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Mukhopadhyaya, Phalguni; Van Reenen, David; Bundalo-Perc, Sladana

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Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads

Task 2 — Building Component Hygrothermal Properties Characterization

Phalguni Mukhopadhyaya, David van Reenen and Sladana Bundalo-Perc

17 March, 2014

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STO Corporation
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Summary

A benchmark assembly and a series of ten client wall assemblies were developed as part of the project "Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads".

The purpose of this project was to assess the performance of wall drainage components and sheathing membranes (drainage system) in their ability to provide sufficient drainage and drying in Canadian climates with a moisture index (MI) greater than 0.9 and less than 3400 degree-days, or MI greater than 1.0 and degree days ≥ 3400 (primarily coastal areas). In these regions, the 2010 National Building Code requires a capillary break behind all Part 9 claddings. Currently, acceptable solutions to the NBC capillary break requirement include:

(a) A drained and vented air space not less than 10 mm deep behind the cladding;

(b) An open drainage material, not less than 10 mm thick and with a cross-sectional area that is not less than 80% open, behind the cladding;

(c) A cladding loosely fastened, with an open cross section (i.e. vinyl, aluminum siding)

(d) A masonry cavity wall or masonry veneer constructed according to Section 9.20 (i.e. 25 mm vented air space)

In this project, the performance of proposed alternative solutions for the capillary break was compared through laboratory evaluation and modeling activities to the performance of a wall built to minimum code requirements. The proposed drainage system would be deemed an alternative solution to the capillary break requirement in the National Building Code for use with all code compliant Part 9 claddings provided it exhibits adequate moisture performance as compared to a NBC-compliant benchmark wall assembly.

In This Report — A set of reliable and representative hygrothermal property data were generated of a number of selected building materials, including all drainage components and sheathing membranes, for hygrothermal simulation of wall assemblies.

In addition to regular measurements, additional tests were conducted to quantify the air flow performance of several drainage components used in the drainage cavities of the client recommended wall assemblies.

Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 2 – Building Component Hygrothermal Properties Characterization

Authored by:

Phalguni Mukhopadhyaya, David van Reenen and Sladana Bundalo-Perc

A Report for the

AIR BARRIER ASSOCIATION OF AMERICA

National Research Council Canada
Ottawa ON K1A 0R6 Canada

March 17, 2014

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Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 2 – Building Component Hygrothermal Properties Characterization

Final Report Task 2

Phalguni Mukhopadhyaya, David van Reenen and Sladana Bundalo-Perc

1. Introduction

In this project, the hygrothermal performance of proposed solutions for wall assemblies incorporating drainage components was compared through laboratory evaluation and modeling activities to the performance of a NBC[1]-compliant wall built to minimum code requirements. The hygrothermal properties and air flow characteristics were determined to quantify the hygrothermal performance of different wall assemblies. The wall assemblies consisted of a reference wall system and the respective wall assemblies of interest to the project clients, each assembly having a different method for drainage of the wall cavity; a list of these walls is provided in Table 1 and horizontal sectional details are given in Appendix 2.

To carry out hygrothermal performance assessments of wall assemblies using the numerical simulation tool hygIRC-C, the hygrothermal properties of all materials used for the construction of the different wall assemblies was required. Many of the hygrothermal properties of materials of the respective wall assemblies are available in NRC's material properties database. For several materials, however, appropriate hygrothermal properties were not available and tests to determine hygrothermal properties of these materials were completed as part of this project. Accordingly, the hygrothermal properties have been determined for the materials listed in Table 1 and in which the designated wall section in which they were used is also given. The results of the testing, together with the methods used to determine the respective hygrothermal properties, are provided in §2 of this report and in the order provided in Table 1 starting with Client A.

In addition, to permit quantifying the drying potential of various drainage layers, the air flow characteristics along the height of a wall of the respective drainage components were also examined using the method to determine the air permeability of materials, as described in §2, and according to the procedure given by Bomberg and Kumaran (1986). The drainage configurations tested are given in Table 2 and the results and test methods used in the testing for air flow characteristics of these products are provided in §3 of this report.

It should also be noted that the air flow characteristics of clear cavities (i.e. 10, 20 and 25 mm) as well as cavities incorporating drainage components (i.e. Clients C, G, E and I) were characterized using another apparatus, a description of which is given, and for which results are provided, in the Task 4 report[2].

[1] NBC- National Building Code Canada 2010

[2] A list of project reports is provided in Appendix 1

Table 1 – List of wall assemblies for which hygrothermal properties were sought

Designations	Description of Drainage Component	Description of component tested for hygrothermal properties
Reference wall	Air space created by 19 mm plywood strapping; on NBC Code-compliant building paper*	NBC Code-compliant stucco
Client A Wall	Code compliant building paper* / cap fasteners provide 2 mm gap / Drainable SBPO** sheathing membrane	Drainable SBPO sheathing membrane
Client B Wall	10 mm air space / Water repellent insulation board (76 mm) / liquid applied membrane	Water repellent insulation board
Client C Wall	Code compliant building paper* / Nylon mesh (10 mm; open matrix) / PP† nonwoven sheathing membrane	Nylon mesh (10 mm; open matrix) bonded to PP nonwoven sheathing membrane
Client D Wall	Code compliant building paper* / Cap fasteners provide 2 mm gap / Cross woven, micro-perforated polyolefin sheathing membrane with polyolefin coating	Cross woven, micro-perforated polyolefin sheathing membrane with polyolefin coating
Client E Wall	PP† fabric (stucco screen) / Dimpled HDPE‡ (11 mm) membrane / Code compliant building paper*	PP† fabric bonded to dimpled HDPE‡ membrane
Client F Wall	Stucco-clad wall having 25 mm air space / Code compliant building paper*	Nil (25 mm air space)
Client G Wall	Non-woven PP† fabric (stucco screen) / PP† mat (10 mm; 3-dimensional extruded PP mono-filament mesh) / Code compliant building paper*	Non-woven PP† fabric (stucco screen) / PP† mat (10 mm; PP mono-filament mesh)
Client H Wall	Porous PS†† insulation board (52 mm) / liquid applied membrane	Porous PS†† insulation board (52 mm)
Client I Wall	2 ply, corrugated asphalt impregnated paper*; Grade D!! (4.2 mm) / Code-compliant building paper*	2 ply, corrugated asphalt impregnated paper* - Grade D!!
Client J Wall	Building paper*; Grade D!!; 60 Minute / Air space created by 9.5 mm plywood strapping / 2 layers of Code compliant building paper*	Three coat stucco with expanded diamond metal lath
Client K Wall	Building paper*, Grade D!!; 60 Minute / Air space created by 9.5 mm plywood strapping / 2 layers of Code compliant building paper*	Three coat stucco with paper backed welded wire metal lath

* Conforming to CGSB standard CAN2-51.32-M77; ** SBPO – Spun bonded polyolefin; † PP - polypropylene; ‡ HDPE – high density polyethylene; †† PS – polystyrene; !! Conforming to US Federal Specification UU-B-790a (Type I - Barrier paper; Grade D Water-vapor permeable; Style 2 - Uncreped, not reinforced, saturated)

Table 2 – List of drainage layers for which air flow was characterized[3]

Description of drainage layer	Designations
Clear (empty) cavity (7mm)	Reference wall
Open matrix Nylon mesh; alone (7mm)	Client C Wall
Nylon mesh (10 mm; open matrix) bonded to PP† nonwoven sheathing membrane	Client C Wall
Non-woven PP† fabric (stucco screen) bonded to PP† mono-filament mesh providing a 10 mm mat	Client G Wall
PP† fabric bonded to dimpled HDPE‡ membrane	Client E Wall
2 ply, corrugated asphalt impregnated paper* - Grade D!!	Client I Wall

† PP - polypropylene; ‡ HDPE – high density polyethylene; * Conforming to CGSB standard CAN2-51.32-M77; !! Conforming to US Federal Specification UU-B-790a (Type I - Barrier paper; Grade D Water-vapor permeable; Style 2 - Uncreped, not reinforced, saturated)

[3] The air flow characteristics of clear cavities (i.e. 10, 20 and 25 mm) as well as cavities incorporating drainage components (i.e. Clients C, G, E and I) were also characterized using another apparatus, a description of which is given, and for which results are provided, in the Task 4 report (see Appendix 1).

2. Hygrothermal Properties Determination

2.1 Drainable SBPO Sheathing Membrane (Client A)

The test specimens used for the various measurements presented in this report were taken from SBPO membranes (Figure 1) having a nominal membrane thickness of 0.16mm. The thickness of the membrane, when crinkled, was 0.62 mm. The properties shown below are calculated with the nominal membrane thickness.

Figure 1 – SBPO Sheathing Membrane

Density: 560 kg m^{-3}

Heat Capacity: 1250 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

Thermal conductivity measurements were not conducted due to practical limitations of the test method for this material.

Sorption Measurements:

The measurements were done following the procedure described in ASTM Standard C1498 (ASTM International, 2010). The results from these tests are shown in Table 3.

Table 3 – Sorption Characteristic of SBPO Sheathing Membrane

Relative Humidity (% RH)	Moisture Content ($kg \cdot kg^{-1}$)
50.0	0.00035
70.8	0.00024
90.3	0.00019
94.3	0.00123

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure given in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used to determine the water vapour permeability of the SBPO sheathing membrane. For each test condition, a minimum of 3 circular specimens of 150 mm diameter were tested.

As shown in Table 4, the water vapour permeability had a constant value of 4.41×10^{-13} kg m^{-1} s^{-1} Pa^{-1}.

Table 4 – Water Vapour Permeability of SBPO Sheathing Membrane

Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})	Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})
10	4.41×10^{-13}	60	4.41×10^{-13}
20	4.41×10^{-13}	70	4.41×10^{-13}
30	4.41×10^{-13}	80	4.41×10^{-13}
40	4.41×10^{-13}	90	4.41×10^{-13}
50	4.41×10^{-13}	100	4.41×10^{-13}

Water Absorption Coefficient:

The value for the water absorption coefficient of the SBPO sheathing membrane is very low and is not measureable.

Air Permeability:

The measurements and calculations were conducted according to the procedure reported by Bomberg and Kumaran (1986). Three circular test specimens, with the same dimensions as the specimens used to determine the water vapour permeability of the SBPO sheathing membrane were used for measurements of air permeability. Measurements were conducted at a temperature of 22 ± 1 ° C.

The resulting air permeability was:

$$(4.07\pm1.00)\times10^{-6}\ \mathrm{L}(75\ \mathrm{Pa})^{-1}\cdot \mathrm{m}^{-1}\cdot \mathrm{s}^{-1}$$

2.2 Water Repellent Insulation Board (Client B)

The test specimens (Figure 2) used for the various measurements presented in this report were taken from insulation boards having a nominal thickness of 70 mm. The water repellent insulation board was made with mineral fibre insulation.

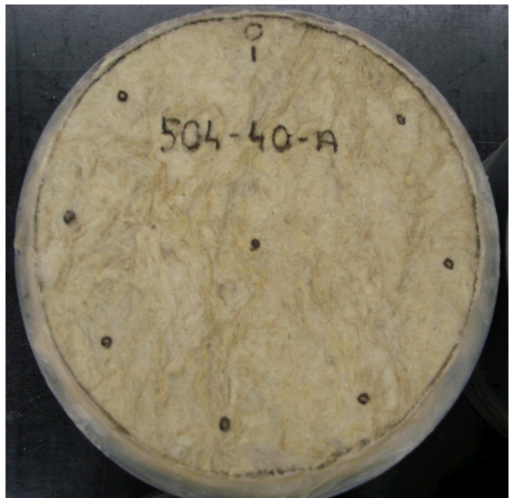

Figure 2 – Water Repellent Insulation Board

Density: 75.3 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

Measurements were conducted in accordance with ASTM Standard C518 (ASTM International 2010). The specimens were tested in an apparatus with a nominal 600 mm x 600 mm cross section. Heat flow was perpendicular to this primary surface. Also note that, for materials tested in the heat flow apparatus used to conduct the tests, the measurement uncertainties are within 2%. The measured thermal conductivity values are shown in Table 5.

Table 5 – Thermal Conductivity of Water Repellent Insulation Board

Specimen Thickness (mm)	Hot Surface Temperature (°C)	Cold surface Temperature (°C)	Conductivity (W m^{-1} K^{-1})
69.93	35.08	13.08	0.035
69.75	35.00	13.00	0.035
69.42	34.99	13.00	0.035

The average thermal conductivity was 0.035 W m^{-1} K^{-1} tested with a mean temperature of 24.0 °C.

Sorption Isotherm:

Six specimens with nominal size of 51 mm x 51 mm x 50 mm were used in these measurements. The tests were done following the procedure described in ASTM Standard C1498 (ASTM International, 2010). The results from these tests are shown in Table 6.

Table 6 – Sorption Characteristic of Water Repellent Insulation Board

Relative Humidity (% RH)	Moisture content (kg•kg^{-1})
50.3	0.0011
69.3	0.0014
88.7	0.0022
94.2	0.0099

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used to determine the water vapour permeability of the water repellent insulation board. For each test condition, a minimum of 3 circular specimens of 150 mm diameter (Figure 1) were tested.

As shown below (Table 7), the water vapour permeability had a constant value of 1.47×10^{-10} kg m^{-1} s^{-1} Pa^{-1}.

Table 7 – Water Vapour Permeability of Water Repellent Insulation Board

Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})	Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})
10	1.47×10^{-10}	60	1.47×10^{-10}
20	1.47×10^{-10}	70	1.47×10^{-10}
30	1.47×10^{-10}	80	1.47×10^{-10}
40	1.47×10^{-10}	90	1.47×10^{-10}
50	1.47×10^{-10}	100	1.47×10^{-10}

Water Absorption Coefficient:

The value for the water absorption coefficient of the water repellent insulation board is very low and is not measureable.

Air Permeability:

The measurements and calculations were conducted according to the procedure reported by Bomberg and Kumaran (1986). Three circular test specimens, of the same dimensions as specimens used for the water vapour permeability tests were used for the air permeability measurements. Measurements were conducted at a temperature of 22 ± 1 ° C.

The resulting air permeability was:

$$(1.97 \pm 0.15)\ \mathrm{L(75\ Pa)^{-1} \cdot m^{-1} \cdot s^{-1}}$$

2.3 Open matrix Nylon mesh bonded to nonwoven sheathing membrane (Client C)

The test specimens used for the various measurements presented in this report were taken from samples of Open matrix Nylon mesh bonded to nonwoven sheathing membrane (Figure 3) having a nominal thickness of 10 mm. The measured thickness was 10.5 mm.

Figure 3 – Open matrix Nylon mesh bonded to nonwoven sheathing membrane

Density: 43.5 kg m^{-3}
Heat Capacity: 1210 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

The thermal conductivity of the open matrix Nylon mesh bonded to nonwoven sheathing membrane was determined in accordance with ASTM Standard C518 (ASTM International 2010). The specimen enclosed in a wood-frame was tested in an apparatus with a nominal cross section of 300 mm x 300 mm. Heat flow was perpendicular to this primary surface. Also note that, for materials tested in the heat flow apparatus used to conduct the reported tests, the measurement uncertainties are within 2%. The measured thermal conductivity value is shown in Table 8.

Table 8 – Thermal Conductivity - Open Nylon mesh bonded to nonwoven sheathing membrane

Specimen Thickness (mm)	Hot Surface Temperature (°C)	Cold surface Temperature (°C)	Conductivity (W m^{-1} K^{-1})
10.69	35.0	13.0	0.065

The thermal conductivity was 0.065 W m^{-1} K^{-1} tested with a mean temperature of 24.0 °C

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used to determine the water vapour permeability of the open matrix Nylon mesh bonded to nonwoven sheathing membrane. For each test condition, a minimum of 3 circular specimens, having a 150 mm diameter, were tested. Results are shown in Table 9.

Table 9 – Water Vapour Permeability of Open matrix Nylon mesh bonded to nonwoven sheathing membrane

Relative Humidity (%)	Water Vapour Permeability ($kg\ m^{-1}\ s^{-1}\ Pa^{-1}$)	Relative Humidity (%)	Water Vapour Permeability ($kg\ m^{-1}\ s^{-1}\ Pa^{-1}$)
10	2.89×10^{-12}	60	2.89×10^{-12}
20	2.89×10^{-12}	70	2.89×10^{-12}
30	2.89×10^{-12}	80	2.89×10^{-12}
40	2.89×10^{-12}	90	2.89×10^{-12}
50	2.89×10^{-12}	100	2.89×10^{-12}

Water Absorption Coefficient:

The water absorption coefficient of the open matrix Nylon mesh bonded to nonwoven sheathing membrane is very low and is not measureable.

Air Permeability:

The measurements and calculations to determine the air permeability of the open matrix Nylon mesh bonded to nonwoven sheathing membrane were carried out as described in §3. Average permeability values derived from tests undertaken at different heights were determined and from which:

The resulting air permeability was determined as:

$$9.4\times10^{3}\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

The air permeability for air flow perpendicular to the mesh was also measured; the resulting air permeability was:

$$7.5\times10^{-3}\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

2.4 Cross woven, micro-perforated polyolefin sheathing membrane (Client D)

The test specimens for the cross woven, micro-perforated polyolefin sheathing membrane (Figure 4) used for the various measurements had a nominal thickness of 0.76 mm.

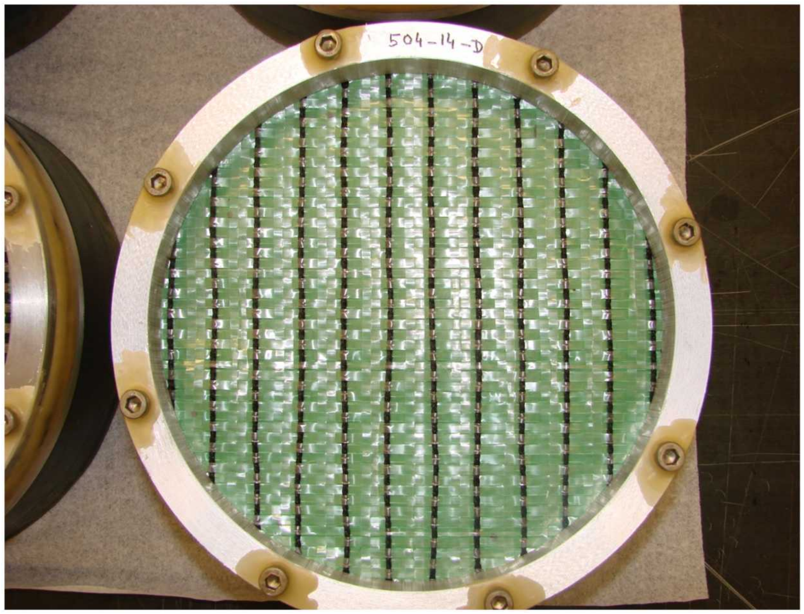

Figure 4 – Drainage Building Wrap

Density: 167.5 kg m^{-3}
Heat Capacity: 1250 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

Thermal measurements were not conducted due to practical limitations of conducting the test on this material.

Sorption Isotherm:

The sorption capacity of this material was extremely low and not measureable.

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure given in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used to determine the water vapour permeability of the cross woven, micro-perforated polyolefin sheathing membrane. For each test condition, a minimum of 3 circular specimens having a 150 mm diameter were tested.

As shown in Table 10, the water vapour permeability had a constant value of
5.80×10^{-13} kg m^{-1} s^{-1} Pa^{-1}.

Table 10 – Water Vapour Permeability of the cross woven, micro-perforated polyolefin sheathing membrane

Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})	Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})
10	5.80×10^{-13}	60	5.80×10^{-13}
20	5.80×10^{-13}	70	5.80×10^{-13}
30	5.80×10^{-13}	80	5.80×10^{-13}
40	5.80×10^{-13}	90	5.80×10^{-13}
50	5.80×10^{-13}	100	5.80×10^{-13}

Water Absorption Coefficient:

The water absorption coefficient of the cross woven, micro-perforated polyolefin sheathing membrane is very low and is not measureable.

Air Permeability:

The air permeability measurements and calculations were conducted according to the procedure reported by Bomberg and Kumaran (1986). Three circular test specimens, with the same dimensions as specimens used to determine the water vapour permeability were used for measurements of air permeability. Measurements were conducted at a temperature of 22 ± 1 ° C. The resulting value for the air permeability of the cross woven, micro-perforated polyolefin sheathing membrane was:

$$(4.87\pm0.12)\times10^{-5}\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

2.5 HDPE[4] dimpled membrane bonded to PP[4] fabric (Client E)

The test specimens of the HDPE dimpled membrane bonded to PP fabric used for the various measurements presented in this report were taken from samples having a nominal thickness of 10 mm (Figure 5). The measured thickness was 10.6 mm. Note that this measurement is representative of the overall thickness comprised of the HDPE dimpled membrane and the PP fabric.

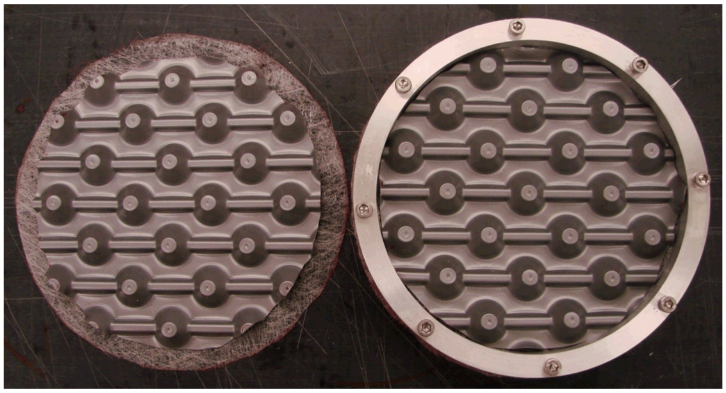

Figure 5 – HDPE dimpled membrane bonded to PP fabric

Density: 59.4 kg m^{-3}

Heat Capacity: 1210 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

The thermal conductivity of the HDPE dimpled membrane bonded to PP fabric was determined in accordance with ASTM Standard C518 (ASTM International 2010). The specimen enclosed in a wood-frame was tested in an apparatus with a nominal cross section of 300 mm x 300 mm. Heat flow was perpendicular to this primary surface. Also note that, for materials tested in the heat flow apparatus used to conduct the tests for thermal conductivity, the measurement uncertainties are within 2%. The measured thermal conductivity value is shown in Table 11.

Table 11 – Thermal Conductivity of HDPE dimpled membrane bonded to PP fabric

Specimen Thickness (mm)	Hot Surface Temperature (°C)	Cold surface Temperature (°C)	Conductivity (W m^{-1} K^{-1})
10.63	35.2	13.0	0.048

The average thermal conductivity was 0.048 W m^{-1} K^{-1} tested with a mean temperature of 24.1 °C

[4] HDPE – high density polyethylene; PP - polypropylene

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used to determine the water vapour permeability of the HDPE dimpled membrane bonded to PP fabric. For each test condition, a minimum of 3 circular specimens, having a 150 mm diameter, were tested. Results are shown in the Table 12.

Table 12 – Water Vapour Permeability of HDPE dimpled membrane bonded to PP fabric

Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})	Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})
10	2.56×10^{-13}	60	2.56×10^{-13}
20	2.56×10^{-13}	70	2.56×10^{-13}
30	2.56×10^{-13}	80	2.56×10^{-13}
40	2.56×10^{-13}	90	2.56×10^{-13}
50	2.56×10^{-13}	100	2.56×10^{-13}

Water Absorption Coefficient:

The water absorption coefficient of the HDPE dimpled membrane bonded to PP fabric is very low and is not measureable.

Air Permeability:

The measurements and calculations were carried out as described in the §3. The average permeability values of various channel heights of the HDPE dimpled membrane bonded to PP fabric were determined and the resulting air permeability was:

$$5.92\times10^{3}\ \mathrm{L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}}$$

The air permeability for air flow perpendicular to the HDPE dimpled membrane was also measured and was found impermeable.

2.5 Non-woven PP[5] fabric bonded to PP mono-filament mesh (Client G)

The test specimens of non-woven PP fabric bonded to PP mono-filament mesh and used for the various measurements presented in this report were taken from samples with a nominal thickness of 10 mm (Figure 6). The measured thickness was 9.3 mm.

Figure 6 – Non-woven PP fabric bonded to PP mono-filament mesh

Density: 48.7 kg m-3

Heat Capacity: 1210 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

The thermal conductivity of the non-woven PP fabric bonded to a PP mono-filament mesh was determined in accordance with ASTM Standard C518 (ASTM International 2010). The specimen enclosed in a wood-frame was tested in an apparatus with a nominal cross section of 300 mm x 300 mm. Heat flow was perpendicular to this primary surface. Also note that, for materials tested in the heat flow apparatus used to conduct tests of thermal conductivity, the measurement uncertainties are within 2%. The measured thermal conductivity value is shown in Table 13.

Table 13 – Thermal Conductivity of non-woven PP fabric bonded to PP mono-filament mesh

Specimen Thickness (mm)	Hot Surface Temperature (°C)	Cold surface Temperature (°C)	Conductivity (W m^{-1} K^{-1})
9.37	35.0	13.0	0.060

The average thermal conductivity was 0.060 W m^{-1} K^{-1} tested with a mean temperature of 24.0 °C

[5] PP - polypropylene

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on the relative humidity was used to determine the water vapour permeability of the non-woven PP fabric bonded to PP mono-filament mesh. For each test condition, a minimum of 3 circular specimens, having a diameter of 150 mm, were tested. Results are shown in Table 14.

Table 14 – Water Vapour Permeability of non-woven PP fabric bonded to PP mono-filament mesh

Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})	Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})
10	1.21×10^{-10}	60	1.21×10^{-10}
20	1.21×10^{-10}	70	1.21×10^{-10}
30	1.21×10^{-10}	80	1.21×10^{-10}
40	1.21×10^{-10}	90	1.21×10^{-10}
50	1.21×10^{-10}	100	1.21×10^{-10}

Water Absorption Coefficient:

The water absorption coefficient of the non-woven PP fabric bonded to PP mono-filament mesh is very low and is not measureable.

Air Permeability:

The measurements and calculations were carried out as described in the §3. The average permeability values of various channel heights were determined and the resulting air permeability was determined to be:

$$4.7\times10^{3}\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

The air permeability for air flow perpendicular to the mesh was also measured. The resulting air permeability was:

$$8.1\times10^{1}\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

2.7 Porous PS[6] insulation board (Client H)

The test specimens (Figure 7) of porous PS insulation board used for the various measurements presented in this report were taken from insulation boards with a nominal thickness of 51 mm.

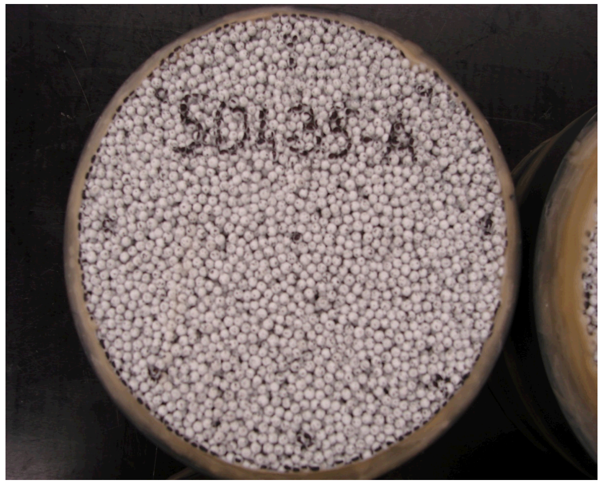

Figure 7 – Porous PS insulation board

Density: 29.2 kg m^{-3}

Heat Capacity: 1470 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

Measurements were conducted in accordance with ASTM Standard C518 (ASTM International 2010). The specimens were tested in an apparatus with a 600 mm x 600 mm cross section. Heat flow was perpendicular to this primary surface. Also note that, for materials tested in the heat flow apparatus used to conduct the tests, the measurement uncertainties are within 2%. The measured thermal conductivity values are shown in Table 15.

Table 15 – Thermal Conductivity of Porous PS insulation board

Specimen Thickness (mm)	Hot Surface Temperature (°C)	Cold surface Temperature (°C)	Conductivity (W m^{-1} K^{-1})
51.64	34.95	13.03	0.039
51.23	34.97	13.03	0.039
51.34	35.03	12.97	0.038

The average thermal conductivity was 0.038 W m^{-1} K^{-1} tested with a mean temperature of 24.0 °C.

[6] PS – polystyrene

Sorption Measurements:

Six specimens with a nominal size of 50 mm x 50 mm x 100 mm were used in these measurements. The measurements were done following the procedure described in ASTM Standard C1498 (ASTM International, 2010). The results from these tests are shown in Table 16.

Table 16 – Sorption characteristic of Porous PS insulation board

Relative Humidity (% RH)	Moisture Content ($kg \cdot kg^{-1}$)
50.3	0.0057
69.3	0.0092
90.5	0.0259
94.2	0.0677

Derived Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure given in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used to determine the water vapour permeability of the Porous PS insulation board. For each test condition, a minimum of 3 circular specimens of 150 mm diameter (Figure 7) were tested.

As shown in Table 17, the derived water vapour permeability had a constant value of 3.56×10^{-11} kg m^{-1} s^{-1} Pa^{-1}.

Table 17 – Water Vapour Permeability of Porous PS insulation board

Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})	Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})
10	3.56×10^{-11}	60	3.56×10^{-11}
20	3.56×10^{-11}	70	3.56×10^{-11}
30	3.56×10^{-11}	80	3.56×10^{-11}
40	3.56×10^{-11}	90	3.56×10^{-11}
50	3.56×10^{-11}	100	3.56×10^{-11}

Water Absorption Coefficient:

The value for the water absorption coefficient of the porous PS insulation board is very low and was not measureable.

Air Permeability:

The measurements and calculations were conducted according to the procedure reported by Bomberg and Kumaran (1986). Three circular test specimens, with the same dimensions as the specimens used to test for water vapour permeability were used for the measurements of air permeability. Measurements were executed at a temperature of 22 ± 1 ° C. The resulting air permeability was:

$$(25.3 \quad \pm 3.6)\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

2.8 Corrugated asphalt impregnated paper board (Client I)

The test specimens of 2-ply corrugated asphalt impregnated paper board (Figure 8) used for the various measurements presented in this report were taken from samples having a nominal thickness 3.77 mm.

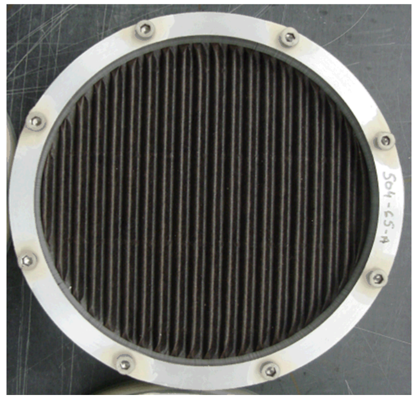

Figure 8 – Corrugated asphalt impregnated paper board

Density: 147.5 kg m^3

Heat Capacity: 1250 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

Thermal measurements were not conducted given practical limitations in completing the test.

Sorption Measurements:

The measurements to determine the sorption of the corrugated asphalt impregnated paper board were done following the procedure described in ASTM Standard C1498 (ASTM International, 2010). Five specimens were used in these measurements. The results of the testing are shown in Table 18.

Table 18 – Sorption Characteristic of corrugated asphalt impregnated paper board

Relative Humidity (% RH)	Moisture Content (kg•kg^{-1})
49.9	0.028
71.0	0.0493
90.5	0.122
94.4	0.210

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used to determine the water vapour permeability of the corrugated asphalt impregnated paper board. For each test condition, a minimum of 3 circular specimens, having a diameter of 150 mm, were tested. The results of the water vapour testing are shown in Table 19.

Table 19 – Water Vapour Permeability of corrugated asphalt impregnated paper board

Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})	Relative Humidity (%)	Water Vapour Permeability (kg m^{-1} s^{-1} Pa^{-1})
10	4.98×10^{-13}	60	3.35×10^{-12}
20	7.22×10^{-13}	70	5.06×10^{-12}
30	1.05×10^{-12}	80	7.83×10^{-12}
40	1.53×10^{-12}	90	1.26×10^{-11}
50	2.26×10^{-12}	100	2.20×10^{-11}

Water Absorption Coefficient:

Five test specimens, each having dimensions of 50 mm × 50 mm × 50 mm, were used for measurements to determine the water absorption coefficient of the corrugated asphalt impregnated paper board. Water was maintained at 22 ± 1 °C during the test period. The values for water absorption are given in Table 20. The numbers in parentheses give the standard deviations of the resulting values for water absorption as a function of time.

Table 20 – Water Absorption Coefficient of corrugated asphalt impregnated paper board

Square Root of time ($s^{½}$)	Water Absorption (kg m^{-2})
24.5	0.109 (0.005)
34.6	0.118 (0.010)
42.4	0.123 (0.007)
60.0	0.138 (0.007)
73.5	0.146 (0.009)
84.9	0.158 (0.009)
103.9	0.173 (0.012)
120.0	0.186 (0.008)
148.0	0.222 (0.006)
169.7	0.242 (0.011)
201.2	0.272 (0.008)
295.5	0.376 (0.010)
311.8	0.393 (0.018)

Linear regression using all the data from the first linear part of the absorption process for the five specimens derives the water absorption coefficient for the corrugated asphalt impregnated paper board which was determined to be 0.0010 kg m^{-2} $s^{-½}$.

Air Permeability:

The measurements and calculations were carried out as described in §3. The average permeability values of various channel heights were determined and the resulting air permeability was:

$$1.75\times10^{3}\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

The air permeability for air flow perpendicular to the paper board was also measured. The resulting air permeability was:

$$(1.59\pm0.29)\times10^{-4}\ L(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$$

2.9 Three Coat Stucco with Expanded Diamond-Mesh Metal Lath (Client J)

The test specimens of three coat stucco with expanded diamond-mesh metal lath (Figure 9) used for the various measurements presented in this report were constructed at the NRC. The specimens that were tested had a nominal thickness of 26.4 mm.

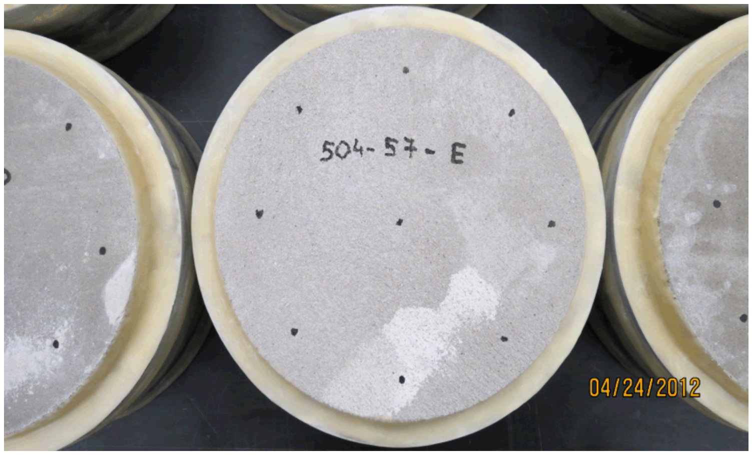

Figure 9 – Three coat stucco with expanded diamond-mesh metal lath

Density: 1890 kg m^{-3}

Heat Capacity: 840 J K^{-1} kg^{-1} (Kumaran, et al. 2002)

Thermal Conductivity:

Measurements were conducted in accordance with ASTM Standard C518 (ASTM International 2010). The specimens were tested in an apparatus with a 300 mm x 300 mm cross section. Heat flow was perpendicular to this primary surface. Also note that, for materials tested in the heat flow apparatus that was used to conduct the tests, the measurement uncertainties were within 2%. The measured thermal conductivity value is shown in Table 21.

Table 21 – Thermal Conductivity of 3 coat stucco with expanded diamond-mesh metal lath

Specimen Thickness (mm)	Hot Surface Temperature (°C)	Cold surface Temperature (°C)	Conductivity (W m^{-1} K^{-1})
29.28	27.2	18.4	0.71

The average thermal conductivity of the three coat stucco was 0.71 W m^{-1} K^{-1} tested with a mean temperature of 24.6 °C

Sorption Isotherm:

Five specimens of size 250 mm x 250 mm x 27 mm were tested to determine the sorption isotherm of the three coat stucco. The measurements were done following the procedure described in ASTM Standard C1498 (ASTM International, 2010). The results from these tests are shown in Table 22.

Table 22 – Sorption characteristic of Three Coat Stucco

Relative Humidity (% RH)	Moisture content ($kg \cdot kg^{-1}$)
50.3	0.025
69.3	0.028
89.9	0.048
93.9	0.059

Water Vapour Permeability:

Water vapour permeability testing was conducted following the procedure given in ASTM Standard E96/96M (ASTM International 2010). The procedure specified in this standard for calculating the dependence of water vapour transmission rate on relative humidity was used. For each test condition, a minimum of 3 circular specimens, having a diameter of 150 mm, were tested. The results from these tests are shown in Table 23.

Table 23 – Water Vapour Permeability of Three Coat Stucco

Relative Humidity (%)	Water Vapour Permeability ($kg\ m^{-1}\ s^{-1}\ Pa^{-1}$)	Relative Humidity (%)	Water Vapour Permeability ($kg\ m^{-1}\ s^{-1}\ Pa^{-1}$)
10	2.06×10^{-12}	60	4.28×10^{-12}
20	2.50×10^{-12}	70	4.73×10^{-12}
30	2.94×10^{-12}	80	5.18×10^{-12}
40	3.39×10^{-12}	90	5.64×10^{-12}
50	3.83×10^{-12}	100	6.09×10^{-12}

Water Absorption Coefficient:

Ten test specimens, each having dimensions of 50 mm x 50 mm x 50 mm, were used to determine the water absorption coefficient of the three coat stucco. Over the course of the test, water was maintained at (22 ± 1) °C. The results (average) from these measurements are shown in Table 24. The numbers in parentheses give the standard deviations.

Table 24 – Water Absorption Characteristics of Three Coat Stucco

Square Root of Time ($s^{½}$)	Water Absorption ($kg\ m^{-2}$)
24.5	0.38 (0.12)
34.6	0.55 (0.16)
42.4	0.69 (0.20)
60.0	1.01 (0.26)
84.9	1.38 (0.31)
103.9	1.61 (0.33)
120.0	1.75 (0.34)
169.7	2.02 (0.37)
199.0	2.11 (0.37)
293.9	2.25 (0.37)
317.5	2.26 (0.37)
339.4	2.27 (0.37)
417.1	2.29 (0.37)
432.0	2.28 (0.37)
449.3	2.28 (0.37)

Linear regression using all the data from the first linear part of the absorption process for the ten specimens gives the value of the water absorption coefficient; this value was 0.0157 $kg\ m^{-2}\ s^{-½}$.

Air Permeability:

The measurements and calculations for air permeability of the three coat stucco were executed according to the procedure reported by Bomberg and Kumaran (1986). Three circular test specimens, with the same dimensions as specimens used for the water vapour permeability tests were used for the measurements of air permeability. Measurements were executed at a temperature of 22 ± 1 ° C.

The resulting air permeability was:

$$(2.2 \pm 2.0) \times 10^{-5}\ L(75\ Pa)^{-1} \cdot m^{-1} \cdot s^{-1}$$

3 Air flow Characterization of Drainage Components

The objective of this portion of the study was to quantify the air flow characteristics of the ventilation systems used in the various wall sections. The air permeability values derived from these tests would be used for simulations of vertical airflow through the drainage plane.

3.1 Test Method

The specimens were tested according to the same procedure used for all of the air permeability testing conducted as described in the report by (Kumaran and Bomberg 1986). In order to quantify the air flow in the drainage channels and to examine the effects of the height of the channel on experimental results, four channel heights were tested; these were: 14.3 cm; 28.5 cm; 42.8 cm; and 57.0 cm. The air permeability of the ventilation components was tested using the test configuration shown in Figure 10 and includes photos of the test set-up for the smallest (14.3 cm) and greatest (57 cm) heights tested.

3.2 Drainage Systems Tested

The air flow characteristics of six different drainage system ventilation components were examined as provided in Table 25. The tests were conducted on specimens with varying height as specified in the previous section. Several of the ventilation matting materials also had different cross sections in directions parallel and perpendicular to the channel flow. For these meshes, tests were conducted in two directions. The tests that were conducted are shown in Table 25. Results from these tests are provided in the subsequent section.

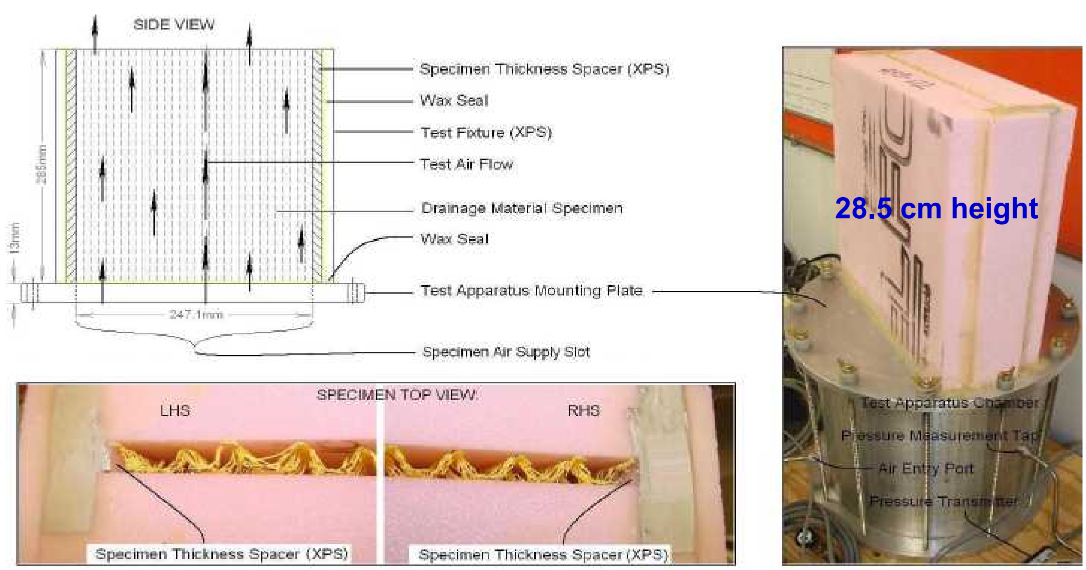

Figure 10 – Test Setup for Air Flow Characterization of Drainage Components

Table 25 – Tested Ventilation Components

Test No.	Description	Parallel Flow (Y)	Perpendicular Flow (X)
1	Clear (empty) cavity (7mm)	X	N/A
2	Open matrix Nylon mesh; alone (7mm)	X	X
3	Nylon mesh (10 mm; open matrix) bonded to PP† nonwoven sheathing membrane	X	X
4	Non-woven PP† fabric (stucco screen) bonded to PP† mono-filament mesh providing a 10 mm mat	X	N/A
5	PP† fabric bonded to dimpled HDPE‡ membrane	X	X
6	2 ply, corrugated asphalt impregnated paper* - Grade D!!	X	X

† PP - polypropylene; ‡ HDPE – high density polyethylene; * Conforming to CGSB standard CAN2-51.32-M77; !! Conforming to US Federal Specification UU-B-790a (Type I - Barrier paper; Grade D Water-vapor permeable; Style 2 - Uncreped, not reinforced, saturated)

3.3 Test Results

3.3.1 Test Number 1 – Clear (empty) Cavity (Reference wall)

The values of permeability and permeance of the board in the Y-direction are provided in Table 26; as well, values of permeability and permeance of the board for different board heights (X- and Y-direction) are likewise given. In Figure 11 values of permeability are plotted as a function of test height.

The results suggest that the values for permeability in the Y-direction did vary significantly with test height; average permeability in the Y- direction was ca. 2.09E+04 L/m•s @75 Pa with a variance of 0.585 E+03 L/m•s @75 Pa or ca. 30%.

This variability is more evident in Figure 11 and perhaps suggests that the highest value is an outlier.

Table 26 – Air Permeability and Permeance of Clear (empty) Cavity

Specimen	Height m	Permeability $L\cdot(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$	Permeance $L\cdot(75\ Pa)^{-1}\cdot m^{-2}\cdot s^{-1}$
459-115	0.143	1.576E+04	1.106E+05
459-113	0.285	2.236E+04	7.844E+04
459-119	0.428	2.985E+04	6.974E+04
459-117	0.570	1.557E+04	2.732E+04

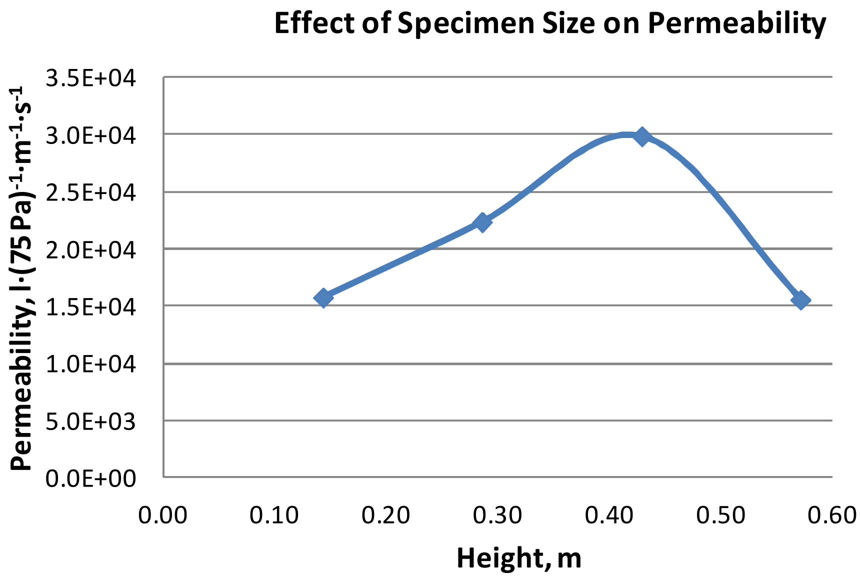

Figure 11 – Permeability as a function of specimen height

3.3.2 Test Number 2 - Open matrix Nylon mesh (7mm) (Client C)

A photo of the open matrix Nylon mesh is given in Figure 12. The values of permeability and permeance of the component in the X, Y, and Z-directions are provided in Table 27; as well, values of permeability and permeance of the component for different heights (X- and Y-direction) are likewise given. In Figure 13 values of permeability are plotted as a function of test height.

The results suggest that the values for permeability in either the X- or Y-directions did not significantly vary with test height; average permeability in the X- direction was ca. 1.8E+03 L/m•s @75 Pa and in the Y-direction was ca. 4.3E+03 L/m•s @75 Pa.

The permeability in the Z-direction was not measurable although in this instance it did not offer any measurable resistance to flow.

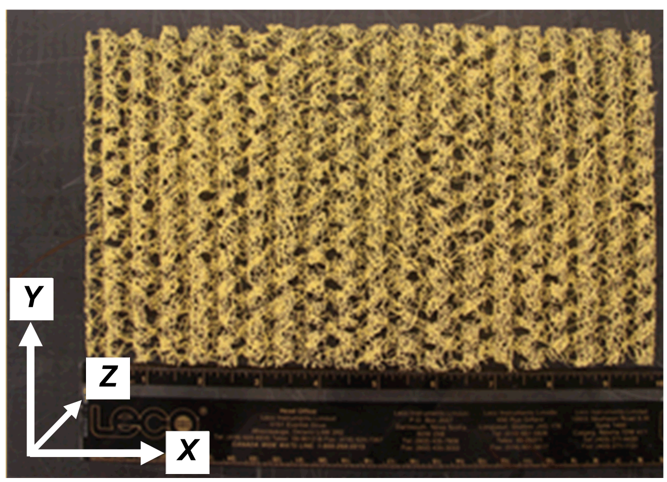

Figure 12 – Open matrix Nylon mesh (Client C)

Table 27 – Air Permeability and Permeance of Open matrix Nylon mesh

Flow Direction	Height m	Permeability $l\cdot(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$	Permeance $l\cdot(75\ Pa)^{-1}\cdot m^{-2}\cdot s^{-1}$
Y-direction	0.143	3.235E+03	2.270E+04
	0.285	4.018E+03	1.410E+04
	0.428	5.134E+03	1.200E+04
	0.570	4.690E+03	8.228E+03
X-direction	0.143	1.517E+03	1.056E+04
	0.285	1.885E+03	6.614E+03
	0.428	2.033E+03	4.751E+03
	0.570	1.785E+03	3.132E+03
Z-direction	NA	NA	NA

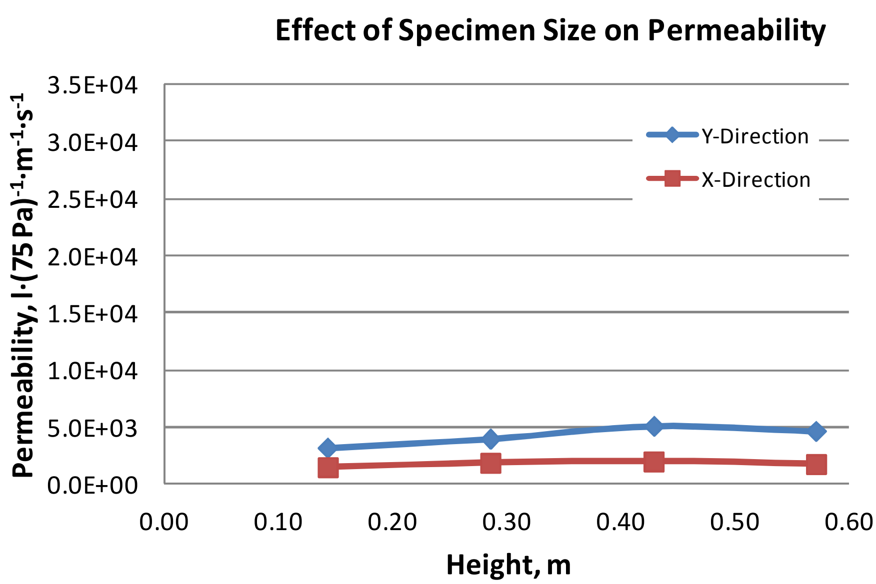

Figure 13 – Permeability as a function of specimen height (Client C)

3.3.3 Test Number 3 – Nylon mesh bonded to PP non-woven sheathing membrane (Client C)

A photo of the Nylon mesh bonded to a PP non-woven sheathing membrane is given in Figure 14. The values of permeability and permeance of the component in the X, Y, and Z-directions are provided in Table 28; as well, values of permeability and permeance of the component for different heights (X- and Y-direction) are likewise given. In Figure 15 values of permeability are plotted as a function of test height.

The results suggest that the values for permeability in either the X- or Y-directions did not significantly vary with test height; average permeability in the X- direction was ca. 4.1E+03 L/m•s @75 Pa and in the Y-direction was ca. 9.5E+03 L/m•s @75 Pa.

The permeability in the Y-direction (7.5E-03 L/m•s @75 Pa) was 6 orders of magnitude less than that of the permeability in the X- or Y-directions; it represents the permeability of the membrane to air.

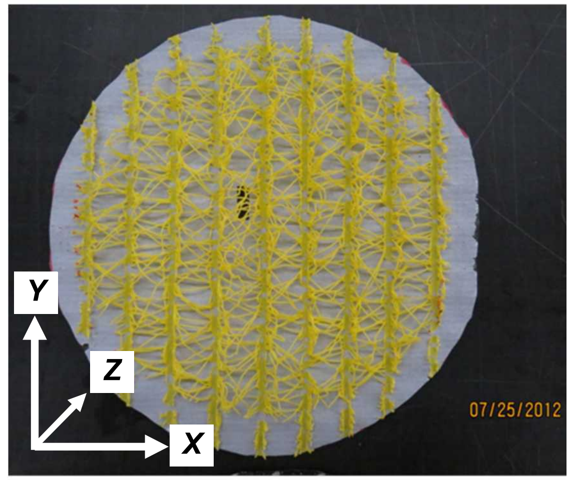

Figure 14 – Nylon mesh bonded to PP non-woven sheathing membrane (Client C)

Table 28 – Air Permeability and Permeance of Nylon mesh bonded to PP non-woven sheathing membrane

Flow Direction	Height m	Permeability $L\cdot(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$	Permeance $L\cdot(75\ Pa)^{-1}\cdot m^{-2}\cdot s^{-1}$
Y-Direction	0.143	7.492E+03	5.239E+04
	0.285	8.405E+03	2.949E+04
	0.428	1.231E+04	2.875E+04
	0.570	9.676E+03	1.698E+04
X-Direction	0.143	3.669E+03	2.565E+04
	0.285	4.216E+03	1.479E+04
	0.428	3.765E+03	8.796E+03
	0.570	4.608E+03	8.085E+03
Z-Direction	0.011	7.489E-03	7.103E-01

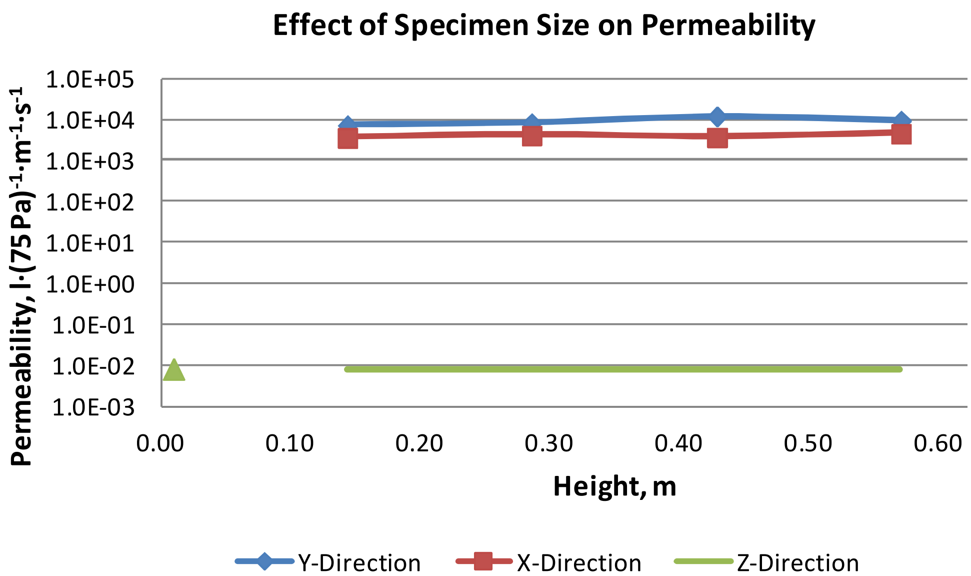

Figure 15 – Permeability as a function of specimen height (Client C)

3.3.4 Test Number 4 – Non-woven PP fabric (stucco screen) bonded to PP mono-filament mesh (Client G)

A photo of the Non-woven PP fabric (stucco screen) bonded to PP mono-filament mesh is given in Figure 16. The values of permeability and permeance of the component in the X, Y, and Z-directions are provided in Table 29; as well, values of permeability and permeance of the component for different heights (X- and Y-direction) are likewise given. In Figure 17 values of permeability are plotted as a function of test height.

The results suggest that the values for permeability of the component do not vary in the X- or Y-direction, and thus do not depend on the test height; average permeability in the X- (or Y-direction was ca. 4.7E+03 L/m•s @75 Pa.

The permeability in the Y-direction (8.1E+01 L/m•s @75 Pa) was much less than that of the permeability in the X- or Y-directions, (ca. 2 orders of magnitude); it represents the permeability of the membrane to air.

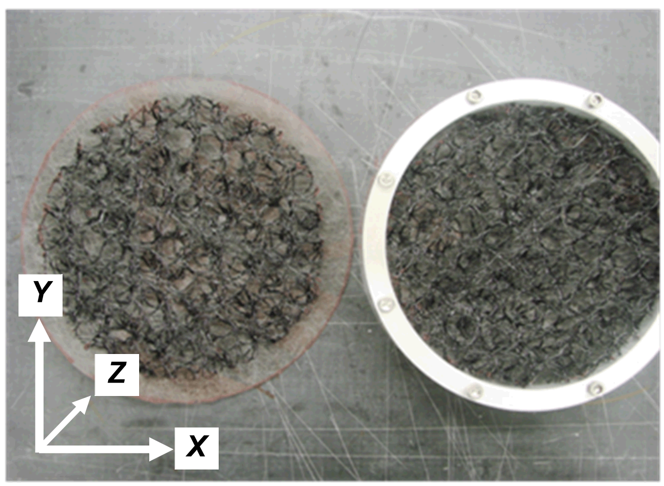

Figure 16 – Non-woven PP fabric (stucco screen) bonded to PP mono-filament mesh (Client G)

Table 29 – Air Permeability and Permeance of Non-woven PP fabric (stucco screen) bonded to PP mono-filament mesh

Flow Direction	Height m	Permeability $L\cdot(75\ Pa)^{-1}\cdot m^{-1}\cdot s^{-1}$	Permeance $L\cdot(75\ Pa)^{-1}\cdot m^{-2}\cdot s^{-1}$
X and Y	0.143	3.611E+03	2.525E+04
	0.285	3.532E+03	1.239E+04
	0.428	6.251E+03	1.461E+04
	0.570	5.286E+03	9.274E+03
Z	0.00940	8.069E+01	8.545E+03

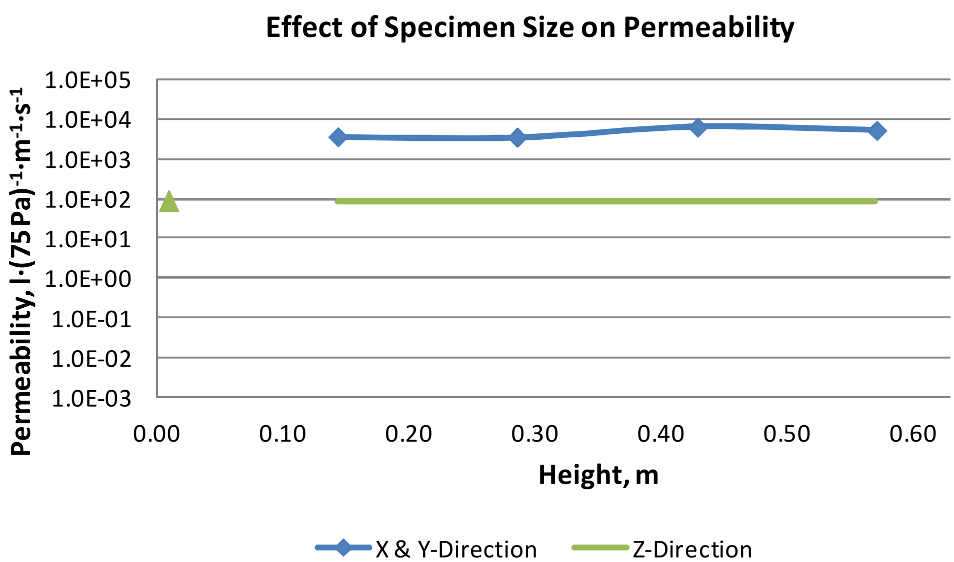

Figure 17 – Permeability as a function of specimen height (Client G)

3.3.5 Test Number 5 – PP fabric bonded to dimpled HDPE membrane (Client E)

A photo of the PP fabric bonded to dimpled HDPE membrane is given in Figure 18. The values of permeability and permeance of the component in the X, Y, and Z-directions are provided in Table 30; as well, values of permeability and permeance of the component for different heights (Y-direction) are likewise given. In Figure 19 values of permeability are plotted as a function of test height.

The results suggest that the values for permeability of the component do not vary in the X- or Y-direction, and thus do not depend on the test height; average permeability in the X-direction was ca. 3.30E+03 L/m•s @75 Pa and in the Y-direction ca. 5.92E+03 L/m•s @75 Pa.

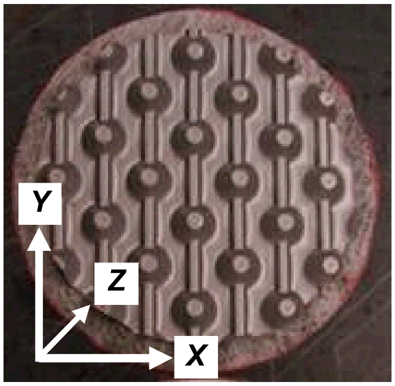

Figure 18 – PP fabric bonded to dimpled HDPE membrane (Client E)

Permeability in the X-direction is slightly less than that in the Y-direction; i.e. 2.6E+03 L/m•s @75 Pa. Given that the permeability of the membrane in the Z-direction was not measurable it was deemed essentially impermeable to air.

Table 30 – Air Permeability and Permeance of PP fabric bonded to dimpled HDPE membrane

Flow Direction	Height m	Permeability L·(75 Pa)$^{-1}$·m^{-1}·s^{-1}	Permeance L·(75 Pa)$^{-1}$·m^{-2}·s^{-1}
Y-Direction	0.143	5.837E+03	4.082E+04
	0.285	5.621E+03	1.972E+04
	0.428	6.459E+03	1.509E+04
	0.570	5.773E+03	1.013E+04
X-Direction	0.143	3.425E+03	2.395E+04
	0.285	3.123E+03	1.096E+04
	0.428	3.491E+03	8.156E+03
	0.570	3.170E+03	5.562E+03
Z-Direction	0.011	Not measurable	Not measurable

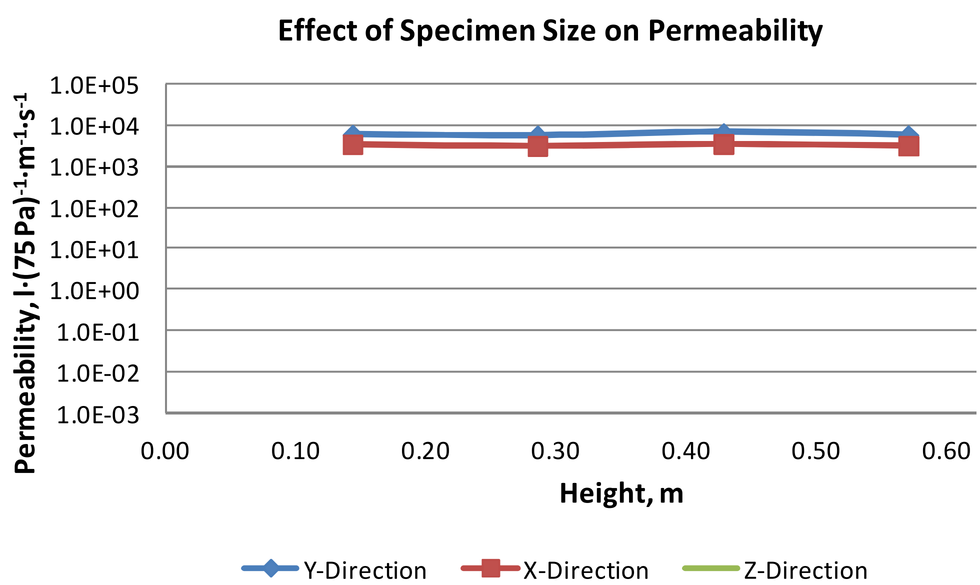

Figure 19 – Permeability as a function of specimen height (Client E)

3.3.6 Test Number 6 – Corrugated asphalt impregnated paper board (Client I)

A photo of the corrugated asphalt impregnated paper board is given in Figure 20. The values of permeability and permeance of the component in the X, Y, and Z-directions are provided in Table 31; as well, values of permeability and permeance of the component for different heights (Y-direction) are likewise given. These same values are plotted in Figure 21.

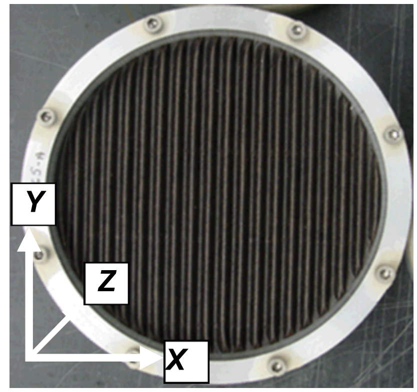

Figure 20 – Corrugated asphalt impregnated paper board (Client I)

The results suggest that the values for permeability of the component do not vary in the Y-direction, and thus do not depend on the test height; average permeability value in the Y-direction is ca. 1.75E+03 L/m•s @75 Pa.

Permeability in the X-direction is ca. two (2) orders of magnitude less than that in the Y-direction and the least permeability is that in the Z-direction (7.5E-03 L/m•s @75 Pa); this value represents the permeability of the membrane to air.

Table 31 – Air Permeability and Permeance of corrugated asphalt impregnated paper board

Flow Direction	Height (m)	Permeability $l \cdot (75\ Pa)^{-1} \cdot m^{-1} \cdot s^{-1}$	Permeance $l \cdot (75\ Pa)^{-1} \cdot m^{-2} \cdot s^{-1}$
Y-Direction	0.143	1.405E+03	9.823E+03
	0.285	1.849E+03	6.489E+03
	0.428	2.021E+03	4.721E+03
	0.570	1.737E+03	3.047E+03
X-Direction	0.143	6.885E+01	4.815E+02
Z-Direction	0.011	7.489E-03	7.103E-01

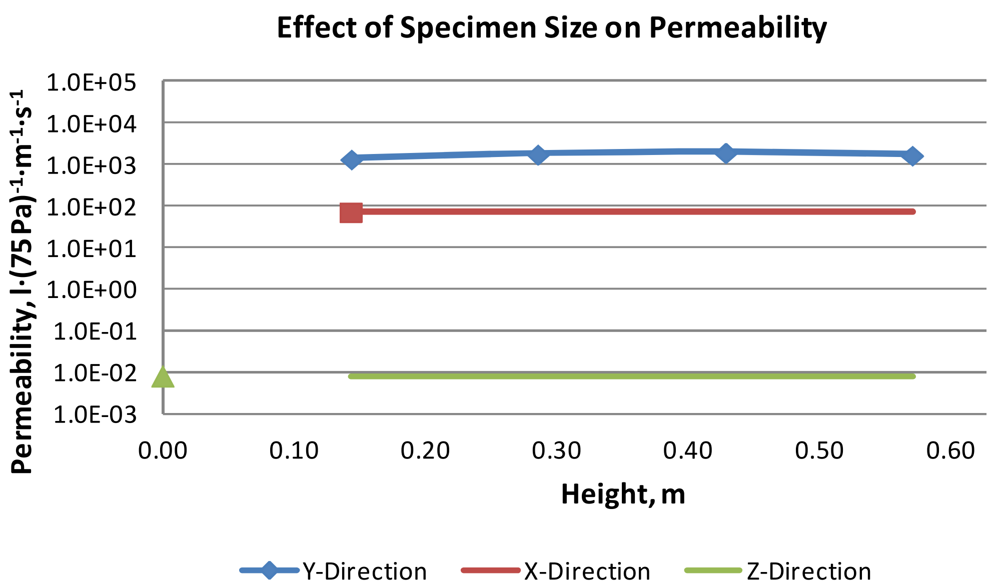

Figure 21 – Permeability as a function of specimen height (Client I)

4. References

ASTM Standard C1498-04a "Standard Test Method for Hygroscopic Sorption Isotherms of Buidling Materialas". West Chonshocken, PA: ASTM International, 2004.

ASTM Standard C518-10 "Standard Test Method for Steady-State Thermal Transmission Properties by Means of the Heat Flow Meter Apparatus". West Conshohocken, PA, 2010.

ASTM Standard E96/E96M - 10 "Standard Test Method for Water Vapor Transmission of Materials". West Conshohocken, PA: ASTM International, 2010.

Kumaran, M. K., and M. T. Bomberg (1986), "A Test Method to determine air flow resistane of exterior membranes and sheathings"." *Journal of Thermal Insulation*: 9: 224-235.

Kumaran, Mavinkal K, John K Lackey, Nicole Normandin, Fitsum Tariku, and David van Reenen (2002), "A Thermal and Moisture Transport Property Database for Common Building and Insulating Materials: Final Report"; ASHRAE Research Project 1018-RP.

Appendix 1
List of Project Reports

Report	Reference
Task 1	M. Armstrong and B. Di Lenardo (2014), Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 1 – Wall Assembly Specifications; Client Report A1-000030.01; National Research Council Canada; Ottawa, ON; 52 pgs.
Task 2	P. Mukhopadhyaya, D. van Reenen and S. Bundalo-Perc (2014), Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 2 – Building Component Hygrothermal Properties Characterization; Client Report A1-000030.02; National Research Council Canada; Ottawa, ON; 58 pgs.
Task 3	H. H. Saber, W. Maref, and G. Ganapathy, (2015) Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 3 –Hygrothermal Model Benchmarking; Client Report A1-000030.04; National Research Council Canada; Ottawa, ON; 63 pgs.
Task 4	W. Maref, H. H. Saber and G. Ganapathy (2015), Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 4 – Characterization of Air Flow within Drainage Cavities; Client Report A1-000030.05; National Research Council Canada; Ottawa, ON; 115 pgs.
Task 5	Steven M. Cornick and Khaled Abdulghani (2013), Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task – Defining Exterior Environmental Loads; Client Report A1-000030.03; National Research Council Canada; Ottawa, ON; 99 pgs.
Task 5	T. Moore and M. Nicholls (2015), Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 5 – Characterization of Water Entry to, Retention and Dissipation from Drainage Components; Client Report A1-000030.06; National Research Council Canada; Ottawa, ON; 43 pgs.
Task 6	H. H. Saber (2015) Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 6 – Hygrothermal Performance of NBC-Compliant Reference Wall for Selected Canadian Locations; Client Report A1-000030.07; National Research Council Canada; Ottawa, ON; 59 pgs. H. H. Saber (2015) Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 6 – Hygrothermal Performance of Wall Assemblies Incorporating Drainage Components for Selected Canadian Locations; Client Report A1-000030.08; National Research Council Canada; Ottawa, ON; 167 pgs. H. H. Saber (2015) Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 6 – Hygrothermal Performance of Wall Assemblies Incorporating Drainage Components: Results for wall components having Medium Resistant (MR) Mould Growth Sensitivity Class; Client Report A1-000030.10; National Research Council Canada; Ottawa, ON; 85 p.
Task 7	M. A. Lacasse (2015) Performance Evaluation of Proprietary Drainage Components and Sheathing Membranes when Subjected to Climate Loads – Task 7 – Summary Report on Experimental and Modelling Tasks and Recommendations; Client Report A1-000030.09; National Research Council Canada; Ottawa, ON; 43 pgs.

Appendix 2
Horizontal Sectional Details of Wall Assemblies

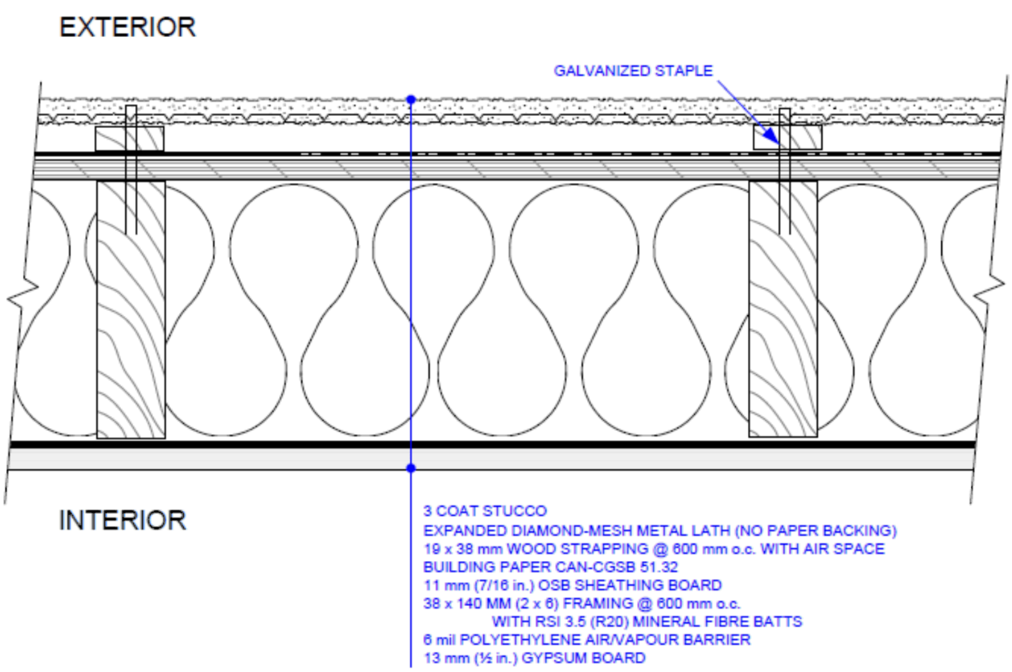

Figure A 1 – Reference Wall Cross-Section

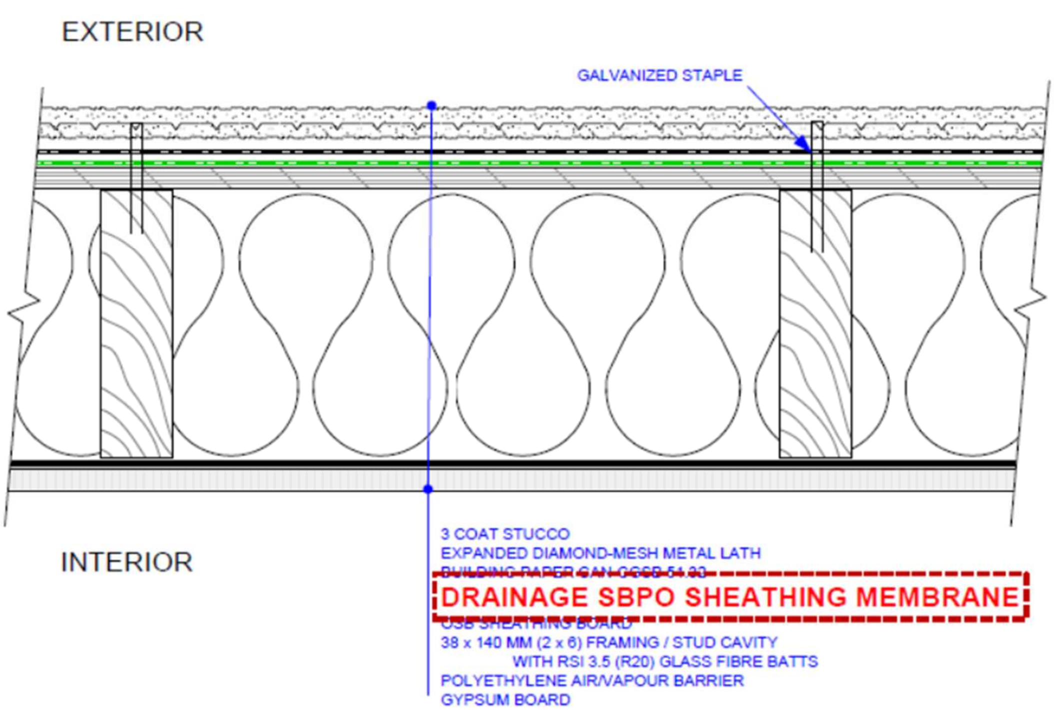

Figure A 2 – Client A Wall Cross-Section

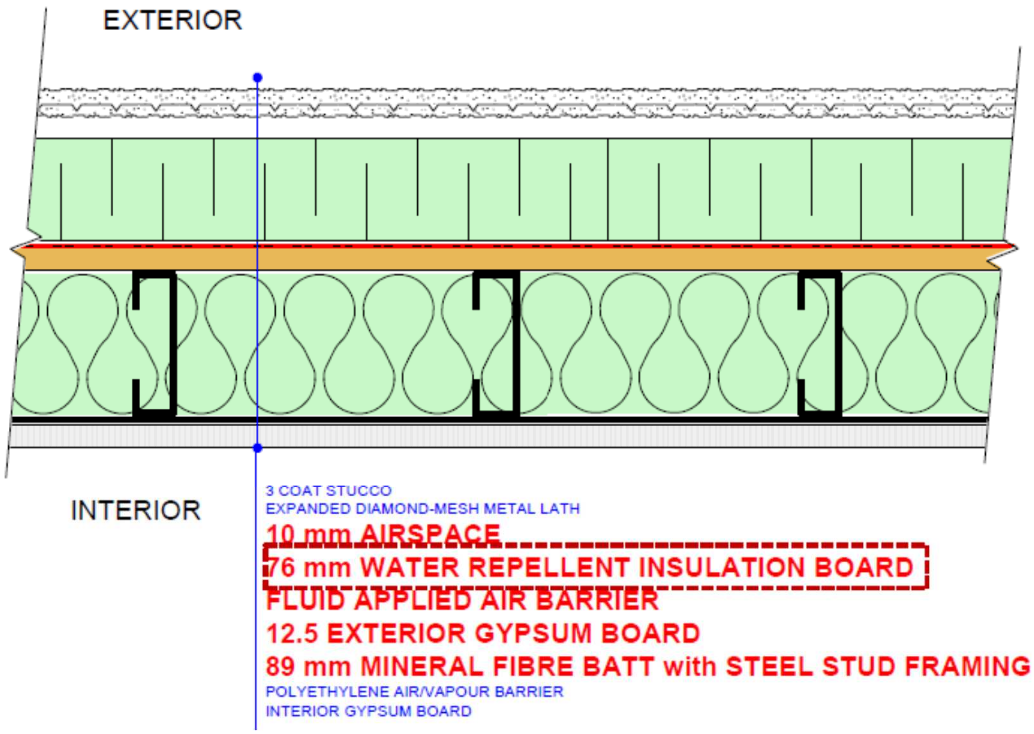

Figure A 3 – Client B Wall Cross-Section

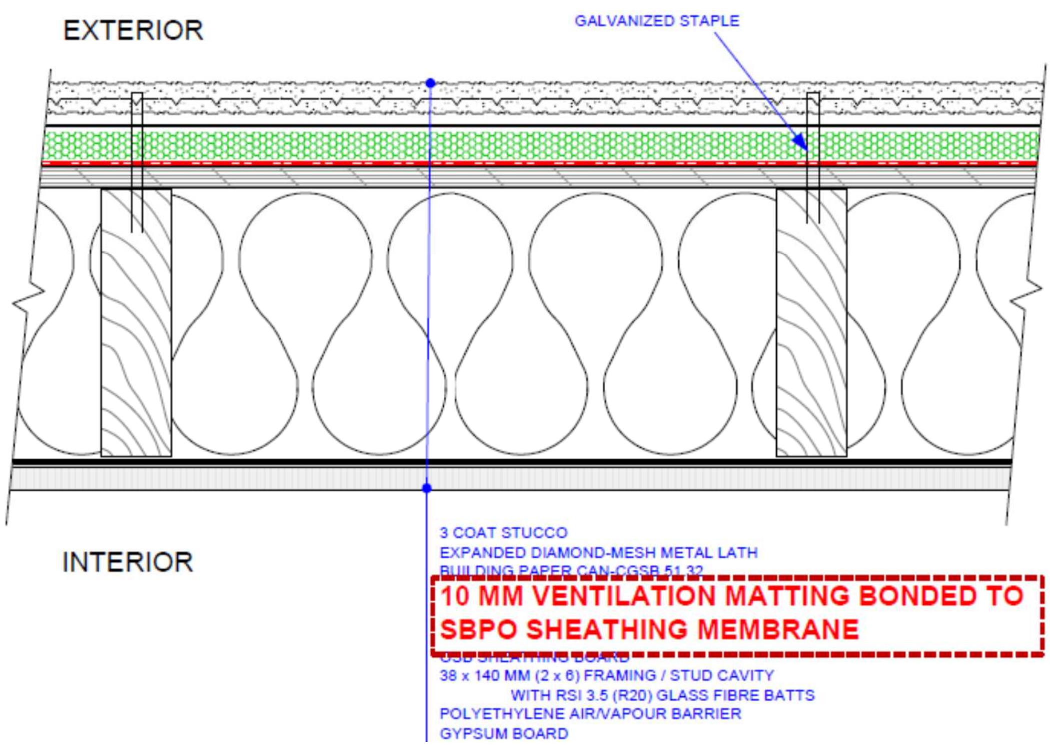

Figure A 4 – Client C Wall Cross-Section

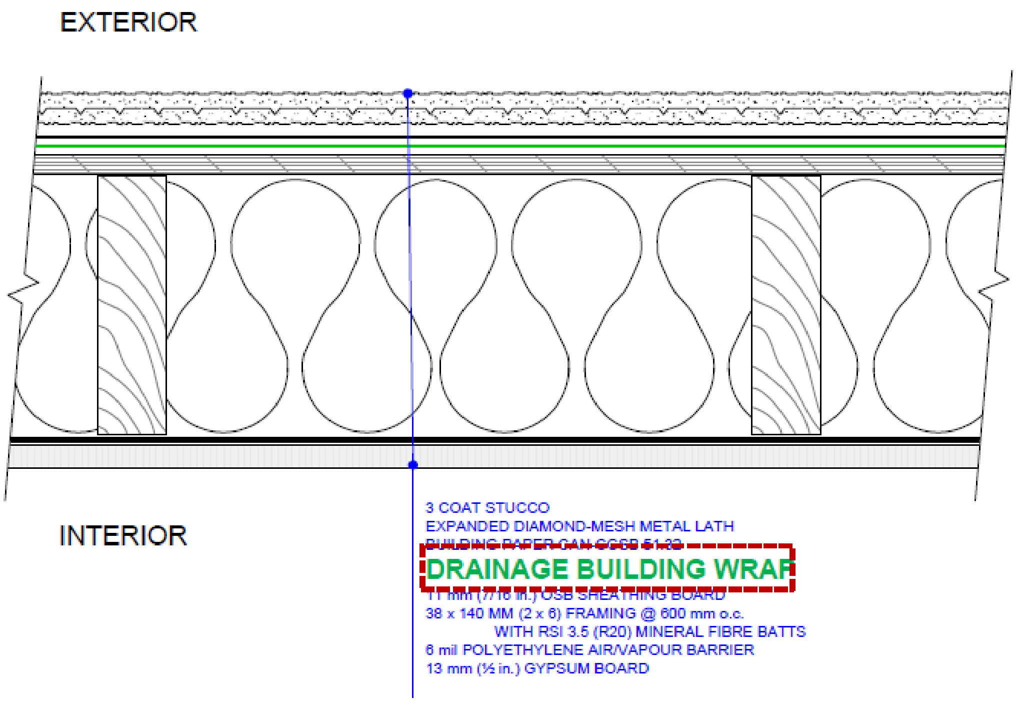

Figure A 5 – Client D Wall Cross-Section

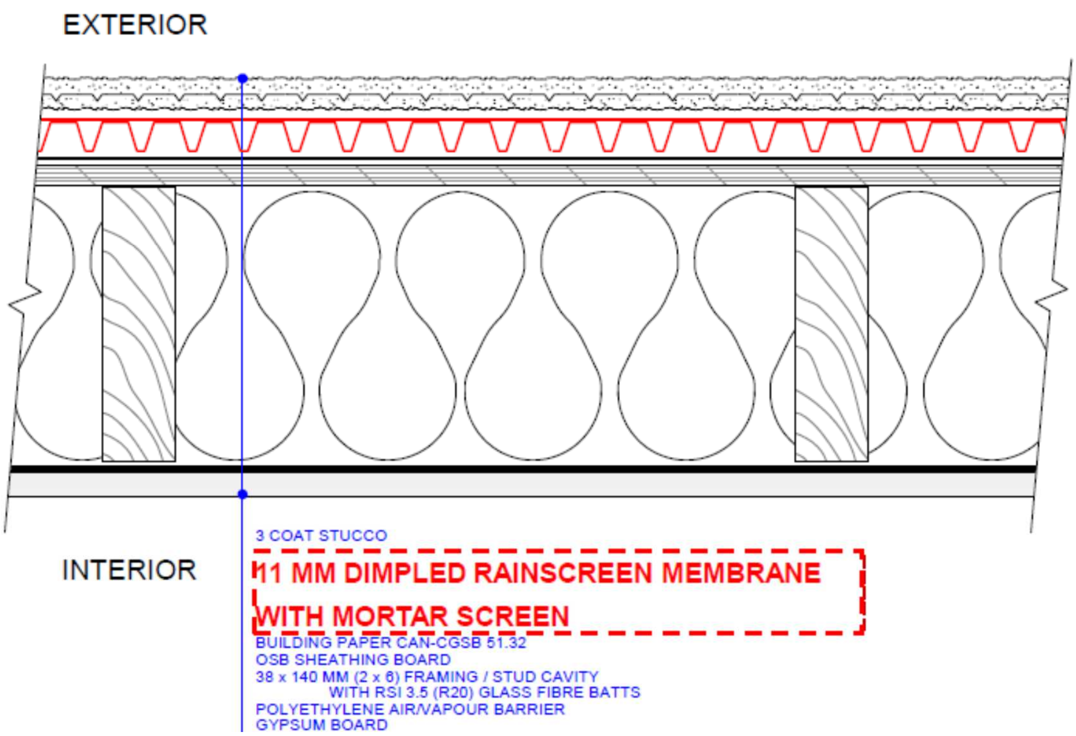

Figure A 6 – Client E Wall Cross-Section

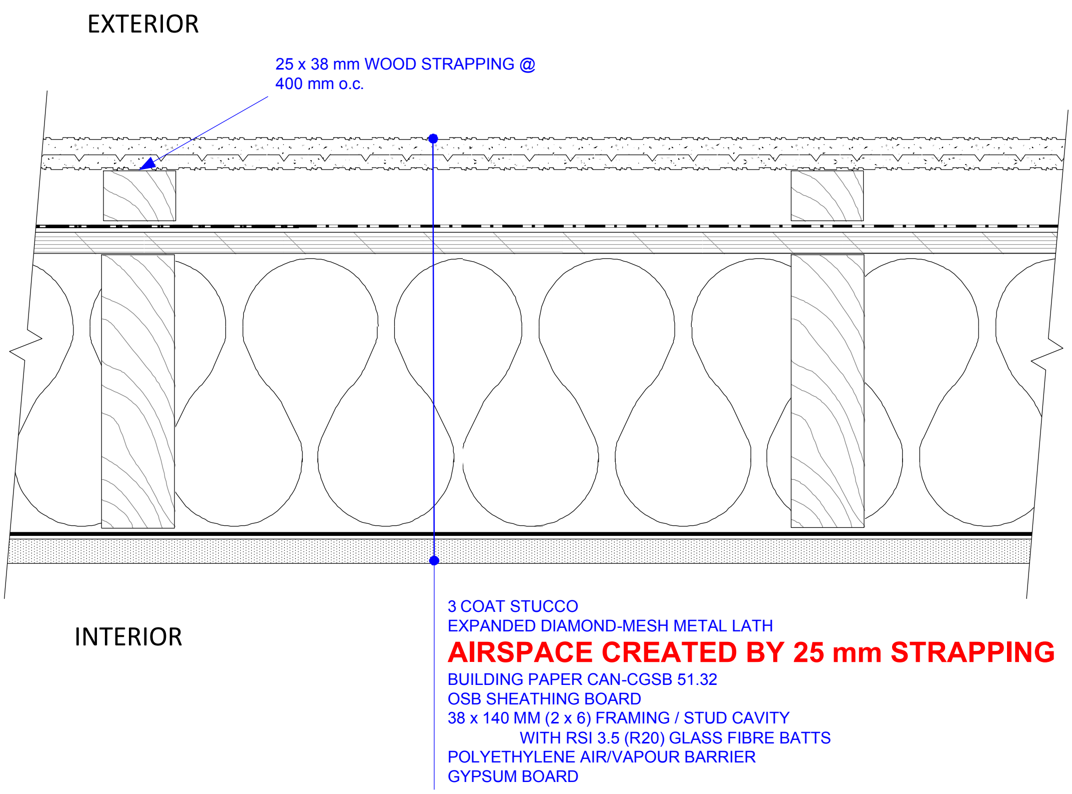

Figure A 7 – Client F Wall Cross-Section

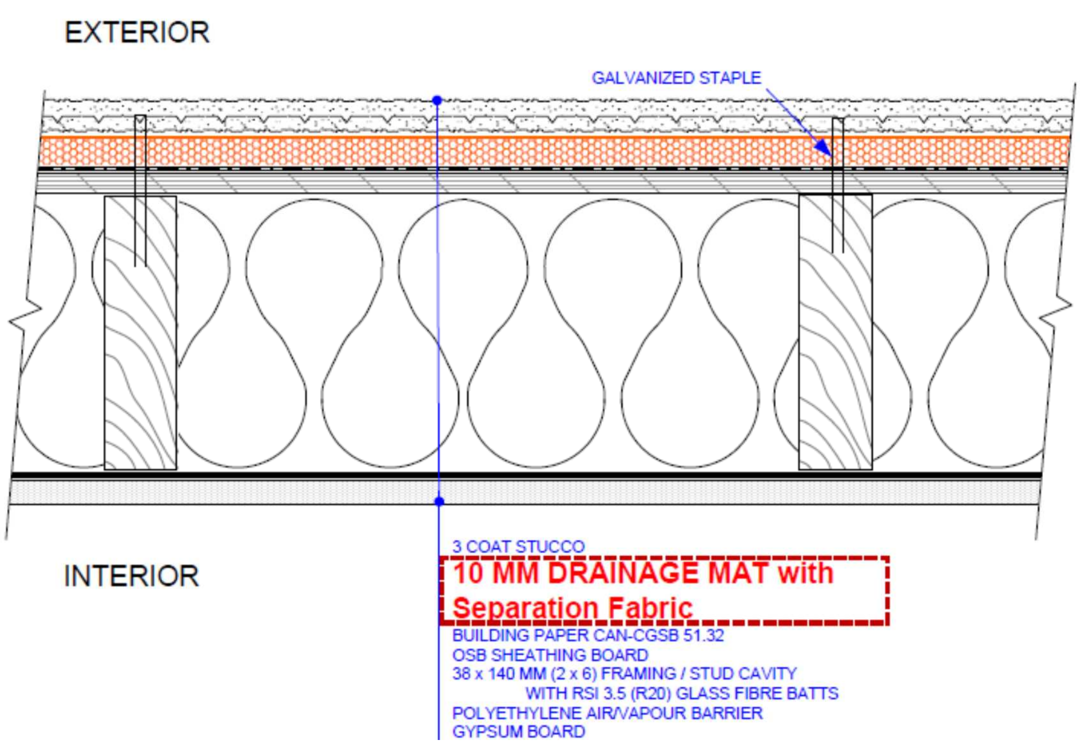

Figure A 8 – Client G Wall Cross-Section

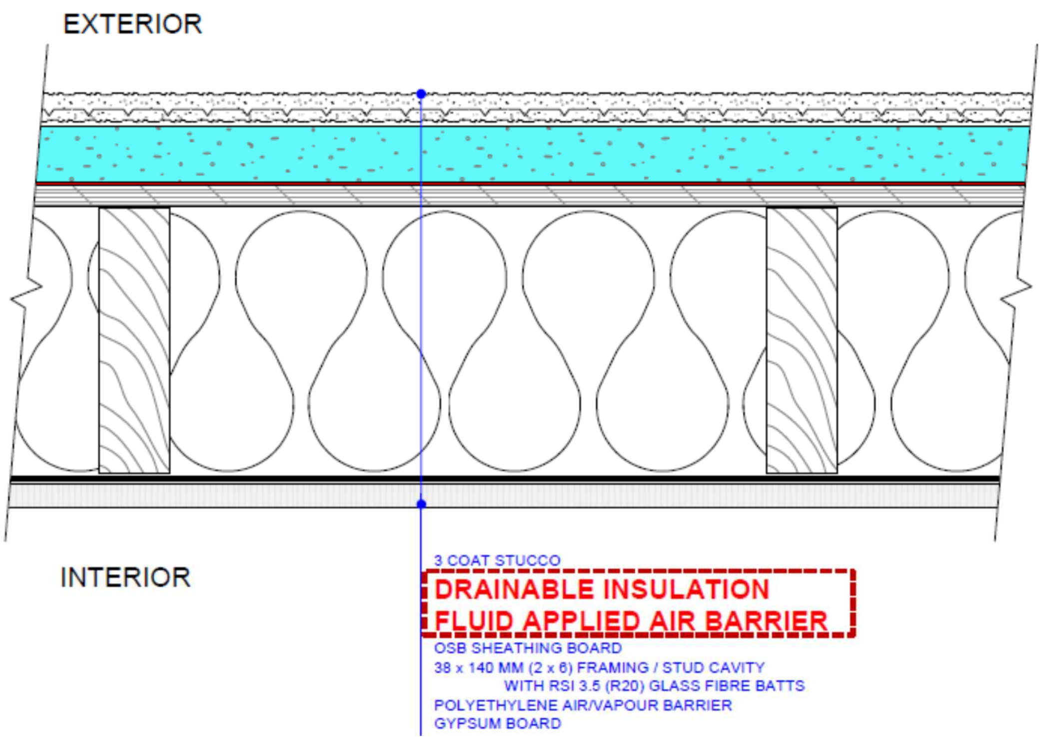

Figure A 9 – Client H Wall Cross-Section

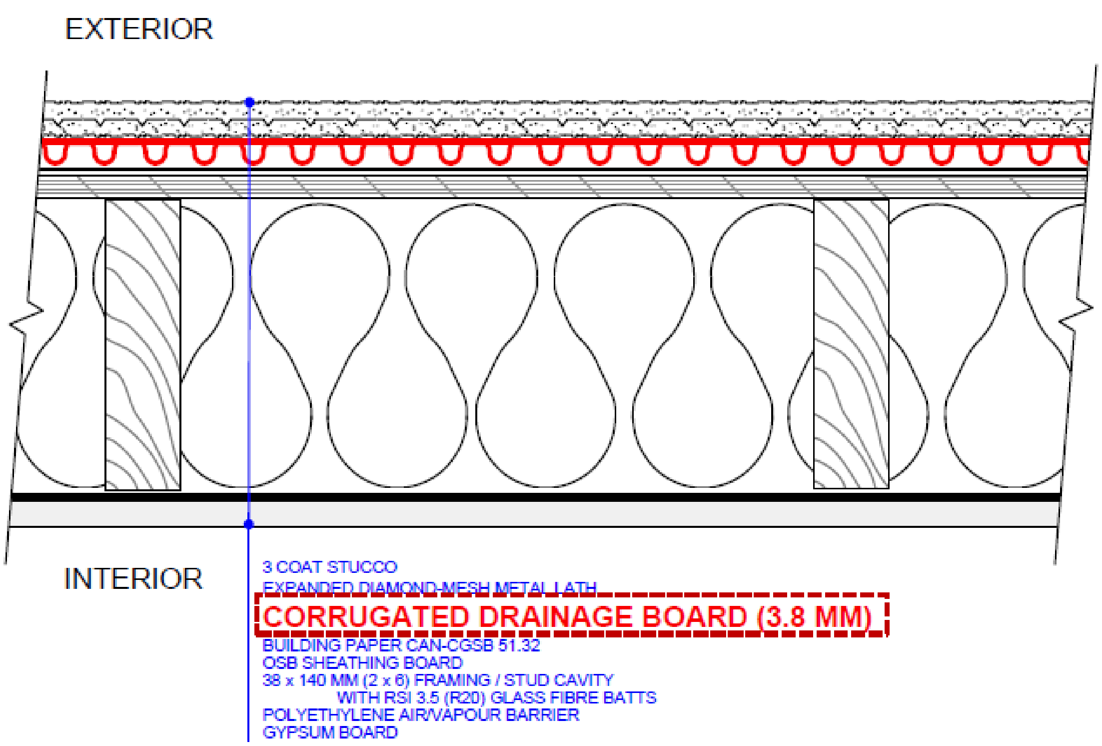

Figure A 10 – Client I Wall Cross-Section

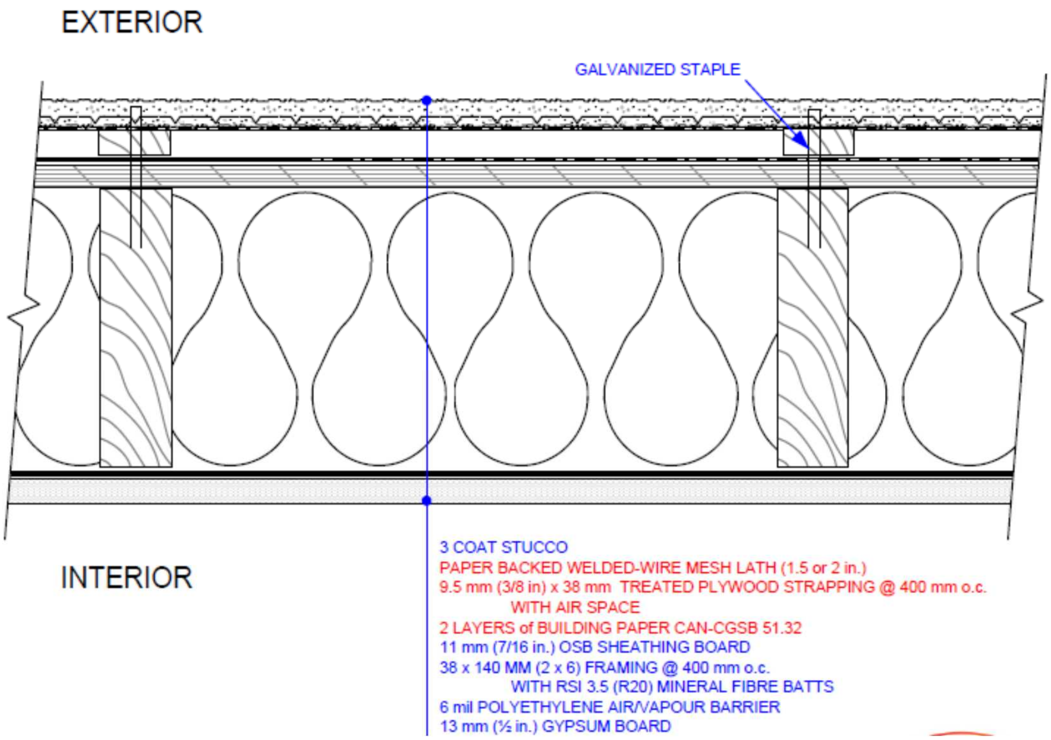

Figure A 11 – Client J Wall Cross-Section