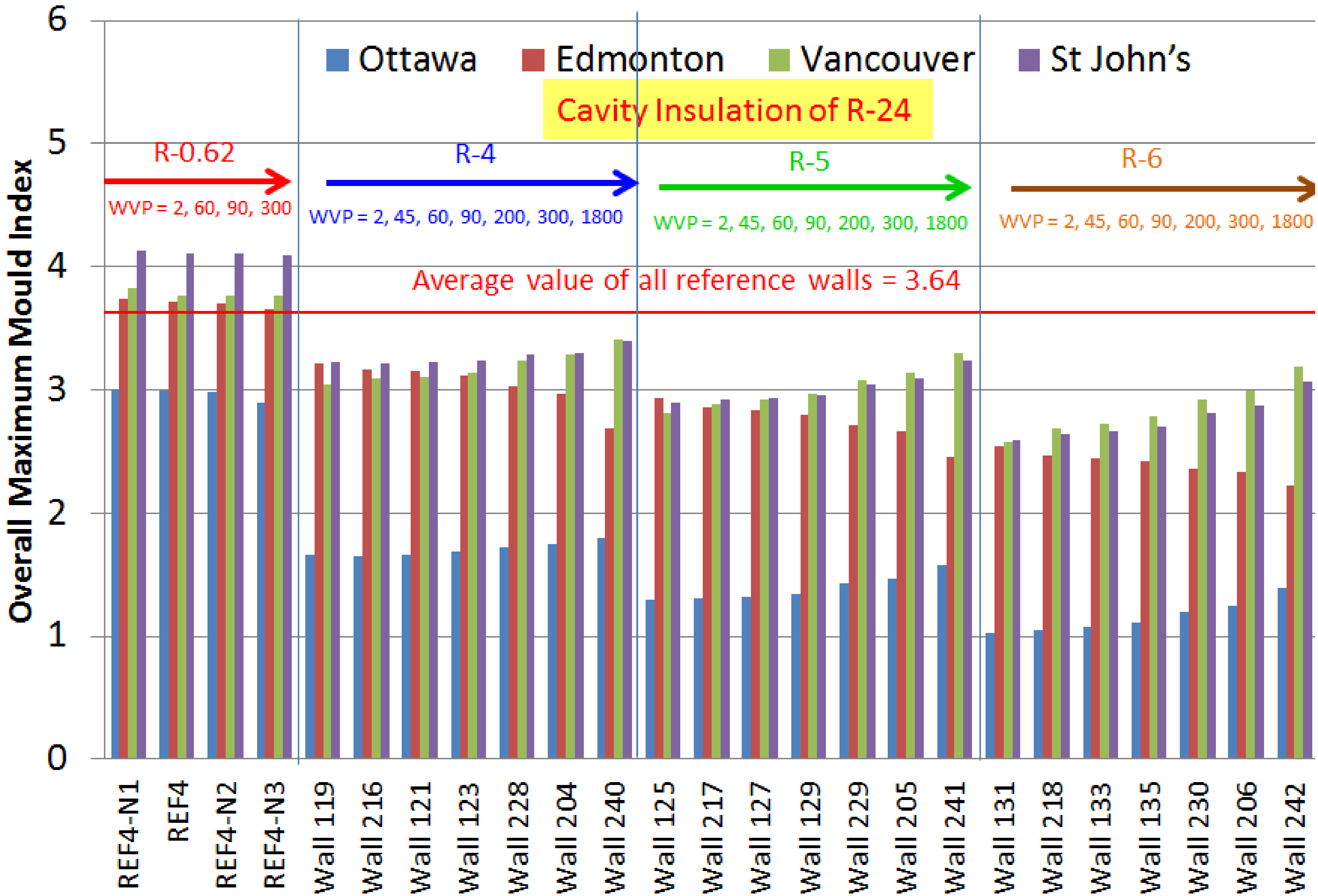

Figure A - 14. Comparison of the overall maximum mould index for walls without structural sheathing (insulation cavity of R-24)