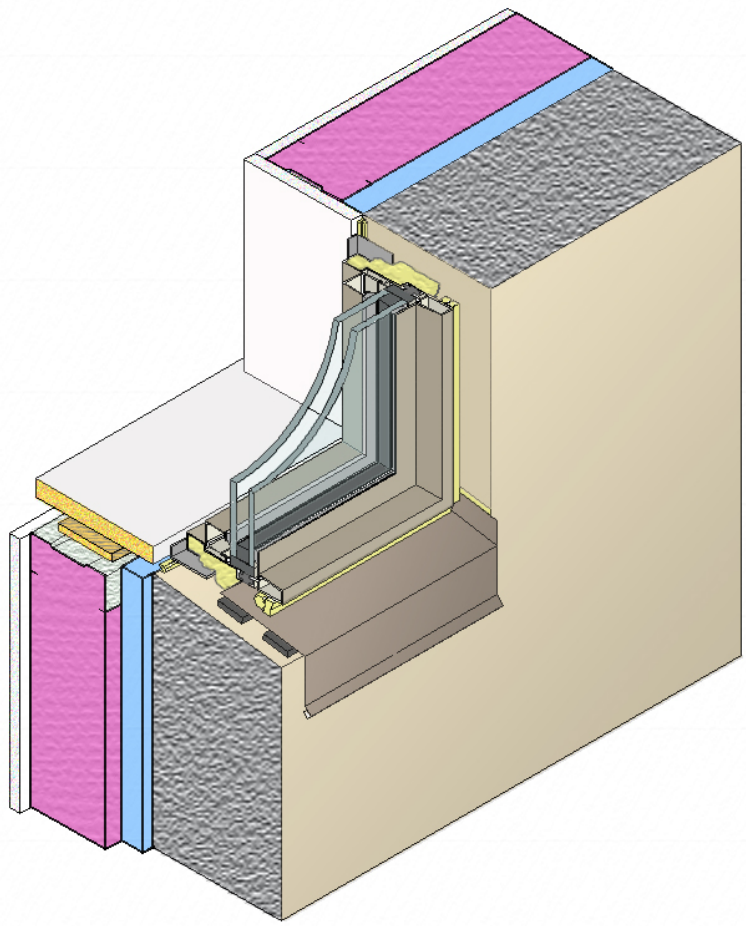
STUDY OF POURED-IN-PLACE CONCRETE WALL PERFORMANCE IN COASTAL BRITISH COLUMBIA



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EXECUTIVE SUMMARY

Poured-in-place concrete walls have historically provided an acceptable level of performance in multi-unit residential buildings. This was illustrated through a number of the case studies. Where problems did appear they were isolated and not systemic in nature. However, many of the problems were difficult to fully isolate, and repairs often involve dismantling the wall assembly from the interior. Poured-in-place concrete buildings constructed in the 1970s and 1980s were also simpler in form with fewer interface details. In addition these buildings had higher levels of air leakage than more recent buildings thereby providing ventilation to moderate interior moisture levels.

As poured-in-place concrete wall assemblies are used more often as an element in current new construction this study identifies the reasons why older buildings of similar wall assembly type have performed well. In addition, strategies for design and construction are presented that address changes in newer buildings.

Building Form and Pour Configuration

Building form has a profound impact on the risk of water penetration since building form impacts the amount of wetting that can occur on a wall, as well as the extent to which problematic details occur. Choices made with respect to building form determine how dependent rain penetration control performance is on the quality of the details. Building form that minimizes wetting and construction joints provides lower risk.

Assemblies

All three of the concrete wall assemblies studied provide adequate performance based on both the case study findings and the analysis. However, Wall Type 1 introduces higher risk of thermal problems including stud shadowing, and condensation on the inside surface of the concrete. It is recommended that wall assemblies incorporate polystyrene or polyurethane foam insulation applied directly to the inside face of the concrete to mitigate this risk and place less reliance on detailing.

The use of coatings improves the water shedding surface by reducing the impact of small cracks and other defects on water absorption. Guidance is provided with respect to attributes and selection of various coatings.

The use of alternate vapour retarder layers does not have a significant impact on performance for normal interior operating conditions. However, evaluation of specific building and space needs will be necessary in order to determine an appropriate vapour diffusion strategy.

Poured-in-place concrete wall assemblies do not perform as well as exterior insulated rainscreen assemblies either from a water penetration perspective or thermally.

Details

Several details are critical with respect to water penetration control and thermal performance and condensation potential. These include construction joints and control joints, interfaces with other assemblies such as windows and penetrations such as vents and louvers. Guidance illustrating good practice principles is illustrated.

Materials

Adequate guidance on appropriate selection and use of most of the materials used in poured-in-place concrete wall assemblies is provided in other documents and by manufactures. The exception to this is the concrete itself, where only general guidance is provided through existing standards. More specific guidance is therefore provided with respect to its use as a primary water penetration control element. Control of the location and frequency of cracking and construction joints is the most important element for water penetration control.

Maintenance and Renewals

Concrete, and the associated coating and sealant materials are also the only part of the wall assembly that is exposed and are likely to require periodic maintenance and renewals.

RÉSUME

Les murs de béton coulé sur place ont traditionnellement fourni un niveau de performance acceptable dans les collectifs d'habitation et de nombreuses études de cas l'ont démontré. Les problèmes qui sont survenus étaient isolés et non pas systémiques. Toutefois, nombre des problèmes ont été difficiles à isoler complètement et il a souvent fallu démonter les murs de l'intérieur pour procéder aux réparations. Les bâtiments en béton coulé sur place construits dans les années 1970 et 1980 étaient de forme plus simple et comportaient moins de détails d'interface. De plus, ces bâtiments étaient moins étanches à l'air que les bâtiments plus récents, ce qui assurait une certaine ventilation et modérait les niveaux d'humidité intérieure.

Comme les nouvelles constructions font un plus grand usage des murs en béton coulé sur place, la présente étude détermine les raisons pour lesquelles les bâtiments plus âgés ayant des types de murs similaires se sont bien comportés. En outre, elle présente des stratégies pour la conception et la construction, qui portent sur les changements dans les bâtiments plus récents.

Forme du bâtiment et configuration du bétonnage

La forme du bâtiment a un impact profond sur le risque d'infiltration d'eau, puisqu'elle a des incidences sur l'humidification éventuelle d'un mur et sur la mesure dans laquelle les détails problématiques se produisent. Les choix faits en fonction de la forme du bâtiment déterminent l'importance de la qualité des détails pour le contrôle efficace des infiltrations de pluie. Une forme de bâtiment qui permet de réduire l'humidification au minimum et requiert le moins possible de joints de construction présente le moins de risques d'infiltration.

Assemblages

Les trois assemblages de murs en béton étudiés fournissent un rendement adéquat, selon les conclusions des études de cas et de l'analyse. Cependant, le mur de type 1 présente des risques plus élevés de problèmes thermiques, dont le spectre des poteaux et la condensation sur la surface intérieure du béton. Il est recommandé d'appliquer de l'isolant de polystyrène ou de la mousse de polyuréthane directement sur la face intérieure du béton pour réduire ce risque et moins se fier aux détails.

L'utilisation d'enduits améliore la face évacuant l'eau en réduisant l'impact des petites fissures et d'autres défauts sur l'absorption de l'eau. L'étude fournit des conseils quant aux caractéristiques et au choix de divers enduits.

L'utilisation de couches alternées de pare-vapeur n'a pas d'impact important sur la performance dans des conditions normales de fonctionnement intérieur. Toutefois, il sera nécessaire d'évaluer les besoins d'un bâtiment ou d'espaces particuliers pour déterminer une stratégie adéquate de diffusion de la vapeur.

Les assemblages de murs en béton coulé sur place ne sont pas aussi performants que les assemblages d'écrans pare pluie isolés de l'extérieur, tant du point de vue de l'imperméabilité que sur le plan thermique.

Détails

Plusieurs détails sont cruciaux pour ce qui est du contrôle des infiltrations d'eau, de la performance thermique et du risque de condensation, y compris les détails de joints de construction et de joints de contrôle, les détails d'interfaces avec d'autres assemblages, tels

que des fenêtres ou des pénétrations, comme des évents et des louvres. Des principes de bonnes pratiques sont illustrés dans le document.

Matériaux

Il est possible de trouver des conseils adéquats sur le choix et l'utilisation appropriés de la plupart des matériaux utilisés dans les murs en béton coulé sur place auprès des fabricants et dans divers documents. Ce n'est pas le cas pour le béton, pour lequel les normes existantes ne donnent que des conseils généraux. Le présent document fournit donc des conseils plus précis sur l'utilisation du béton comme principal élément de contrôle des infiltrations d'eau. Le contrôle de l'emplacement et de la fréquence des fissures et des joints de construction est l'élément le plus important du contrôle des infiltrations d'eau.

Entretien et renouvellement

Le béton et ses enduits et produits d'étanchéité sont également la seule partie du mur qui est apparente et ils devront faire périodiquement l'objet d'entretien et de renouvellement.

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1 INTRODUCTION

1.1 Background

Increasing awareness of building envelope design issues in British Columbia has resulted in a general recognition that face seal and concealed barrier wall assemblies in multi-unit residential construction will not provide acceptable performance. These wall assembly types are therefore generally inappropriate for high-rise construction or other buildings where high exposure conditions prevail. As a result of the recognition that wall assemblies with improved water penetration control properties are required, many new multi-unit residential construction projects are incorporating rainscreen wall and window assemblies to provide acceptable long-term performance. A great deal of information and guidance exists regarding the design and construction of appropriate rainscreen assemblies and it is not anticipated that any significant long term performance problems will emerge with these assemblies.

More recently however, builders and the design community are increasingly utilizing lower cost poured-in-place concrete wall assemblies in combination with rainscreen windows to provide acceptable long-term envelope performance. Although, the acceptable performance of uninsulated mass masonry walls has been documented, there is very little information regarding the performance history of insulated poured-in-place concrete wall assemblies, nor is there any significant guidance available with respect to the best design and construction practices. Unfortunately, the building group studied as part of the initial *Study of High-Rise Envelope Performance in the Coastal Climate of British Columbia* [1] (High-Rise Study) project did not include a significant number of poured-in-place concrete wall assemblies.

In order to confidently continue with this form of construction there is a need to analyze and document potential performance issues, as well as develop a guideline for appropriate design and construction practices. This report documents the findings of the study of performance issues related to this form of wall construction in the coastal climate zone of British Columbia. The results of the study utilize information from the authors' files for both investigative and new construction projects, as well as data generated by accepted analysis techniques and computer programs.

1.2 Objectives

The primary objectives of the study are as follows:

- Investigate the performance and condition of components and materials that are utilized with poured-in-place concrete wall assemblies in multi-unit residential construction. Identify key performance issues and methods of addressing those issues.
- Analyze the heat, air and moisture control requirements of Part 5 of the building code for poured-in-place concrete wall assemblies. These control requirements include:
    - Water penetration control
    - Air leakage control
    - Vapour diffusion control
    - Thermal performance, and
    - Durability of materials

- Examine several specific aspects of construction practices that impact the performance characteristics of poured-in-place concrete wall assemblies including:
    - Merits of various coatings on exterior concrete surfaces
    - Concrete mix design
    - Crack control techniques
    - Concrete joint detailing
- Examine penetration and interface detailing associated with poured-in-place concrete wall assemblies
- Identify design and construction factors that impact the performance of poured-in-place concrete wall assemblies.

All of these factors have been evaluated in the context of the relatively wet and mild coastal climate zone of British Columbia and of buildings where walls can expect to be regularly exposed to wetting. This assumption is considered to be reasonable since the most common current usage of poured-in-place concrete wall construction is in taller multi-unit residential building construction.

The primary focus of the study is on the design and construction of above grade concrete walls. Issues relating to interfaces with horizontal concrete elements such as floor and roof slabs, and projecting fins are also discussed. However, the study does not deal with issues specific to the performance of horizontal concrete elements or below-grade walls.

1.3 Project Team

This study was led by RDH Building Engineering Limited (RDH). The team also included Levelton Engineering Ltd. (Levelton) who authored, and provided input on sections of the report related to concrete mix design and concrete construction practices. Don Onysko reviewed and provided comments on the analysis section of the study. The study was supported financially and guided by Canada Mortgage and Housing Corporation (CMHC) and the Homeowner Protection Office (HPO) in British Columbia.

1.4 Report Organization

A brief introduction to the study as well as relevant background information is provided in Chapter 1 of this report. Chapter 2 develops and presents the key performance issues that need to be addressed in the design and construction of poured-in-place concrete wall assemblies. These issues are based on field performance data gathered from existing buildings as well as an examination of the heat, air and moisture control functions and other applicable requirements of Part 5 of the current *British Columbia Building Code* [3] (BCBC). Individual case studies are summarized in Appendix B.

In Chapter 3, strategies for addressing the performance issues are presented and discussed where possible. Also included in Chapter 3 are the results of thermal and hygrothermal analyses used to compare the relative performance of various poured-in-place concrete wall assemblies. Appendix C contains more detailed results of the thermal and hygrothermal modeling. Chapter 4 examines concrete as a material including mix design issues, and construction issues that can impact performance with respect to the issues identified in Chapter 2. A general discussion of performance issues and recommendations is presented in Chapter 5.

A glossary of technical terms used within the report is included in Appendix A.

2 WALL PERFORMANCE ISSUES

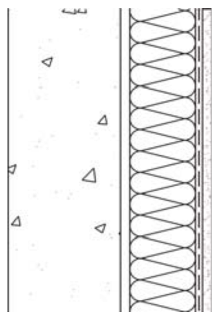
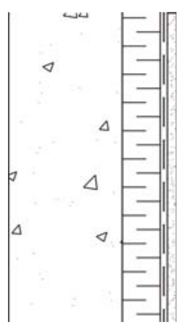
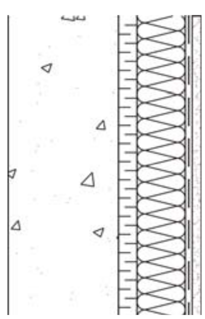
This chapter identifies the typical wall systems considered and examines information gathered from three different sources to arrive at a list of key performance issues that need to be addressed in order to design and construct effective and durable poured-in-place concrete walls.

1. The ability of poured-in-place concrete walls to perform effectively with respect to control of heat, air and moisture to avoid premature deterioration of materials is impacted by many variables. Building codes provide basic performance requirements and these need to be examined to identify potential performance issues associated with poured-in-place concrete wall assemblies.
2. Since poured-in-place concrete walls have been used to some extent for many years in the coastal British Columbia environment, it is important to examine why these older poured-in-place concrete walls have apparently worked, and what if any changes have occurred in building practices that may impact performance. Therefore case studies of existing buildings are examined in the field to verify how well poured-in-place concrete walls have performed, and to confirm the nature of performance problems where they exist.
3. In the previous chapter it is noted that poured-in-place concrete walls are becoming a more prevalent form of building envelope construction. Therefore information from case studies of buildings under construction is examined.

2.1 Typical Wall Assemblies Considered

Poured-in-place concrete wall assemblies are commonly constructed utilizing a variety of materials built up in layers to the interior of the concrete, in addition to the application of a coating and sealants to the exterior surface of the concrete. Three commonly used variations of assemblies are shown in Table 2.1. These wall assemblies are examined and analyzed with respect various performance issues in this study. In some instances the discussion of performance issues is relevant to all three assemblies, while in others, there is a need to differentiate between the three assemblies. In addition, small variations in the assemblies are also examined. For example, the replacement of polyethylene with alternate vapour retarding materials, or no intentional vapour retarder layer, is considered.

Table 2.1: Typical Poured-In-Place Concrete Wall Assemblies

Wall Type	Assembly Materials
 W1	Exterior 150 mm concrete (with or without coating) 13 mm airspace 92 mm steel studs & batt Insulation 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior
 W2	Exterior 150 mm concrete (with or without coating) 50 mm Extruded Polystyrene (XPS) with integral T-shaped steel supports *(Alternate assembly of this type would utilize spray-in-place polyurethane foam instead of XPS. This variation is also discussed in Chapter 3)* 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior
 W3	Exterior 150 mm concrete (with or without coating) 25 mm XPS 64 mm steel studs & batt insulation 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior

2.2 Building Code Performance Requirements

The building codes set out basic performance requirements for the entire building envelope, and these requirements are clearly applicable to poured-in-place concrete walls. This study uses the requirements of BC Building Code (BCBC) as a reference. The BCBC is similar in many respects to the Vancouver Building By-law (VBBL). However, a key difference with respect to the design of exterior wall systems is in VBBL 5.6.1.1.(1) C, which requires that assemblies exposed to precipitation be designed to drain any accumulated water to the exterior. Since it is impossible for water that accumulates on the interior of the concrete to drain back to the exterior, it is important to ensure that exterior water shedding surface and moisture barriers preclude the infiltration of any water to the interior of the concrete. The current popularity of these wall assemblies in Vancouver suggests that the City of Vancouver has accepted this rain penetration control strategy to be equivalent to clause 5.6.1.1.(1)C.

The following sections describe the primary performance requirements in the context of poured-in-place concrete wall assemblies.

Water Penetration Control

BCBC requirements with respect to water penetration control require that the wall assembly *minimize ingress of precipitation into the component or assembly, and prevent ingress of precipitation into interior space* (BCBC Article 5.6.1.1). The clarification of the intent of this requirement and in particular of the word 'minimize' is provided in the Appendix to BCBC. The appendix note acknowledges that it is not generally possible to totally prevent ingress of precipitation in its entirety, and that the intent of the requirement is to limit the accumulation of moisture such that it does not impact the expected long term performance or durability of the assemblies, and that any moisture dries out or is drained away before it initiates deterioration of building materials. Therefore, BCBC would suggest that an ability of poured-in-place concrete walls to drain (deflect) the majority of the precipitation at the face of the wall and to store small amounts of moisture within the concrete to later be dried to the exterior is a reasonable strategy, since the presence of moisture within the concrete is not likely to deteriorate this inherently durable material. However, it is also clear from the BCBC requirement that a wall assembly that permitted precipitation to migrate through the wall to damage materials that are more susceptible to moisture damage such as steel studs, gypsum board and interior finishes does not meet performance expectations.

Poured-in-place concrete wall assemblies are not easy to categorize with respect to the intended water penetration control strategy. The concrete has a moisture storage capability that would suggest that it may behave similar to mass masonry walls that have historically performed well. However, there are some key differences between these two wall assemblies that suggest their behaviour and performance expectations are not as similar as they may at first appear.

Newer poured-in-place concrete walls must perform functions that were of lesser importance to older mass masonry walls. They must be insulated, and in many cases, they incorporate more vapour impermeable layers within the assembly than were typical for mass masonry walls. Mass masonry walls were also built using several layers (wythes) of masonry units, thereby creating a discontinuous path for water to penetrate through the wall assembly, while also facilitating absorption and storage of the moisture, which can later dry out of the assembly. Poured-in-place concrete walls on the other hand are monolithic (one layer) so that cracks that occur due to shrinkage or movement, or because of construction joints between pours, generally provide a path for moisture migration through the complete wall assembly to the interior. (Cold joints in concrete could also provide such a pathway, for further details on joint terminology refer to Appendix A at the end of this document). In this sense, a poured-in-place concrete wall performs more like a face seal or barrier wall assembly with only one line of defense against water penetration. The challenge therefore, is to provide some redundancy in the design of concrete wall construction, particularly at joints and interfaces within wall assemblies, so that they can utilize the inherent 'mass' character of the concrete. The critical nature of this requirement is clearly documented in the *Survey of Building Envelope Failures in Coastal British Columbia* [4] (Low-Rise Study) and the *High-Rise Study* [1].

For poured-in-place concrete walls the key details include:

- Window to wall interface
- Wall to horizontal deck or balcony surface
- Construction joints within the concrete
- Cracks within the concrete
- Protection of the top horizontal surface of wall elements
- Deflection (drip) provisions so that water does not tend to run on the vertical wall elements

Due to the inherent difficulty in controlling all factors related to crack control and water penetration at joints, at all locations, poured-in-place concrete walls cannot be expected to achieve the reliability of water penetration performance anticipated from rainscreen wall assemblies.

Air Leakage Control

The BCBC requirements for air tightness (Article 5.4) are similar in intent to water penetration requirements with respect to limiting air leakage so that intended use and operation of the building are not adversely affected. However, air leakage also impacts thermal comfort within the building, air quality, energy performance, and operation of mechanical ventilation systems providing several other reasons to control air leakage.

Poured-in-place concrete is inherently air tight. Therefore, air movement through the wall assembly itself is not normally an issue that requires a significant amount of attention. Rather, it is continuity of air tightness at interfaces with other assemblies, in particular windows and at penetrations such as vents, that must be addressed during the design and construction of a building.

Another issue that is related to air tightness can be significant for some types of concrete wall assemblies. For example, wall type W1 in Table 2.1 indicates an air space between the interior concrete surface and the interior steel stud wall. A lack of air tightness within the interior steel stud wall portion of the assembly combined with a driving force to move interior air into the air space could result in increased potential for condensation on the inside surface of the concrete.

Vapour Diffusion Control

The BCBC requirements for vapour diffusion (Article 5.5.1.2) require that a vapour barrier shall be provided *to minimize moisture transfer by diffusion, to surfaces within the assembly that would be cold enough to cause condensation at the design temperature and humidity conditions*. The requirements elaborate on this basic requirement to clarify that it is the *accumulation of moisture to cause deterioration* that is the actual performance criteria.

Generally in cold climates, the vapour pressure gradient across building envelopes is a significant consideration in building envelope design. The difference between the relatively mild BC coastal climate and other areas of Canada suggests that driving forces for water vapour flow from interior spaces to the exterior across typical wall assemblies are lower in coastal BC. However, there can be unique interior environmental conditions created by occupant use (intentional or otherwise), that could result in a significant outward vapour drive which may dictate the use of a low vapour permeable material near the inside surface of the wall assembly to control condensation.

Conversely, the use of concrete as an absorbent cladding can create conditions where the outside layer of the wall assembly contains sufficient moisture so that the vapour drive is to the interior. This can create problems in the context of drying potential to the exterior, which is minimal for much of the winter months in coastal BC. In addition, concrete is relatively vapour impermeable (23 to 31 ng/Pa·sm^2 - the same order of magnitude as vapour retarder paint). Thus, the determination of requirements for vapour diffusion control for poured-in-place concrete walls is not immediately obvious and requires further analysis and discussion as can be found in Chapter 3 of this report.

Finally, concrete starts out wet, so we do not want our vapour diffusion control strategy to prevent drying of initial construction moisture. Typically coatings are added to concrete only after a significant amount of the initial drying has taken place.

Thermal Performance

The Part 5 BCBC requirements for thermal resistance (Article 5.3.1.2) are similar in intent to requirements for other moisture control functions with respect to minimizing accumulation of moisture due to condensation and the impact on long-term performance and durability. An additional BCBC requirement in the vapour diffusion section is that convective airflow through or around the insulating material be prevented. This requirement is relevant with respect to the air space potentially located adjacent to the interior surface of the poured-in-place concrete as discussed above in the section on air tightness.

Concrete is a relatively thermally conductive building material and when combined with other highly conductive metal elements typically included within the building envelope (steel studs and windows) can present some significant challenges with respect to thermal bridging and surface condensation control.

There are also some challenges introduced with respect to thermal performance as a result of the interaction of the building envelope with mechanical ventilation and heating systems, as well as architectural design factors, that potentially lower the temperature of surfaces at walls and windows. These issues include:

- Lack of perimeter heating
- Air tightness of envelope impacts assumptions for mechanical ventilation
- Poor delivery of ventilation air flow to the perimeter walls and windows
- Architectural layout that results in furnishings against perimeter walls

In addition, internal environmental conditions created by the occupant use of the interior space can impact thermal performance with respect to condensation potential.

Due to the relatively conductive nature of concrete as a material, poured-in-place concrete wall assemblies also have significant challenges with respect to overall thermal performance and energy usage. The analysis and discussion in Chapter 3 of this report addresses many of these thermal performance issues.

2.3 Field Investigation of Performance

Appendix B contains a summary of the findings from the examination of 5 case studies where poured-in-place concrete walls represented a significant portion of the exterior walls of the buildings involved. Two of these case studies are buildings that were examined as part of an investigation of a known water leakage problem. Two of the case studies are from buildings that were examined as part of an overall building envelope condition assessment project. The fifth case study reports on observations from several recently constructed projects examined during the initial construction stages.

It is important to note that the case studies are not intended to provide a statistical representation of failures and successes, nor suggest that these are the only potential problems that poured-in-place concrete walls experience. The purpose of the case studies is simply to help identify a fairly comprehensive range of performance issues that need to be addressed in the design and construction of poured-in-place concrete wall assemblies.

Performance problems can be visually evident through deterioration of interior finishes or staining on the exterior side of the walls. Damage can also be hidden within the walls with little or no visual evidence of a performance problem. In some cases seemingly minor symptoms such as staining can be indicative of greater damage occurring within the assembly. A collection of pictures from field investigations is arranged below to describe visual symptoms and performance issues associated with poured-in-place concrete walls (Figures 2.1 to 2.12). The figures therefore describe typical symptoms of performance problems and issues as seen at the case study buildings. These problems and issues are grouped into interior, exterior and 'within the wall' categories, and include a description of both the visual symptoms and deficiencies leading to the presence of moisture that caused the symptom.

INTERIOR SYMPTOMS AND ISSUES

Figure 2.1 Staining on Ceiling

Condensation formation or water leakage at the floor level has resulted in staining and deterioration of the finish on the ceiling.

Figure 2.2 Staining on Wood Window Stool

Staining and deterioration of the finish on the wood stool at the window sill due to condensation formation on the window frame.

Figure 2.3 Water Pooling and Damage to Floor Finishes

Water pooling on floor due to water leakage or condensation results in decay of carpet tack strips, staining of carpeting and mold growth.

SYMPTOMS AND ISSUES WITHIN THE WALL ASSEMBLY

Figure 2.4 Water Leakage at Vertical Construction Joint

The portion of concrete wall under the window has been poured after the adjacent wall assembly resulting in a construction joint. Ineffective sealing of the construction joint results in water penetration. This type of joint is also a control joint, placed beneath the window corner to encourage crack formation (see Appendix A for more detailed terminology).

Figure 2.5 Water Leakage at Horizontal Construction Joint

The portion of concrete wall under the window has been poured after the adjacent wall assembly resulting in a construction joint. Ineffective sealing of the construction joint results in water penetration.

Figure 2.5 Water Leakage at Cracks

A crack within the concrete wall assembly results in water penetration that appears as a small pool of water on the floor and staining and efflorescence on the interior surface of the concrete. No staining on the interior gypsum board was visible.

Figure 2.6 Leakage at Form Tie Location

Water penetration occurs at poorly sealed form tie locations.

Figure 2.7 Corrosion of Metal Components

Water leakage has resulted in corrosion of the steel studs and stud track.

Figure 2.8 Mold on Surfaces Within the Wall Assembly

Mold found on exterior side of the interior gypsum board due to water wicking up from the floor at a vertical joint in the concrete.

EXTERIOR SYMPTOMS AND ISSUES

Figure 2.9 Efflorescence on Exterior

Formation of white efflorescence staining on the exterior surface of the concrete wall due to moisture migrating through the concrete where moisture then evapourated to the exterior from the concrete surface. Moisture migration to the construction joints at the floor slab level in this case occurred because the concrete wall was uncapped, which allowed water into construction joints from above.

Figure 2.10 Staining on Exterior Concrete Surface Finishes

Staining and organic growth has occurred due to concentrated water run-off.

Figure 2.11 Staining on Exterior Concrete Surface Finishes

Due to lack of drip flashing

Figure 2.12 Leakage at Interface With Adjacent Assemblies

Water penetration occurs due to failed and discontinuous sealant between concrete wall assembly and window assembly.

In addition to the specific performance issues identified and illustrated in Figures 2.1 to 2.12, there are several general conclusions that can be reached based on the review of performance of the five case studies, and other existing buildings, that utilize poured-in-place concrete walls. These include:

- While there is no evidence to suggest the occurrence of systemic failure of these wall assemblies, similar to the systemic failure of the face seal wall assemblies that typified the leaky condominium buildings in coastal BC, there are performance issues related to the use of poured-in-place concrete walls.
- Water penetration control is the most significant performance issue associated with this wall assembly in coastal BC.
- Control of condensation potential is important for effective performance of this type of wall assembly.
- Water penetration issues are primarily related to construction joints and cracks in the concrete, and to details at interfaces and penetrations.

- Water penetration through the concrete (i.e. uncracked and sound sections of concrete) is not a significant concern.
- Changes in the air tightness characteristics of newer concrete buildings, trends in mechanical ventilation and heating system design and the size of suites can have a significant impact on condensation control at the exterior walls.
- Older poured-in-place concrete walls achieved acceptable performance due to a combination of a number of factors including; simple building form (fewer details), avoidance of problematic vertical construction joints, higher levels of air leakage, higher levels of conductive heat flow, and relatively long time frame for moisture damage becoming significant enough to be noticed and require remedial work.

2.4 Summary of Performance Issues

The review of performance of poured-in-place concrete wall assemblies in existing buildings and building code performance requirements has identified a number of issues that need to be addressed in the design and construction of poured-in-place concrete walls in order to achieve effective and durable performance. Table 2.2 summarizes these performance issues. Subsequent chapters analyze many of these issues in more detail and where possible present conclusions with respect to possible ways of addressing each issue.

Table 2.2: Summary of Performance Issues

1.	Water penetration control at the surface of the concrete, and concentrated run-off on surfaces
2.	Water penetration control utilizing concrete as a waterproofing material
3.	Water penetration control at construction joints
4.	Water penetration control at cracks
5.	Water penetration control at interfaces and penetrations
6.	Air leakage control at details
7.	Air leakage control into air space at inside surface of concrete
8.	Vapour diffusion control, both outward and inward, as well as the overall wetting and drying potential of the wall assembly
9.	Thermal bridging and condensation control
10.	Mechanical ventilation and heating system impact on condensation control
11.	Overall thermal efficiency of wall assembly
12.	Coating durability, maintenance and renewals
13.	Sealant durability, maintenance and renewals
14.	Building form and overhang protection can influence water penetration performance significantly

3 ANALYSIS AND DISCUSSION OF PERFORMANCE ISSUES

In this chapter, the performance issues identified in the previous chapter are explored in greater detail. Similar to Chapter 2 they are discussed under the general headings of water penetration, air leakage, vapour diffusion, and thermal performance. Strategies for addressing these issues are also presented. Secondary issues that arise due to addressing certain performance criteria are also presented since strategies to address one criteria can have a significant impact on other issues, e.g., the thermal insulation strategy can have a significant impact on vapour control strategy.

Refer to Table 2.1 for a description of the wall assemblies that are discussed and modeled.

Subsequent to the discussion of the various performance issues, the results of hygrothermal and thermal modeling are presented to demonstrate relative performance of various wall assemblies.

Hygrothermal analysis software is used to determine the overall wetting and drying potentials, interstitial relative humidity and condensation potentials, and to identify possible material degradation concerns. The result of the modeling is presented and the relative impact of variables such as coatings, polyethylene vapour retarders, and different insulation strategies is discussed.

Thermal analysis software is used to determine the overall R-value and surface temperatures at key thermal bridge details to compare wall thermal performance and identify potential surface condensation concerns.

Some general conclusions attained through the modeling exercises are provided within this section of the report. A discussion based on the conclusions can be found in Chapter 5 of this report. The computer analysis software used in this study are:

1. WUFI Pro 3.3. (WUFI) Developed by Fraunhofer – Institut Für Bauphysik. A one-dimensional hygrothermal modeling software. WUFI models the flow of heat and moisture through building cross sections accounting for weather characteristics of specified locations, including rain wetting and solar radiation.
2. THERM 5.2. (THERM) Developed by Lawrence Berkeley National Laboratory. A two-dimensional heat transfer modeling software. THERM models the flow of heat through building cross sections for specified interior and exterior temperatures.

Refer to Appendix C for details' regarding these two models as well the modeling data and results.

Durability of materials is not dealt with separately but rather is addressed within discussions of other performance criteria where appropriate.

3.1 Discussion of Performance Issues

3.1.1 Water Penetration Control

Control of moisture is the most important design consideration for building envelope assemblies and moisture in all forms and from all sources needs to be considered. However, rain penetration control is typically the most critical moisture source.

As previously discussed, poured-in-place concrete walls are a combination of face-seal and mass wall in terms of rain penetration control strategy and the key issue is leakage at interface details. In general, water may enter the wall assembly via one or more of the following paths:

1. At interfaces between dissimilar building assemblies (i.e. window to wall interfaces).
2. At construction and cold joints.
3. Through unintentional cracks in the concrete.
4. By absorption (in contact with liquid water). Because absorbed (stored) moisture can be transported by diffusion and capillary transport, absorbed/stored moisture is also addressed under vapour diffusion control.
5. By adsorption (increase and decrease stored moisture due to changes in atmospheric relative humidity). Control of this mode of water penetration is also discussed under vapour diffusion control.

To address leakage at interface joints, sealants are typically utilized and, in some cases, two stage joints can be used to provide some level of redundancy.

Similarly, larger cracks that develop can be addressed with sealants, but often only single stage joints are feasible. Various water stop materials can be used to supplement the sealant and provide some redundancy to minimize leakage at construction and cold joints. The advantages and disadvantages of various water stop materials are discussed in Chapter 4.

Similar to mass masonry walls, poured-in-place concrete walls utilize their inherent mass to control moisture by absorbing and storing the moisture during wet periods and subsequently drying when conditions allow. However, typical older mass masonry walls are uninsulated and do not include impermeable layers towards the interior, where much of the drying occurs, particularly during the winter months. This reduction in drying capability of concrete walls is likely not an issue with respect to the durability of the concrete because of the relatively mild climate of coastal BC (freeze-thaw is not a major concern), however, the moisture stored in the concrete can be a significant source that can migrate inward and cause conditions that accelerate deterioration of other more moisture sensitive materials. As such, controlling the amount of moisture that is absorbed by concrete walls may prove to be a critical issue for poured-in-place walls unlike older, uninsulated masonry walls. Coatings are typically used to control rain water absorption and to bridge small hairline cracks. However, coatings also need to be permeable enough to allow drying of either interior moisture or initially built-in moisture to the exterior. As part of the hygrothermal modeling that is presented in section 3.5, the relative impact of the wall assemblies with and without coatings is discussed.

3.1.2 Air Leakage Control

In poured-in-place concrete buildings the air barrier system is comprised of the concrete building elements and window/door elements, as well as the joints between these building elements. The continuity of the air barrier is dependent on the effectiveness of these joints. In general, the performance of these buildings in terms of air leakage control is relatively good since the majority of the resistance to air flow is provided by the concrete, which is inherently air-tight.

Despite the inherently air tight nature of concrete wall construction there is the possibility of air movement within wall assemblies that could lead to condensation, particularly with wall W1. Convective air movement may be initiated by differences in surface temperatures adjacent to the air mass or other pressure differences that may exist between suites or between the interior space and the wall air space next to the concrete. If this occurs, water vapour can potentially condense on the colder surface at the interior of the concrete. Modeling tools such as WUFI are not capable of simulating this complex behaviour within interstitial air spaces, however potential concerns may be addressed qualitatively.

Two possible locations through which interior air may enter the wall assembly are through electrical service penetrations or at partition-wall intersections. Taking care to eliminate paths for air to migrate into the wall assembly from these paths is one way of managing the potential problem.

Providing a continuous layer of insulation immediately against the concrete surface thereby eliminating the cold condensing surface is another way of managing this potential for condensation.

3.1.3 Vapour Diffusion Control

It is common practice to place a sheet of polyethylene film between the insulation and the interior gypsum board in poured-in-place concrete wall construction to function as a vapour retarder for controlling outward (wintertime) vapour diffusion. An alternative approach is to use a vapour retarding paint coating on the interior side of the gypsum board. The provision of a vapour retarder on the interior side of the insulation slows the migration of water vapour towards the concrete during the heating season thus reducing the potential of condensation forming on the interior surface of the concrete. The use of polyethylene is consistent with common construction practice in colder parts of Canada, where a vapour retarder with a low permeance is required for vapour diffusion control in typical insulated stud wall construction without exterior insulation. However, for the poured-in-place walls being considered in this study, it is not immediately clear if the inclusion of polyethylene is required or beneficial since the outward vapour drive is lower than in colder parts of the country as well as the possibility that the polyethylene will hinder the drying potential towards the interior.

Concrete, although a porous material, is a relatively effective vapour retarder itself capable of providing vapour diffusion resistance similar to a layer of vapour retarding paint. When combined with the use of a vapour retarder material on the warm side of the insulation this results in a unique scenario where there are two relatively vapour diffusion resistant layers on either side of the wall assembly.

There are advantages to using polyethylene rather than vapour retarding paint because of their relative positions in the wall section. Polyethylene is typically placed between insulation and the interior gypsum board where it will protect the exterior face of the gypsum in the event that the relative humidity within the wall cavity is elevated high enough to support mold growth. However the question of whether the presence of the polyethylene is responsible for the higher RH in the cavity since the wall cannot dry to the interior needs to be evaluated. Thus, the performance of walls with and without a polyethylene vapour retarder is evaluated using WUFI and the results are presented and discussed in section 3.5.

The necessity of a vapour retarder is also impacted by the insulation strategy. Rigid plastic foam insulation is relatively vapour impermeable compared to glass fibre insulation and thus a polyethylene vapour retarder may not provide any benefit in walls that use plastic foam type insulation.

3.1.4 Thermal Performance

Thermal performance of any wall assembly is important for several reasons, including controlling energy use for heating and cooling and providing good thermal comfort. Thus building codes mandate a minimum insulation level (R-value) and meeting the required R-value is left up to the designer. For poured-in-place walls the option of whether to place the insulation on the interior or exterior side of the concrete is probably the first consideration. Although insulating on the exterior of the concrete has better thermal performance, insulating on the interior is far less expensive. Since cost is the driving force behind the use of poured-in-place concrete walls, only the option of insulating on the interior is considered in this study.

The walls considered for this study have different insulation strategies that meet the minimum requirements of the code. However, the strategy used for achieving the desirable level of thermal performance has some additional considerations other than simply meeting a minimum R-value.

Additional considerations include:

1. "Overall" thermal performance. Thermal bridging at floor slab edges, balcony slab edges, and at steel studs used to attach the interior finishes can have a significant affect on the overall R-value of the wall assembly.
2. Interior surface temperature and condensation. Thermal bridging will also affect interior surface temperatures, which directly impacts condensation potential on these surfaces.

3.2 Hygrothermal Performance

Hygrothermal modeling was undertaken to compare the performance of the proposed wall assemblies and evaluate the impact of select variables. Variables considered for comparison are the inclusion of a polyethylene vapour retarder, exterior coatings, and various insulating strategies. Wall performance is evaluated based on the following criteria:

1. Overall wetting and drying potential. The moisture content of the hygroscopic wall layers will fluctuate over the course of a year, however the total moisture content of the assembly should not gain moisture year after year once an equilibrium level has been reached. To evaluate the balance of wetting and drying, the water content of the concrete layer is evaluated since this layer will demonstrate the wetting and drying cycles.
2. Condensation potential at the interior face of the concrete during the winter due to an outward vapour drive. The likelihood of condensation and high RH increase the risk of corrosion of light gauge steel framing. To evaluate the wintertime condensation potential, the relative humidity at the interior surface of the concrete is evaluated.
3. Condensation potential at the exterior face of the interior gypsum board sheathing or exterior face of the polyethylene during the summertime due to an inward vapour drive. The likelihood of condensation and high RH increase the risk of corrosion of light gauge steel framing and mold growth on the paper faced gypsum board sheathing. To evaluate the summertime condensation potential, the relative humidity at the exterior face of the interior gypsum board sheathing or exterior face of the polyethylene is evaluated.

3.2.1 Summary of Modeling

WUFI Pro 3.3 was used to model the hygrothermal performance of the wall systems. WUFI utilizes hourly weather data including rain, solar radiation, temperature and relative humidity to model 1-D transient behavior. WUFI does not model air leakage.

For the purpose of this study, average 10% coldest weather for Vancouver, BC, which is included with the WUFI software, was used. Interior conditions varied between 22˚C and

60% RH in August to 20˚C and 40% RH in February. Simulations are of east facing walls at the upper floors of a high-rise building since these walls receive the greatest quantity of wind driven rain. Models are 5-year simulations. Initial conditions for material layers were set at their respective 80% RH equilibrium moisture content, except for the concrete. The initial moisture content of the concrete was set to the ending moisture content of an initial model of a 200 mm concrete wall exposed to late fall Vancouver weather on both sides for a period of three months. This exposure would be representative of the moisture content of a recently constructed concrete wall at the wettest time of year.

To facilitate interpretation of the figures, the following conventions are used to more easily identify each wall system and the various options:

- (W1, W2, or W3)_(P or NP)_(NC, SE, or AE) where:
    - W1, W2, and W3 = Wall configuration (insulation strategy, see Figure 2.1)
    - P or NP: P=polyethylene, NP= No polyethylene
    - NC, SE, or AE: NC=No coating,
      SE=Silicone elastomeric coating (permeance = 2485 ng/Pa·sm^2),
      AE=Acrylic elastomeric coating (permeance = 630 ng/Pa·sm^2)

In total, 18 hygrothermal simulations were conducted; 6 simulations for each of walls W1, W2, and W3. The results of all the simulations are included in Appendix C. Interpretation of the simulation results are discussed under the sub-headings that follow.

To model the affect of the exterior coatings, we employed the following approximations for the simulations. For a high-rise building, WUFI's default rainwater absorption factor is 0.7, which means that 70% of the rain incident on the wall is available for absorption by the cladding. For this to be meaningful, the suction coefficients of the cladding material must be known. The suction coefficients for concrete are included in the WUFI material database, however the suction coefficients for coated concrete are not available and can only be determined by physical testing. To estimate the effect of the coating for modeling purposes, the suction coefficient of the outer 5mm of concrete was estimated to be a factor of 10 lower than that of uncoated concrete. We compared our estimate of the suction coefficient to the effect of reducing the rainwater absorption factor to 0.05, and found the results to be comparable for the SE coating. For the AE coating, reducing the suction coefficient of the outer 5mm resulted in slightly higher concrete moisture content than models where the rain absorption factor was reduced to 0.05.

3.2.2 Effect of Exterior Coatings

As previously discussed, exterior coatings are often utilized to improve the rain penetration performance of poured-in-place concrete walls by bridging small cracks and reducing rainwater absorption in the concrete. However, the impact of these coatings on wall drying potential has been questioned. To determine the overall impact of coatings, we conducted hygrothermal simulations of the walls without an exterior coating, as well as with either a silicone elastomeric coating or an acrylic elastomeric coating with permeance values of 2485 ng/Pa·sm^2 and 630 ng/Pa·sm^2 respectively. Comparisons between walls W1, W2 and W3 are discussed later in this section under the heading Effect of Insulation Strategy on Hygrothermal Performance.

Figures 3.1a, 3.1b, and 3.1c present the moisture content of the concrete for walls W1, W2 and W3 with and without coatings. For clarity, only walls that include a polyethylene vapour barrier are shown. Results for walls W1, W2, and W3 without polyethylene are presented in Figures 3.1d, 3.1e and 3.1f and are included in Appendix C.

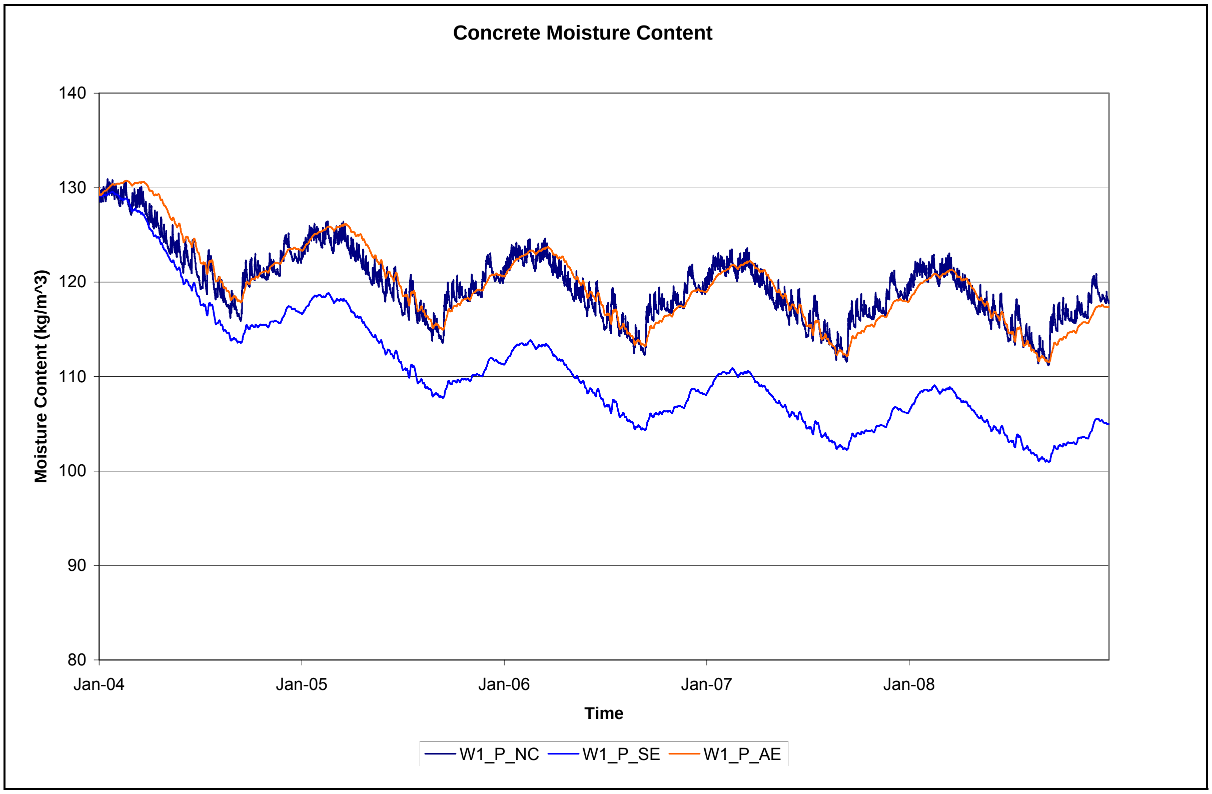


Figure 3.1a: Concrete moisture content for wall W1 with NC, SE and AE exterior coatings.

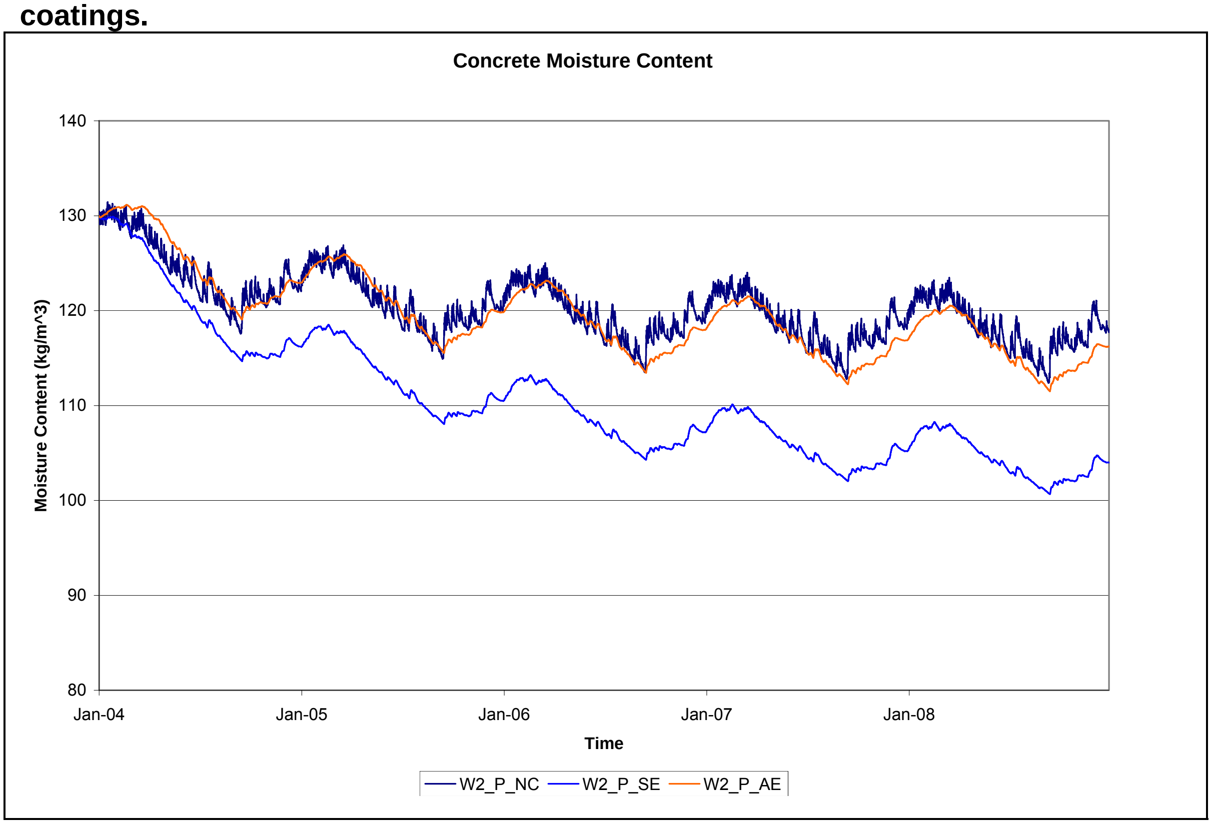


Figure 3.1b: Concrete moisture content for wall W2 with NC, SE and AE exterior coatings. Water content shown in units of kilograms per cubic meter.

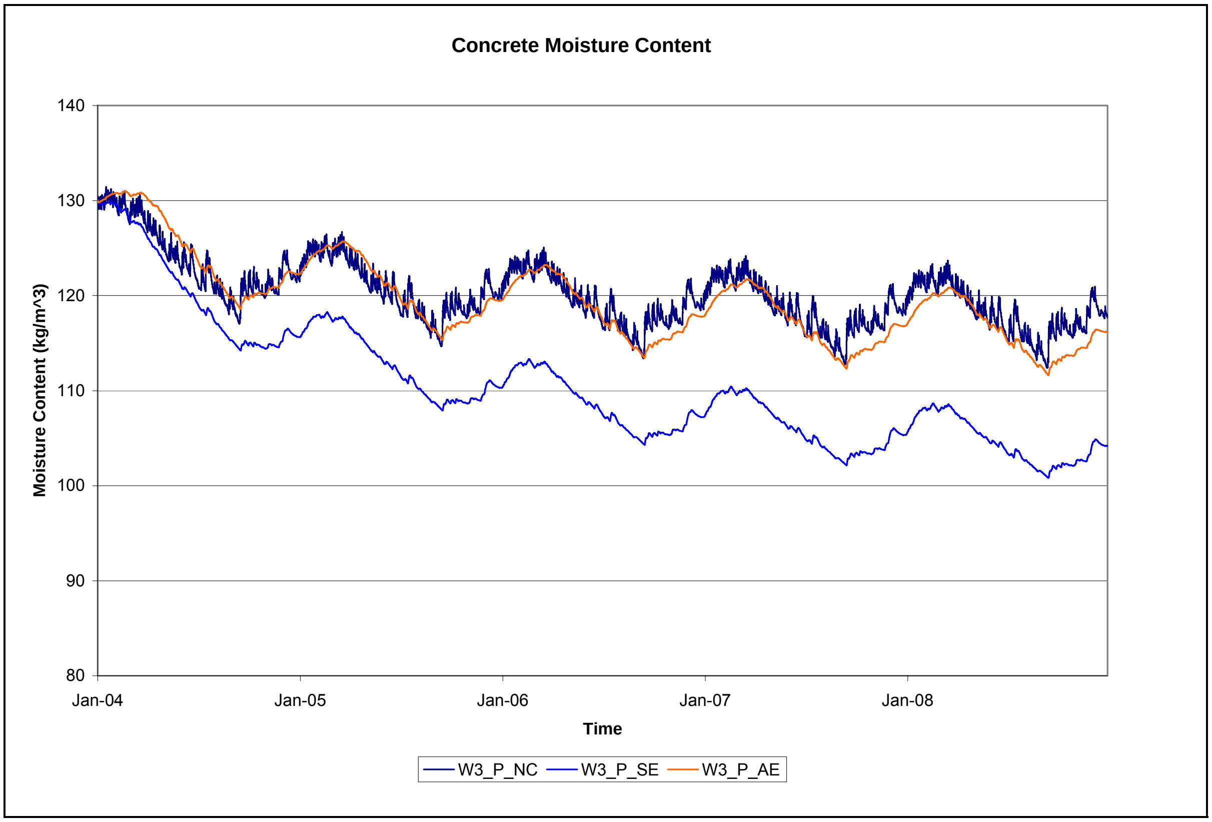


Figure 3.1c: Concrete moisture content for wall W3 with NC, SE and AE exterior coatings. Water content shown in units of kilograms per cubic meter.

As is shown in the figures, all the walls demonstrate an overall drying trend from the initial conditions and approach acceptable concrete moisture content levels. However, the concrete moisture content of the coated walls is generally lower than the moisture content of uncoated walls, indicating that the reduction in rain absorption outweighs the reduction in diffusive drying potential. Note that with the higher permeance silicone coating the concrete moisture content is significantly lower, indicating that it offers the best balance between restricting absorption while allowing drying.

It is clear that the reduction in rainwater absorption is of greater consequence than the reduction in diffusion drying potential to the exterior. The addition of coatings is beneficial not only for limiting water penetration at hairline cracks, but also to maintain lower concrete moisture content levels. Lower concrete moisture contents are important for controlling inward vapour drives during the summertime, which is discussed later in this section.

Because of the 1-D nature of the model, it is not possible to model the additional wetting that might occur at a crack. However, we expect that the results would be similar to that shown in the figures above. Coatings will reduce the drying potential, however their affect on reducing rainwater absorption is of greater consequence.

The RH at the interior surface of the concrete and at the polyethylene is also affected by the application of an exterior coating to the concrete because coatings reduce the overall moisture content of the concrete.

Figure 3.2a presents the effect of exterior coatings on the RH at the interior surface of the concrete for wall W1.

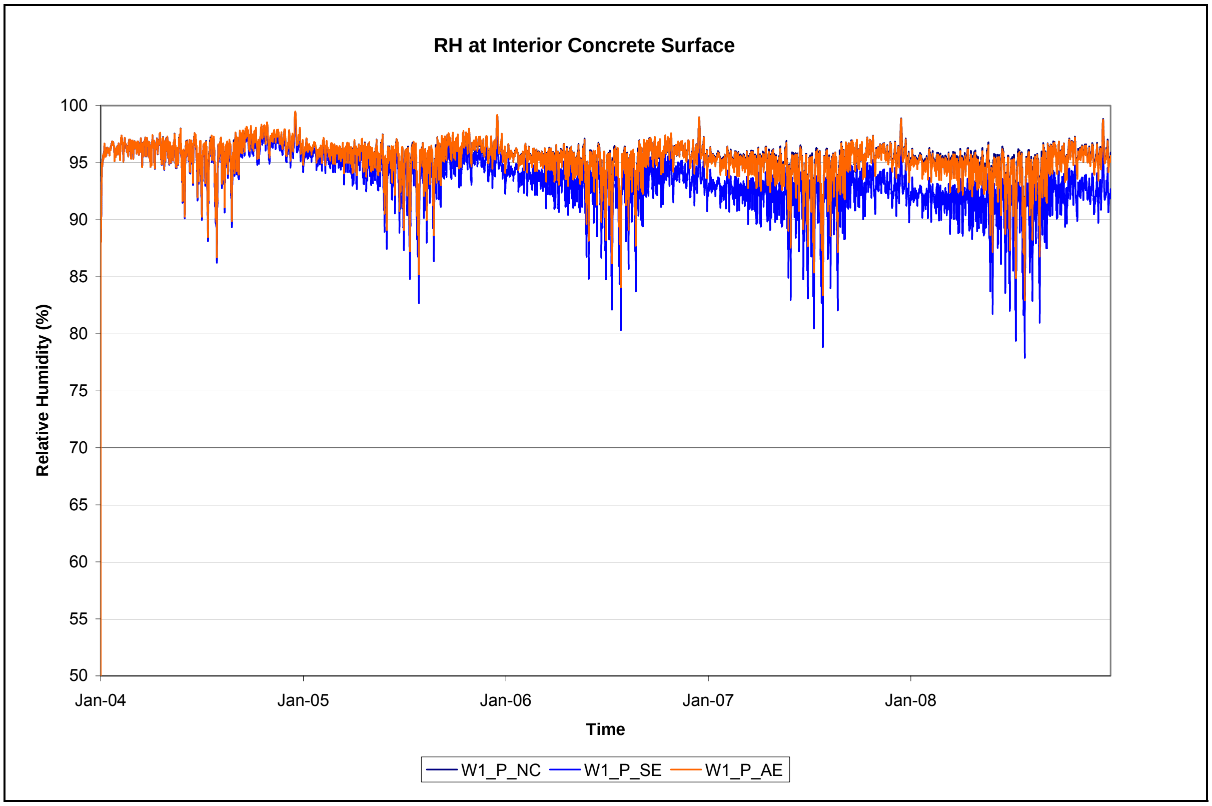


Figure 3.2a: Effect of exterior coatings on RH at interior surface of concrete for wall W1.

Results for the other wall assemblies can be found in Appendix C, however the trends are similar.

Note that the RH remains high throughout the year regardless of the treatment of the exterior concrete surface. However, the RH at the interior surface of the concrete is lower for walls with coatings than those without because of the lower concrete moisture content. Again, the wall simulations are 1-D and therefore do not include the thermal effects of the steel studs. Localized temperatures at the steel studs will be warmer because of their high thermal conductivity and thus the RH at the studs will be lower.

Figure 3.3a presents the effect of exterior coatings on the RH at the polyethylene for W1.

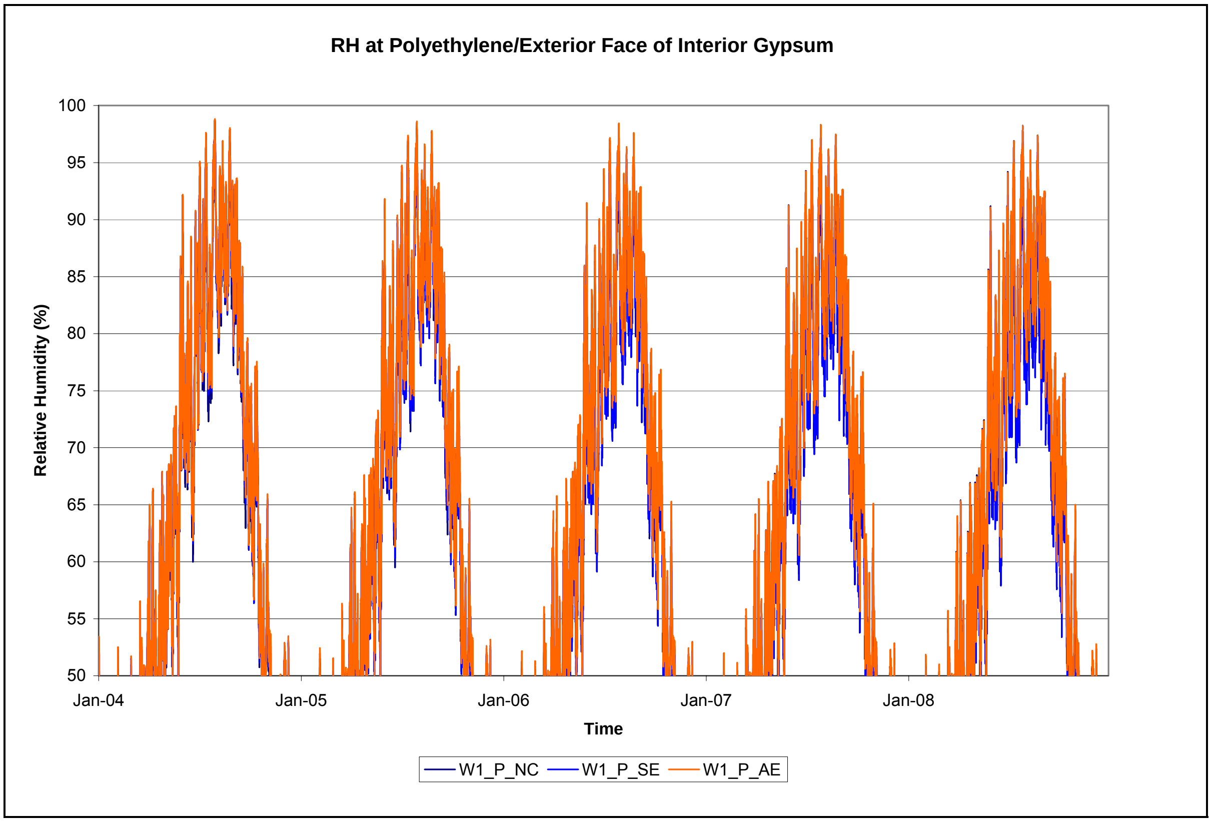


Figure 3.3a: Effect of exterior coatings on RH at the polyethylene layer for wall W1.

Results for the other wall assemblies can be found in Appendix C, however the trends are similar.

Note that the RH spikes over 95% during the summer months for W1 regardless of the treatment of the exterior of the concrete, although the RH at the polyethylene is slightly lower for walls with an exterior coating.

3.2.3 Effect of Polyethylene Vapour Retarder/Barrier

Similar to questions that have been raised regarding exterior coatings, the inclusion of polyethylene vapour retarders has also been questioned. The benefit of polyethylene for vapour diffusion control for walls exposed to the relatively mild climate of the B.C. Lower Mainland is not clear, nor is the reduction of the drying potential towards the interior, which maybe important since the concrete is relatively resistive and thus drying to the exterior is slow at best.

To demonstrate the overall impact of polyethylene vapour retarders on wall performance, the result of the simulations with and without the polyethylene are presented in the following figures. Note that only walls without exterior coatings are shown for clarity. Figures 3.4a, 3.4b, and 3.4c present the concrete moisture content for walls W1, W2 and W3 respectively. Figures 3.4d, 3.4e, and 3.4f present the results for walls W1, W2, and W3 with coatings and are included in Appendix C.

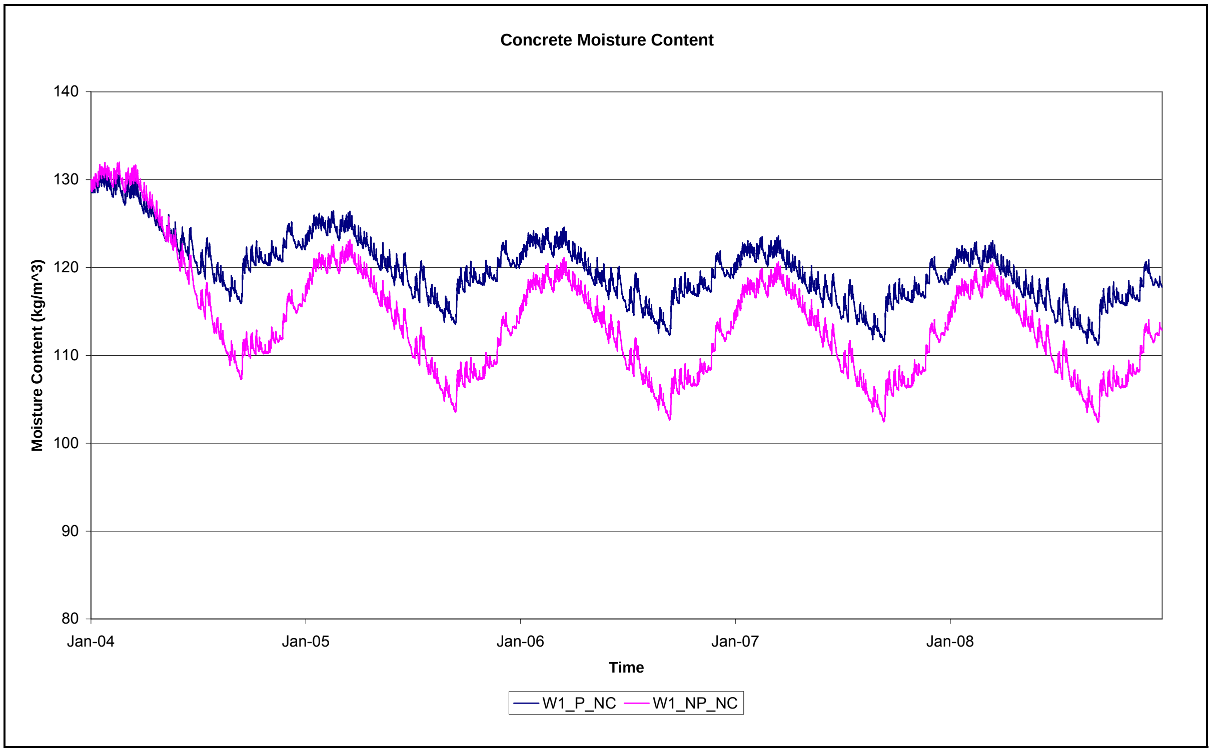


Figure 3.4a: Concrete moisture content for wall W1 with and without polyethylene. Water content shown in units of kilograms per cubic meter.

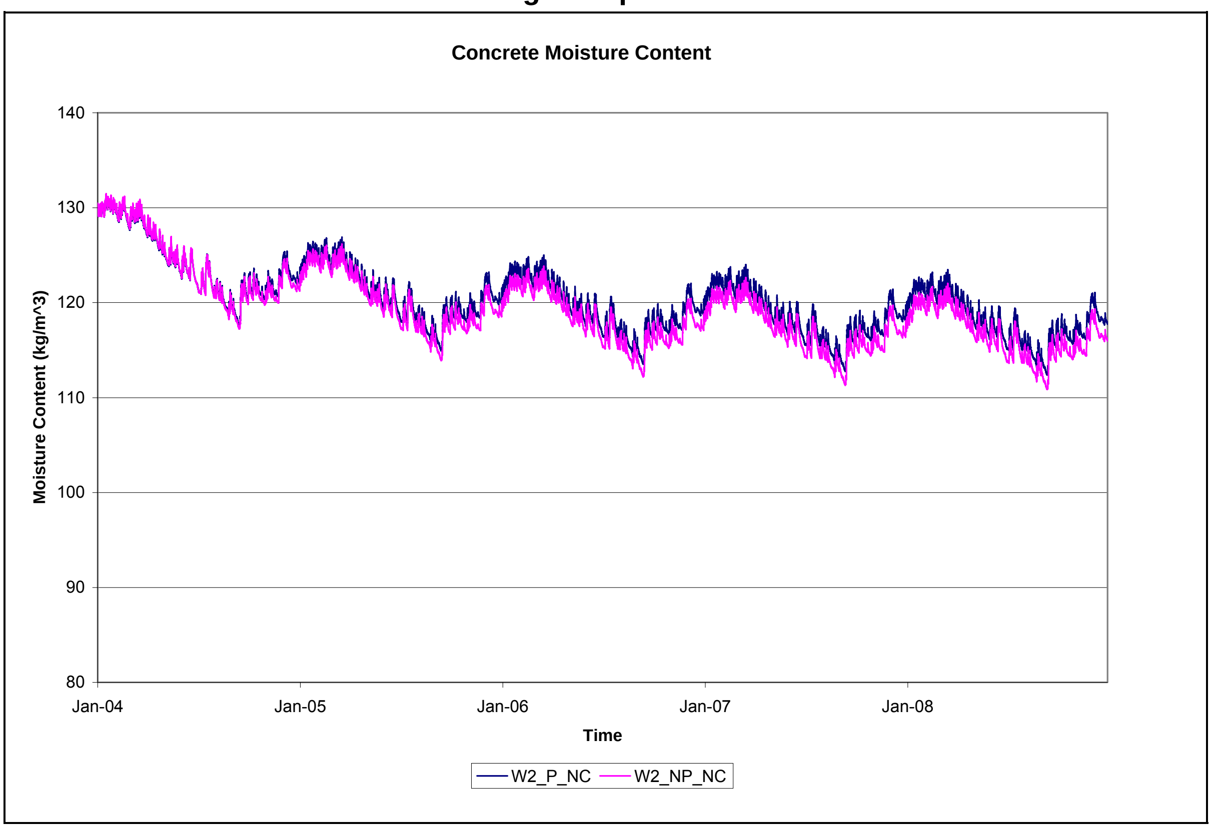


Figure 3.4b: Concrete moisture content for wall W2 with and without polyethylene. Water content shown in units of kilograms per cubic meter.

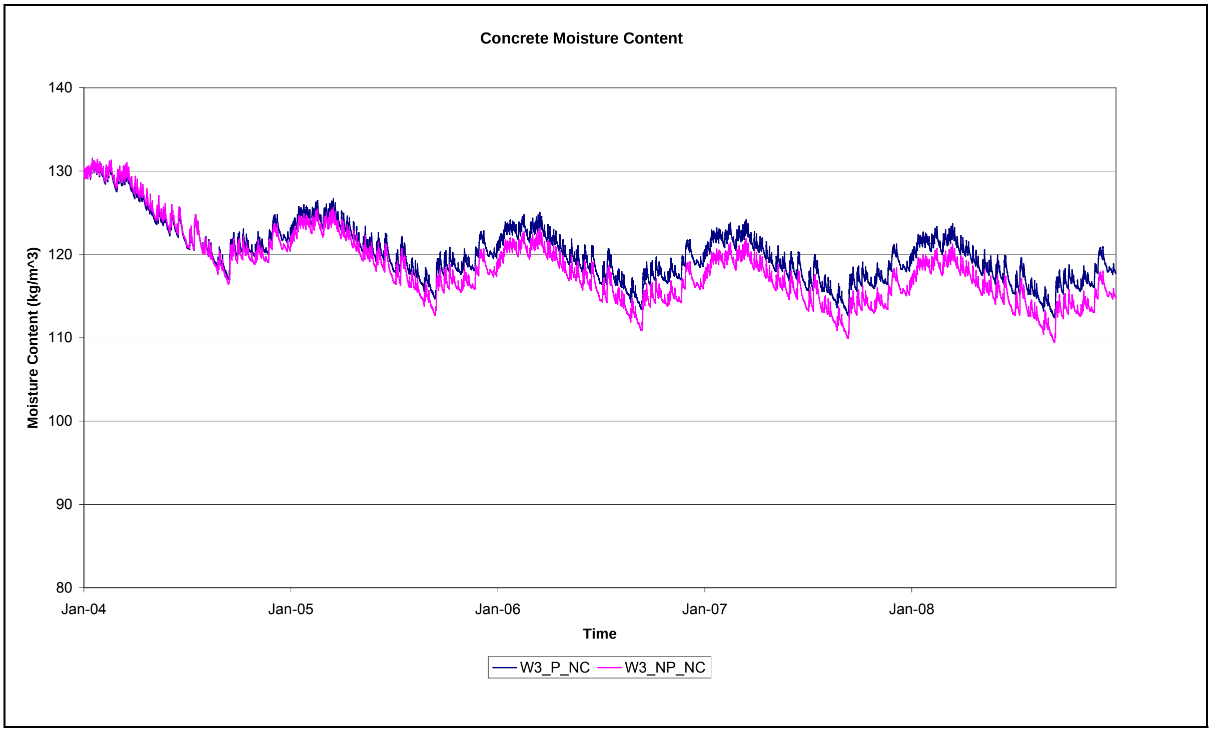


Figure 3.4c: Concrete moisture content for wall W3 with and without polyethylene. Water content shown in units of kilograms per cubic meter.

For wall W1, it is clear that the polyethylene reduces the drying potential of the wall to the interior. Without the polyethylene, the concrete moisture content is much lower for wall W1 because drying to the interior is relatively uninhibited by the batt insulation and the painted interior gypsum board. For walls W2 and W3, the concrete moisture content is lower without the polyethylene, however to a lesser extent because the semi-permeable extruded polystyrene insulation limits drying to the interior.

Walls with coatings (refer to Appendix C) demonstrate the similar performance trends with and without the polyethylene, however concrete moisture contents are generally lower due to the reduced rain absorption associated with the coatings.

Figures 3.5a, 3.5b, and 3.5c present a comparison of the relative humidity at the interior concrete surface for walls W1, W2 and W3 with and without polyethylene. For clarity, only simulations without exterior coatings are shown in Figures 3.5. The results for wall W1, W2 and W3 with coatings are included in Appendix C (Figures 3.5d, 3.5e, 3.5f).

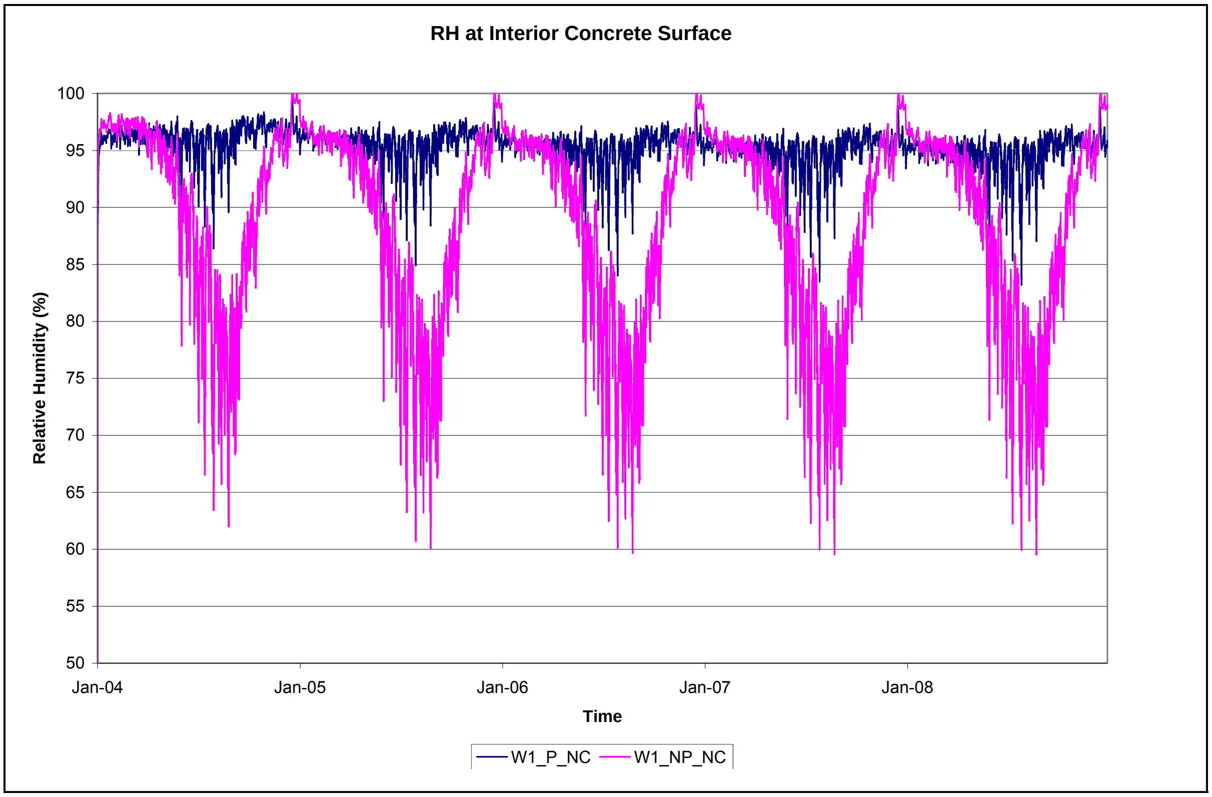


Figure 3.5a: Comparison of RH at interior concrete surface for wall W1 with and without polyethylene.

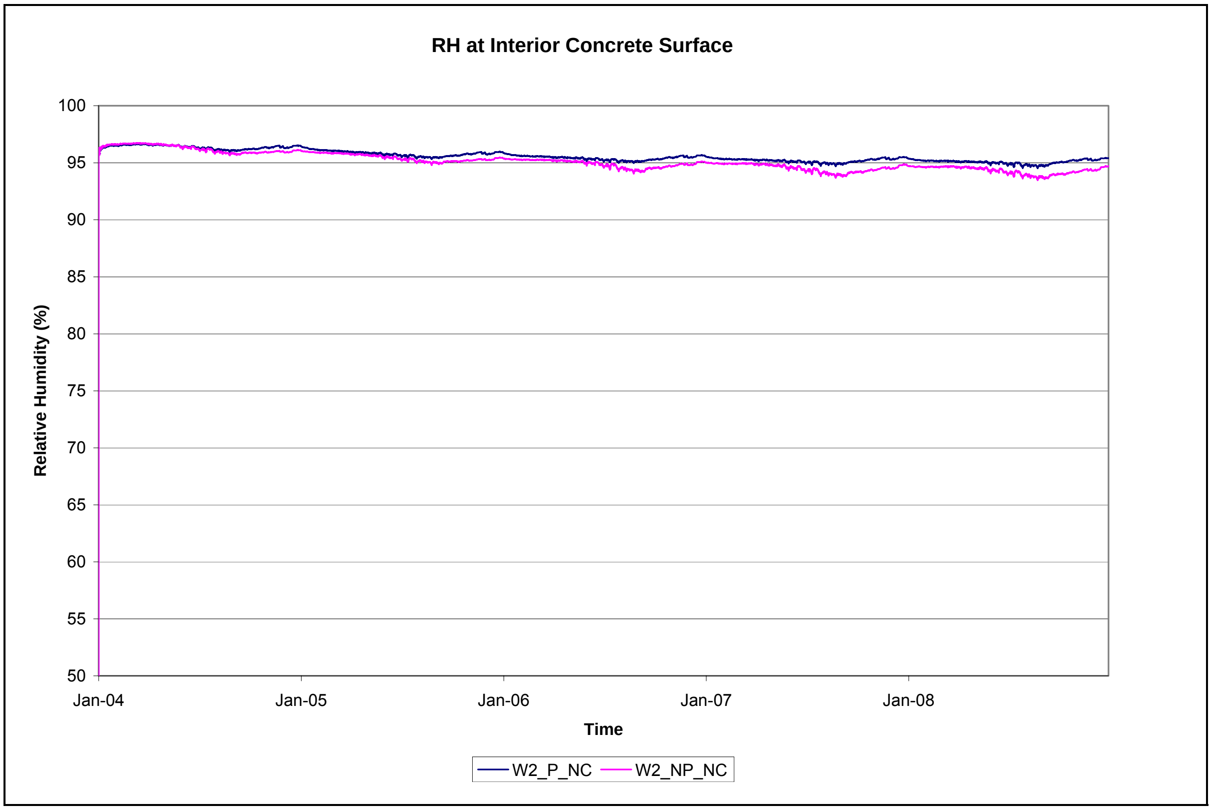


Figure 3.5b: Comparison of RH at interior concrete surface for wall W2 with and without polyethylene.

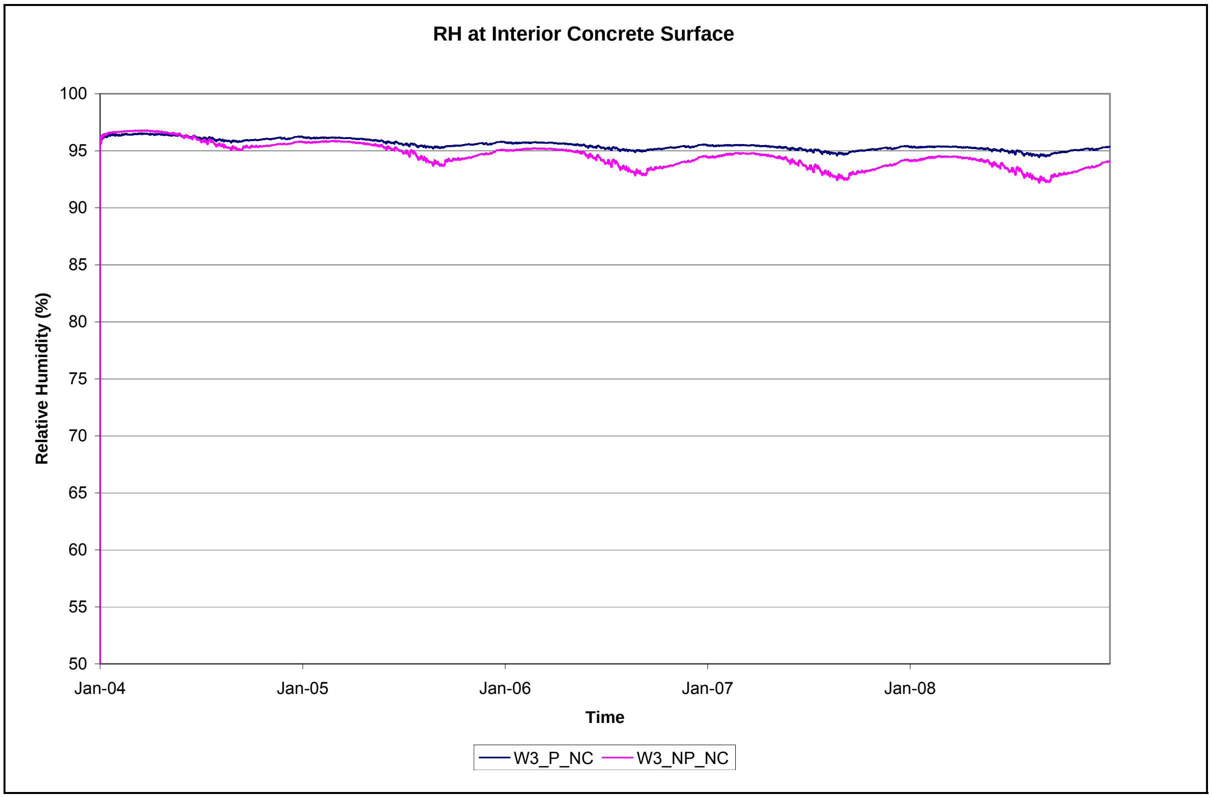


Figure 3.5c: Comparison of RH at interior concrete surface for wall W3 with and without polyethylene.

Not surprisingly, the RH at the interior concrete surface is lower during the summer months for wall W1 without polyethylene. However, during the winter the RH at the interior concrete surface spikes to 100% for wall W1 without polyethylene indicating that condensation forming at this surface is probable during cold spells.

For walls W2 and W3, the relative humidity at the interior concrete surface remains in the 90% range regardless of the exclusion of the polyethylene. The vapour resistance of the extruded polystyrene insulation effectively controls wintertime outward vapour diffusion, rendering the polyethylene redundant for vapour diffusion control. Thus for walls W2 and W3, the polyethylene has negligible effects on the RH at the interior concrete surface.

Note that for all the walls, air leakage reaching the concrete will likely result in condensation during colder periods and thus control of air leakage is important. Also note that the RH values presented represent the conditions between the steel studs. The relative humidity at the studs will be lower than that shown in the figures since the steel studs are highly conductive and thus create thermal bridges, which results in higher (warmer) stud temperatures. In other words, during the winter, the exterior flange of the studs will be warmer than the interior face of the concrete between the studs resulting in lower RH at the studs.

Figures 3.6a, 3.6b, 3.6c present a comparison of the relative humidity at the polyethylene surface or exterior gypsum board surface for walls W1, W2 and W3 with and without polyethylene. For clarity, only simulations without exterior coatings are shown in Figures 3.6. The results for walls W1, W2 and W3 with coatings are included in Appendix C (Figures 3.6d, 3.6e, and 3.6f).

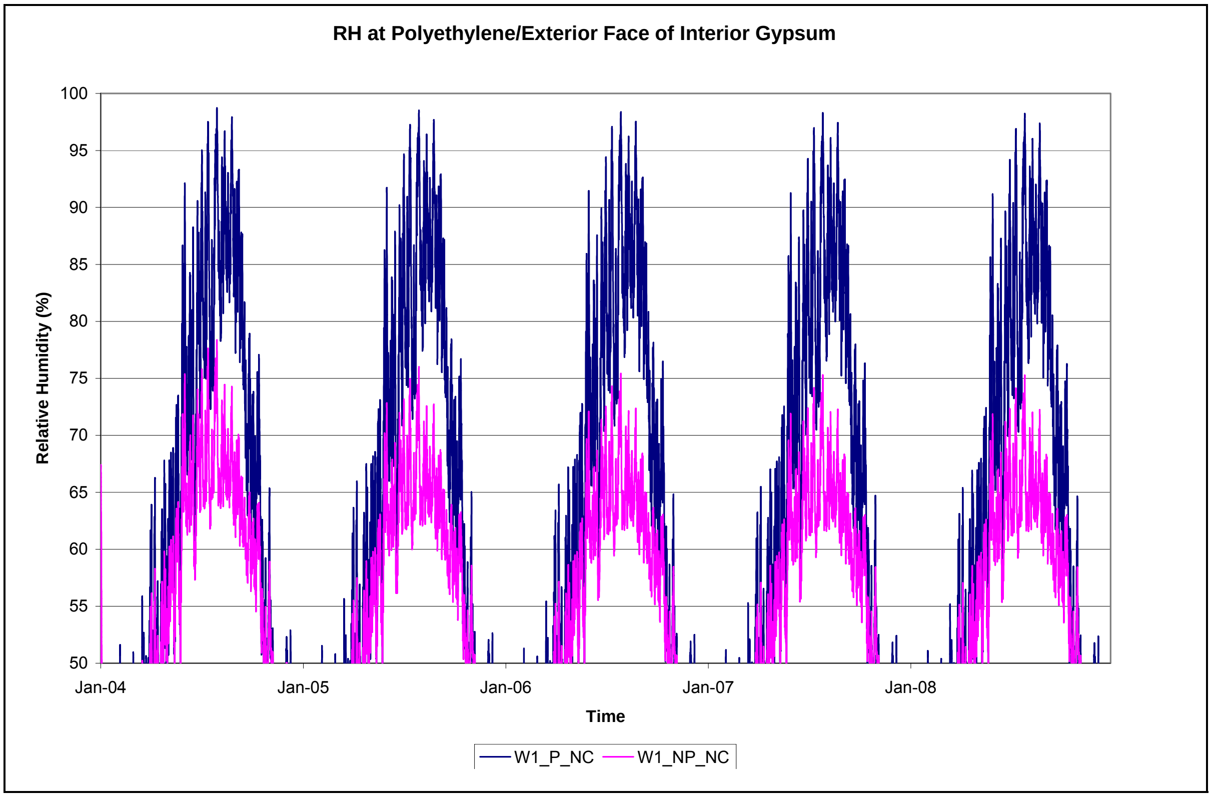


Figure 3.6a: Comparison of RH at polyethylene/exterior gypsum board surface for wall W1 with and without polyethylene.

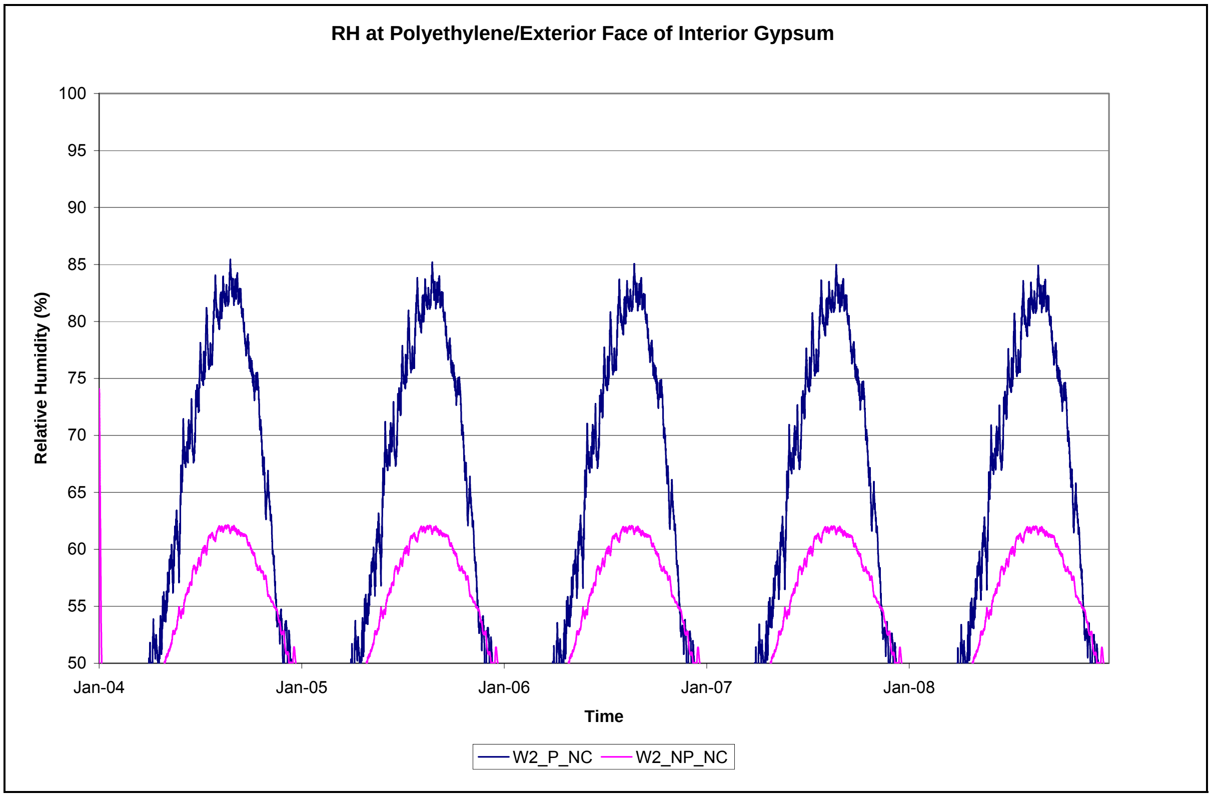


Figure 3.6b: Comparison of RH at polyethylene/exterior gypsum board surface for wall W2 with and without polyethylene.

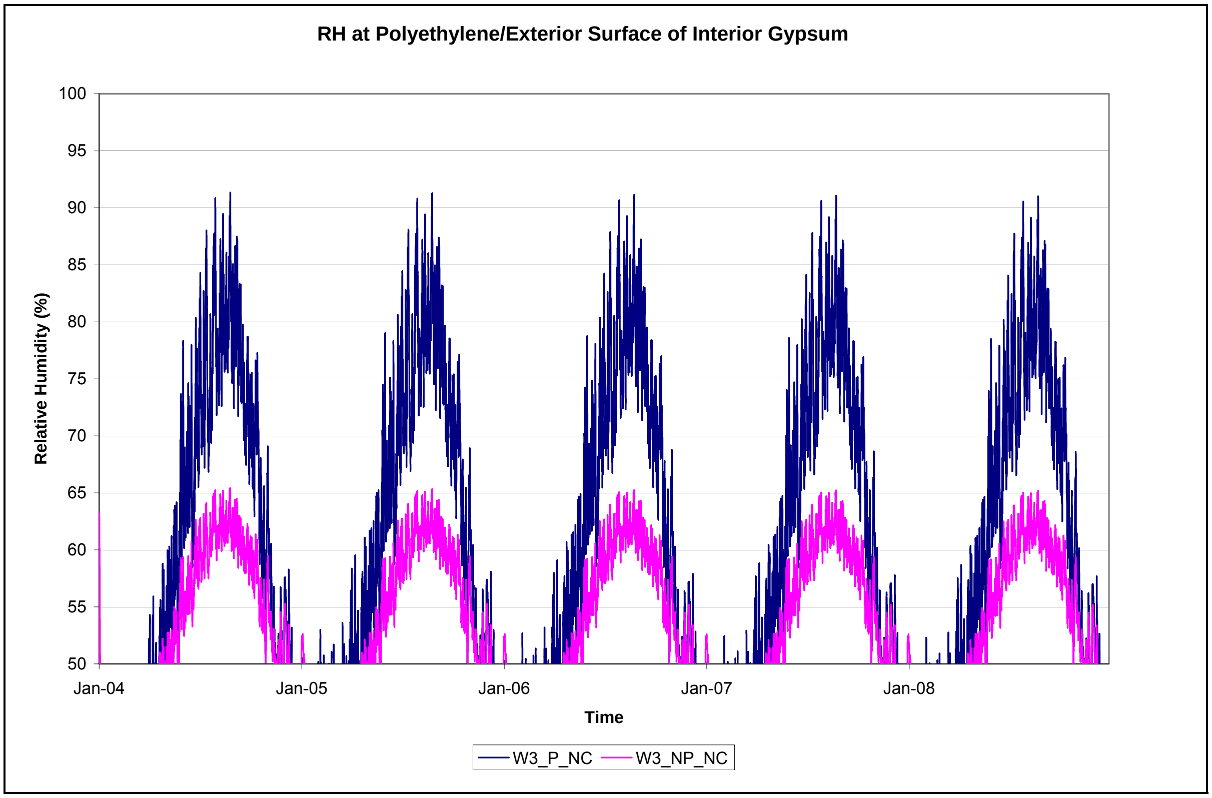


Figure 3.6c: Comparison of RH at polyethylene/exterior gypsum board surface for wall W3 with and without polyethylene.

Without the polyethylene, inward driven moisture is able to pass through the interior wall layers and dry to the interior resulting in much lower RH at the polyethylene layer/exterior surface of the gypsum board. In general, the polyethylene reduces wintertime wetting of the concrete due to vapour diffusion, however it also reduces summertime drying to the interior for all walls.

For wall W1, including polyethylene in the wall assembly has a net reduction of drying potential resulting in higher concrete moisture contents than if the polyethylene is excluded. For wall W1, deleting the polyethylene results in lower concrete moisture content.

Also for wall W1 with polyethylene, the RH at the polyethylene frequently exceeds 90% and for short durations reaches levels upward of 97% during the summer months indicating that there is a potential for condensation to form on the exterior face of the polyethylene. Without the polyethylene, the RH at this surface remains below 80%. Again, these values represent the conditions between the steel studs. The relative humidity at the studs will be lower than that shown in the figures since the steel studs create thermal bridges, which results in higher (warmer) stud temperatures. In other words, during the summer, the interior flange of the studs will be warmer than the polyethylene between the studs, thus the RH will be lower.

For walls W2 and W3, the RH levels are lower without the polyethylene, however even with the polyethylene, RH levels rarely exceed 85% since the vapour resistance of the extruded polystyrene insulation helps to control the summertime inward vapour drives.

In general, the RH in the insulated cavity remains much higher in walls that include the polyethylene because the concrete retains more moisture and the polyethylene resists the diffusion of the water vapour to the interior. High RH can accelerate corrosion of steel components and provide conditions conducive for microbial growth on surfaces that provide a food source. However, what constitutes "high" is subject to some debate, but RH levels over 80% are generally considered high with respect to corrosion of steel and supporting microbial growth. Equally important is the duration of exposure to high RH conditions.

For the conditions modeled, the polyethylene reduces the drying potential to the interior resulting in higher concrete moisture content. In general, hygrothermal performance of all walls improves without the polyethylene. Arguably, W1 requires a semi-permeable vapour retarder (in the range of 57 perms-SI) to control wintertime vapour drives and reduce the potential for condensation forming on the interior face of the concrete. For W2 and W3, the inclusion of the polyethylene has a lesser affect on performance, but wall performance improves without the polyethylene.

Caution must be used in the interpretation of this modeling however. As noted for walls that integrate polystyrene insulation (W2 & W3), the RH levels were generally acceptable throughout the year with or without polyethylene. However, as mentioned in Section 3.1.3 there are other reasons why the inclusion of polyethylene may be beneficial. Most significantly polyethylene effectively limits the inward migration of moisture so that mold growth on the interior gypsum board (next to the occupied space) is less likely to occur. Furthermore, for intentional high humidity interior occupancies located adjacent to exterior walls such as washrooms or steam showers, or unintentionally due to high moisture load generated by occupants, the polyethylene more effectively controls outward vapour drive.

3.2.4 Effect of Insulation Strategy on Hygrothermal Performance

Walls W1, W2, and W3 represent common options available for insulating poured-in-place concrete wall systems. However, these variations in insulation type, location, and R-value also impact hygrothermal performance. Figure 3.7 present the results concrete moisture content of walls W1, W2, and W3 with SE coatings and without polyethylene to compare the hygrothermal performance of the insulation strategies. Walls with SE coatings and without polyethylene represent the walls with the greatest drying potential and thus have been chosen for comparison of the insulation strategies.

With an SE coating and without polyethylene, wall W1 has the greatest wetting potential during the winter and greatest drying potential in the summer. Thus wall W1 has greatest fluctuation in concrete moisture content. Wall W2 has the lowest wetting and drying potential and wall W3 is somewhere between walls W1 and W2 because of the combination of glass fiber and extruded polystyrene insulation.

Considering concrete moisture content, wall W3 demonstrates the best of both worlds scenario, where wintertime wetting is effectively controlled while still allowing some summertime drying to the interior. Lower concrete moisture content is desirable to reduce the quantity of water available to be driven into the insulation cavity and deteriorate insulation and steel components or provide the necessary moisture for mold growth.

Figure 3.8 compares the RH at the interior concrete surface.

With an SE coating and without polyethylene, the RH at the interior concrete surface for wall W1 remains below 80% RH for most of the summer, but increases to over 95% for most of the winter. The RH at the interior concrete surface for wall W2 remains steady in the 90% to 95% range over the course of the 5-year simulation. For wall W3, the RH at the interior concrete surface resides in the 85% to 90% range towards the end of the 5-year simulation. For wall W3, equilibrium is reached in about year 8 with the RH residing in the 85% to 90% range.

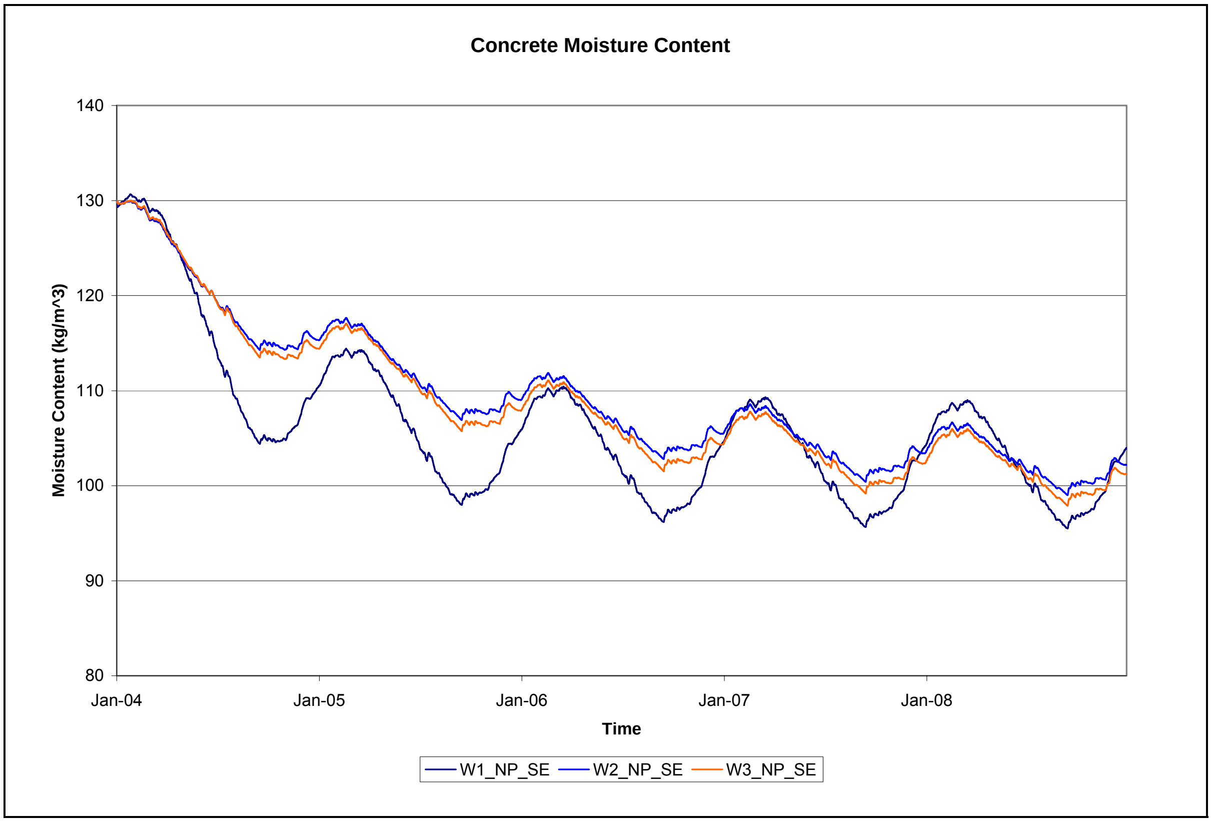


Figure 3.7: Comparison of concrete moisture content for walls W1, W2 and W3 with SE coatings and without polyethylene.

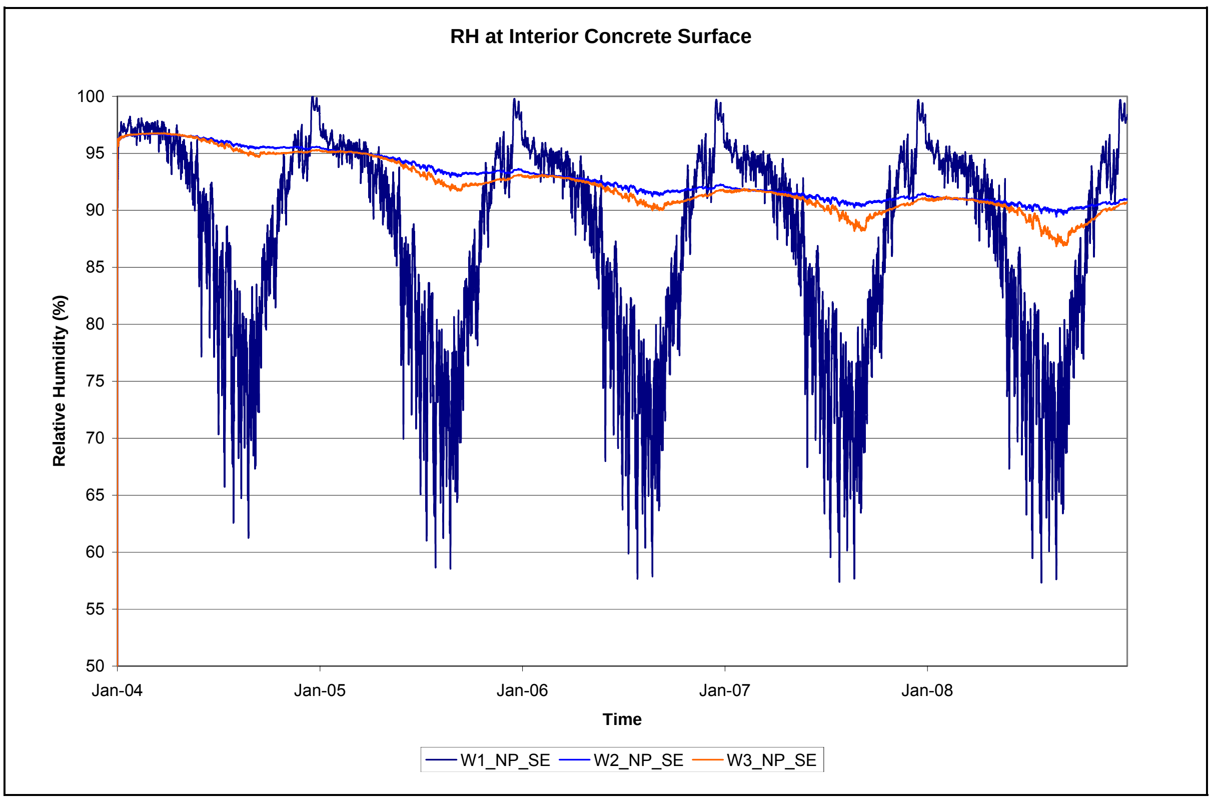


Figure 3.8: Comparison of RH at the interior concrete surface for walls W1, W2 and W3 with SE coatings and without polyethylene.

The consequences of high RH are corrosion of steel and increases risk of mold growth. Similar to concrete moisture content, W3 provides a good balance between allowing some drying while minimizing wetting. Ideally, the XPS insulation would be continuous and not interrupted by steel framing. Thus the steel would be at a more favourable temperature and RH environment.

Figure 3.9 compares the RH at the exterior gypsum sheathing.

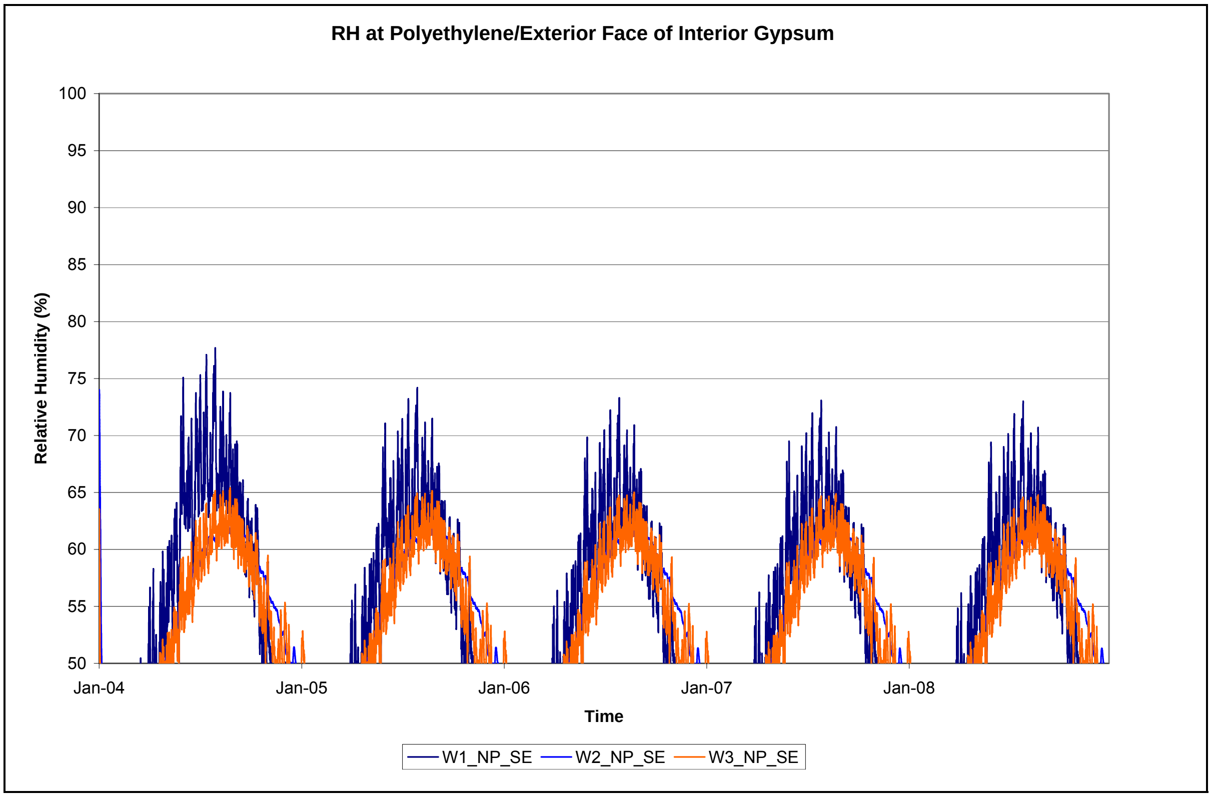


Figure 3.9: Comparison of RH at polyethylene/exterior gypsum board surface for walls W1, W2 and W3 with SE coatings and without polyethylene.

In these cases without polyethylene, the RH at the exterior gypsum surface is in an acceptable range below 80% RH for all three wall systems.

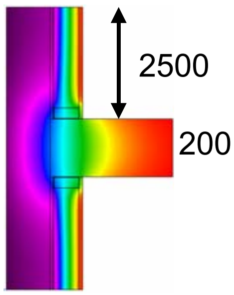
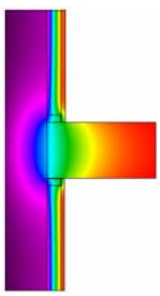
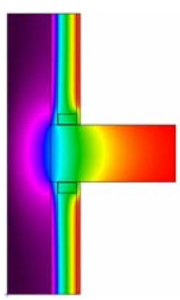
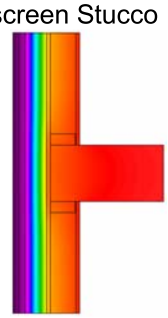
3.3 Thermal performance

Thermal modeling was undertaken to evaluate the overall thermal performance, or R-value of the wall systems and to determine surface temperatures at key thermal bridge locations to evaluate surface condensation potential. THERM 5.2 software, developed by the Lawrence Berkeley Laboratories, was used to perform the thermal simulations. THERM models two-dimensional, steady state heat transfer.

3.3.1 Overall Thermal Resistance

The overall thermal resistance of wall assemblies W1, W2 and W3 are summarized in Table 3.1. The overall thermal performance of a rainscreen stucco wall, which is common in the B.C. Lower Mainland, is also in included in Table 3.1 for comparison purposes. The first column lists the nominal thermal resistance of the individual components of each assembly. The overall R-value listed in Table 3.1 is an area weighted average of the R-values determined using THERM, which accounts for thermal bridging of steel components and of the floor-to-wall intersection.

Table 3.1: Summary of the overall thermal resistance of typical wall assemblies

Wall Assembly	Description	Nominal Thermal Resistance RSI (m^2K/W)	Effective Thermal Resistance (m^2K/W)
W1 	150 mm Concrete 13 mm Airspace 92 mm Batt Insulation (with steel studs @ 400) 0.15 mm Polyethylene Film 13 mm Gypsum Wallboard	Air film 0.03 0.13 0.16 2.10 ----- 0.08 Air film 0.12	1.24
W2 	150 mm Concrete 50 mm Extruded Polystyrene Foam (with 500mm x 25mm T-bar system) 0.15 mm Polyethylene Film 13 mm Gypsum Wallboard	Air film 0.03 0.13 1.72 ----- 0.08 Air film 0.12	1.27
W3 	150 mm Concrete 25 mm Extruded Polystyrene Foam 64 mm Batt Insulation (with steel studs @ 400) 0.15 mm Polyethylene Film 13 mm Gypsum Wallboard	Air film 0.03 0.13 0.86 1.52 ----- 0.08 Air film 0.12	1.44
Rainscreen Stucco 	22 mm Stucco 22 mm Airspace 76 mm Semi Rigid Fibre Insulation (with steel studs @ 400) Waterproofing membrane 13 mm Exterior sheathing 92mm Airspace c/w steel studs 13 mm Gypsum Wallboard	Air film 0.03 0.14 0.21 2.11 0.01 0.08 0.20 0.08 Air film 0.12	1.96

Note that by accounting for thermal bridging using two-dimensional heat transfer analysis, the overall wall R-values are much lower than calculating R-values using nominal values and not accounting for the thermal bridging at the studs and floor slab. For example, an area weighted RSI value using nominal insulation value for wall type W1 is 2.19 m^2K/W. Using the ASHRAE method with an area weighted average incorporating steel studs and slab edge the effective value is 1.7 m^2K/W. Using THERM, the effective RSI-value is 1.24 m^2K/W because the THERM analysis accounts for the two-dimensional heat transfer where the ASHRAE method does not.

When undertaking thermal calculations for poured-in-place concrete walls designers are currently using area weighted nominal insulation values that do not account for two-dimension heat transfer effects. When these values are compared with output from THERM (which accounts for two-dimensional heat flow) it is clear that traditional approaches significantly overestimate the actual thermal performance of these wall types.

Of the poured-in-place walls considered, the thermal resistance of wall W1 is affected the most by thermal bridging of the steel studs, resulting in the lowest overall thermal performance of the wall systems. For walls W2 and W3, the continuous extruded polystyrene insulation resists the thermal bridging effects of the steel studs.

Wall W3 has the highest overall R-value, but also includes the highest nominal R-value of insulation. Considering thermal efficiency, which is defined as the ratio of insulation R-value to the overall R-value, wall W2 has the best thermal efficiency at 1.35 compared to 1.69 and 1.65 for walls W1 and W3 respectively.

To demonstrate the impact of thermal bridging at floor slabs, the figures shown in Table 3.1 are colour isotherms depicting the thermal gradient through the wall sections at the floor slab intersection, corresponding to an exterior temperature of -6°C and an interior temperature of 21°C. Clearly there is significant heat loss that occurs through the floor slab to wall intersection that is avoided when walls are insulated from the exterior. Similarly, it is also desirable to provide a thermal break between the steel framing and the exterior concrete walls to reduce losses through these thermal bridges.

When comparing overall thermal performance, the effects of thermal bridging make poured-in-place concrete walls much less efficient than walls that are continuously insulated from the exterior such as the rainscreen assembly shown in Table 3.1. Note that the thermal efficiency of the stucco clad rainscreen wall is 1.08.

3.3.2 Condensation Potential

One of the main concerns associated with thermal bridging is the potential for condensation to form on interior surfaces during periods of cold exterior temperatures. Typical interior environmental conditions for residential occupancy during the winter in the B.C. Lower Mainland can be expected to be in the range of 20 to 22°C and 40 to 60% relative humidity.

A number of areas where thermal bridging is a concern are identified and modeled under expected winter temperatures to determine the risk of condensation forming on interior surfaces. Detailed results of the thermal modeling conducted is provided in Appendix C.

In general, locations of thermal bridging through the wall areas, including steel stud supports and floor-to-wall intersections, are at low risk of forming condensation. However, there is sufficient surface temperature difference at these areas to cause ‘stud shadowing’, or the accumulation of particulates at cold spots. These particle deposits are also a potential food source for mold growth. The results are discussed briefly in the following sections.

Windows are another area of concern regarding condensation risk since the thermal performance of windows can be adversely affected by the interface with cast-in-place concrete.

3.3.3 Thermal Bridging at Walls and Floors

Providing a thermal break between the concrete wall and the interior finish-framing members reduces the effect of thermal bridging and the potential for stud shadowing to occur. One approach is to insulate along the face of concrete walls continuously using a rigid board type of insulation (wall types W2 and W3). For wall W1, which does not include rigid insulation installed continuously against the concrete, the studs can be installed some distance away from the concrete instead of tight against exterior concrete walls. We conducted thermal analysis of wall W1 with studs in contact with the concrete, and at a distance of 12.5 mm away from the concrete to compare the difference in gypsum surface temperature over the stud location. Also included are the results of placing a 25mm continuous layer of extruded polystyrene insulation between the studs and the concrete. The results are presented in Figure 3.10.

1. Steel studs are in contact with the concrete wall.	2. A 12.5 mm airspace is left between the steel studs and the concrete wall	3. A 25mm layer of extruded polystyrene foam placed between the steel studs and the concrete wall.

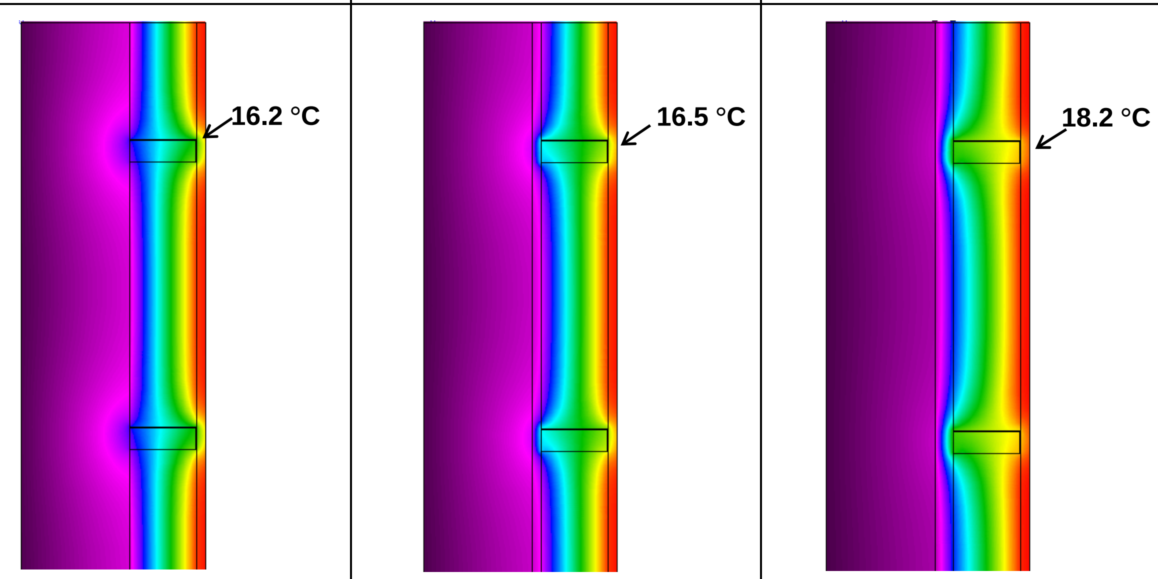


Figure 3.10: Colour isotherms of the temperature profile through a typical poured-in-place wall assembly in plan view. The effect of thermal bridging was compared between walls with and without a thermal break between the interior finish framing and the concrete wall. The simulation was conducted corresponding to an exterior temperature of –6°C and an interior temperature of 21°C. Providing continuous insulation behind the studs reduces the differential surface temperatures at stud areas.

As shown in Figure 3.10, providing an air space between the studs and the concrete provides a marginal improvement. Providing 25mm of XPS insulation provides a significant improvement.

Thermal bridging also occurs at intersections between structural concrete elements with the exterior wall, such as floors and shear/partition walls. A series of thermal simulations were conducted for a partition wall intersecting an exterior concrete wall (Figure 3.11) where the partition wall is not insulated, or insulated for a length of 400 mm or 900 mm towards the interior of the unit. Insulating the partition wall has the benefit of increasing the interior surface temperatures of the interior finish at the corners. However, these types of intersections with the exterior wall are sensitive to the potential for air leakage paths to develop. Although the risk of condensation on the interior finishes is reduced with the interior concrete walls insulated, the temperature of the concrete partition wall behind the finishes is cooler to a greater depth into the interior, increasing the potential for condensation to occur at areas that are sensitive to air leakage. The surface area of concrete that falls below dewpoint temperature increases directly with the depth of insulation along partition walls.

1. Insulation is placed along the exterior wall surfaces only.	2. The partition walls are insulated to a depth of 400 mm (16 inches) towards the interior.	3. The partition walls are insulated to a depth of 914 mm (3 ft) towards the interior.

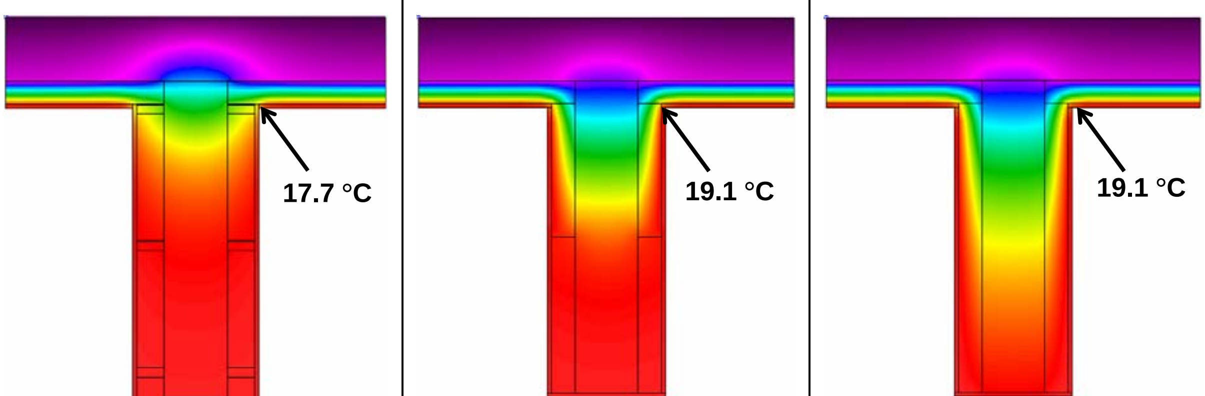


Figure 3.11: Colour isotherms of a concrete partition wall intersecting with an exterior concrete wall in plan view. Various lengths of insulation along the interior of the partition wall are compared to investigate the effects of thermal bridging at these locations and potential remedies. The simulation shown below was conducted corresponding to an exterior temperature of –6°C and an interior temperature of 21°C. Insulating along partition walls to a depth of 400 mm reduces the effect of thermal bridging at these interior corners.

Referring to Figure 3.11, it is clear that providing some insulation along the partition wall will help increase surface temperatures at corners. However, it also introduces the risk associated with having the interior partition wall cavities remaining cooler further into the suite.

The effects of thermal bridging at floor slab to wall intersections was also investigated. Poured-in-place concrete construction frequently incorporates floor slab projections, commonly referred to as 'eyebrows' at each floor level for aesthetics and/or to reduce rain deposition on the walls and windows. The effect of using concrete eyebrows was investigated using thermal modeling. Figure 3.12 presents the temperature profile at the floor to wall intersection for wall W2 with and without an eyebrow.

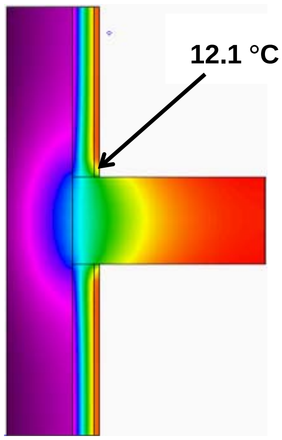
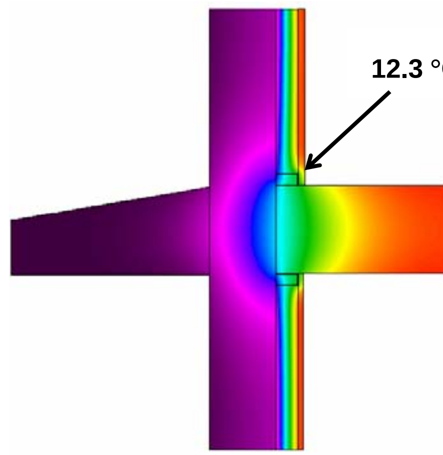
1. Floor slab to wall intersection of W2.	2. Floor slab to wall intersection or W2 incorporating a concrete eyebrow on the exterior side.
	

Figure 3.12: Colour isotherms of a concrete floor slab to wall intersection. The thermal bridging that occurs at these areas generally has greater risk of condensation when compared to the other wall examples described above. However, the increased impact of thermal bridging through concrete eyebrows is negligible in terms of interior surface temperatures. The simulation shown above was conducted corresponding to an exterior temperature of –6°C and an interior temperature of 21°C. For exterior temperatures of –6°C, the interior relative humidity would have to be held below 60% to avoid the formation of condensation at this location. Furnishings of insulating flooring such as carpeting or raised hardwood will lower the surface temperature of the concrete and thus increase the risk of condensation. For example, ¼" of carpet and underlay will reduce the temperature of the concrete to 9.1°C. This corresponds to the dewpoint of interior air of 21°C and 48%RH. Control of the interior operating conditions (temperature, relative humidity through mechanical ventilation) is imperative in managing condensation risk in poured-in-place concrete buildings.

Somewhat surprisingly, it was found that there is little difference in interior surface temperatures when comparing a typical floor slab to wall intersection to one where a concrete eyebrow is placed on the outside. This is likely due to the steady state nature of the simulations. Under dynamic conditions (transient), details with eyebrows are likely to cool off more quickly because of the increased surface areas exposed to the exterior conditions. Also note that it is common to have a floor finish in poured-in-place construction that would raise the interior surface temperatures at these locations but lower the temperature of the concrete thus increasing the risk of concealed condensation.

3.3.4 Thermal Bridging at Windows

Window frames are particularly susceptible to condensation due to the lower thermal resistance of window framing and glazing material. Several factors can affect window thermal performance and condensation resistance including location of the window with respect to the insulation in the surrounding wall, attachment method of window, and depth of recess in the window opening.

Thermal modeling of various depths of window recesses were performed to assess the effect of the window recess on condensation potential. Figure 3.13 presents the interior frame surface temperatures for various configurations of window installation.

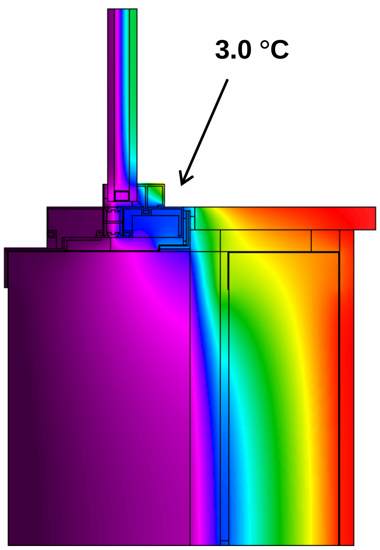
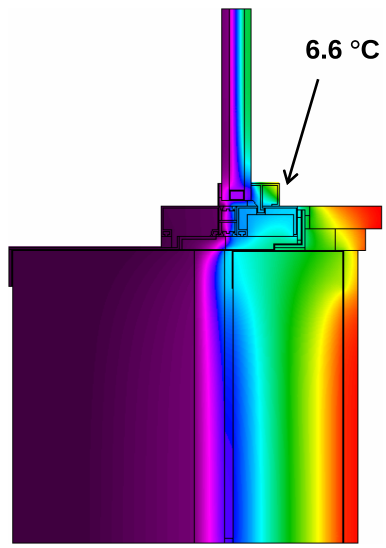
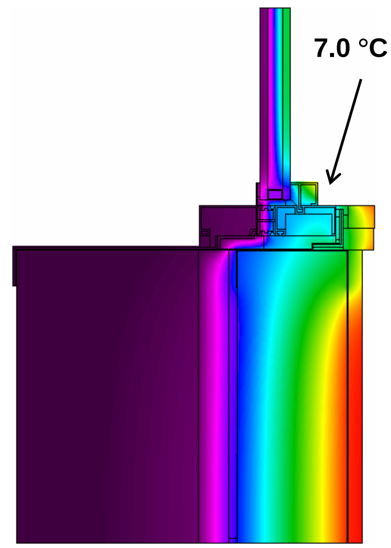
1. Window frame aligned with the concrete wall opening.	2. Window glazing aligned with the exterior side of the insulation within the wall assembly.	3. Window glazing aligned near the center of the insulation within the wall assembly.
		

Figure 3.13: Colour isotherms of various locations for window placement in a concrete opening. The interior frame surface temperature of the window is highly dependent on the depth of recess into the opening and the level of thermal insulation from the concrete surfaces. The simulation was conducted corresponding to an exterior temperature of –6°C and an interior temperature of 21°C.

As depicted in Figure 3.13, the interior frame surface temperature of the window is highly dependent on the depth of recess into the opening and the level of thermal insulation from the concrete surfaces. To reduce heat loss through window framing elements and lessen condensation potential, windows should be aligned with the plane of the insulation. However, the further the window is placed to the interior the more difficult it is to construct adequate interface details (for water penetration control) due to the need to bridge the interior stud wall to the concrete. When the risk of condensation is balanced with the risk of water penetration it often makes sense to align the window with the concrete portion of the wall assembly and find alternate methods for improving condensation resistance.

An alternative solution to increasing the temperature of window frames while maintaining its position within the concrete portion of the wall assembly is to install a conductive element such as a metal angle to transfer heat from the interior to the window frame as shown in Figure 3.14. Installing a 1.2 mm thick aluminum angle so that it is in contact with the window frame and the interior steel studs results in the minimum interior frame temperature being raised approximately 2.3 °C. See Figure 3.14.

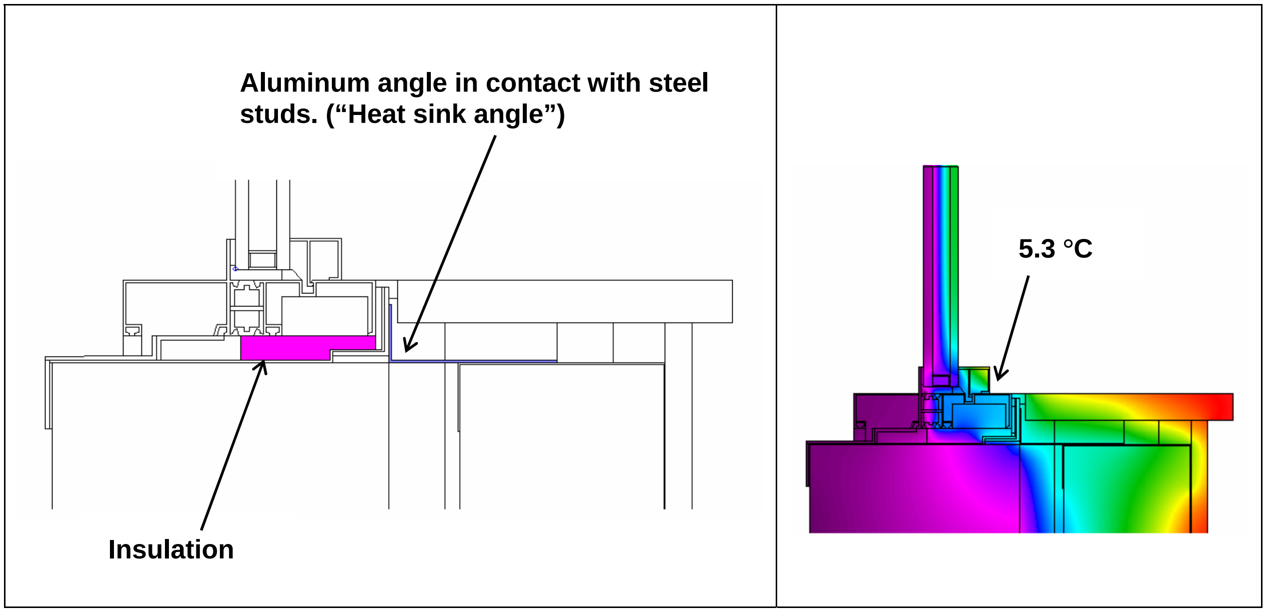


Figure 3.14: Addition of metal angle and insulation to interior of window frame linking to studs

Since the window and the window to wall interface have the coldest surface temperatures they are the critical factor in managing condensation. Condensation must be managed by controlling the interior environmental conditions. The optimum interior operating conditions of temperature and relative humidity are determined to avoid the condition where interior surface temperatures are below the dewpoint of interior air. When comparing a window sill that is aligned with the concrete in the opening to a similar sill configuration that has been fitted with a heat sink angle, it can be seen that there is a greater range of allowable interior operating conditions that will not result in condensation.

For example, if the exterior temperature is -6°C and interior room temperature is 21°C, the interior relative humidity must be kept below 31% in order to avoid condensation on the frame surfaces when the frame is located within the concrete opening. In comparison, recessing the window so that the glazing is just in line with the insulation layer raises the allowable relative humidity for prevention of condensation to approximately 40%. With the window remaining within the concrete opening but with the addition of heat sink angle the allowable RH is raised to 36%. At 0°C outdoor temperatures these relative humidity thresholds increase to approximately 41%, 50% and 46% respectively, an increase of 10% in each case.

Note that minor amounts of condensation are not usually a problem, so that these thresholds can be exceeded periodically without moisture accumulation and resulting damage to wall assembly materials.

3.4 Summary

The hygrothermal and thermal analysis of poured-in-place concrete wall assemblies has helped to establish the relative importance of some variables with respect to performance issues that need to be addressed in the design and construction of these wall assemblies. Table 3.3 summarizes conclusions reached following the analysis of these assemblies.

Table 3.3: Summary of Conclusions

1.	All of the basic wall assemblies analyzed will provide acceptable hygrothermal performance in the absence of defects that introduce water into the assembly. This assumes however, that no materials sensitive to high RH are placed within the wall on the exterior side of the insulation.
2.	Condensation control at windows and slab edges is an issue that requires careful balancing of building envelope assemblies, details and mechanical systems.
3.	Water penetration at cracks and construction joints requires careful detailing and attention to quality control during construction to ensure acceptable performance.
4.	More accurate thermal analysis should be undertaken in order to compare poured-in-place concrete wall assemblies with other wall assemblies.
5.	The net effect of adding a coating to the exterior surface of the concrete to reduce absorption and bridge small cracks is beneficial, particularly silicone elastomeric coatings.
6.	Polyethylene or other interior vapour retarders help control winter wetting in W1 but prevent drying in the summer, making this a higher risk assembly.
7.	The ease at which air movement into wall assembly W1 can reach the concrete surface and potentially condense also makes this wall assembly higher risk.
8.	Wall assembly types W2 & W3 that incorporate polystyrene insulation (XPS) effectively moderates both interior and exterior vapour drives and reduces the potential for condensation due to air leakage into the wall assembly.
9.	Wall type W3 with a silicone elastomeric coating demonstrates the best balance of hygrothermal performance. The presence of polyethylene does not significantly impact the hygrothermal performance and can be deleted from the assembly depending on how reliably interior conditions can be predicted and controlled.

4 PROPERTIES OF CONCRETE AFFECTING PERFORMANCE

Concrete is the common material in all the wall assemblies under consideration for this study. Its behaviour as a material has a profound impact on the performance of the wall assembly as a whole. It is also unlike most other materials in the wall assembly in that it is a mixture of constituent materials that are mixed together at the building site to create a material. The following sections examine concrete design and construction practices as they pertain to the successful performance of the poured-in-place concrete wall assembly.

4.1 The Nature of Concrete

Concrete consists of constituent materials in various proportions as summarized in Table 4.1.

Table 4.1: Constituents of Concrete

Constituent	Proportion	
	Mass	Volume
Sand and Gravel Aggregate:	80 – 85%	70 – 75%
Cementing Materials: (Portland cement, fly ash, ground blast furnace slag)	10 – 15%	7 – 10%
Water	6%	15%
Air	0%	5%
Chemical Admixtures: (Air entrainment, water reduction, workability enhancement, shrinkage reduction)	< 1%	< 1%

From the relative proportions of the constituents of concrete it can be seen that the physical and thermodynamic properties of the material will be influenced predominantly by the aggregate properties, and to a lesser extent by the binder properties. The mixture proportions, which will be discussed in more detail, can significantly affect the permeability of concrete to water and vapour.

Hydration is the process that occurs when Portland cement and other supplementary cementing materials react with water to create hardened concrete. The amount of water normally required to fully hydrate the cementing materials is approximately 26 to 28% by mass of the cementing material. The amount of water normally added to fresh concrete used for structural purposes is in the range of 40 to 60% of the cementing materials. The excess water is required to facilitate mixing, placing, consolidation and finishing. During the hydration process some water combines chemically with the cementing materials, resulting in a slight volume reduction. A larger amount of water is lost to drying and evaporation, which leads to a larger volume reduction known as “drying shrinkage”. This reduction in volume is typically of the order of 0.05 to 0.10%, and occurs over many months. The rate of drying shrinkage diminishes significantly over time, typically being high during the first month and becomes very small after 6 to 12 months. Figure 4.1 shows a typical drying shrinkage curve for structural concrete. Note that the actual amount of shrinkage experienced by a particular structure can vary widely and depends on a number of factors.

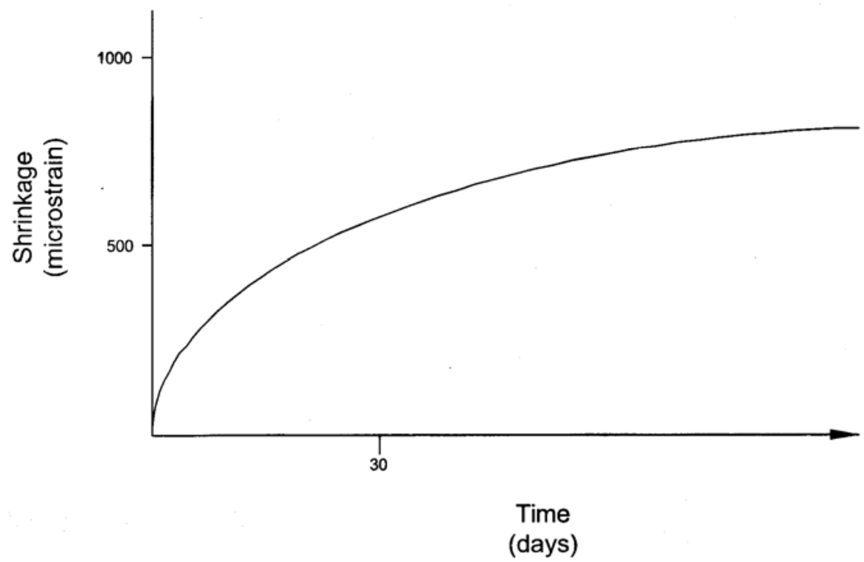


Figure 4.1: Typical Drying Shrinkage Curve for Structural Concrete

As drying shrinkage occurs the concrete will undergo length change in three dimensions. If the length change is restrained, as it usually is in building applications, a tensile stress will occur in the concrete. At such time that the tensile stress exceeds the tensile strength of the concrete a crack will occur. The width and spacing of the cracks will be a function of the amount of shrinkage, the concrete strength, the reinforcing details and the restraint conditions. Further information and discussion of how to predict crack width and spacing can be obtained from ACI 209. [5]

Clearly, cracks will allow moisture and vapour to travel relatively freely through the concrete. The concrete matrix itself will also allow the movement of vapour and moisture. Hardened concrete of the type normally used for building construction is not considered to be "waterproof" in the purely scientific sense, however, for practical purposes the movement of moisture will be negligible unless the concrete is of high permeability and there is a sustained head of water. The movement of vapour through the pore structure of the concrete does occur and can become important in some circumstances.

Hence, for design of structural concrete for building envelope assemblies the properties of interest are volume stability, permeability, resistance to cracking, and thermal conductivity.

4.2 Cracking of Concrete

Cracking of concrete is caused by:

- working stresses which exceed the tensile capacity of the concrete;
- <u>restrained </u>drying shrinkage;
- deterioration processes.

Therefore, success in controlling cracking in concrete requires a combination of sound design and construction practices. The recommended approach is to:

- limit working loads to avoid exceeding the tensile strength;
- eliminate restraint conditions which may lead to cracking;
- reduce drying shrinkage.

Note that the first two requirements are design-related, while the last two are design and construction-related. It should also be noted that at early ages of the concrete the rate of shrinkage is high and the development of tensile and flexural strength are low. Therefore particular attention is required at early ages. Figure 4.2 illustrates the normal development of compressive and tensile strength of concrete.

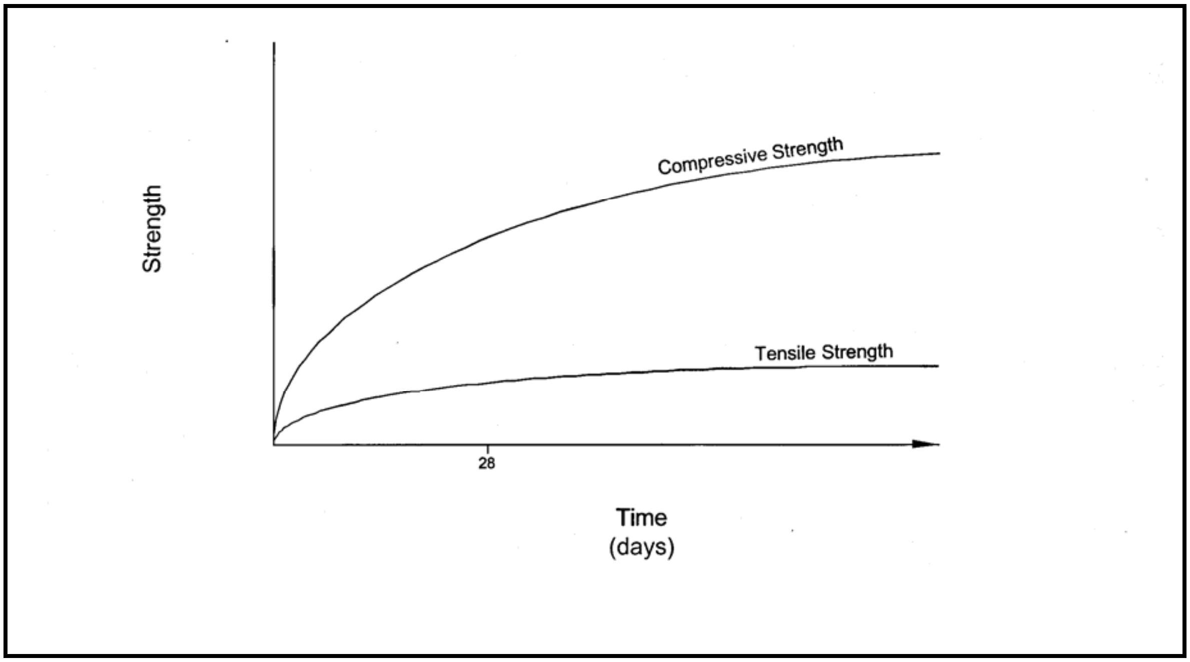


Figure 4.2: Typical Development of Compressive and Tensile Strength

Additional information on crack control can be obtained from ACI 224R [4] and 224.1.[5]

4.3 Thermal Transmisssion Properties

The thermal conductivity of structural concrete is influenced primarily by the aggregate properties, and to a lesser extent by the moisture content of the hardened concrete. The mixture proportions will have a negligible affect on thermal conductivity.

Typical values for thermal conductivity of structural concrete are in the range of 1.5 to 3.0 W/m-K. The actual thermal conductivity of a given concrete mixture cannot be controlled to any significant degree without major changes to the aggregates. Hence, it is usually not practical to attempt to specify or control thermal properties, and published typical values are normally used for design purposes.

For applications requiring lower thermal conductivity, the use of lightweight or semi-lightweight concrete can be considered, for which values as low as 0.3 to 0.5 W/m-K can be achieved. [2]

4.4 Durability of Concrete Walls

Concrete as a material is inherently very durable. The most common form of deterioration to affect structural concrete in buildings is corrosion of the reinforcing steel. Normally concrete is highly alkaline, with pH in the range of 12 to 13. This promotes the formation of a protective oxide on the surface of the reinforcing steel, which will prevent corrosion, even in the presence of moisture and oxygen.

Two processes can act on concrete to break down the protective layer:

- The diffusion of chloride ions, commonly derived from road salt, sea water or some fertilizers. When chlorides diffuse over a long period of time to the level of the reinforcing steel, the protective oxide is destroyed; if moisture and oxygen are available the reinforcing steel will then corrode.
- Atmospheric carbon dioxide will react with the alkaline components of the cement paste, resulting in a reduction in pH at the concrete surface. As CO_2 diffuses into the concrete over a long period the zone of reduced pH advances into the concrete and eventually reaches the level of the reinforcing steel. This process is known as "carbonation". The reduced alkalinity causes the protective oxide on the reinforcing steel to break down and again, the steel will corrode in the presence of moisture and oxygen.

When the steel corrodes the corrosion products that accumulate on the steel surface occupy 5 to 10 times more volume than the original steel. This causes an internal bursting force which eventually causes the concrete to split or delaminate along the plane of the reinforcing steel. As the process advances the structural capacity of the member is reduced.

It is important to note that reinforced concrete exposed to fresh water from rain or groundwater will not deteriorate due to corrosion unless there has been sufficient diffusion of chlorides or carbon dioxide to destroy the passive layer. The concentration of chlorides necessary to initiate and sustain corrosion is approximately 0.03 to 0.05% by total mass of concrete. In the presence of moderate exposure to chlorides this process typically takes 10 to 20 years, but can be less in the case of parking slabs, which see frequent exposure to road salt. The time to onset of corrosion is highly dependent on the thickness and permeability of the cover layer.

The carbonation process also takes many years to develop and depends on the permeability and thickness of the concrete cover layer. The advancement of the carbonation front is roughly proportional to the square root of time. In most areas of Canada concrete buildings exhibit varying depths of carbonation, but the majority have not seen carbonation sufficiently advanced to depassify the rebar. In some cases localized corrosion of rebar in balcony edges and similar locations has been observed, however the majority of buildings less than 20 to 25 years old are not affected by carbonation. Additional information on carbonation in Canadian Buildings can be obtained from "Concrete Carbonation in Canadian Buildings". [13]

4.5 Efflorescence

In some circumstances water will migrate through the pore structure of the concrete, as well as through cracks, joints and penetrations such as form tie holes. As the water migrates it dissolves calcium hydroxide from the hydrated cement paste. When this solution reaches the opposite surface of the concrete it reacts with atmospheric carbon dioxide and the calcium hydroxide is converted to calcium carbonate. Being less soluble in water, the calcium carbonate precipitates on the surface as a white, fluffy powder, or along cracks and joints as a hard, white encrustation. Occasionally, small white stalactites may be formed.

This process is known as efflorescence and is generally not harmful to the concrete in terms of significant loss of strength or durability. It is, however often unsightly and should therefore be prevented by minimizing the migration of water through the concrete.

Water leaking through cracks in parking structures often becomes sufficiently alkaline to damage the paint on vehicles.

4.6 Summary

With appropriate design and construction practices, poured-in-place concrete as an element within the overall wall assembly can provide adequate performance. However, focus on crack control and construction joints by the design and construction team is the critical element in achieving this performance. Failure to take adequate precautions to reduce cracking and prevent leakage at cracks and joints is the most common source of performance problems in poured-in-place concrete wall construction. Table 4.2 provides a summary of the various factors to be considered in providing an effective poured-in-place concrete wall.

Table 4.2 Summary of Considerations for Poured-in-place Concrete as an Element

1.	Permeability of the concrete can be controlled through adequate mix design and quality control during placement.
2.	Control of cracking can be accomplished using a combination of: ▪ Limiting working loads to avoid exceeding the tensile strength of concrete ▪ Eliminating restraint conditions which may lead to cracking ▪ Reducing drying shrinkage of the concrete through good mix design and curing techniques ▪ Appropriate location of control joints

5 CONCLUSIONS & CONSIDERATIONS FOR DESIGN AND CONSTRUCTION

The design and construction of a successful poured-in-place concrete wall assembly is dependent on consideration of number of variables, many of which are discussed in previous chapters of this report. This chapter changes focus from the study and analysis of the variables to providing guidance regarding the various choices that need to be made throughout the design and construction process.

5.1 Design of Wall Assemblies

5.1.1 Performance Objectives and Priorities

The successful long-term performance of a poured-in-place concrete wall clearly involves achieving many performance objectives as are listed (Table 5.1). A combination of initial design, construction, maintenance and renewals activities is needed to achieve these objectives.

Table 5.1 – Principal Requirements and Function of the Building Envelope
(Based on Canadian Building Digest #48, with additions)

• Control heat flow	• Transfer structural loads
• Control air flow	• Be durable
• Control water vapour flow	• Be economical
• Control rain penetration	• Be aesthetically pleasing and marketable
• Control light, solar and other radiation	• Provide privacy and views
• Control noise	• Be constructable
• Control fire and smoke	• Interact with mechanical system
• Provide security	• Be maintainable

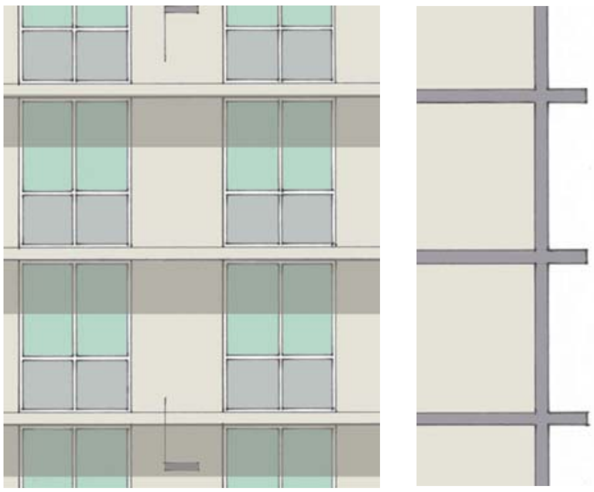
The designer must accommodate all of the functions of the building envelope and develop exterior wall assemblies that meet all requirements and performance criteria. The balancing of these potentially competing objectives is clearly the challenge in the creation of an effective poured-in-place concrete wall. Rain penetration control should be considered a priority performance criterion since achieving this objective is not easy in the BC coastal climate. Many of the other objectives can be achieved in a variety of ways, and relatively easily, once the rain penetration control strategy is defined.

It may be possible to use variations of the techniques, details and materials proposed for the concrete poured-in-place wall assemblies presented in this chapter, provided that appropriate consideration is given to each of the variables affecting performance of the assemblies. Performance testing and/or analysis of new or alternate assemblies are required in the determination of their performance characteristics.

5.1.2 Building Form

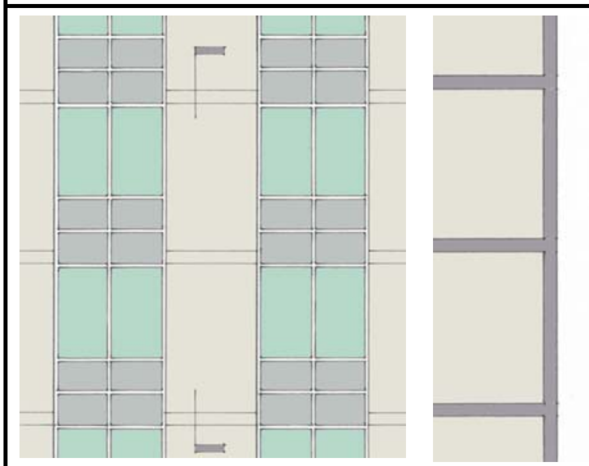
Building form has a profound impact on the risk of water penetration since building form determines the amount of wetting that can occur on a wall, as well as the extent to which problematic details occur. Table 5.2 illustrates how two aspects of building form can impact risk of water penetration.

Table 5.2: Alternate arrangements of projections and poured-in-place concrete wall configurations create differing levels of risk of water penetration



1. Projection, no vertical control joints and structural concrete columns

2. Projection, vertical control joint at window and concrete infill



3. No projection, no vertical control joints, and structural concrete columns

4. No projection, vertical control joint at window and concrete infill

RISK	FORM & DETAILING SCENARIO
LEAST	1. Good overhead protection provided by slab projection. Concrete wall is in compression due to vertical loads and no vertical construction joints used.
	2. Good overhead protection provided by slab projection. Use of upstand wall under window creates vertical control joints and an uncompressed infill concrete element (no significant vertical loads).
	3. No overhead protection. Only exposed concrete occurs between windows and is in compression. No vertical control joints used.
MOST	4. No overhead protection. Use of upstand wall under window creates vertical control joints and uncompressed concrete element.

In summary, part of the design strategy should be to avoid higher risk arrangements that introduce uncompressed construction and control joints such as upstand walls, and to limit the amount of wetting that occurs by using projections, such as eyebrows, at each floor level.

Choices made with respect to building form will affect the dependence of the water penetration control strategy on other design and construction factors such as the quality of the details, or reliance on sealant and coatings.

5.1.3 Rain Penetration Control

Some materials and assemblies are capable of providing effective rain penetration control utilizing a face seal, or perfect barrier, strategy. Examples of this would include glass and total vision systems (TVS) where the use of very durable materials, and simple design provides acceptable long-term performance of what is essentially a face seal assembly with no second line of resistance or redundancy. In practice however, residential buildings dictate the use of more complicated combinations of materials and geometry that limit the ability to achieve acceptable performance with face seal assemblies and interfaces. Even with complicated facades there are exceptions, such as when design elements reduce exposure conditions. For example, consider the control joint configuration as shown in Case 2 of Table 5.2 which is located in a protected environment such as under a balcony or immediately beneath a large floor slab eyebrow projection. It will perform relatively well with respect to water penetration because it is rarely wetted.

A rainscreen water penetration control strategy incorporates redundancy through the provision of a water resistive barrier that is rarely wetted and is therefore more likely to provide acceptable long-term performance.

Poured-in-place concrete walls by their nature are unable to provide redundancy in the same way that rainscreen walls provide redundancy, suggesting a need to find other ways to achieve an acceptable level of risk in environments where the wall is subjected to regular wetting.

For the monolithic concrete wall area the first line of water penetration resistance is the face of the concrete, which is usually made more watertight through the use of a coating. The second line of resistance (or redundancy) is created by the concrete itself, since the concrete has sufficient thickness and mass to restrict the movement of water and to absorb some moisture and dry back to the exterior at some point in the future. For portions of the poured-in-place concrete wall area that are free of cracks and joints, the key variables for effective water penetration control are therefore the properties of the coating applied to the concrete and the characteristics of the concrete matrix.

The real challenge with respect to water penetration control for poured-in-place concrete walls is in achieving effective redundancy at cracks, construction joints, cold joints and control joints in the concrete. At these locations the coating will not bridge any significant crack in a durable manner. Cracks or joints essentially represent a hole through the concrete. Gravity, pressure gradients created by the wind, and capillary forces can all act to drive water through these cracks.

It is generally not possible to eliminate the forces driving water penetration for this type of wall assembly, and therefore the focus has to be on the elimination or sealing of the holes. As a first line of water penetration resistance, design and construction efforts need to reduce the size and frequency of cracking, control the location of cracking and provide a durable seal to the crack where it occurs at the face of the concrete. Redundancy, or the second line of water penetration control at a crack is created through the use of water stop materials and other joint treatments that effectively create a dam so that the water can be absorbed by the concrete and later dry to the outside.

Longer walls will crack and are best designed in a similar manner to precast walls with definite and regularly spaced expansion or control joints in the wall. Infill walls located under windows and poured integrally with the adjacent full height walls will also typically crack under the lower window corners. This should be anticipated by locating an effectively detailed control joint at this location. Some details for joints and cracks, as well as crack control measures are presented and discussed in greater detail later in this chapter.

Due to the lesser certainty in predicting the location of cracks, and variable performance of the waterstop materials, there will always be greater risk of water penetration associated with poured-in-place concrete walls than with most rainscreen wall assemblies.

5.1.4 Air Leakage Control

Primary air tightness is readily achieved in poured-in-place concrete walls by the concrete itself, and by continuity of air tightness at joints and interfaces.

For wall assemblies such as type W1, where an air space exists between the insulated portion of the wall assembly and the poured-in-place concrete, air flow into the cavity can create the potential for condensation to occur (See Figure 5.1). A lack of air tightness within the interior steel stud wall portion of the assembly combined with a driving force to move warm moist interior air into the air space could result in condensation on the inside surface of the concrete.

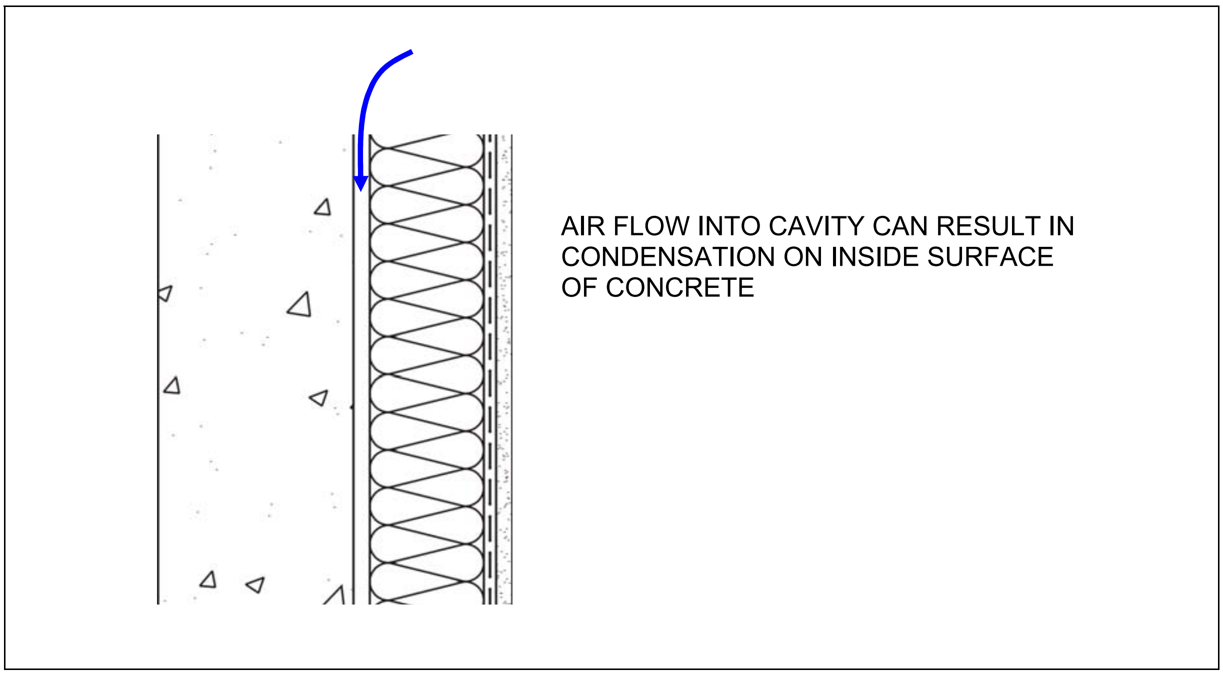


Figure 5.1: Air flow into cavity creates risk of condensation

When using this type of wall assembly care must therefore be taken to limit air flow paths and driving forces into this cavity. Primary paths would include through intersecting partition walls, electrical outlets and other penetrations through the stud wall assembly and possibly through a dropped ceiling assembly.

5.1.5 Vapour Diffusion Control

Hygrothermal modeling of these wall assemblies indicates that vapour diffusion control is important both for inward and outward acting vapour drives. Many of the wall assemblies examined provide acceptable hygrothermal performance. However, walls that incorporate a layer of polystyrene insulation (XPS) or spray-in-place polyurethane foam (wall type W2 & W3) immediately adjacent to the inside surface of the concrete have the least overall risk for condensation moisture problems related to vapour diffusion, air movement and thermal bridging. Not only does this insulation layer provide an effective balance for inward and outward acting vapour drives but it eliminates the potential for air leakage related condensation as discussed in section 5.1.4 and provides a relatively continuous thermal insulation layer within the wall to reduce the impact of the highly conductive steel studs.

Arguably the walls will function well with or without polyethylene within the wall assembly. However, as mentioned in Section 3.1.3 there are other reasons why the inclusion of polyethylene may be beneficial. Most significantly polyethylene effectively limits the inward migration of moisture (due to any source) so that mold growth on the interior gypsum board (next to the occupied space) is less likely to occur. Furthermore, for high humidity interior occupancies located adjacent to exterior walls such as washrooms or steam showers, or unintentionally through occupant mis-use, the polyethylene more effectively controls outward vapour drive.

Clearly, if rain penetrates the poured-in-place concrete to accumulate within the wall assembly then the presence of a low permeability layer such as polyethylene will greatly restrict drying to the interior. However, the quantity of moisture supplied through water penetration through a crack will generally overwhelm the ability of any wall assembly to dry through vapour diffusion.

5.1.6 Thermal Performance

The overall thermal resistance provided by the insulating layers in poured-in-place concrete wall assemblies is reduced by thermal bridging provided by both the steel studs and intersecting concrete walls and floor slabs. Detailed descriptions and values of effective thermal resistance for the three typical wall assemblies, W1, W2 and W3 are summarized in Table 3.1. In a relative sense, significant additional insulation is required to be used in poured-in-place concrete wall assemblies to achieve thermal resistance characteristics similar to exterior insulated rainscreen wall assemblies.

As described in Chapters 2 and 3 of this document, issues such as thermal bridging and condensation risk pose design challenges in poured-in-place walls. It is clearly beneficial to design walls assemblies such that there are thermal breaks between the concrete and other thermally conductive building components such as steel studs and window frames. For example, wall assemblies that incorporate a layer of insulation immediately to the interior of the concrete perform better with respect to thermal bridging and condensation potential. Similarly placing windows so that they contact the interior steel studs or utilize a heat sink angle to the interior of the widow frame keep interior window surfaces warmer and reduce the risk of condensation. See section 3.3.4.

There are also some challenges introduced with respect to mechanical ventilation and heating system designs, particularly those that potentially lower surface temperatures of walls and windows. Newer multi-unit residential buildings are generally being constructed with much improved air-tightness levels than existed in buildings constructed even ten years ago. A higher level of air tightness leads to lower levels of infiltration and exfiltration through the building envelope, thus lessening the amount of natural ventilation. This places greater reliance on mechanical ventilation systems and other outside air sources to control the interior environment generally, and specifically to control humidity levels and the potential for condensation. It is therefore critical that mechanical ventilation systems be designed and constructed to provide adequate quantity and distribution of ventilation air to the suite. In addition, heating systems must adequately control temperatures at the exterior walls to minimize the potential for condensation.

It is therefore essential that the interaction between the mechanical heating and ventilation systems and the building envelope be examined on a project specific basis. In addition to ensuring adequate mechanical ventilation and heating, it may be necessary to specify design provisions to disrupt thermal bridging through wall sections on one hand and then encourage thermal bridging at window frames on the other in order to reduce the risk for condensation at various envelope locations.

5.1.7 Durability

The concrete portion of poured-in-place concrete walls is inherently durable. Even in the presence of prolonged moisture, damage to the concrete can be expected to be minimal in our climate except when corrosion of the reinforcing steel becomes significant. To ensure durable behaviour for exposed concrete however, attention must be paid to mix design, exposure classes and cover to reinforcing steel. Primary guidance on these issues is provided in CSA Standard A23.1 and supplementary guidance is provided in Chapter 4 of this document.

Several materials used to the interior of the concrete are not as durable however, particularly the steel studs and interior gypsum board. If these materials are subjected to regular cycles of wetting then they can be expected to deteriorate and mold can grow or develop on the gypsum board.

Poured-in-place concrete walls have no cladding detachment or secondary support structural issues to contend with as the building ages as compared to wall assemblies that incorporate distinct claddings.

The critical materials from a maintenance and renewals perspective are those that form part of the water shedding surface, specifically the coatings and sealants. Since these materials are fully exposed to the exterior and subject to physical wear, thermal cycling and exposure to UV they are likely to deteriorate over time. Failure of these materials can lead to water penetration to the interior of the concrete portion of the wall assembly and resulting damage.

5.2 Details

As is true for all wall assemblies, the success of poured-in-place concrete wall assembly is only as good as the details that address the various interfaces and penetrations. The details provided in Appendix D are intended to illustrate appropriate responses to some of the key detailing situations that arise in poured-in-place concrete construction. They should be used in conjunction with appropriate assemblies as presented earlier in this chapter. An actual building design would require an analysis of its unique set of conditions since each building has a different combination of interior environment, exterior exposure and desired aesthetics, all of which impact on the design of details.

The following details are provided:

SK1: Horizontal Construction Joints

SK2: Vertical Construction Joints

SK3: Vertical Control Joints

SK4: Typical Membrane Terminations

SK5: Window-Wall Bypass

SK6: Window Sill

SK7: Window Jamb

SK8: Window Head

SK9: Window-Wall Termination At Wall

SK10: Balcony Membrane Termination

SK11: Louvre Penetration

SK12: Fireplace Vent Penetration

5.3 Concrete Design

Key aspects of water penetration control at cracks and joints are:

- Limit working loads to avoid exceeding the tensile strength of concrete
- Eliminate restraint conditions which may lead to cracking
- Reduce drying shrinkage of the concrete
- Where cracking and joints do occur, provide effective waterproofing

This section provides guidance regarding key elements in the design of concrete materials for use in poured-in-place concrete walls that impact the above factors. Some aspects of water penetration control are optimally addressed in the design of the material itself, whereas others are more appropriately addressed in construction practices (Section 5.4).

5.3.1 Specifications

In Canada, CSA Standard A23.1, “Concrete Materials and Methods of Construction” [7] is almost universally incorporated into building code requirements for buildings. This standard sets requirements for constituent materials, mixture designs and construction practices to achieve acceptable performance of concrete for buildings with respect to concrete strength and durability. If the requirements of CSA-A23.1 are followed, acceptable performance will be achieved for almost all building purposes. Extra attention is often required to achieve adequate crack control, durability and permeability for some applications. Extra attention is also required to achieve acceptable performance of joints and penetrations with respect to control of moisture movement.

5.3.2 Permeability Reduction

Water penetration control in poured-in-place concrete wall assemblies relies on the permeability of the concrete to restrict moisture migration through the concrete itself.

The permeability of concrete to water is influenced to a substantial degree by the water cementing materials (w/cm) ratio. For the range of w/cm ratio normally used for structural concrete, permeability coefficient in the range of 1 to 20 x 10^{-12} m/sec is typical.[2]

Specific measures to reduce the permeability of structural concrete are usually not required if the water to cementing materials ratio, w/cm, is less than 0.55. For special purposes, permeability can be further reduced by:

- Reducing w/cm to 0.40 or lower;
- Use of fly ash or ground slag at 20 to 25% of the total cementing material. This has a moderate effect on permeability, especially for mature concrete;
- Use of silica fume at 5 to 8% of the total cementing materials. This amount of silica fume will result in a dramatic reduction in permeability at moderate cost;
- Use of permeability-reducing admixtures. These products are intended to reduce permeability by promoting crystal growth in the pores of the concrete paste or by altering the contact angle between water droplets and the concrete surface. They are used primarily for special purposes, and provide a similar effect to using supplementary cementing materials. Certain products are available as treatment for sealing cracks and joints in hardened concrete.

The most common method of reducing permeability of the surface of the concrete is through the addition of a coating. Since concrete by its nature is porous and minor amounts of moisture are anticipated to exist behind the face, the coating must be able to allow this moisture to dry back to the exterior when conditions permit. The coating must also be able to perform a number of other functions including:

- Remain watertight
- Span cracks
- Be UV resistant
- Resistant to mechanical damage
- Aesthetically attractive
- Be maintainable
- Be renewable
- Be compatible with adjacent sealants and other assemblies

Table 5.4 presents a summary of performance characteristics of several coatings that could be utilized.

Table 5.4: Comparison of Coatings

Property	Acrylic Latex Paint	Acrylic Latex Elastomeric	Silicone Elastomeric
Thickness (mil)	2-3	10-20	10
Crack Bridging	Poor	Good	Excellent
Elasticity	Poor	Good	Excellent
Recoats before complete removal required	5	2-3	5
Water Penetration Resistance	Poor	Good	Excellent
Vapour Permeability	Good	Poor	Excellent
Relative Cost	1	2	2.2
Life Expectancy (Years)	2-5	5	10
Abrasion Resistance	Good	Good	Poor to Good
Surface Preparation/ Ease of Application	Easy	Easy	Difficult
UV Stability	Poor	Poor	Excellent
Ease of Cleaning	Moderately Difficult	Moderately Difficult	Very Difficult

5.3.3 Construction Joints and Control Joints

Construction joints are the natural locations where cracks will occur. A construction joint is formed where there are interruptions in the placement of the concrete and its associated matrix. These construction joints may exist between the concrete slab to wall pours, or between concrete upstand to column pours. Although bonding agents may be used to improve the tensile strength at these locations, it is often prudent to design for the cracks to occur at these locations, thereby reducing the restraint forces on the concrete panels and associated unwanted cracks at random areas that are more difficult to waterproof.

In order to control the cracking, the concrete panel sizes and aspect ratios must be considered in combination with the mix designs and curing procedures. To facilitate larger single concrete pours control joints are used to locally weaken the panel and induce a crack at a particular location are introduced. The use of control joints allows more efficient placement of concrete, while at the same time allows the locations of the cracks to be better controlled. Cracks will tend to occur at the locations of greatest tensile stresses in the concrete. An example of concentrated tensile stress is the corner of a punch window opening where diagonal cracks often form. It is therefore critical that these concentrations in tensile stresses are considered in the locating the cold and control joints.

Construction joints and control joints are the most common sources of water migration through structural concrete walls. The design of joints must be done carefully to achieve the following:

- Adequate spacing of joints to minimize the number and length of joints;
- Appropriate spacing of joints to minimize shrinkage cracking between the joints;
- Appropriate geometry to prevent initiation of cracks; for example re-entrant corners and similar discontinuities should be avoided.

Where migration of water through construction joints is to be prevented, appropriate detailing is required. This includes judicious use of waterstops and other joint sealants to provide two layers of resistance to water leakage.

Form tie locations, pipe runs and similar penetrations are common locations of water movement through concrete. These must also be detailed to reduce water movement.

Table 5.3: Waterstop Comparison

Bentonite Waterstop		**Crystalline Waterstop**	
Bentonite is a type of clay that expands upon contact with water. A bentonite waterstop is typically configured in long strips that are placed along the length of joints (control, construction and cold) between concrete pours. Water that migrates through the joint will cause the waterstop to swell)		Crystalline type waterstops are chemical based products intended to penetrate voids in concrete when in contact with water and help to restrict further movement of water through the void.	
Advantage	**Disadvantage**	**Advantage**	**Disadvantage**
Flexibility Accommodates moving joint Expands quickly	Shrink cycles when dry Must be installed on dry concrete Potential structural design issues in structural concrete Requires priming and typically fastening to secure it to the concrete	Can be installed in dry or wet form to accommodate rain at time of installation Structural engineers allow it for structural walls Is easily installed around tight rebar	Cracks during movement and needs to regrow crystals In moving joint crystal growth will grow with each movement and eventually stop after chemical reaction is expended Crystal growth is slow

Form tie holes, pipe runs, and honeycombed concrete are common locations of water movement through concrete. These should be filled with crystalline grout from the interior and hydraulic cement from the exterior.

All cracks that appear and are greater than hairline in thickness should be routed and sealed like construction joint or have crystalline grout installed from the interior.

Further information on joint design and construction can be obtained from ACI 504R, “Guide to Sealing Joints in Concrete Structures”. [3]

5.3.4 Shrinkage Reduction

Drying shrinkage is caused primarily by loss of water from the concrete after it has hardened. The recommended approach for shrinkage reduction is therefore:

- reduce the amount of water in the fresh concrete mixture (water cement ratio);
- reduce the amount of water lost through drying, especially at early ages when the tensile strength is low.

Options to reduce the amount of mixing water include:

- Use a larger maximum aggregate size and/or a higher proportion of coarse to fine aggregate. This will result in a reduction of total surface area to be coated with cement paste, and therefore a reduction in water demand.
- Use a lower slump, which will also reduce water demand.

Both of these approaches will reduce the workability of the fresh concrete, so the temptation to compensate by adding more water must obviously be avoided.

Additional water reduction can be achieved by:

- The use of fly ash or ground slag to replace or supplement the Portland cement. The fly ash and slag particles are spherical and glassy in nature and therefore impart a lubricating quality to the concrete, and reduce the amount of water required for workability.
- The use of conventional water-reducing and superplasticizing admixtures. These products are now commonly used in practice and are effective in reducing water demand. Superplasticizers can be used to improve the workability of harsh mixtures that have large size and proportion of coarse aggregate.
- The use of shrinkage reducing admixtures. This is a new generation of product and early field trials are promising. They achieve their effect by reducing the surface tension of the pore water, and thereby reduce the internal tension imparted by the menisci of partially-filled pores. These products are relatively expensive and are therefore only used for special purposes.

The importance and effectiveness of adequate curing for crack control and permeability reduction cannot be over-emphasized. To promote effective curing on the construction site, treatment of curing as a separate pay item in contracts has been effective.

5.3.5 Design for Durability

Measures to reduce susceptibility of structural concrete to this form of corrosion are covered in CSA-A23.1, Chapters 14 and 15. They involve:

- use of low w/cm ratio to reduce permeability and the rate of chloride diffusion;
- use of adequate cover thickness on the reinforcing steel to extend the time required for chlorides to reach the steel surface.

For almost all structural concrete used in buildings the requirements of CSA-A23.1 will provide adequate corrosion protection. Additional information on corrosion due to chloride exposure can be obtained in ACI 201.2R, “Guide to Durable Concrete”. [12]

5.4 Construction Practices

Certain construction practices can have a significant effect on the general quality of structural concrete. Highlighted in this section are construction practices that promote the ability of structural concrete to resist the movement of moisture or vapour.

5.4.1 Curing

Proper curing of concrete is the most effective and least used form of reducing permeability and crack control. Curing requirements for structural concrete are given in detail in Chapter 21 of CSA-A23.1 [7] and take the form of either providing external moisture to maintain the concrete surface in a wet condition or applying a membrane-like coating or sealer to the surface to reduce the loss of water by drying. These actions will enhance the hydration of the cementing materials in the surface zone of the concrete, thereby reducing permeability, and will also reduce the loss of water to drying, which will in turn reduce the amount of drying shrinkage. If an elastomeric coating will later be applied to the concrete surface, the curing compound must be compatible with the coating or must be removed before the coating is applied.

The importance and effectiveness of adequate curing for crack control and permeability reduction cannot be over-emphasized. To promote effective curing on the construction site, treatment of curing as a separate pay item in contracts has been effective.

5.4.2 Concrete Placement Methods

Placing of concrete by pumping generally requires a mixture with higher slump and workability than other placement methods. This is often achieved by contractors by adding water, which increases the w/cm ratio and increases shrinkage and permeability. Where low permeability and/or crack control are desired, workability should be enhanced by the use of chemical admixtures rather than by adding water. Other means of concrete placement, such as by crane and bucket, can sometimes be used to avoid the need for additional mixing water.

5.4.3 Restraint

For critical structural elements where crack control is required it is important to reduce restraint, especially at early ages when the tensile strength of the concrete is low. This can be done by releasing forms from the concrete surface as early as possible after the concrete sets. This approach must, of course, be consistent with the structural requirements of the immature concrete. Provisions to address potential cracks due to plastic shrinkage and drying shrinkage are also important.

Unfortunately, even when measures are taken to minimize the amount of drying shrinkage, and to minimize restraint loads that may be imposed on the concrete elements, cracks in the concrete will occur. Concrete assemblies must therefore accommodate some cracking without adversely affecting the performance of the wall.

5.4.4 Construction Joints and Control Joints

Construction joints and control joints are one of the most common sources of water migration through structural concrete. The design of joints must be done carefully to achieve the following:

- adequate spacing of joints to minimize the number and length of joints;
- appropriate spacing of joints to minimize shrinkage cracking between the joints;
- appropriate geometry to prevent initiation of cracks; for example re-entrant corners and similar discontinuities should be avoided.

Where migration of water through construction joints is to be prevented, appropriate detailing is required. This will include:

- Cleaning of debris from the formwork
- proper preparation of joint surface(s) to remove laitance and other contaminants that may interfere with bonding of fresh concrete to the adjacent hardened concrete;
- judicious use of waterstops to reduce leakage;
- design and detailing of joint sealants where appropriate.

Further information on joint design and construction can be obtained from ACI 504R, “Guide to Sealing Joints in Concrete Structures”. [11]

5.4.5 Surface Preparations

In order to facilitate application of coatings to the full exposed concrete surface, the concrete must be prepared. This preparation typically includes sacking of the concrete surfaces to correct imperfections such as bug holes and honeycombing, and to provide a flat even surface on which the coating can bond to. In addition, contaminants such as form release agents or curing compounds are often present necessitating the need for the removal and cleaning of the concrete substrate. Pressure washing or other similar means may achieve this.

5.5 Quality Assurance

Visual examination of the poured-in-place concrete wall during construction will not always identify defects in the construction that ultimately can lead to performance problems. Movement of waterstops during concrete pours, honeycombing, and poorly sealed form tie locations are not easy to detect but can result in water leakage. These types of defects are also difficult to repair after the building is complete because exterior walls of high rise buildings are not easily accessible, exterior finishes may need to be removed and testing to isolate the origin of the leaks is more difficult.

For these reasons it is recommended that all walls be water tested during construction prior to the installation of any materials located to the interior of the concrete, and prior to the application of any coatings or sealant. This latter recommendation for testing prior to application of coatings and sealant means that it is the second line of defense that is being tested (waterstop and the concrete itself). The subsequent application of coatings and sealants will only lessen the risk of water penetration.

Testing of the walls can be done in conjunction with window testing. However it should be noted that testing uncoated walls at the elevated pressure levels that window testing is normally conducted at may be excessive, given the effort and cost involved in preparing a pressure difference across the wall for testing purposes. It is more reasonable to attempt to test all of the wall areas at low or zero pressure difference, and test selected wall areas with a pressure difference in conjunction with the window testing program.

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APPENDIX A

Terminology

APPENDIX B

Case Studies

APPENDIX C

Hygrothermal and Thermal Modeling Results

APPENDIX D

Details

TERMINOLOGY

Many of the technical terms used in this report are defined below. Several of the terms have meanings specific to this report and may not represent the generally accepted definitions used within the construction industry.

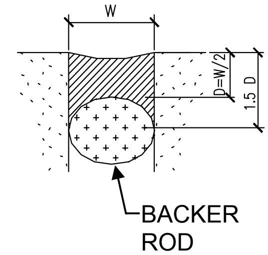
Air Barrier refers to materials and components that together control the flow of air through an assembly and thus limit the potential for water penetration, heat loss and interstitial condensation due to air movement.

Air Space refers to a layer of air within a wall assembly.

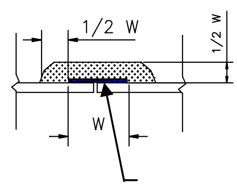
Anchor refers to any device used to secure a building part or component (i.e. window) to adjoining construction or to a supporting member.

Assembly refers to an arrangement of more than one material and/or component to serve specific overall purposes. Together, the collective materials and components comprise the complete cross section of the wall, window or roof.

Backer Rod refers to a round compressible material, either open or closed cell foam, placed into voids between materials to provide a backing for the application of sealant.



Bond Breaker refers to a release type of material used to prevent adhesion of the sealant to the substrate material.



Building Envelope, generally refers to those parts of the building that separate inside conditioned space from unconditioned or outside space, such as windows, doors, walls, roofs, and foundations. Some building envelope elements can be exposed to exterior environmental loads but not separate dissimilar environments (balcony guard walls).

Building Paper refers to asphalt impregnated organic sheet material (breather type sheathing membrane) that creates a water shedding surface behind the cladding.

Butt Joint refers to a meeting of two members squarely.

Capillary refers to void space that exists in the cement paste portion of cured concrete.

Capillarity refers to the movement of water through a network of capillary pores in concrete.

Cladding refers to a material or component of the wall assembly that forms the outer surface and is exposed to the exterior environment.

Cold Joint refers to the visible lineation that is formed when the placement of concrete is delayed. The concrete in place hardens before the concrete adjacent to it is placed leaving a joint between the two areas.

Concealed Barrier refers to a strategy for rain penetration control where the water shedding surface is at different location than the exterior moisture barrier. Discontinuities in the water shedding surface, a poor air barrier, the lack of a air space between the water shedding surface and the exterior moisture barrier, poor pressure equalization characteristics or a combination of these variables results in a more significant amount of water contacting and remaining in contact with the exterior moisture barrier than occurs within a rainscreen assembly.

Concrete is a composite building material comprised of aggregate particles embedded in a paste of cementing materials and water.

Construction Joint refers to the contact area between placed concrete and concrete surfaces, against or upon which new concrete is to adhere. The placed concrete has become rigid enough so that the new concrete cannot be incorporated integrally by vibration with the placed concrete.

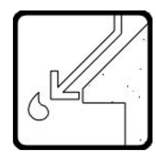
Control Joint is an intentional joint positioned in concrete to encourage cracking due to shrinkage at a specific location.

Cure refers to the method of maintaining environmental factors such as relative humidity and temperature of freshly placed concrete while it sets in order to promote proper hydration of cement and hardening of the concrete.

Damage refers to symptoms of deterioration that have occurred as a result of a particular problem.

Defect refers to the inability of a material or component to meet its normally accepted standard for quality. A defect does not necessarily result in a failure or a problem.

Deflection refers to a water management strategy that utilizes features of the building and assembly geometry to limit the exposure of the assemblies to rain.

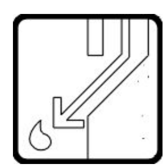


Detail refers to a location within a building envelope assembly where the typical construction is interrupted because it meets a penetration of the assembly or an adjacent assembly. Examples include balcony guardrail connections, dryer and other vent grilles, control joints within a wall assembly.

Dewpoint refers to the temperature at which water vapour in air at a specific temperature condenses.

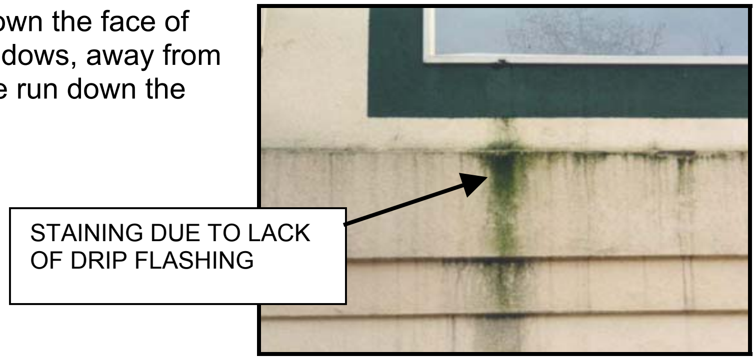
Diffusion refers to the movement of a liquid or gas through a medium in response to a concentration gradient. Using water vapour diffusion through a wall as an example, water vapour moves in the direction from an area of high concentration of water vapour to an area of lower concentration of water vapour.

Drainage refers to a water management strategy that utilizes surfaces of the assemblies to drain water away from the assembly.



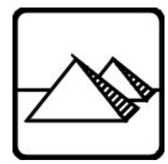
Drained Cavity refers to space behind the water shedding surface (cladding in a wall assembly, or metal and glass in a window) that provides a path for free drainage (provides a capillary break) of bulk water within the assembly.

Drip Flashing directs water flowing down the face of vertical elements, such as walls or windows, away from the surface so that it does not continue run down the surface below the element.



Drying refers to a water management strategy that incorporates features and materials to facilitate diffusion and evaporation of moisture out of an assembly (from materials that get wet within an assembly).

Durability refers to the ability of a material, components, assembly or building to perform its required functions in its service environment over a period of time without maintenance, repair or renewal.



Effective Thermal Resistance Value refers to an improved approximation for the thermal resistance of a building assembly section accounting for the effects of thermal bridging. The effective thermal resistance value is an improved approximation for thermal resistance of a building assembly section in comparison to the nominal thermal resistance value. (See Nominal Thermal Resistance Value).

Efflorescence refers to a crystalline deposit of salts on the surface of concrete that have been leached from lime compounds within the concrete. Typically efflorescence appears white in colour.

Eyebrow refers to a horizontal projection that serves to provide overhead protection to building envelope assemblies below. An Eyebrow is sometimes referred to as a projecting string course.

Exterior Moisture Barrier (also referred to as a water resistive barrier) refers to the surface farthest into an assembly from the exterior that can accommodate some exterior moisture in the form of bulk water without incurring damage to the materials with the assembly or to adjacent materials.

Face Seal refers to a strategy for rain penetration control that relies on the elimination of holes through the cladding or outer surface materials to limit water ingress.

Failure refers to the inability of a material, component, assembly, interface or detail to perform its intended function(s).

Fenestration is the arrangement and proportion of window and door openings in a building.

Flashing refers to materials used to deflect water at interfaces and details within and between assemblies to the exterior.

Formwork refers to the assembly of elements utilized to hold concrete in place when it is being poured and set.

Form Tie refers to the structural fasteners used to hold the formwork in place when the concrete is being poured and set.

Glazing refers to the glass portion of a window.

Hygrothermal refers to the combined effects of moisture and heat transfer through building materials.

Interface refers to a location within the building envelope where two different components or assemblies meet. This could be two different wall assemblies or a wall and a window assembly.

Interior Finish Framing refers to the system of building materials used to structurally support the interior wall finish, typically comprised of wood or steel studs in residential construction.

Isotherm is a contour line depicting areas of the same temperature.

Maintenance refers to a regular process of inspection, minor repairs and replacement of components of the building envelope to maintain a desired level of performance for the intended service life without unforeseen renewal activities. Maintenance activities are typically for items with life cycles of less than one year.

Monolithic refers to the nature of a mass of concrete that has been poured in one piece.

Movement Joint refers to a joint on a wall that provides capability for differential movement of building elements without damage or deformation of the adjacent elements.

Nominal Thermal Resistance Value refers to the composite thermal resistance of a building assembly derived by the summation of individual thermal resistance values for individual components, not accounting for the effects of thermal bridging. (See Effective Thermal Resistance Value).

Operation of the building or the envelope refers to normal functions and use of the building for its intended occupancy.

Penetration refers to an intentional opening through an assembly for ducts, electrical wires, pipes, scuppers, fasteners, etc. to pass through.

Porosity refers to the ratio of the volume of voids in concrete to the total volume of the concrete including the voids, that is usually expressed as a percentage.

Precast Concrete refers to concrete that is cast in a location other than the location of the final position in service.

Pressure Equalized Rainscreen refers to a rainscreen assembly in which additional measures have been taken to reduce pressure differentials across the cladding and therefore further limit water penetration. These measures could include compartmentalization of the exterior drained cavity and optimization of venting arrangement, cavity size, and stiffness of the cladding and air barrier.

Premature Failure refers to the inability of an assembly, interface or detail to perform it's intended function(s) for its expected service life.

Primary Structure refers to structural system that carries the gravity (self weight and live) loads as well as the lateral loads imposed to the foundation.

RSI value refers to the thermal resistance value of a building material, given in units of square meter Kelvin per watt (m^2k/W) in SI

Rainscreen refers to a strategy for rain penetration control where the water shedding surface is at a different location than the exterior moisture barrier and air barrier. The exterior moisture barrier is located to the interior of the water shedding surface and there is an air space between the water shedding surface and the exterior moisture barrier that creates a capillary break. The flow of exterior moisture (rain) through the water shedding surface is effectively minimized and the capillary break facilitates drainage of the minimal water that may be present within the cavities of the assembly. The exterior moisture barrier and air barrier may or may not be at the same location in a rainscreen assembly.

Rehabilitate refers to a program of comprehensive overall improvements to the building envelope assemblies and details so that it can fulfill its originally intended functions.

Relative Humidity refers to the ratio of the amount of water vapour in parcel of air to the maximum amount of water vapour that parcel of air may hold.

Renewals refers to activities associated with the expected replacement of worn out components or materials of a building envelope and are typically for items with life cycles in excess of one year.

Repair refers to replacement or reconstruction of envelope assemblies, components or materials at specific localized areas of the building envelope so that it can fulfill its originally intended functions.

Sealant is an elastomeric material with adhesive qualities used to seal joints or openings against the passage of air and water.

Secondary Structure: refers to the structural support system (framing, clips and fasteners) required to transfer the imposed gravity and lateral loads acting on or through the building envelope to the primary structure. These components typically include the wood or steel studs, exterior sheathing and cladding attachment clips along with associated fasteners.

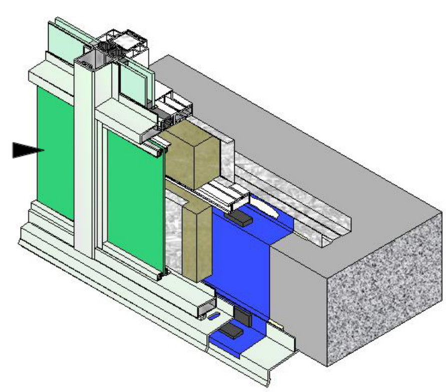
Service Life refers to the actual period of time during which building envelope materials, components, and assemblies perform without unforeseen maintenance and renewals costs.

Sheathing refers to materials (generally gypsum based sheathing or concrete board products for non-combustible construction, plywood or Oriented Strand Board (OSB) for combustible construction) used to provide structural stiffness to the wall framing and to provide structural backing for the cladding and sheathing membranes.

Slab refers to the horizontal concrete building elements, typically floor or roof elements.

Slump refers to a measure that is commonly used in the field to indicate the consistency of plastic concrete that is about to be poured in place.

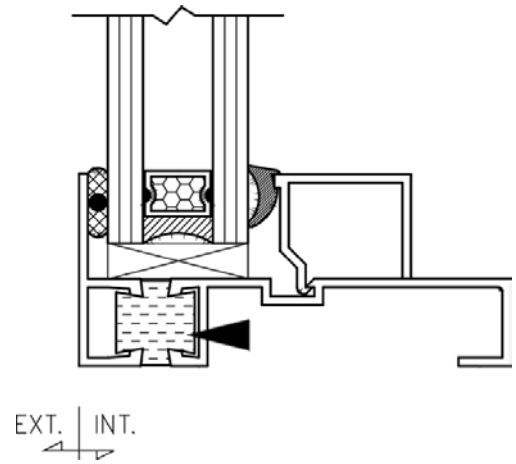
Spandrel refers to opaque glazing material most often used to conceal building elements (typically at floors, ceilings, plenums, or at columns).



Structural Concrete refers to concrete building components that are designed to be load bearing.

System describes a combination of materials and components that perform a particular function such as an air barrier system, or exterior moisture barrier system.

Thermal Break refers to a low heat-conducting layer between the interior and exterior portions of a metal window frame to reduce heat flow and decrease condensation potential.



Thermal Bridging refers to the transfer of heat through wall envelope elements that have relatively low thermal resistance in comparison to adjacent materials providing a pathway where higher degrees of heat flow.

Thermal Conductivity (U-Value) refers to the measure used to describe the conductive heat transmission property of a material or assembly of materials, expressed as a rate of heat flux through a material corresponding to a unit difference in temperature across the material.

Thermal Resistance (RSI-Value) refers to the measure used to describe the conductive resistance to conductive heat transmission of a material or assembly of materials, expressed as the inverse of the rate of heat flux through a material corresponding to a unit difference in temperature across the material.

Through-wall Flashing refers to a waterproof membrane or metal flashing placed under segmented precast concrete, stone masonry or brick copings to prevent water from entering the wall at joints in the coping. Through wall flashing is also used to prevent capillary transfer of moisture through porous materials such as concrete or masonry if they extend from high moisture locations such as below grade.

Form Tie Location refers to the area where structural anchors are used to hold concrete formwork in place. Form ties penetrate through the section of concrete that is being poured and are left embedded within. .

Up-stand Wall refers to a type of concrete wall that is less than the floor to ceiling height. Upstand walls are not load bearing and typically support windows above.

Vapour Barrier refers to material(s) with low vapour permeability that are located within the assembly to control the flow of vapour through the wall assembly and limit the potential for condensation due to diffusion.

Vapour Pressure is the quantity of pressure exerted by moisture in air.

Vapour Drive refers to the vapour pressure difference between the interior and exterior sides of the building envelope.

Waterstop refers to a type of construction material used to prevent the transfer of liquid through a joint in concrete construction.

Water Cementing Material Ratio (w/cm) – the ratio of the amount of water to the amount of cementing materials in a freshly mixed batch of concrete, reported as a decimal. The amount of the water and cementing materials used in the w/cm is by mass.

Water Vapour Permeance refers to the rate of water vapour diffusion through a material.

Water Shedding Surface refers to the surface of assemblies, interfaces and details that deflect and/or drain the majority of exterior moisture impacting on the façade in the form of liquid water.

Case Study 1

Background

AGE: Under Construction

HEIGHT: 8-40 stories

OCCUPANCY: Residential

WALL CONSTRUCTION

- elastomeric paint (not installed at time of testing)
- cast in place concrete
- 25mm polystyrene insulation with T stud system or steel studs/batt insulation
- poly vapour retarder or vapour retarding primer on gypsum board
- gypsum board
- interior paint

This case study is a compilation of information gained during the construction phase of four high rise residential buildings all utilizing similar poured-in-place concrete wall designs. All four towers have similar design strategies and exterior assemblies. The wall assemblies that are common to each of the buildings in this case study are comprised of poured-in-place infill walls, rainscreen windows installed into concrete openings, and rainscreen window wall assemblies.

Photo 1 – Typical Elevation Showing the Mix Between the Concrete and the Windows

Problems

During the initial construction phase of a new high-rise building, typical wall assembly areas are tested for resistance to water penetration. The walls of each of the four buildings in this case study were tested in general conformance with ASTM E1105-00 under a minimum 500 Pa differential pressure across the envelope. During the testing all of the four buildings leaked water to the interior through cold joints, tie holes and cracks in the concrete. Similar leaks were observed during periods of rain that occurred shortly after the installation of the first few floors of windows. All testing and observations were made prior to the completion of the exterior (water shedding) sealant and elastomeric coating application. The primary (exterior moisture barrier) sealant was complete at all interfaces.

Photo 2 – Water Leakage During ASTM E 1105-00 Test at Cold Joint Between Column and Window Upstand Wall

Photo 3 – Water Leakage During Rain Event Through Patched Formwork Tie-Hole

At crack or joint locations these types of wall assemblies cannot rely on the exterior sealants or coatings to provide adequate water penetration control performance. The crack or joint essentially represents a hole through the concrete that allows water to migrate through to a second line of water penetration control created by water stop materials and other joint treatments. It is therefore reasonable that testing be conducted without the sealants and coatings in place.

Remediation

Various testing procedures were used to identify the leakage areas; ASTM E 1105-00, AAMA 501.2-94, and general wetting of the building using a soaking hose without pressure differential. The results of the testing identified the following infiltration paths for this type of construction:

- through cracks at the cold joints (Photo 2)
- through cracks at control joints
- through the formwork tie holes (Photo 3)
- through honeycombed sections of concrete

In most cases water leakage accumulated on the floor during water testing.

Photo 4 – Crystalline Dry Pack Grout Installed in Newly Chipped Interior Reglet

Concealed cold and control joints in the concrete that have not been treated with water-stops could be the source of leaks to the interior of the wall assembly that could go unnoticed for prolonged periods of time. Damages to the wall assembly will not be detected until they affect interior finishes.

The following remedial strategy was incorporated:

- Reglets were chipped at all cold and control joints from the interior and were filled with crystalline concrete waterproofing dry pack grout (Photo 4)
- Tie holes and honeycombed concrete were chipped out and re-patched with crystalline dry pack grout
- Additional fasteners for bentonite waterstops were added to resist movement during concrete pours (Photo 5)

While this remedial work was successful in stopping the leakage, the repairs were very sensitive to the applicator's quality control and environmental conditions. In various locations the remedial work was repeated several times before it was effective.

Conclusions

- Cracking in concrete provides a path that allows bulk water entry into the wall with the potential for penetration to the interior. This cracking occurs primarily at the interfaces between structural columns and infill non-vertically load bearing elements.
- Leakage through the concrete portion of poured-in-place concrete wall assemblies is difficult to investigate and repair, particularly if cracks are active.
- The use of water-stops at concrete cold and control joints is necessary to provide a continuous secondary moisture barrier. Installation of both crystalline and bentonite waterstop systems is difficult due to conditions limitations of installation encountered during concrete placement. Both systems are sensitive to rain during application. Crystalline waterstops require moist curing in hot and dry weather and the effectiveness of bentonite water-stops deteriorate if exposed to rain prior to applying concrete cover. A high level of quality control is required to ensure effectiveness of the details.
- Testing is recommended for all concrete surfaces prior to the application of coatings and sealants

Case Study 2

Background

AGE: 5 years

HEIGHT: 3 stories

OCCUPANCY: office use

WALL CONSTRUCTION

- elastomeric paint
- cast in place concrete
- steel studs/batt insulation
- poly vapour retarder
- gypsum board
- interior paint

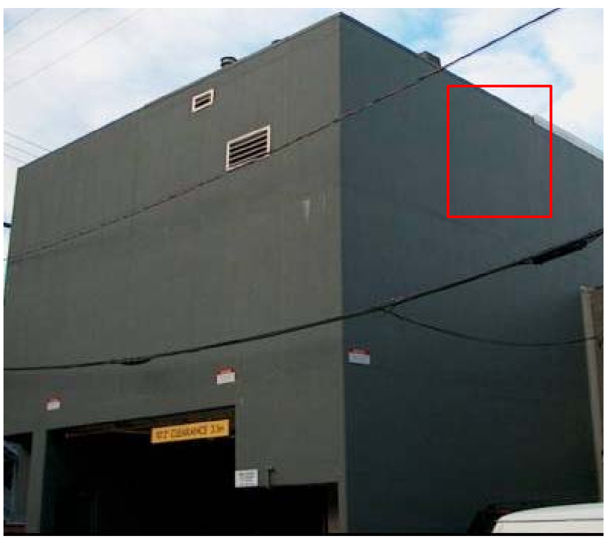


Photo 1 – South and East Elevation, Primary Leak Location

Problems

The building began to experience water infiltration problems during periods of heavy wind driven rain shortly after construction was completed. Attempts to investigate and repair the problem were performed by the original contractor and building maintenance staff. These included routing and sealing cracks on the exterior of the concrete, epoxy injection of cracks from the interior, repainting and re-caulking perimeters. While successful in reducing the volume of leakage, the repairs were not successful in preventing water ingress in several locations.

Investigation

In 2002 a Building Science Firm was retained to test the skylights adjacent to the most prolific wall leaks since all other wall related sources of water penetration were thought to have been repaired (Photo 2).

Photo 2 – Skylight Suspected As Primary Cause of Water Infiltration

Testing was performed by depressurizing the interior of the building to 250 Pa and spraying the test areas with water in general conformance with ASTM E 1105 – 00 and AAMA 501.2-83. Seven tests were performed in sequence to isolate the source of water leakage. Smoke testing was also used to visualize air leakage paths and confirm water infiltration paths. Flood testing was used to rule out roof areas as a potential leakage path.

The results of the testing identified cracks in the concrete wall as the primary cause of the water infiltration to the interior (Photo 3). The cracks appeared to have occurred, either after the building was repainted, or were cyclical and exceeded the crack bridging capabilities of the paint. Other secondary sources of water leakage included:

- Poorly terminated roof membranes and flashings (inadequate reglets, sealant, terminated below roof ballast),
- Skylight/roof terminations (Photo 4) ,

Photo 3 –Cracks In Concrete Identified as Primary Cause of Water Leakage During Testing

Photo 4 – Water Leakage Through Failed Interface at Skylight/Roof Parapet

- Penetrations through the concrete walls such as mechanical louvers (Photo 5),
- Unsealed Interfaces between concrete and masonry walls.

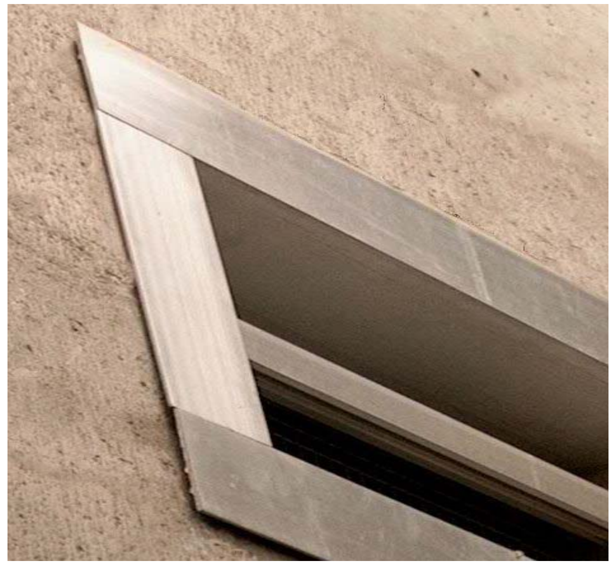


Photo 5 – Poor Louver Interface Detail

Recommendations

The following was recommended to remediate the walls and reduce water infiltration:

- Rout and seal all remaining cracks from the exterior and seal with elastomeric sealant,
- Recoat all walls with a silicone elastomeric coating,
- Repair all interfaces and penetrations,
- Consider over-cladding with metal panels if leakage persists after walls are remediated.

Conclusions

- Cracking in concrete can allow bulk water entry into the wall that will surpass the concrete's ability to absorb water, resulting in water infiltration and possible deterioration.
- Leakage through concrete walls can be very difficult to investigate and repair, particularly if cracks are active.
- The face sealed nature inherent in concrete walls makes interfaces with adjacent claddings and penetrations more complicated and difficult. Proper design and installation of penetrations and interfaces is critical to the long term performance of these walls.

Case Study 3

Background

AGE: 8 years

HEIGHT: terraced 8 stories

OCCUPANCY: multi-unit residential

WALL CONSTRUCTION

- textured acrylic finish
- cast in place concrete
- void
- steel studs/batt insulation
- poly vapour retarder
- gypsum board
- interior paint

Photo 1 – North elevation at terraced end, leaks at deck/wall interface

Problems

As part of an overall building envelope assessment, it was determined that moisture was present behind the interior walls at the shear wall locations. The owners had commissioned maintenance including attempts to seal the cold joints formed at the concrete floor slab transitions. The problem was most notable at the north end wall where water at the interior floor and water stains in the marble finishes were noted. Attempts to seal the concrete cold joints did not eliminate the moisture ingress.

Investigation

The walls were opened from the interior at several locations in the middle of the north wall span and at the terraced corner where the concrete walls joined into the steel stud infill deck area walls on the terraced elevation. Moisture ingress paths were identified at the corner transitions and there was some evidence of moisture ingress at the floor slab cold joints. Test openings at the steel stud roof curb confirmed moisture ingress into the curb from the lack of through wall flashing under the metal cap and moisture ingress into the curb structure from adjacent roof leaks. This moisture was observed entering under the acrylic lamina on the cast-in-place concrete and migrating down the wall under the lamina.

Photo 2 – Roof curb at the top of the mass concrete wall

Photo 3 – Moisture behind flashing and acrylic lamina

In addition, water was entering the wall assembly through leaks in deck drains running through the wall assembly at the deck corner locations.

It was evident from the formation of efflorescence and staining on the backside of the concrete walls that moisture was distributed widespread across the cavity between the concrete wall and the interior, insulated non-structural steel stud wall. The resultant damage to the steel studs and tracks was moderate to severe.

Recommendations

The following was recommended to remediate the walls and reduce water infiltration:

- Re-detail all transitions to adjacent walls, penetrations and the roof curb structure,
- Warm the exterior walls by adding insulation to the exterior of the concrete to reduce the convective air circulation,
- Add an exterior cavity wall cladding system to protect the mass concrete wall and any additional, non-visible cracks or points of moisture ingress,
- The exterior repair approach was selected due to the high cost of the existing interior finishes.

Conclusions

- Moisture can enter through concrete walls at cracks and cold joints.
- Other sources of moisture ingress can include plumbing leaks, transitions to other wall structures or by condensation.
- The source of active moisture ingress can be difficult to diagnose.
- Moisture ingress can be re-distributed over a great distance due to convective air circulation between the mass concrete wall and any interior insulated wall structure.
- The face sealed nature inherent in concrete walls makes interfaces with adjacent claddings and penetrations more complicated and difficult. Proper design and installation of penetrations and interfaces is critical to the long term performance of these walls.

Case Study 4

Background

AGE: 23 years

HEIGHT: 22 stories

OCCUPANCY: Residential

WALL CONSTRUCTION

- poured-in-place concrete
- 2 ½” steel studs (with a 1/2” to 1” gap between the steel studs and the concrete)
- 2 ½”batt insulation
- 4 mil poly vapour retarder
- gypsum board
- interior paint

The exterior walls consist primarily of mass concrete. Approximately 80% of the exterior wall area is protected by balconies at each floor level. The balconies generally provide more than eight feet of overhang protection for the wall below. Approximately 20% of the exterior wall area does not have overhang protection at each floor level. However, there is a continuous overhang at the 21st floor level of the building. See Photo 1.

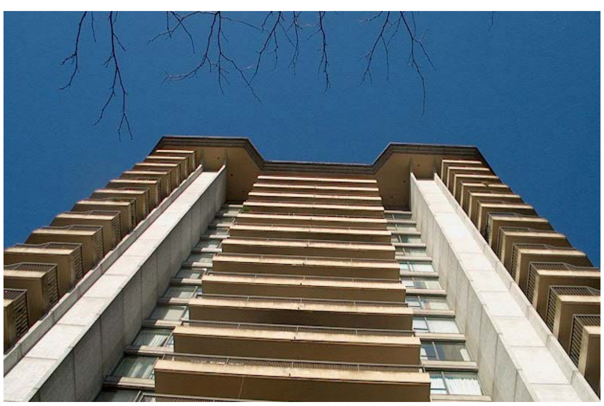


Photo 1 – Protection provided by balconies and roof overhang reduces exposure condition for much of the wall area

Condition Assessment

In 2002, a Building Science Firm was retained to perform a condition assessment on the building envelope.

Although the condition assessment scope of work included the roofs and at-grade assemblies, the focus of this case study is on the findings related to the poured-in-place concrete walls and windows.

Exterior Review

Potentially problematic conditions were observed from the exterior:

- The joint sealant at the window perimeters and ends of sill flashings had failed cohesively at all locations reviewed (Photo 2). The acrylic sealant at the window perimeters is the original sealant from the time of initial construction. Based on the minimal movement capability of this sealant, it is likely that the sealant failed within the first few years and has not been providing an effective seal for many years.

Photo 2 – Typical joint sealant failure at ends of sill flashings

- Cold joints in the mass concrete walls were not sealed. Various cold joints are situated directly below failed joint sealant at the ends of the sill flashings. Concentrated water runoff staining is present at the ends of several sill flashings (Photo 3).

- At a few locations, the reinforcing steel in the mass concrete walls was exposed.
- The formwork tie-holes were not patched at various locations

Photo 3 – Concentrated water runoff staining at ends of sill flashing

Interior Review

An interior review was also performed:

- Ventilation was provided though bathroom fans with no humidistat controls and fresh air intake provided either through the exterior walls or under suite entry doors. There was a continuous hallway pressurization system.
- Evidence of minor to moderate damage due to condensation was observed in some of the suites (in small closets, behind curtains (Photo 4), wood stools adjacent to non-thermally broken windows and sliding doors.
- Evidence of moisture infiltration such as efflorescence and staining on the wood liners was found at various locations on the lower floor levels.

Recommendations

The following was recommended to mitigate potential damage in the walls and reduce water infiltration:

- Clean concrete surfaces and apply a sealer or coating in the near future.
- Install new joint sealants at window perimeters and other interfaces.
- Develop maintenance and renewals program for the exterior walls and windows.

Photo 4 – Condensation staining behind curtains

Conclusions

- The concrete wall assemblies were performing adequately from a water penetration control perspective, despite the presence of poor details and crack control techniques. This can be attributed to a significant extent to the overhang protection and to the simplicity of the exposed wall elements.
- Condensation is an issue for these walls due to the poor thermal performance characteristics of the walls and windows in combination with a poor suite ventilation system.
- Inappropriate choice of sealant type and poor joint design resulted in a potential water leakage point throughout the building.
- The lack of maintenance and renewals planning has resulted in some of the deficiencies and poor performance issues remaining in place for excessive periods of time.

Case Study 5

Background

AGE: 13 years

HEIGHT: 27 stories

OCCUPANCY: Residential above commercial

WALL CONSTRUCTION

- 6” poured-in-place concrete
- 2 ½” steel studs (with a 1/2” gap between the steel studs and the concrete)
- 2 ½” rigid polystyrene insulation
- 6 mil poly vapour retarder
- gypsum board
- interior paint

The exterior walls consist primarily of mass concrete with the east elevation partially clad in EIFS. Both punch windows and curtain wall assemblies are utilized for glazing. The concrete elements are generally restricted to columns and upstand walls under the punch windows. The concrete was sandblasted but not sacked or coated as part of the original construction. There is no overhang protection for the exterior walls except at balcony locations. See Photo 1.

No significant maintenance work has been undertaken on the building since the time of completion of the original construction.

Photo 1 – Typical portion of exterior walls and glazing assemblies

Condition Assessment

In 2002 a Building Science Firm was retained to perform a condition assessment on the building envelope.

Although the condition assessment scope of work included the roofs and at-grade assemblies, the focus of this case study is on the findings related to the poured-in-place concrete walls and windows.

Exterior Review

Performance observations made from the exterior included the following:

- The joint sealant at the window perimeters has failed adhesively at many locations (Photo 2).

Photo 2 – Typical joint sealant failure at window perimeter

- Cold joints in the poured-in-place concrete walls at floor levels and below window jambs were not sealed. Efflorescence and staining was noted at joints throughout the building (Photo 3).
- Dark staining due to concentrated run-off was visible at several locations.

Photo 3 – Efflorescence and dark staining at cold joint

Interior Review

Performance observations made from the interior included the following:

- Condensation was occurring on window and curtainwall framing in some suites leading to damage at wood window sills as well as wall and ceiling finishes and carpet tack strips (Photo 4).
- Interior openings revealed mold present on the exterior face of the interior gypsum board at some locations, most notably in areas of wall below window jambs (Photo 5). This is likely occurring due to leakage at cold joint or window perimeter with the gypsum board absorbing the moisture from the floor.

Photo 4 – Condensation on window frame and damage to wood stool

- Ventilation was provided though bathroom and kitchen fans with no humidistat controls and fresh air intake provided either through the exterior walls and windows or under suite entry doors. There was a continuous hallway pressurization system.

Photo 5 – Mold on interior gypsum boardCondensation staining behind curtains

Recommendations

The following were recommended to mitigate potential damage in the walls and reduce water infiltration:

- Clean concrete surfaces and apply a sealer or coating in the near future.
- Install new joint sealants at window perimeters and other interfaces.

Conclusions

- Water ingress is occurring through cold joints leading to the growth of mold on the exterior face of the interior gypsum board. The wall assembly is performing adequately at all other locations.
- Condensation is occurring due to the poor thermal performance characteristics of the walls and windows in combination with a poor suite ventilation system.
- Moisture accumulation due to condensation on the interior surface of the concrete did not appear to be an issue despite the air space that existed.
- The lack of maintenance has resulted in water penetration at some locations.
- Concentrated run-off has resulted in significant staining on the concrete.

APPENDIX C: Hygrothermal and Thermal Modeling Results

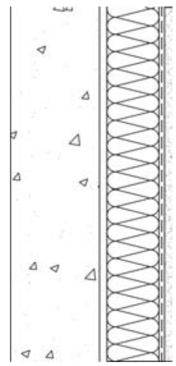
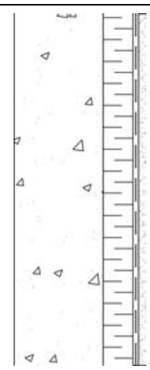
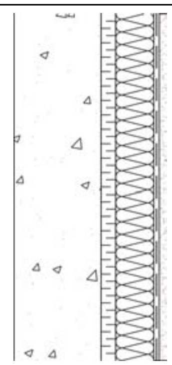
Appendix C: Hygrothermal and Thermal Modeling

Computer simulation software was used to model the thermal and hygrothermal performance of the wall systems. A brief descriptions of the software used for this study are described below.

WUFI Pro 3.3. A one-dimensional, transient hygrothermal simulation software developed by the Fraunhofer – Institut Für Baufphysik. WUFI is capable of simulating the one-dimensional flow of heat and moisture transfer through building envelope assemblies. Boundary conditions include interior temperature and relative humidity, exterior temperature and relative humidity, solar radiation, and rain. WUFI is used to predicting the moisture content of the individual layers of the assembly for a specified climate and simulation period. Other results include expected temperatures and values for relative humidity throughout the cross section

THERM 5.2.1. A two-dimensional, steady-state heat transfer simulation software developed by Lawrence Berkeley National Laboratory. THERM is used to determine the overall heat transfer through building envelope assemblies. The program is also used to predict temperatures at thermal bridges including intersections at walls, floors and partition walls. Estimating surface temperatures is useful for predicting assemblies or details that pose the greatest risk of condensation.

Table C.1: Typical poured in place wall assemblies modeled in this study.

Wall Type		Assembly Materials
W1		Exterior 150 mm concrete (with or without coating) 13 mm airspace 90 mm steel studs & batt Insulation 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior
W2		Exterior 150 mm concrete (with or without coating) 50 mm XPS with integral steel supports 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior
W3		Exterior 150 mm concrete (with or without coating) 25 mm XPS 67 mm steel studs & batt insulation 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior

HYGROTHERMAL MODELING OF TYPICAL WALL ASSEMBLIES

WUFI Pro is a one-dimensional simulation software that models the transfer of heat and moisture through a building assemblies over period of time under specified interior and exterior climatic conditions. The program requires the user to enter information specific to the building in terms of its physical components, position, location and initial conditions. The input data used in this study are described briefly as follows.

Location and Climate Information

WUFI includes a library of climate files for various locations around the globe including Vancouver, Canada. For each city, two weather files are available, the 10% coldest and the 10% hottest, which are derived from historical weather data. The Vancouver 10% coldest weather file is used for all of the simulations presented in this study. The climate files include data for an entire year, and are run continuously for simulations extending beyond a year in duration.

Typical Vancouver weather is presented in the following figures. Figures C1-C2 illustrate the annual variation of exterior air temperature and relative humidity respectively. Figure C3 illustrates the direction of wind driven rain that predominates in Vancouver. WUFI accounts for the effect of the direction of wind driven rain, requiring the user to select the orientation of the building assembly. The critical orientation for buildings in Vancouver is generally the eastern exposure. As such, all simulations are easterly exposures to model the worst-case scenario.

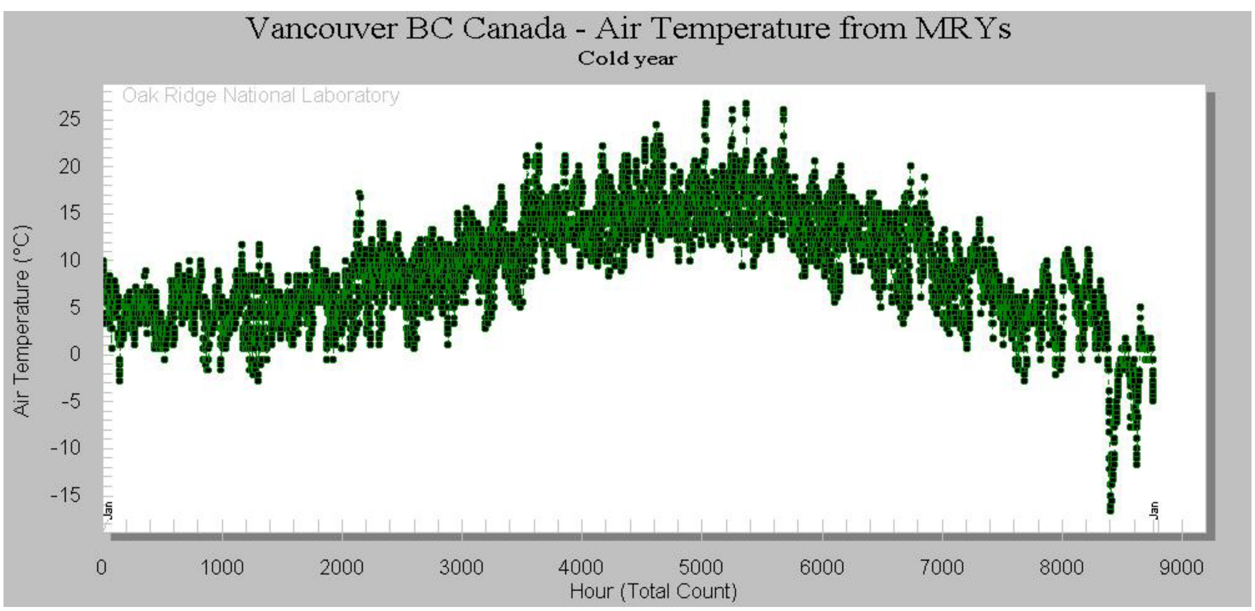


Figure C1: Hourly Vancouver Air Temperature data over a one-year period. (Figure reproduced from WeatherFile Analyzer, ORNL).

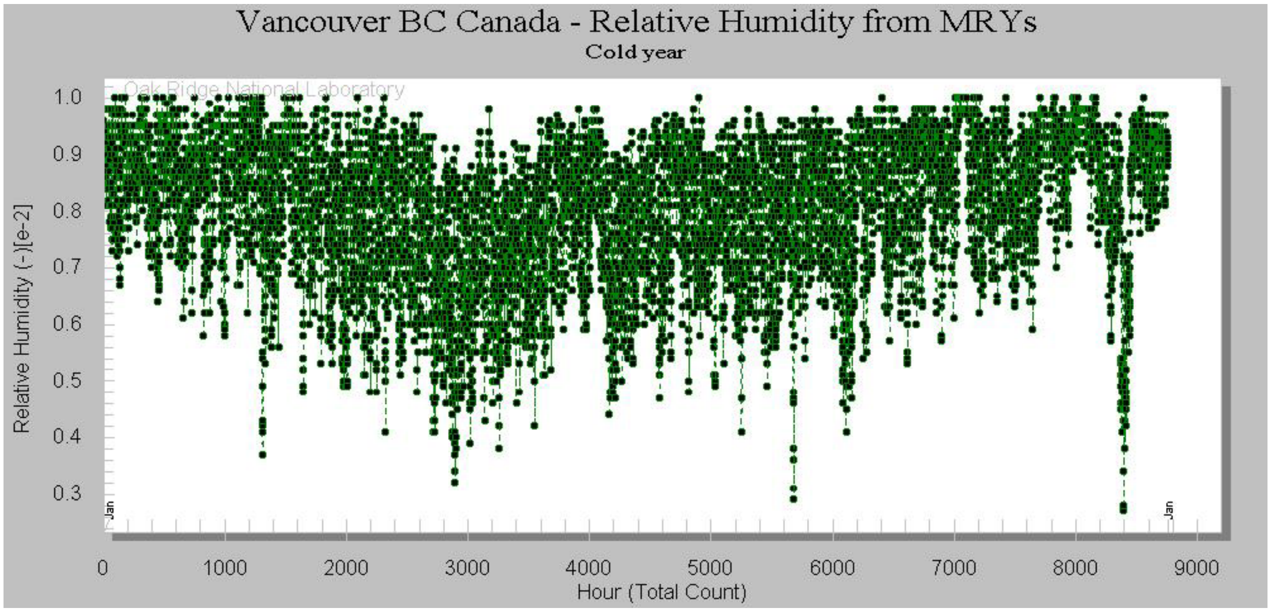


Figure C2: Hourly outdoor relative humidity data for Vancouver. (Figure reproduced from WeatherFile Analyzer, ORNL).

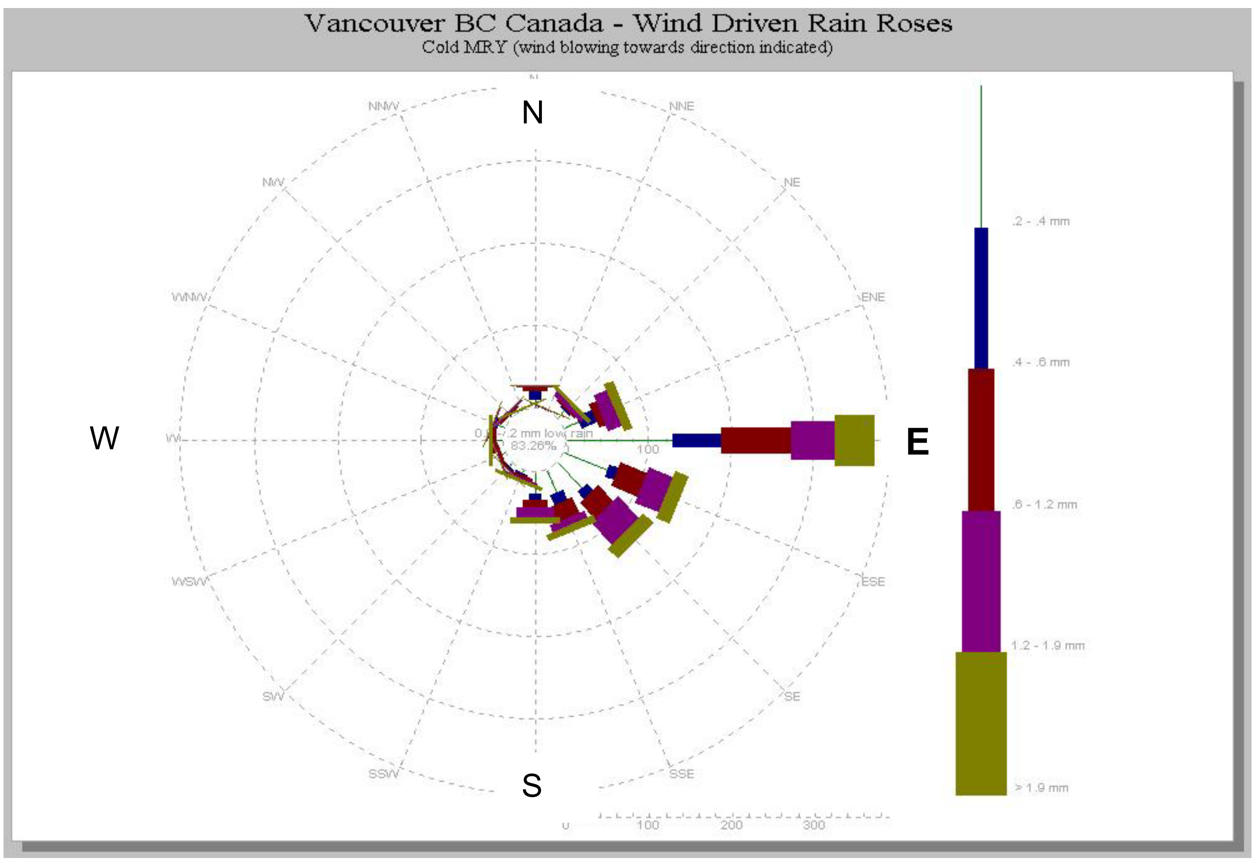


Figure C3: Wind driven rain rose for Vancouver. (Figure reproduced from WeatherFile Analyzer, ORNL).

Building Assemblies: Material Data

WUFI includes a library of material data. Default WUFI material data are used for the majority of materials for this study. Material data supplied by product manufacturers is used for materials that are not included in the WUFI library. The properties of the materials used in the wall assemblies considered in this study are summarized in the Tables C2 and C3. Note that the values for vapour diffusion resistance of concrete and extruded polystyrene are different than those found in the ASHRAE Handbook of Fundamentals 2001. A sensitivity analysis showed that the difference of the material properties is negligible.

Table C2: Material properties of building materials used for modeling wall assemblies W1-W3. Data referenced from the WUFI material library.

Material	Density Kg/m^3	Porosity m^3/m^3	Heat Capacity J/(kg·K)	Thermal Conductivity W/(m·K)	Diffusion Resistance Factor*
Air Layer (10mm)	1.3	0.999	1000	0.071	0.73
Concrete (w/c 0.5)	2 300	0.18	850	1.6	180
Extruded Polystyrene	30	0.95	1 470	0.022	200
Fibre Glass Batt	30	0.99	840	0.035	1.3
Gypsum Wallboard	850	0.65	870	0.163	6
Polyethylene	130	0.001	2 300	2.3	50 000

***The diffusion resistance factor is a convention used in WUFI to represent the ratio of the permeability of water vapour in air to the permeability of water vapour through the material.**

Table C3: Permeance of coatings

Coating	Permeance (ng / Pa m^2 s)
Acrylic Elastomeric Coating (2 coats)	630**
Latex Paint (2 coats)	791**
Silicone Elastomeric Coating (2 coats)	2485**

**** Source: Industry data taken from supplier data tables.**

Since the exterior coatings have a significant effect on the moisture exchange at the concrete surface, but negligible effect on heat transfer, the exterior coatings are modeled as surface transfer coefficients rather than material layers. By doing so, only the effect of additional water vapor permeance of the coating is included in the model. However, the coating will also affect the rainwater absorption of the concrete. We estimated the affect of the coatings on rainwater absorption, in two ways and compared the results.

The coating reduces the rate of moisture absorption of the concrete, however this reduction can only be determined by physical testing. We approximated this reduction by modifying the suction coefficient of the outer 5mm of the concrete layer to simulate a reduced ability to absorbed moisture.

Alternatively, we modify the rainwater absorption factor to reduce the water load on the exterior wall available for absorption. For a high-rise building, WUFI's default rainwater absorption factor is 0.7, which means that 70% of the rain incident on the wall is available for absorption by the cladding. Without changing the suction coefficient of the concrete, reduced the rainwater absorption factor to 0.05.

We compared our estimate of the suction coefficient to the effect reducing the rainwater absorption factor. We found the results to be comparable for the SE coating. For the AE coating, reducing the suction coefficient of the outer 5mm resulted in slightly higher concrete moisture content than models where the rain absorption factor was reduced to 0.05.

Initial Conditions

For the WUFI simulations, the user selects the length of the simulation period and the initial moisture content of each of the layers. Each of the simulations in this study is 5 years, starting on January 1.

With the exception of the concrete layer, the initial moisture content of all layers are set to their equilibrium moisture content at 80% RH. To establish an appropriate, but conservative, initial moisture content for the concrete layer a separate simulation was conducted to model newly cast concrete, exposed to outdoor weather for a duration of 3 months during the wettest time of year. The simulation included only the concrete layer, with a saturated initial moisture content, and exposed to Vancouver weather on both sides for three months starting December 1st. The ending moisture content of 130 kg/m^3 was used as the initial concrete moisture content for all simulations.

Results of Hygrothermal Simulations

The figures referenced in the report (but not included in the main body of the report) are provided on the following pages.

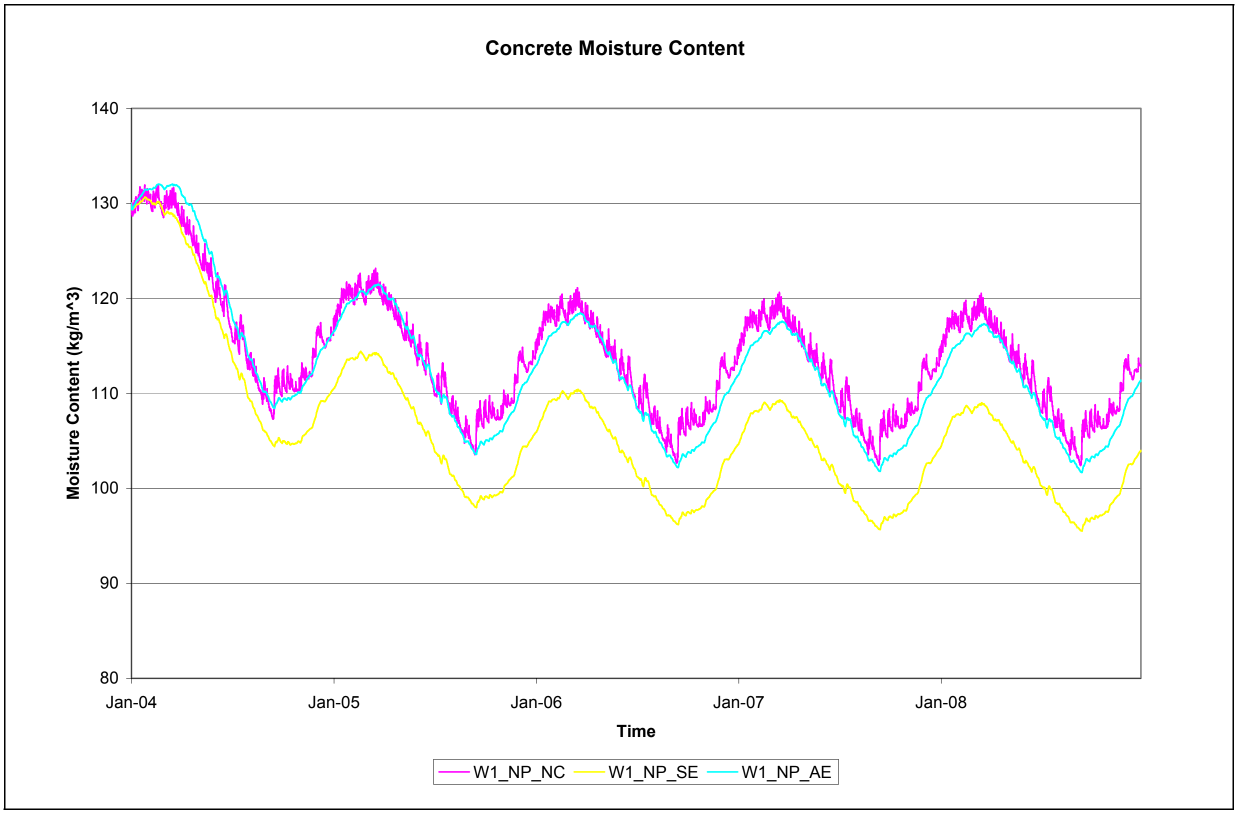


Figure 3.1d: Concrete moisture content for wall W1 with NC, SE and AE exterior coatings and no polyethylene.

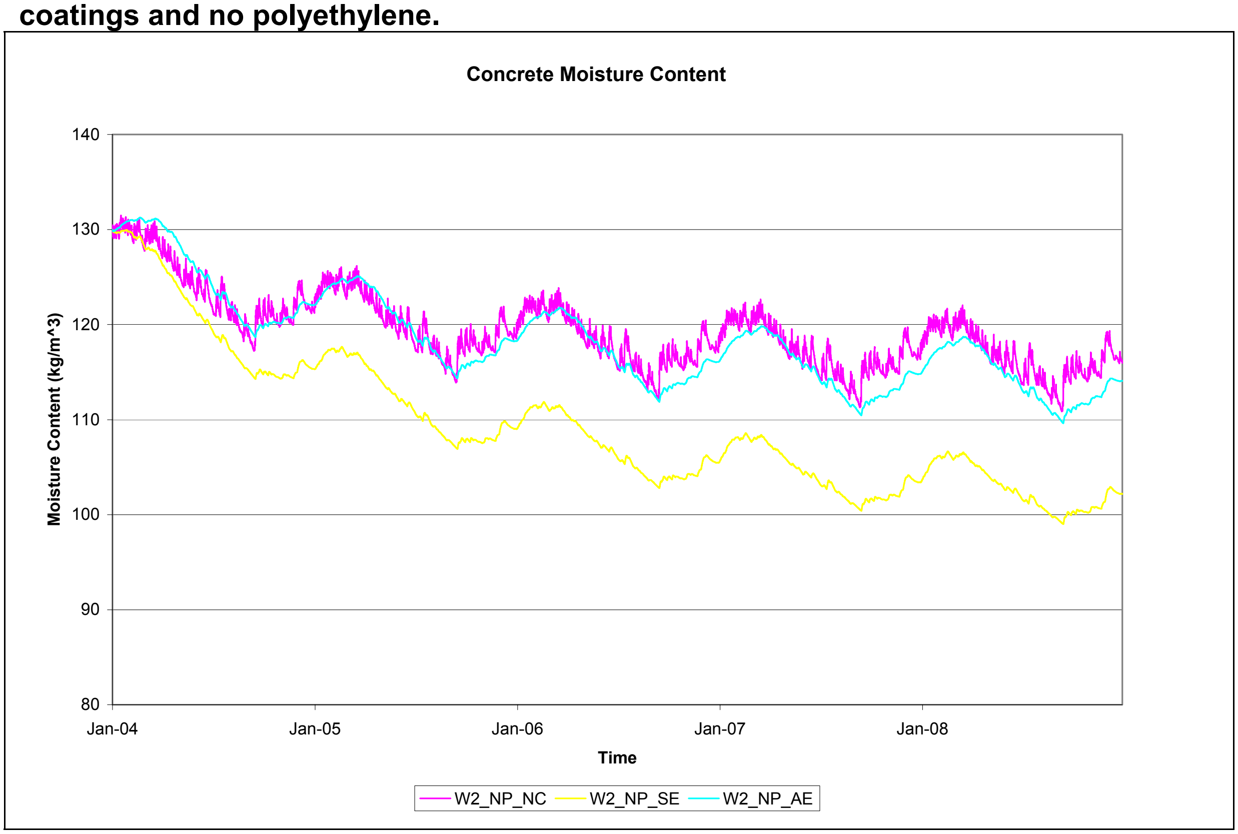


Figure 3.1e: Concrete moisture content for wall W2 with NC, SE and AE exterior coatings and no polyethylene.

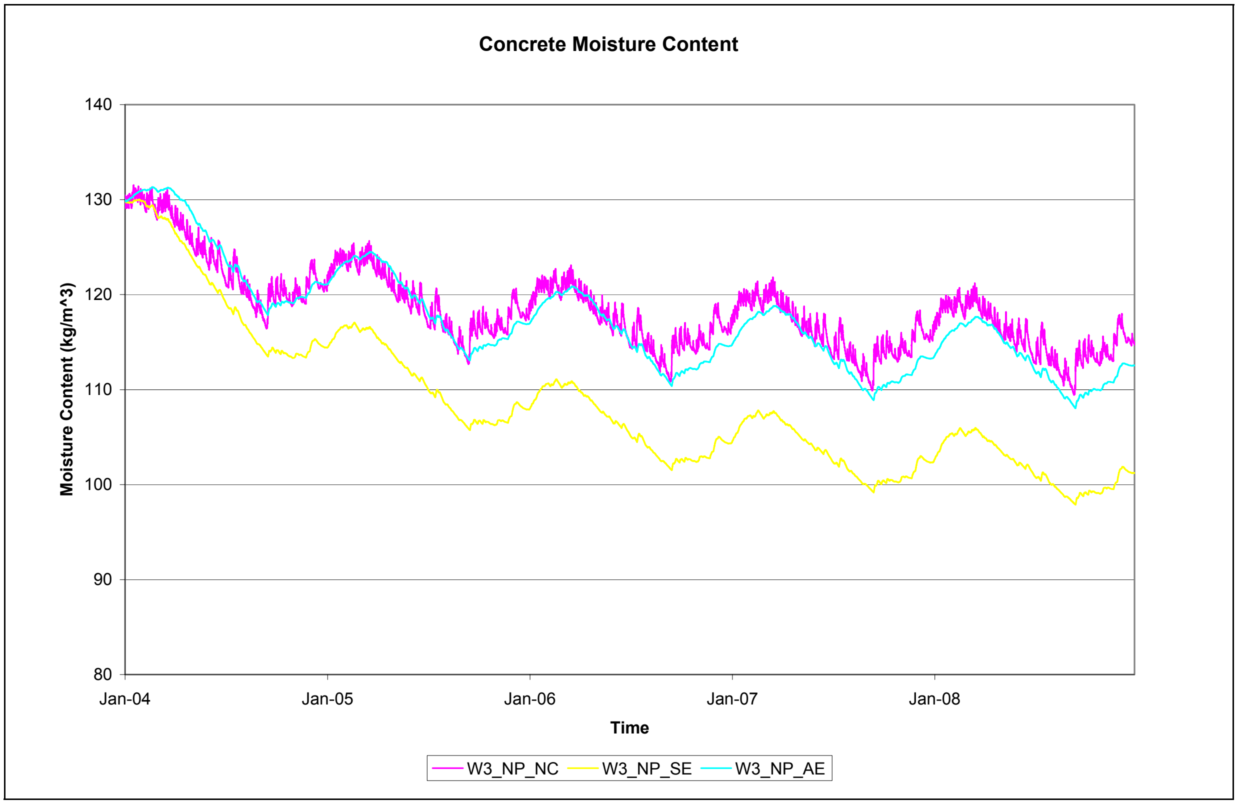


Figure 3.1f: Concrete moisture content for wall W3 with NC, SE and AE exterior coatings and no polyethylene.

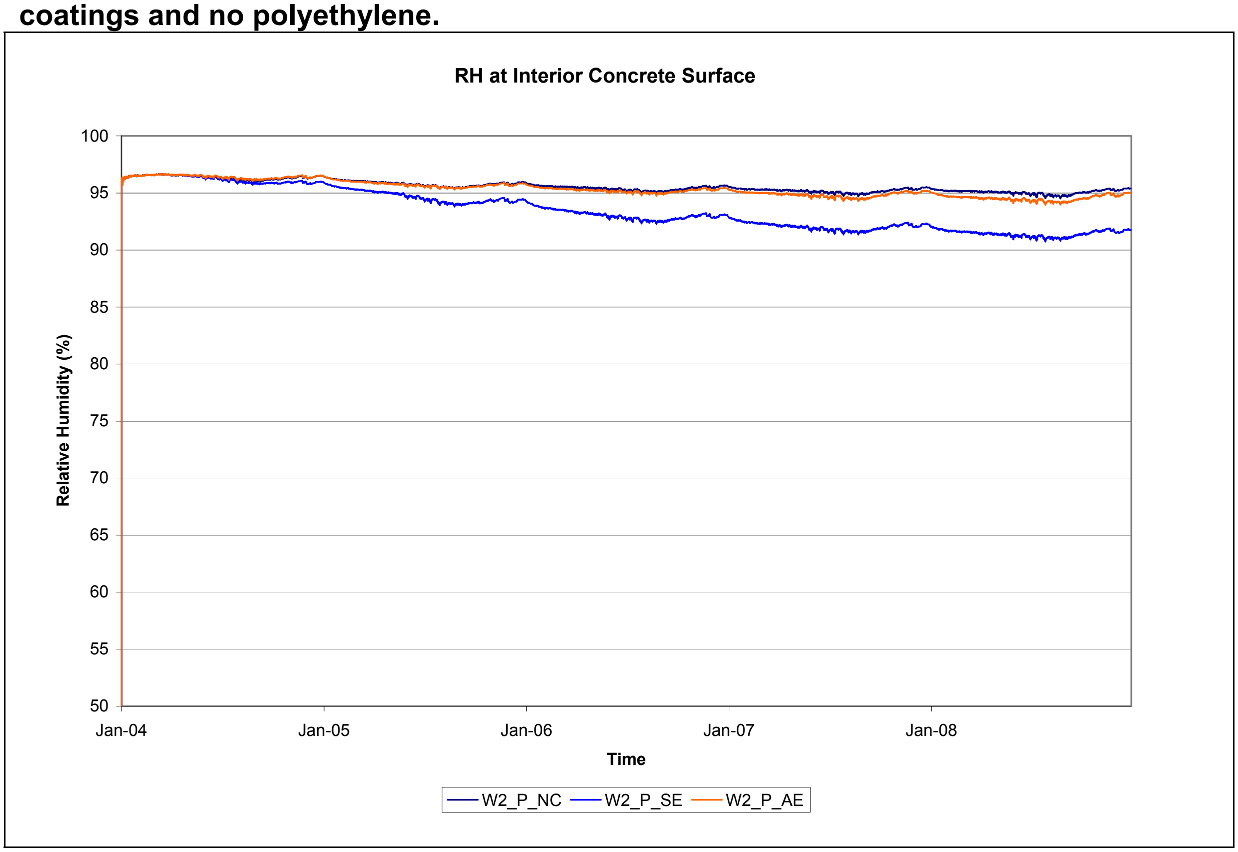


Figure 3.2b: Effect of exterior coatings on RH at interior surface of concrete for wall W2, with polyethylene.

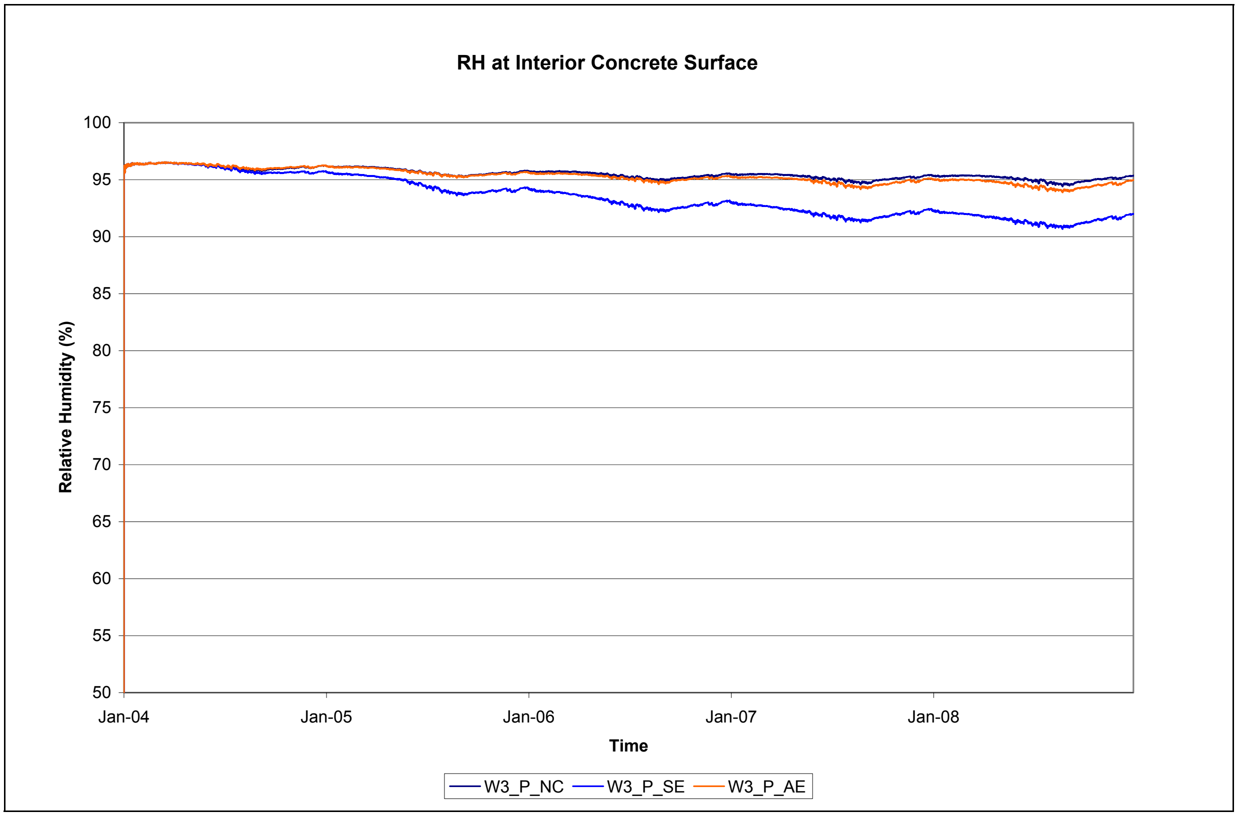


Figure 3.2c: Effect of exterior coatings on RH at interior surface of concrete for wall W3, with polyethylene.

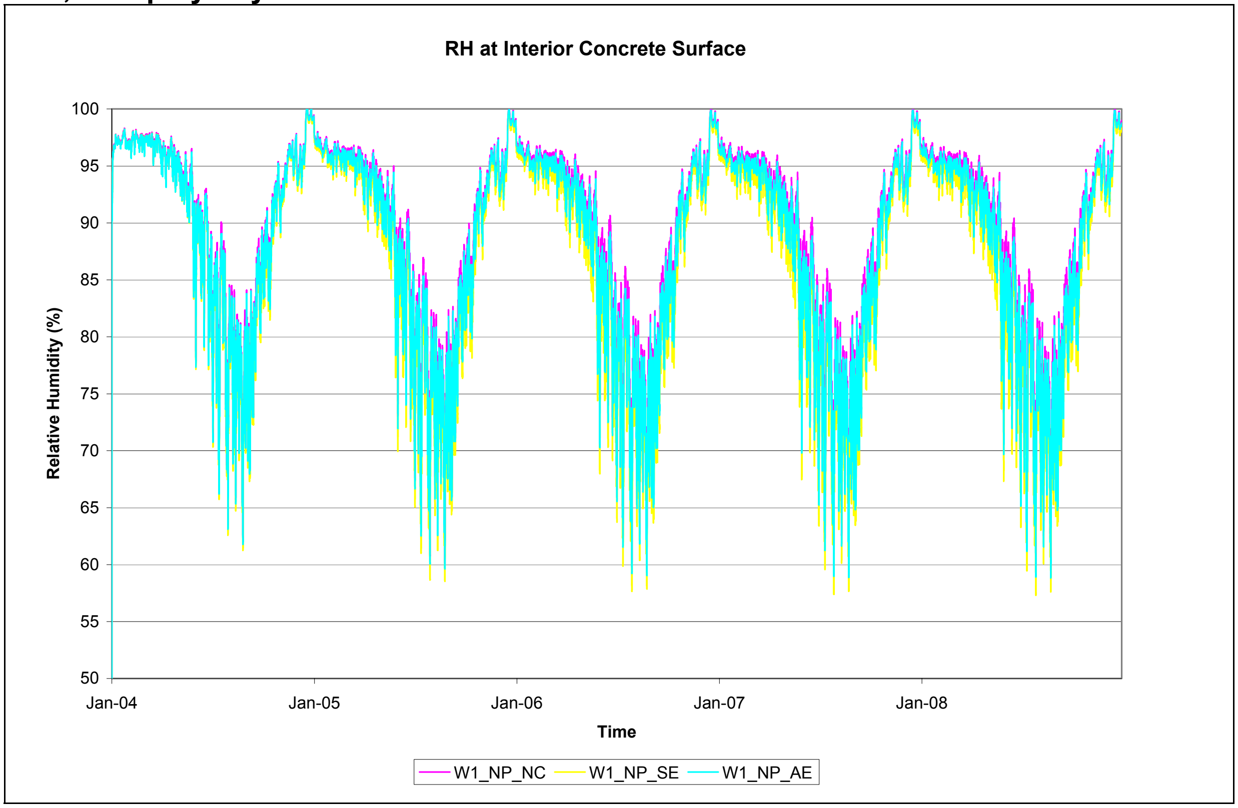


Figure 3.2d: Effect of exterior coatings on RH at interior surface of concrete for wall W1, without polyethylene.

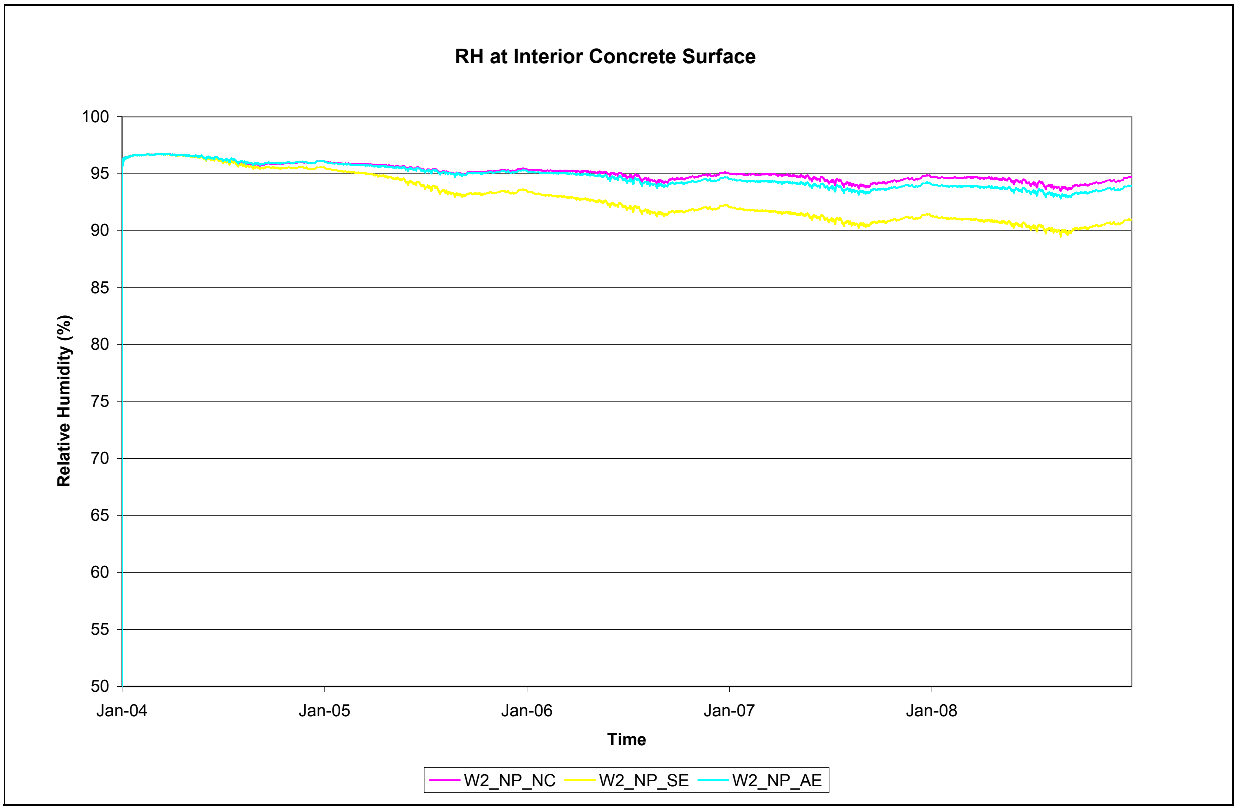


Figure 3.2e: Effect of exterior coatings on RH at interior surface of concrete for wall W2, without polyethylene.

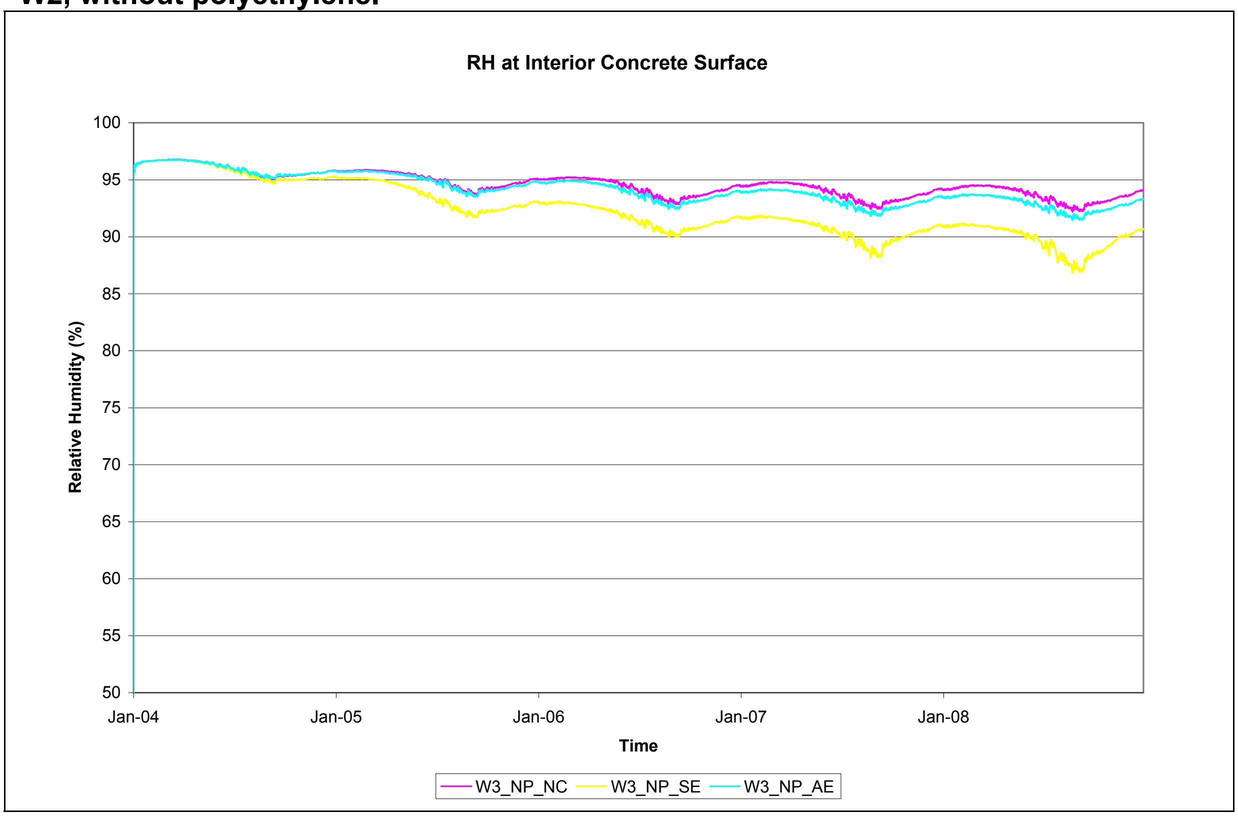


Figure 3.2f: Effect of exterior coatings on RH at interior surface of concrete for wall W3, without polyethylene.

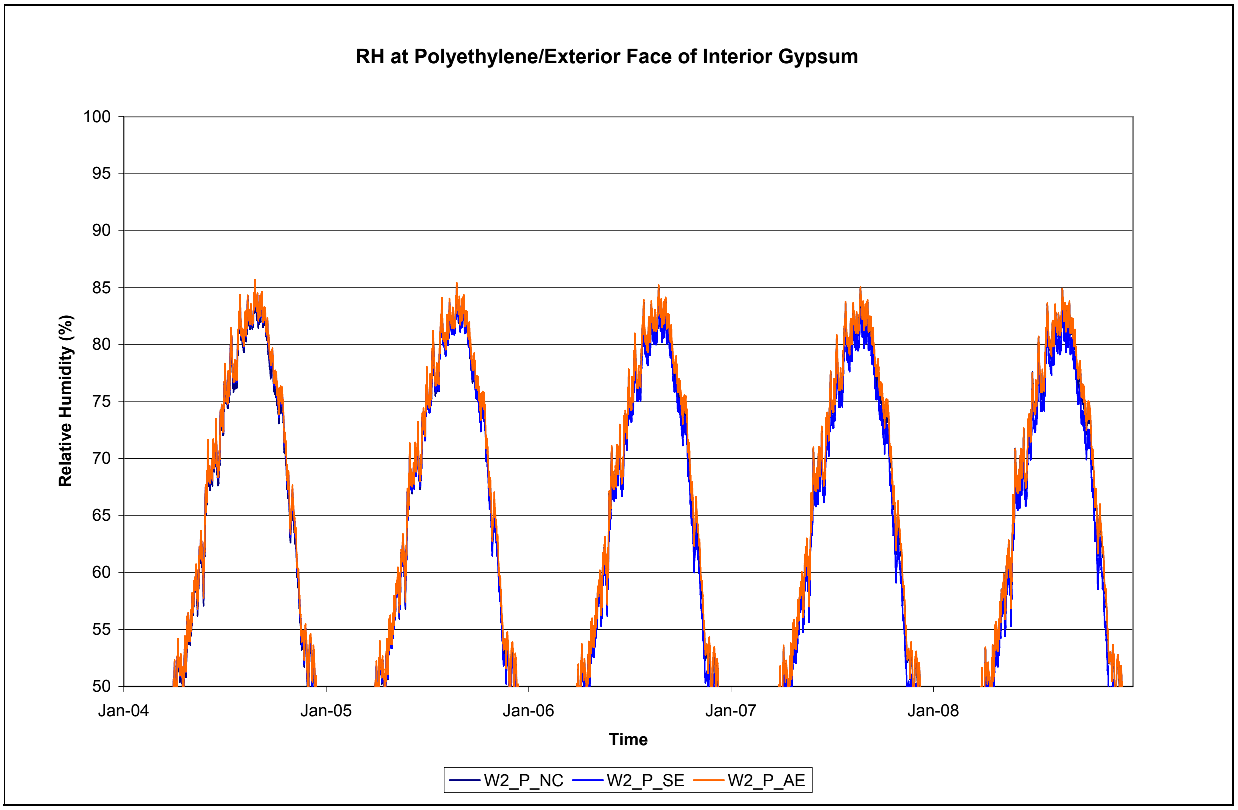


Figure 3.3b: Effect of exterior coatings on RH at the polyethylene layer for wall W2, with polyethylene.

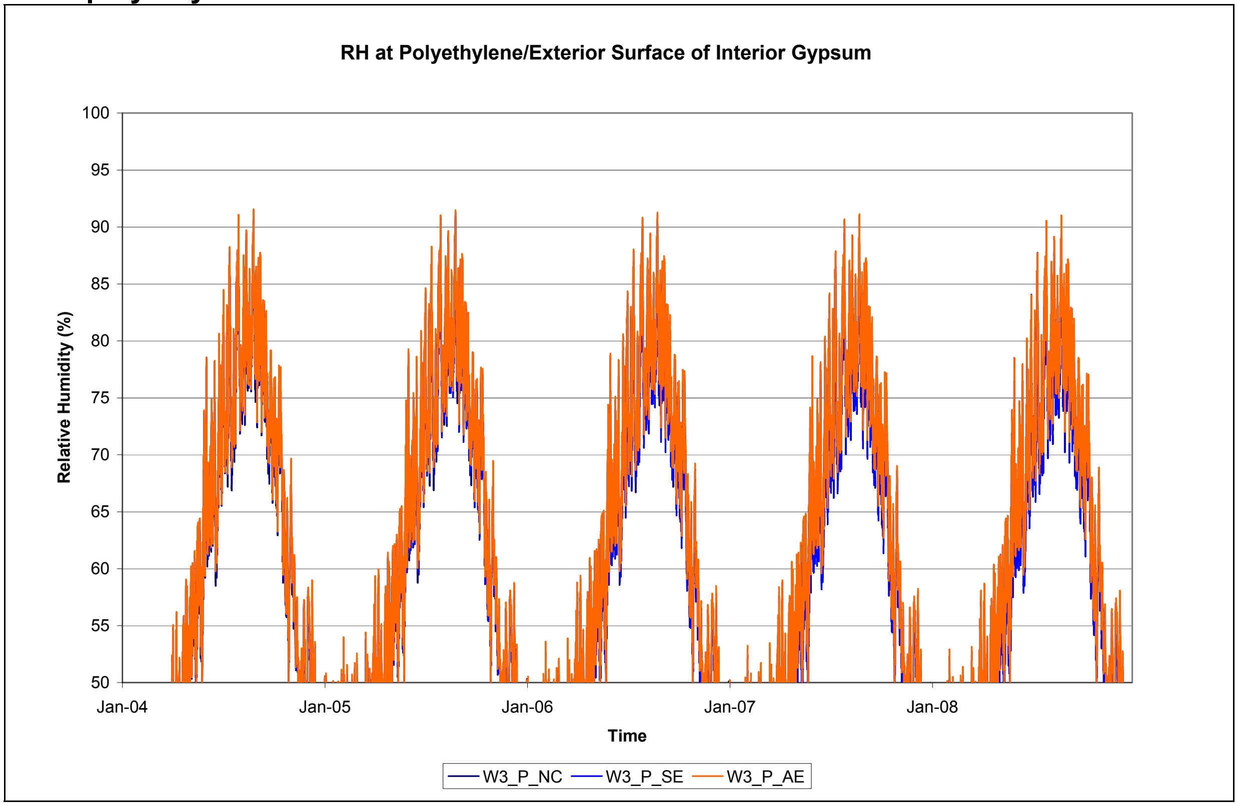


Figure 3.3c: Effect of exterior coatings on RH at the polyethylene layer for wall W3, with polyethylene.

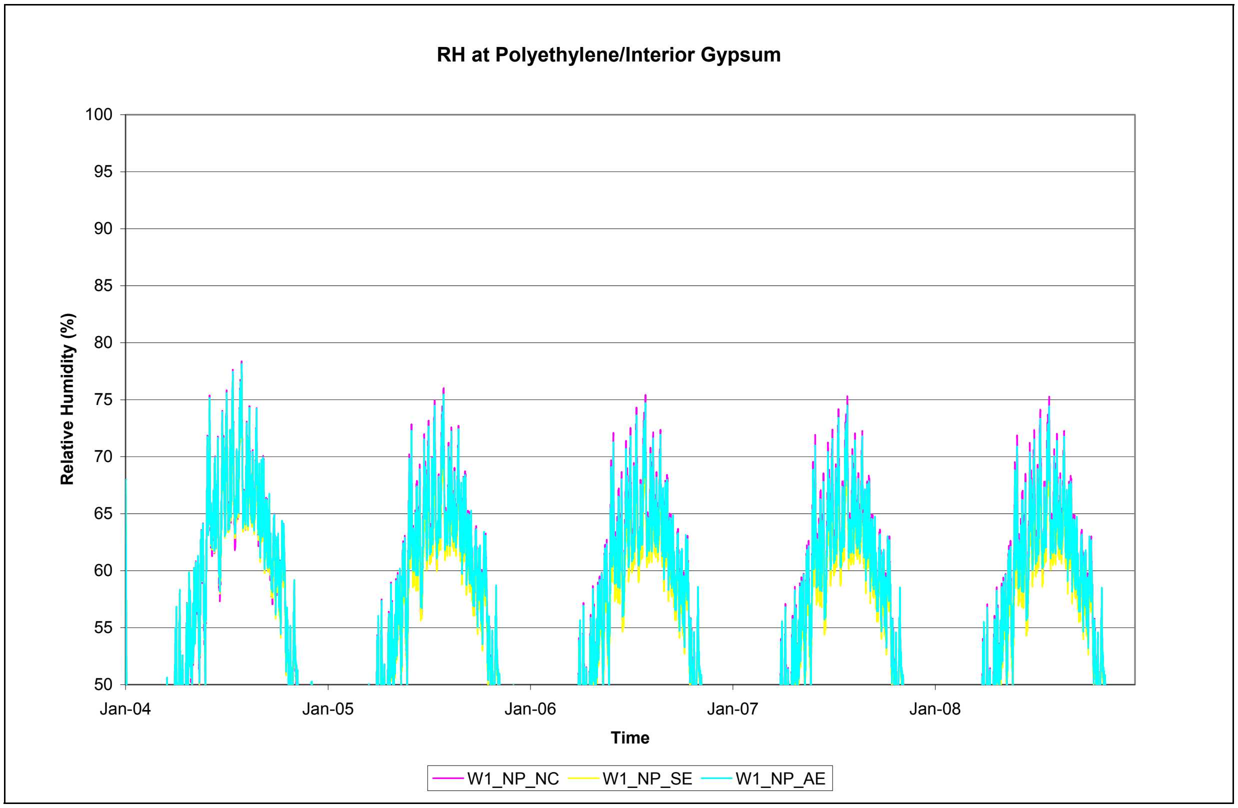


Figure 3.3d: Effect of exterior coatings on RH at the exterior face of the interior gypsum board layer for wall W1, without polyethylene.

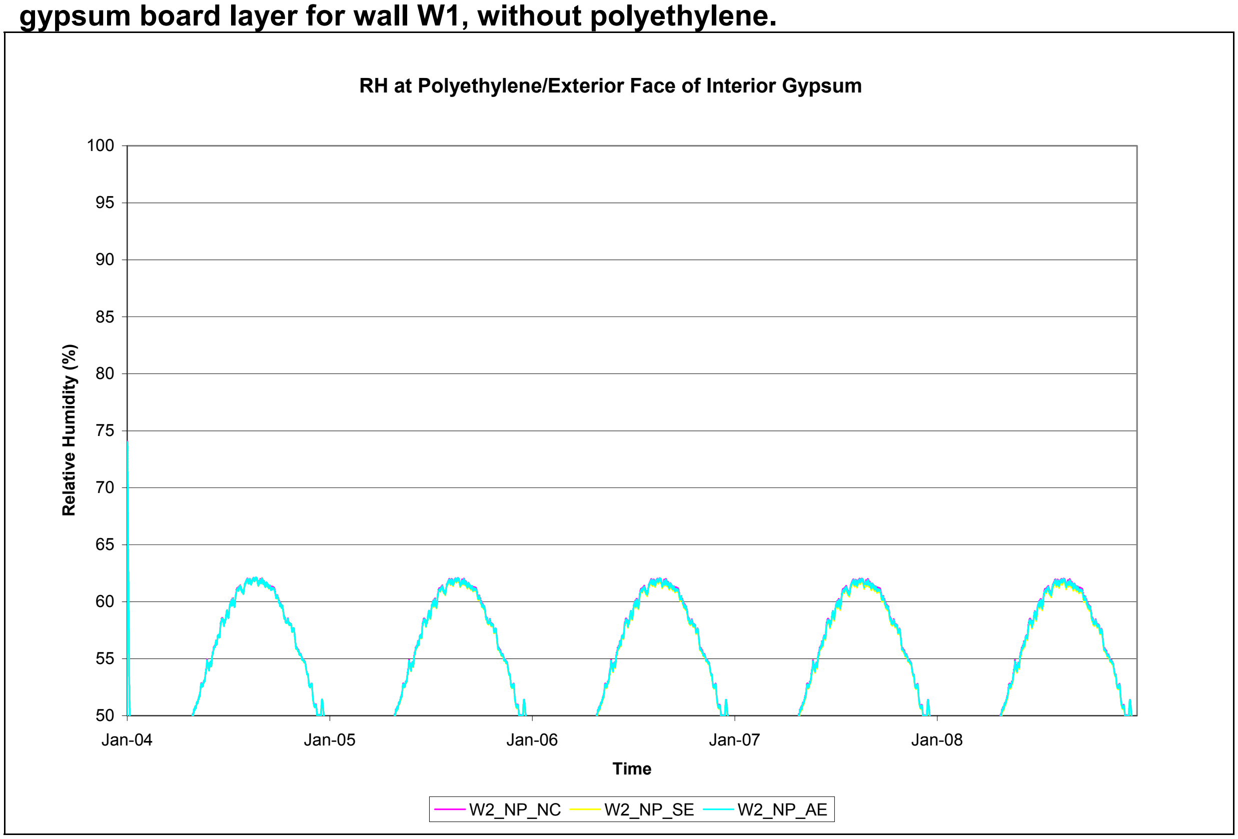


Figure 3.3e: Effect of exterior coatings on RH at the exterior face of the interior gypsum board layer for wall W2, without polyethylene.

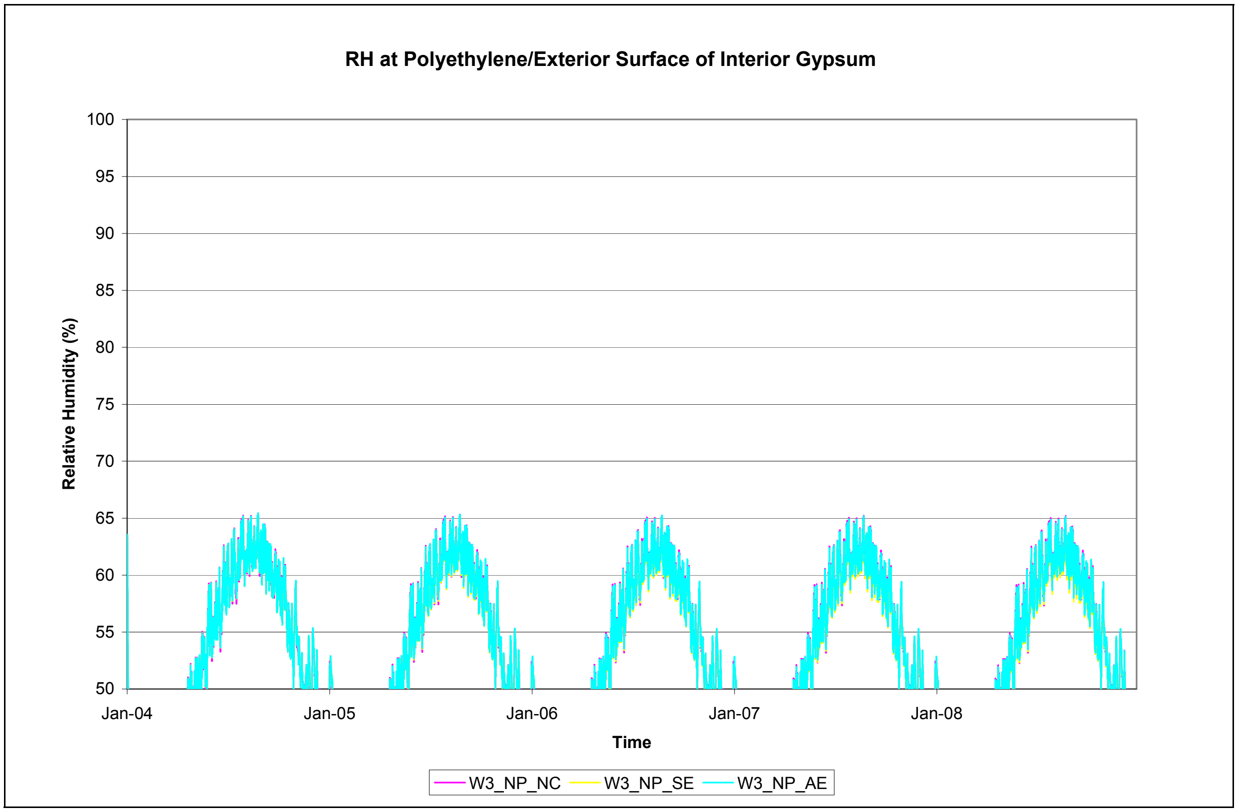


Figure 3.3f: Effect of exterior coatings on RH at the exterior face of the interior gypsum board layer for wall W3, without polyethylene.

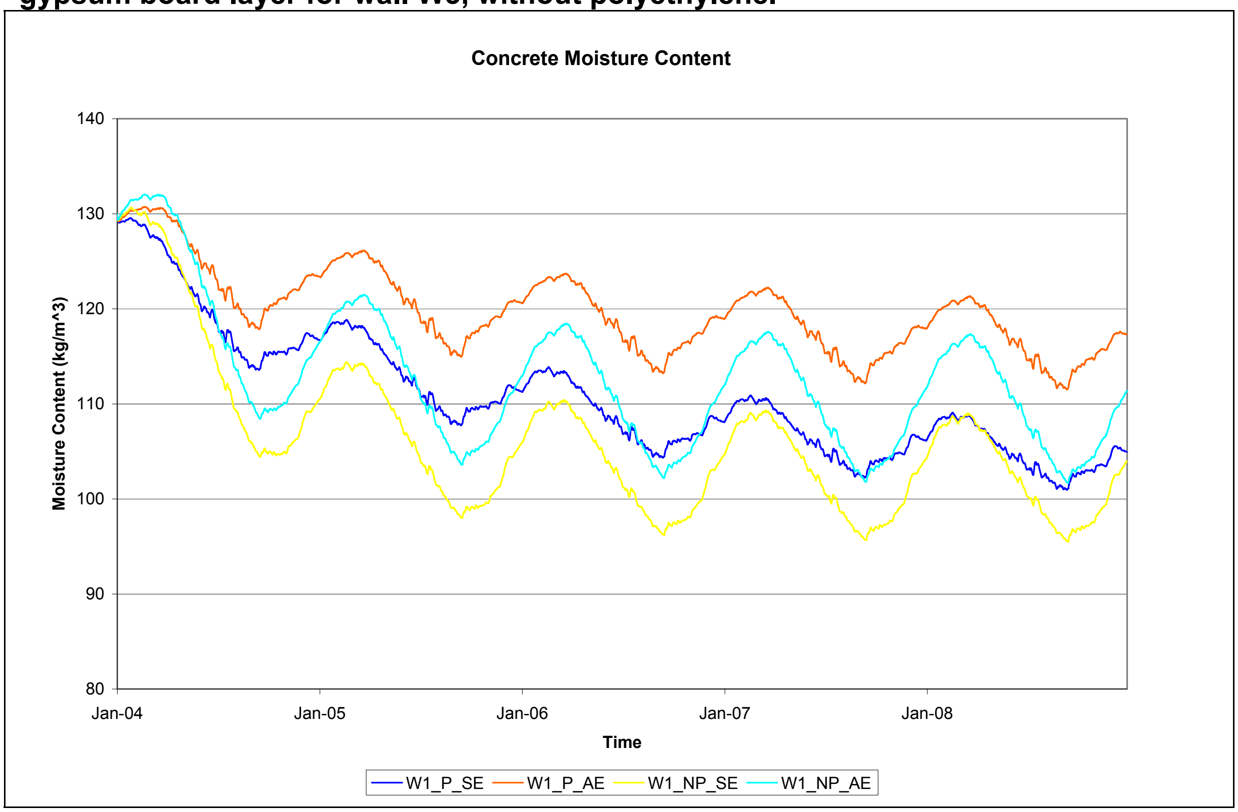


Figure 3.4d: Concrete moisture content for wall W1 with and without polyethylene, with coatings on concrete.

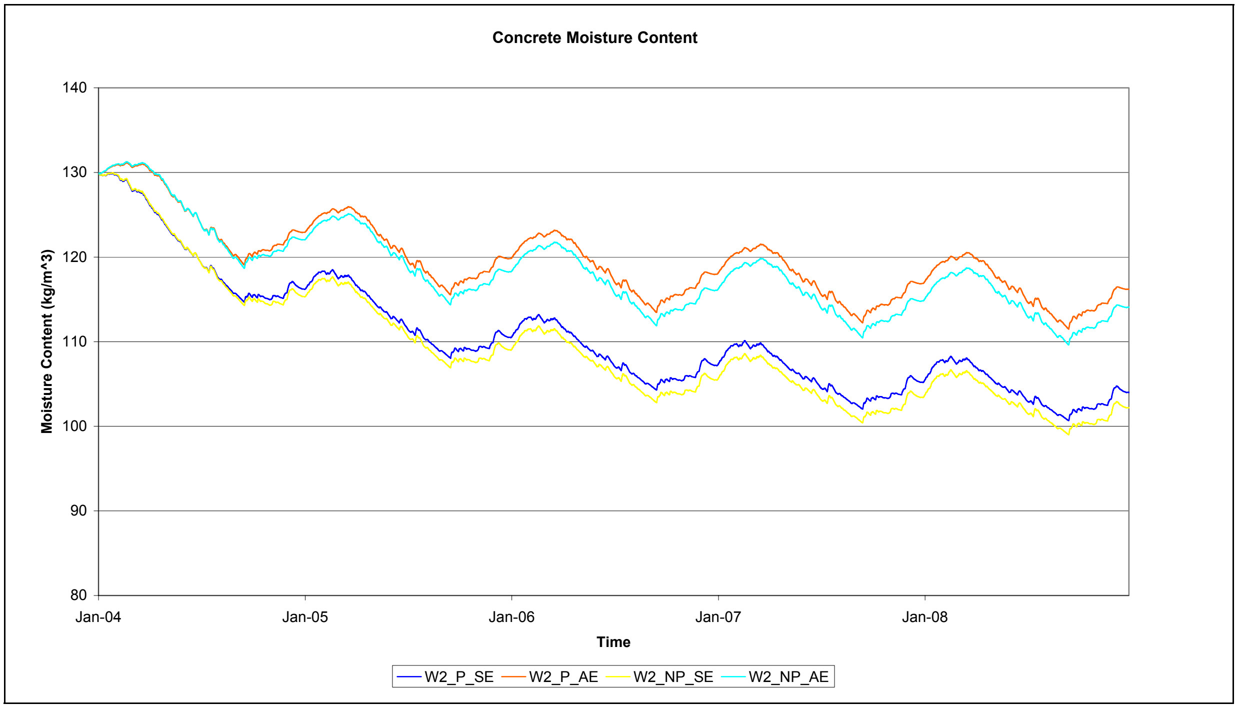


Figure 3.4e: Concrete moisture content for wall W2 with and without polyethylene, with coatings on concrete.

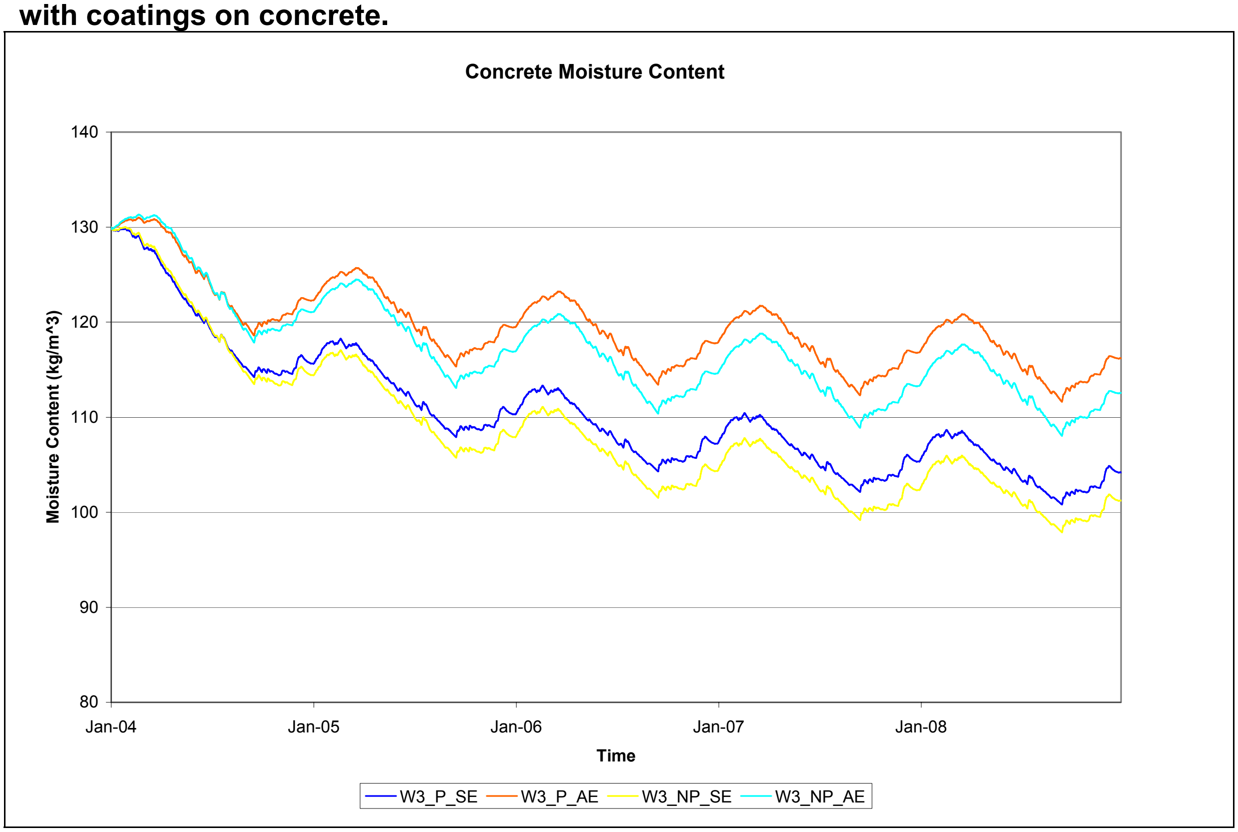


Figure 3.4f: Concrete moisture content for wall W3 with and without polyethylene, with coatings on concrete.

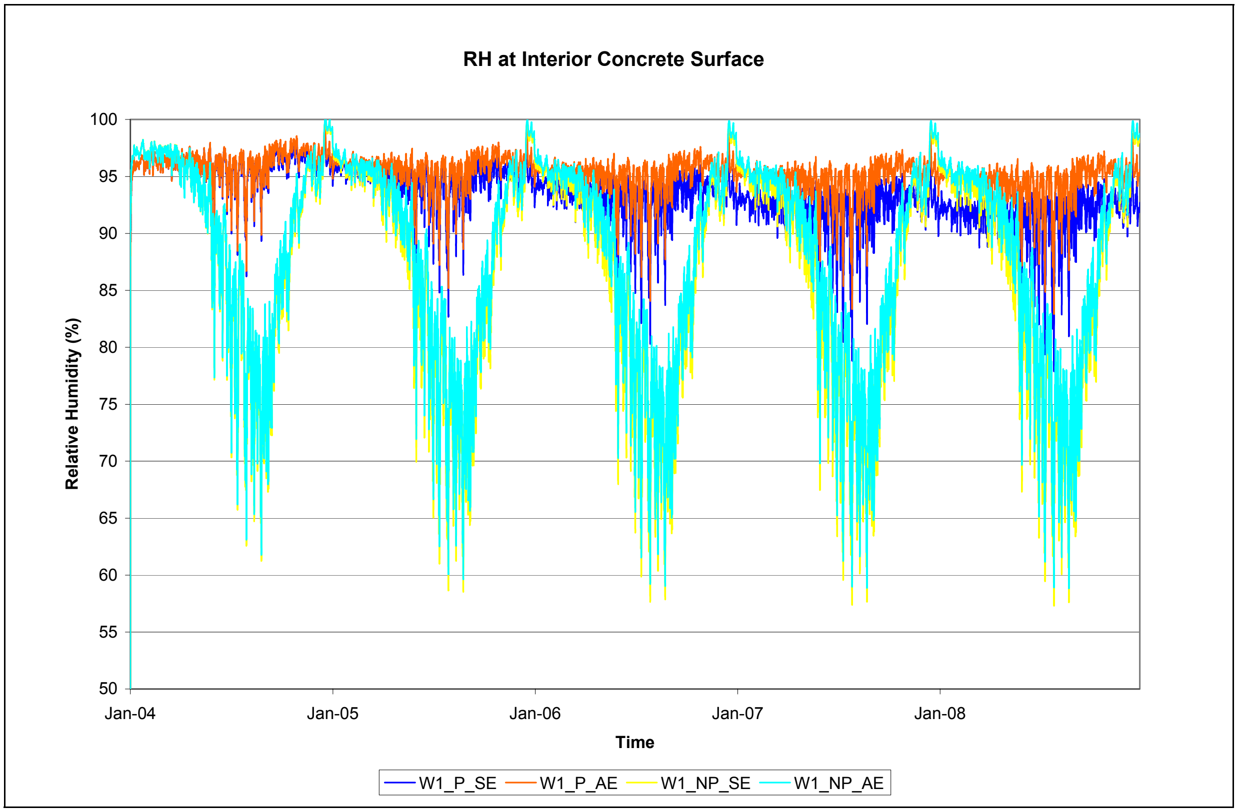


Figure 3.5d: Comparison of RH at interior concrete surface for wall W1 with and without polyethylene, with coatings on concrete.

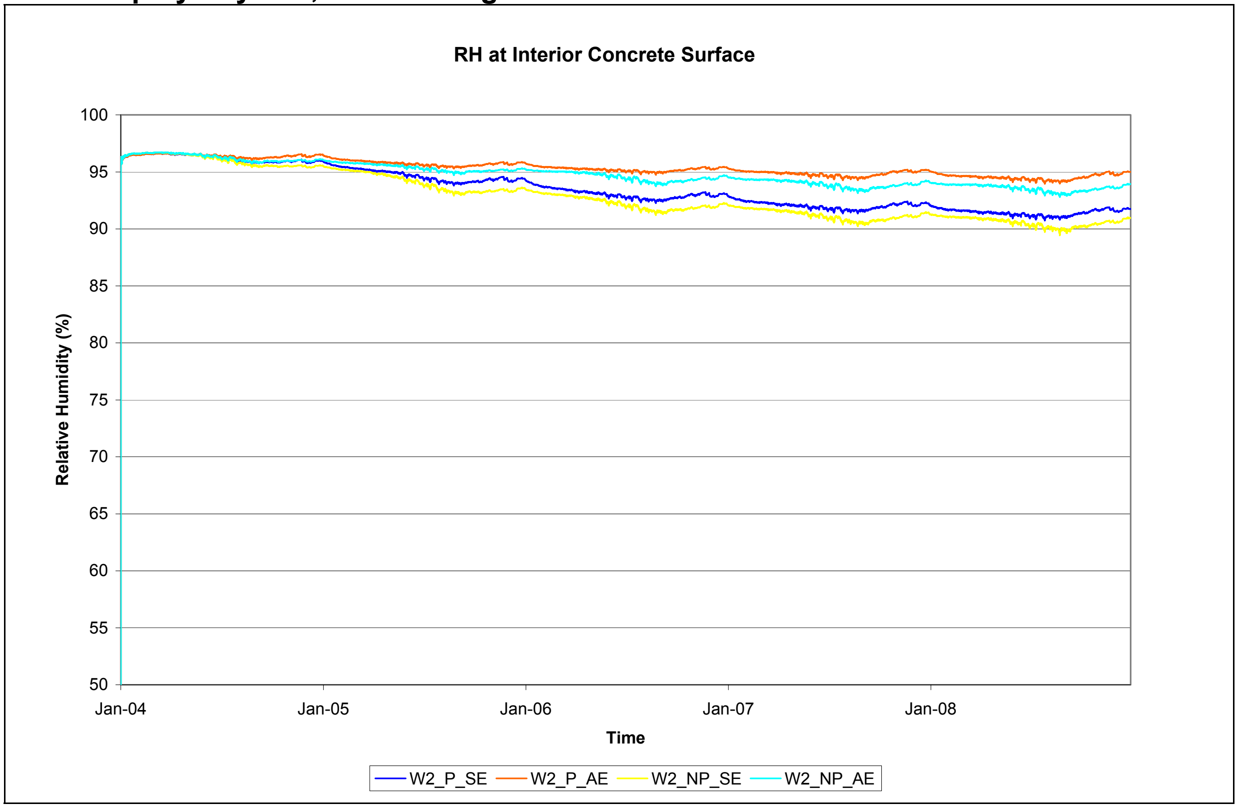


Figure 3.5e: Comparison of RH at interior concrete surface for wall W2 with and without polyethylene, with coatings on concrete.

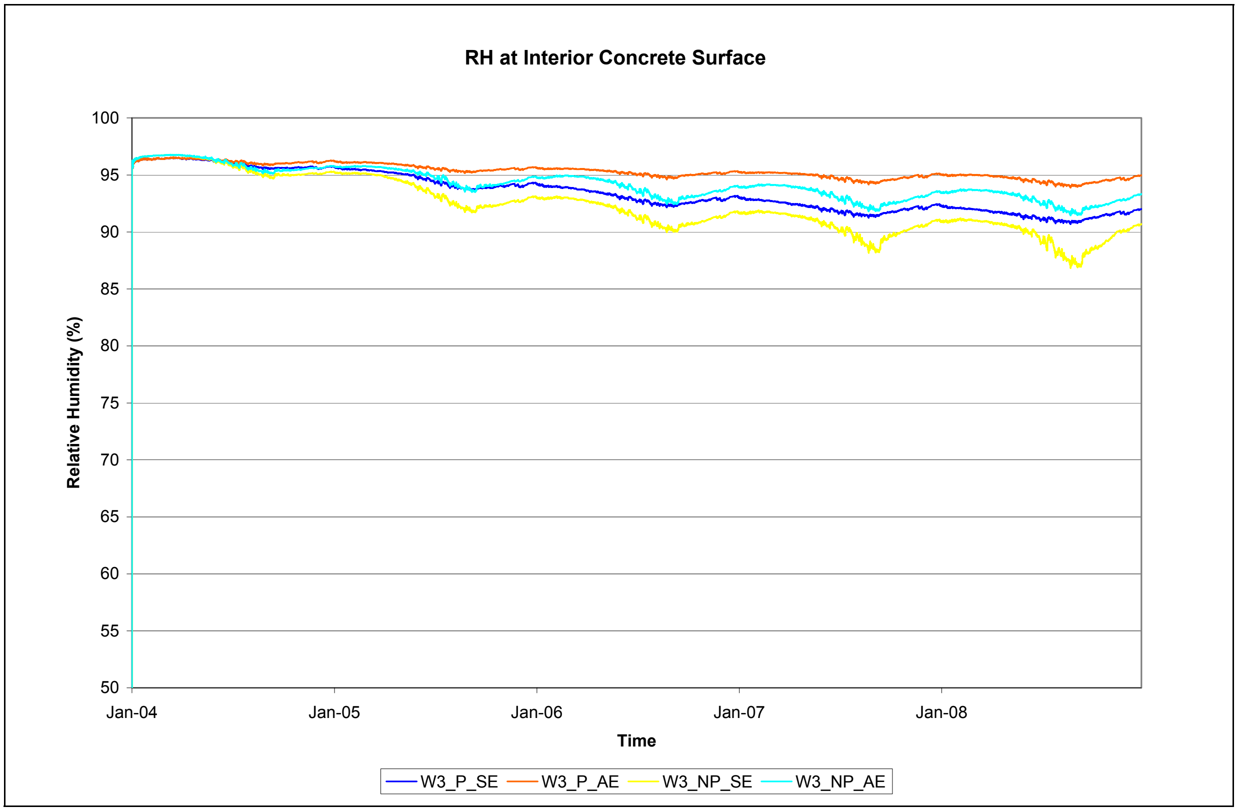


Figure 3.5f: Comparison of RH at interior concrete surface for wall W3 with and without polyethylene, with coatings on concrete.

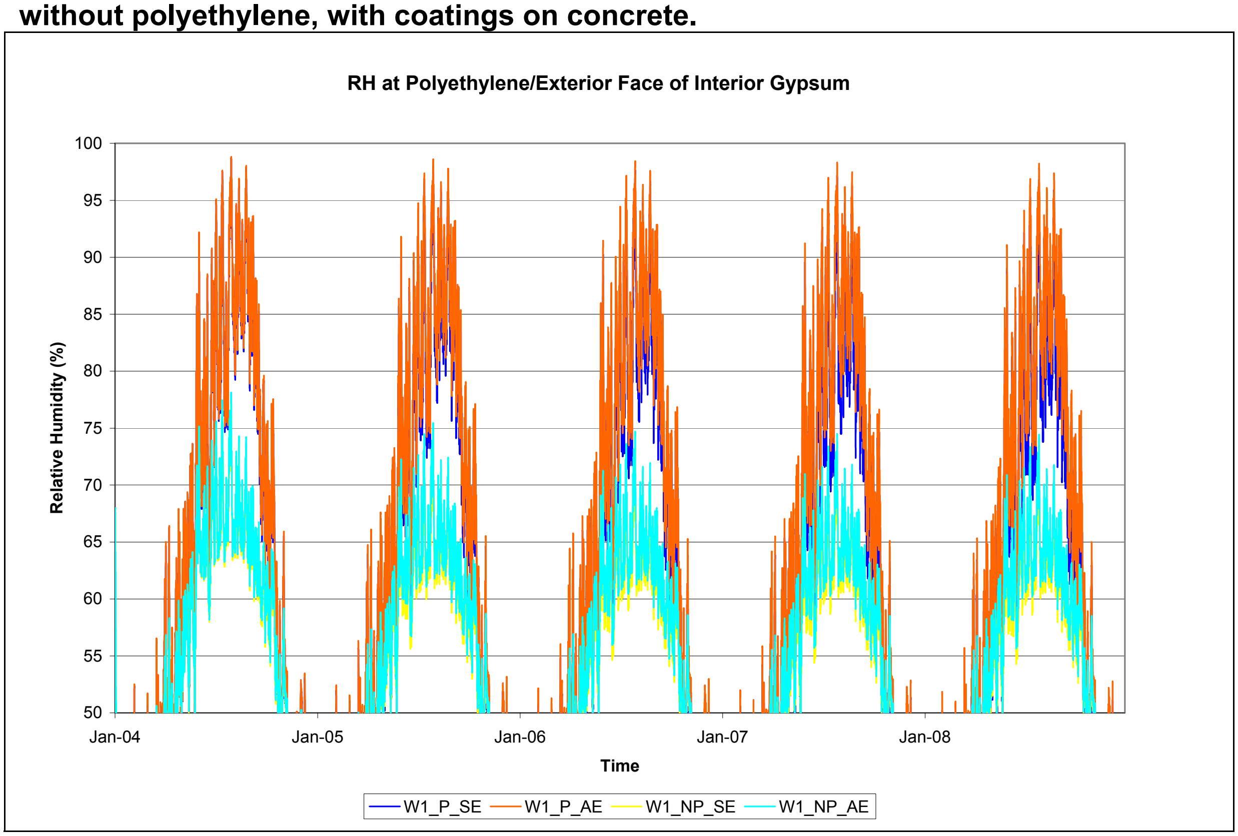


Figure 3.6d: Comparison of RH at polyethylene/exterior gypsum board surface for wall W1 with and without polyethylene, with coatings on concrete.

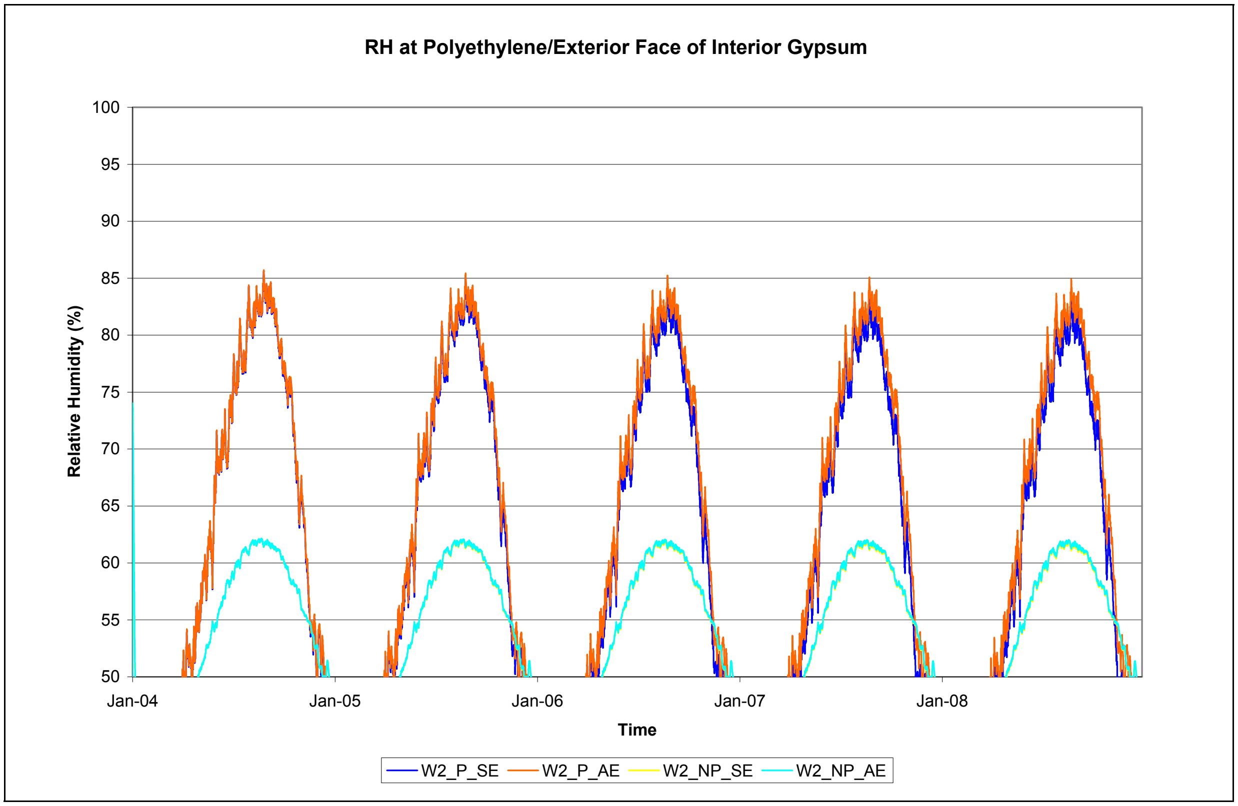


Figure 3.6e: Comparison of RH at polyethylene/exterior gypsum board surface for wall W2 with and without polyethylene, with coatings on concrete.

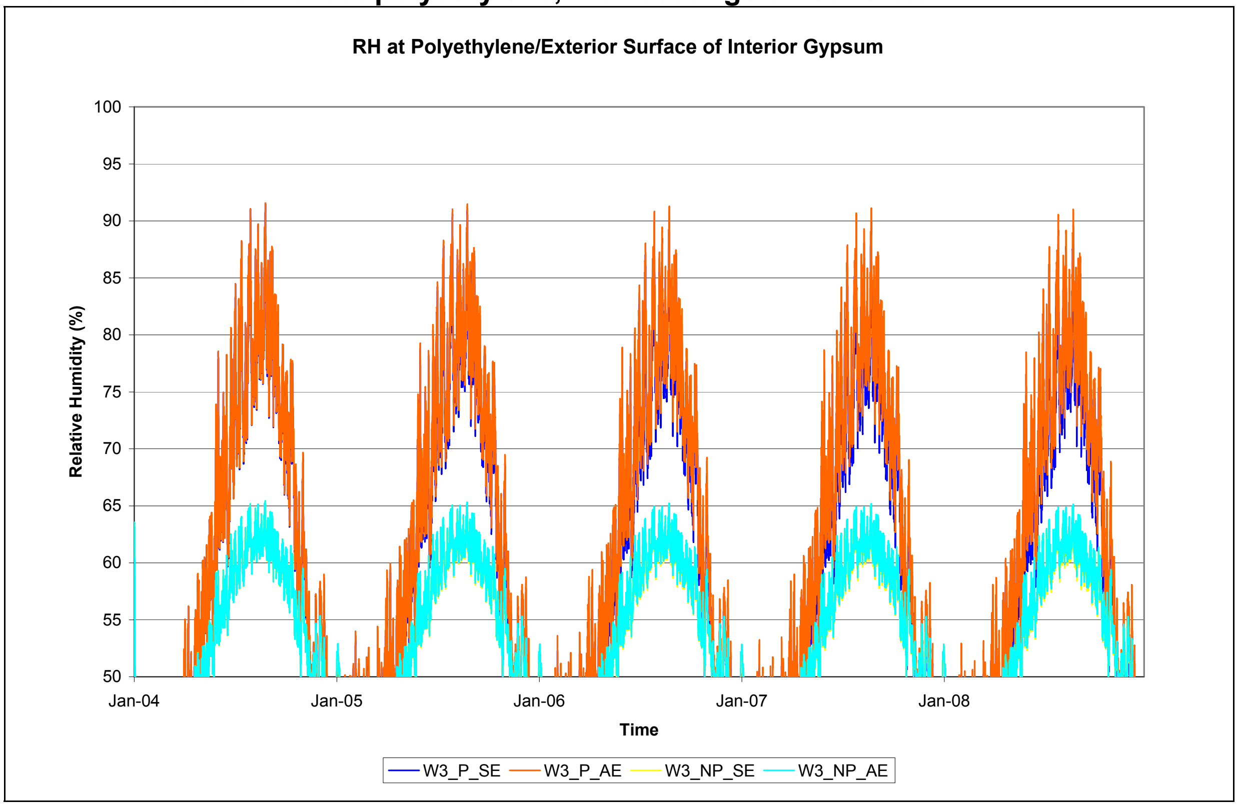


Figure 3.6f: Comparison of RH at polyethylene/exterior gypsum board surface for wall W3 with and without polyethylene, with coatings on concrete.

THERMAL ANALYSIS RESULTS

Boundary Conditions

The 2.5% January design temperatures were used for the exterior boundary condition for the thermal modeling. The 2.5% January design temperatures for various locations in Vancouver are shown in Table C4.

Table C4. 2.5% January design temperatures for Vancouver. (National Building Code of Canada, 1995).

Location	2.5% January Design Temperature
Vancouver Airport	-7°C
Vancouver (Granville Street & 41st Avenue)	-6°C
North Vancouver	-7°C
West Vancouver	-8°C

When analyzing thermal performance, it is useful to also consider average winter temperatures to assess the likelihood of condensation occurring for prolonged durations. Thus models were conducted with two exterior temperatures, -6°C to reflect the 2.5% January design temperature and 0°C to reflect a typical winter temperature expected for Vancouver.

The interior boundary condition was set at a constant temperature of 21°C for all simulations.

Results

The thermal modeling results are presented in the form of colour isotherms in the following figures. Thermal conductivity values are from the 2001 ASHRAE Fundamentals, except for glazing assemblies. The thermal conductance values of the glazing was determined with Window 5, a window thermal modeling program developed by Lawrence Berkeley National Laboratories.

Analysis

A method of determining allowable limits for condensation formation on window frames and glazing was developed for this study. The convention, RH_{allow}, denotes the maximum interior relative humidity allowable to avoid condensation forming on interior surfaces. Realistically, minor amounts of condensation forming on window surfaces during extreme winter weather conditions is not sufficient to lead to damage to the building envelope. An additional convention, RH_{max}, is used to denote the maximum interior relative humidity before serious condensation will occur. In this analysis, a significant amount of condensation was considered to be covering the bottom 50 mm of the glazing, when the exterior temperature is the 2.5% January Design temperature.

Using these two conventions, RH_{allow} and RH_{max}, a relationship between interior relative humidity and exterior temperature is created using a condensation potential index, I. I is determined using the following relationship:

$$I = (\text{Temperature}_{frame} - \text{Temperature}_{Exterior}) \div (\text{Temperature}_{Interior} - \text{Temperature}_{Exterior}).$$

The resulting relationship can be explained graphically, as shown in the Figure C4. It is assumed that the interior temperature is kept constant at 21°C. The two curves present the allowable interior conditions of relative humidity for various exterior temperatures. These curves were used to determine the RH_{allow} and RH_{max} values presented in the tables summarizing the thermal analysis of window sill openings.

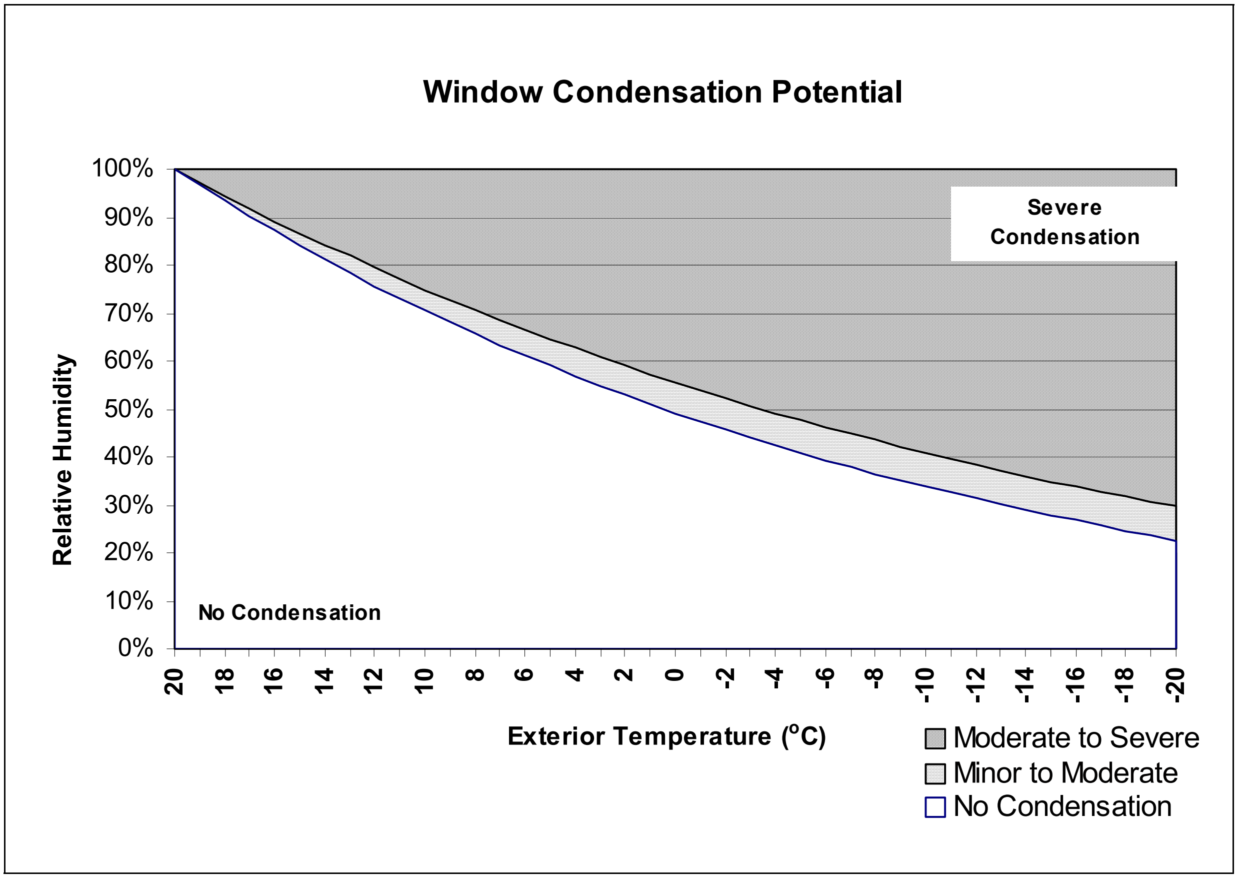
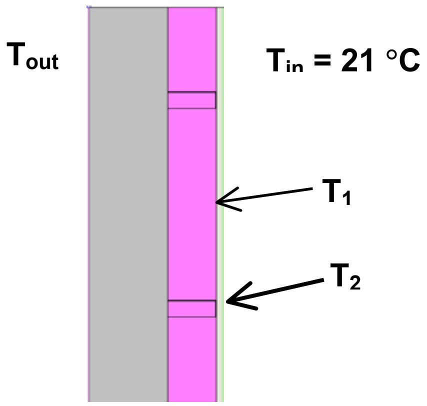


Figure C4: Condensation potential for varying temperature and humidty conditions and a window I value of 50

Table C5: Interior wall surface temperatures for different wall assemblies

<table>
<tr><td colspan="2">Typical Wall Plan View

</td><td colspan="2"><u>Wall Assembly Materials</u>

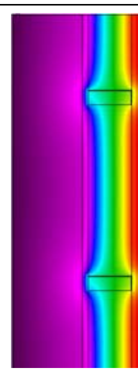
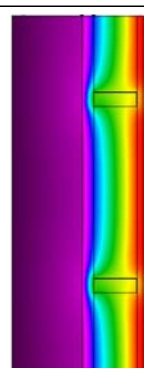
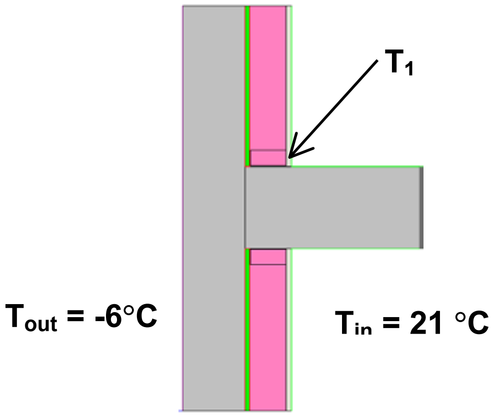
6” Concrete
Airspace
25mm XPS (optional)
89 mm Batt Insulation
26 Gauge Steel Studs
12.5 mm Gypsum Wallboard</td><td><u>Thermal Conductivity</u> (W/mk)
1.14
0.07
0.029
0.036
45
0.16</td></tr>
<tr><th>Description</th><th>Colour Isotherm</th><th>T_{out} (°C)</th><th>T_1 (°C)</th><th>T_2 (°C)</th></tr>
<tr><td rowspan="2">Steel studs in contact with concrete wall.</td><td rowspan="2"></td><td>-6</td><td>20.1</td><td>16.2</td></tr>
<tr><td>0</td><td>20.3</td><td>17.2</td></tr>
<tr><td rowspan="2">A 12.5 mm airspace provided between the insulation and steel studs and the concrete wall.</td><td rowspan="2"></td><td>-6</td><td>20.1</td><td>16.5</td></tr>
<tr><td>0</td><td>20.4</td><td>17.5</td></tr>
<tr><td rowspan="2">A 25mm layer of rigid board insulation placed between the steel studs and batt insulation layer and the concrete.</td><td rowspan="2"></td><td>-6</td><td>20.3</td><td>18.2</td></tr>
<tr><td>0</td><td>20.5</td><td>18.8</td></tr>
</table>

Table C6: Interior wall surface temperatures for different wall assemblies, with and without eyebrows (slab extensions)

Floor Slab to Wall Section	Wall Assembly Materials	Thermal Conductivity (W/mk)
	6" Concrete Wall	1.14
	50mm XPS (optional) or,	0.029
	89 mm Batt Insulation or,	0.036
	67 mm Batt Insulation and 25 mm XPS	0.039
	26 Gauge Steel Studs	45
	12.5 mm Gypsum Wallboard	0.16
	Carpet and Underlayment	0.092

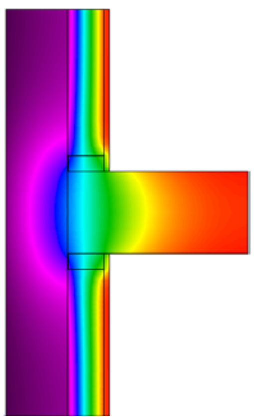
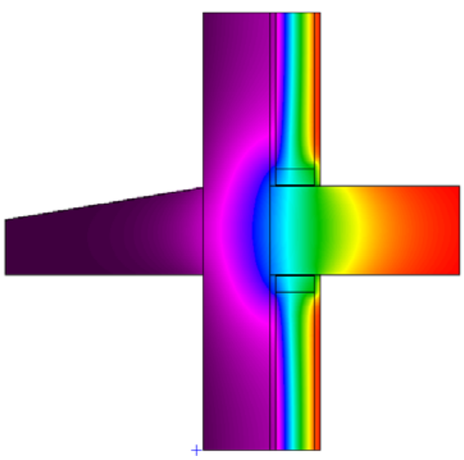
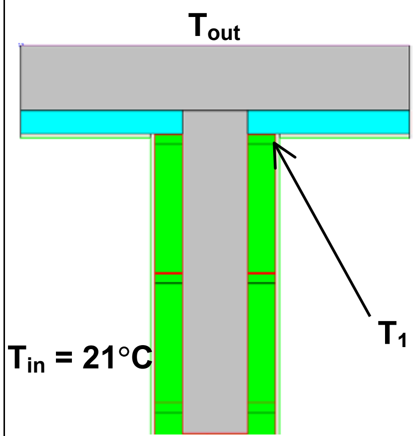
Without Eyebrow	**Wall Type**	**T_1**
	W1	12.3
	W2	12.1
	W3	12.9
With Eyebrow	**Wall Type**	**T_1**
	W1	12.4
	W2	12.1
	W3	13.2

Table C7: Interior wall surface temperatures for differing depths of insulation in partition wall

Partition Wall Intersection Plan



Wall Assembly Materials	Thermal Conductivity (W/m·k)
6" Concrete	1.14
25mm XPS	0.029
Airspace	0.07
89 mm Batt Insulation	0.036
26 Gauge Steel Studs	45
12.5 mm Gypsum Wallboard	0.16

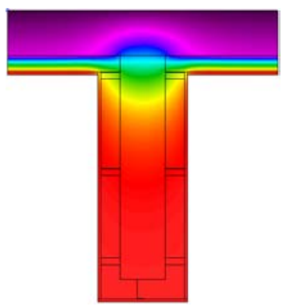
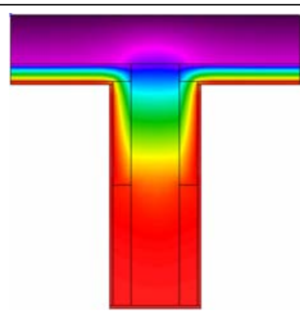
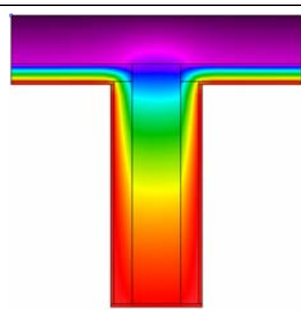
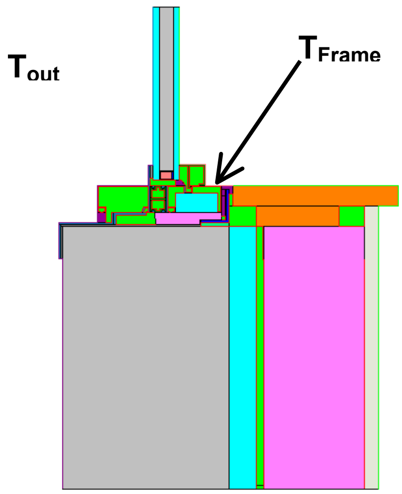
Description	Colour Isotherm	T_{out} (°C)	T_1 (°C)
No insulation is placed along the length of the partition wall, as shown in the diagram above.		-6	17.7
		0	18.5
400 mm of insulation is placed along the partition wall.		-6	19.1
		0	19.7
914 mm of insulation is placed along the partition wall.		-6	19.1
		0	19.7

Table C8: Interior window frame temperature for differing window positions within opening

Window Sill Section	Assembly Materials	Thermal Conductivity (W/m·k)
	Double Glazing	U = 2.754 W/m^2 ·k
	Aluminum Window Frame	160
	Silicone sealant	0.35
	Wood Sill	0.14
	150 mm Concrete	1.14
	25mm Exp. Polystyrene	0.29
	12.5mm Airspace	0.07
	89 mm Batt Insulation	0.036
	26 Gauge Steel Studs	45
	12.5 mm Gypsum Wallboard	0.16

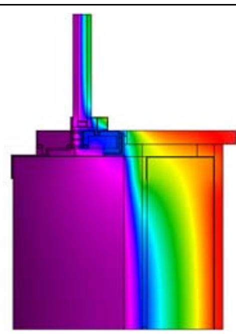
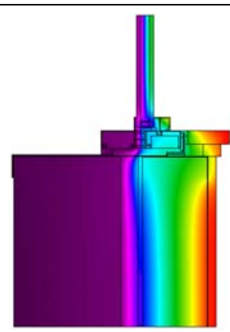
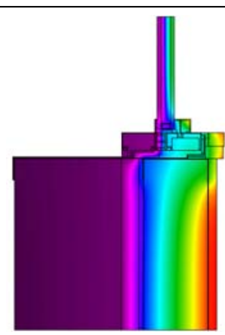
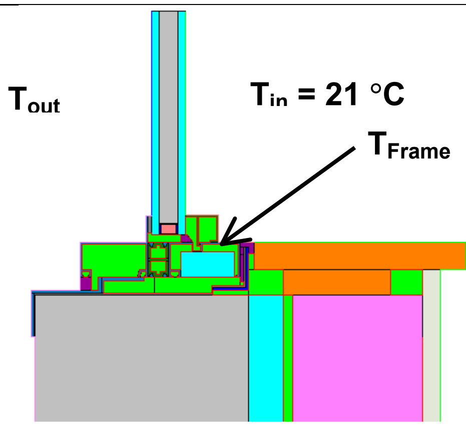
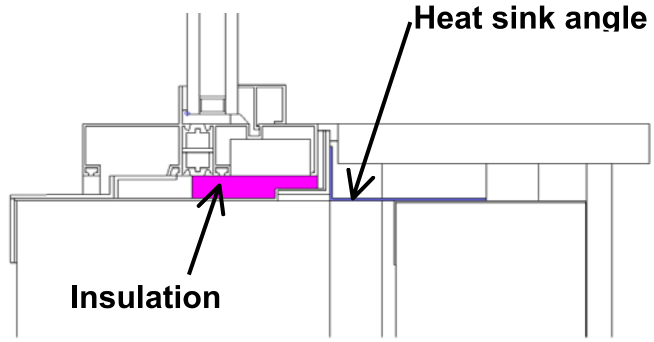
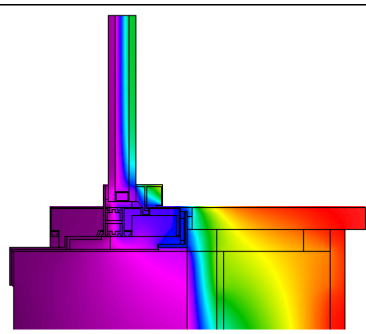
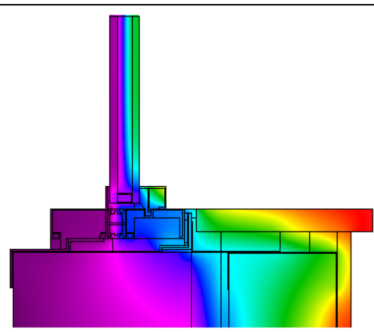
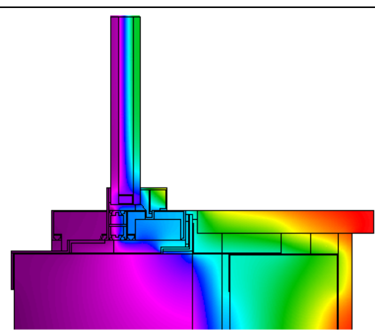
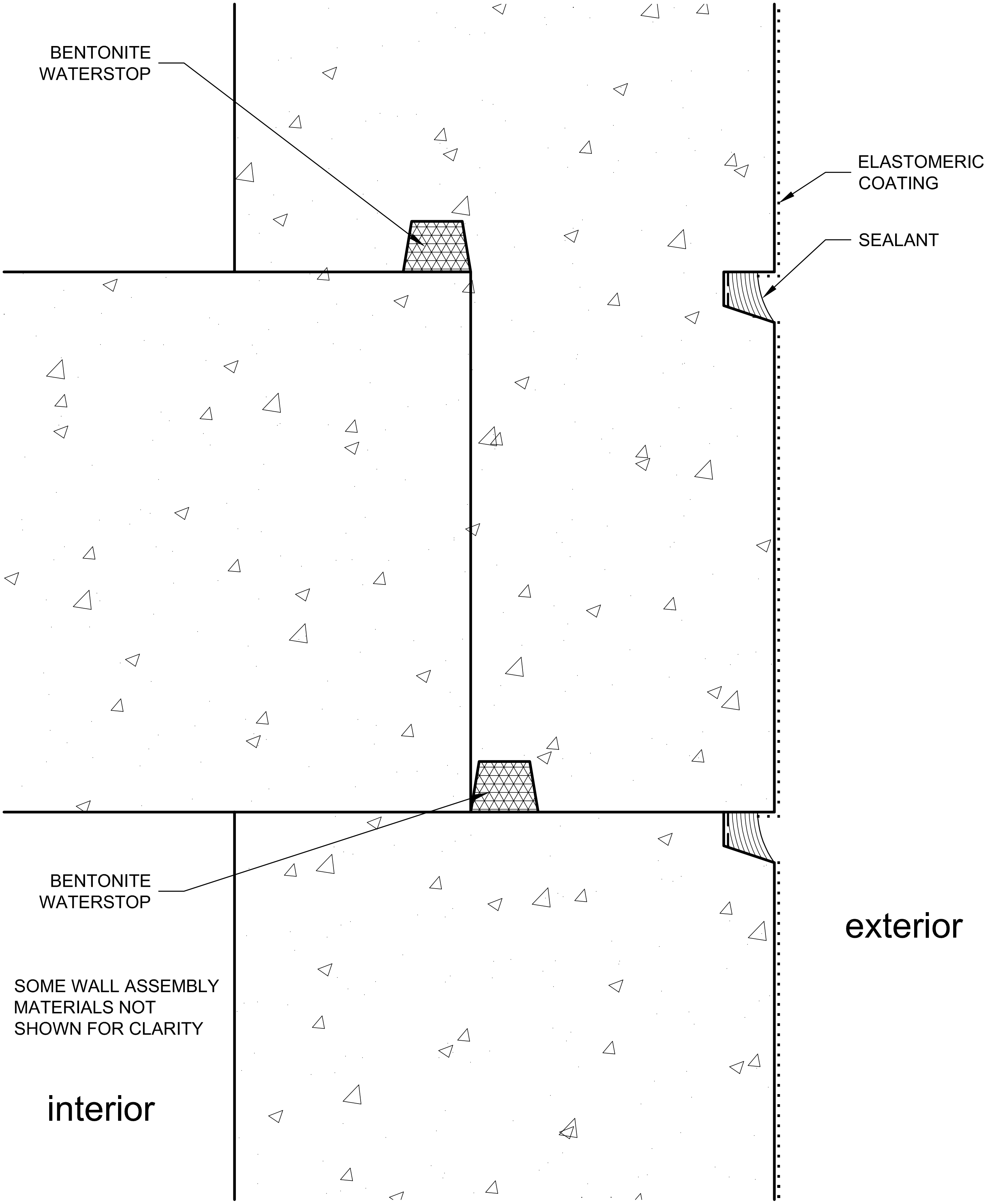
Description	Colour Isotherm	T_{out} (°C)	T_{Frame} (°C)	RH_{allow} (%)	RH_{max} (%)
Window sill aligned with the concrete, insulation is placed between sill frame and concrete		-6	3.0	31	44
		0	7.0	41	54
Window sill aligned with the interior surface of the insulation layer		-6	6.6	40	45
		0	9.7	50	55
Window Sill Aligned with the insulation layer		-6	7.0	41	46
		0	10.0	51	55

Table C9: Interior window frame temperatures, maximum and allowable relative humidity, with or without heat sink angle and/or insulation between frame and rough opening



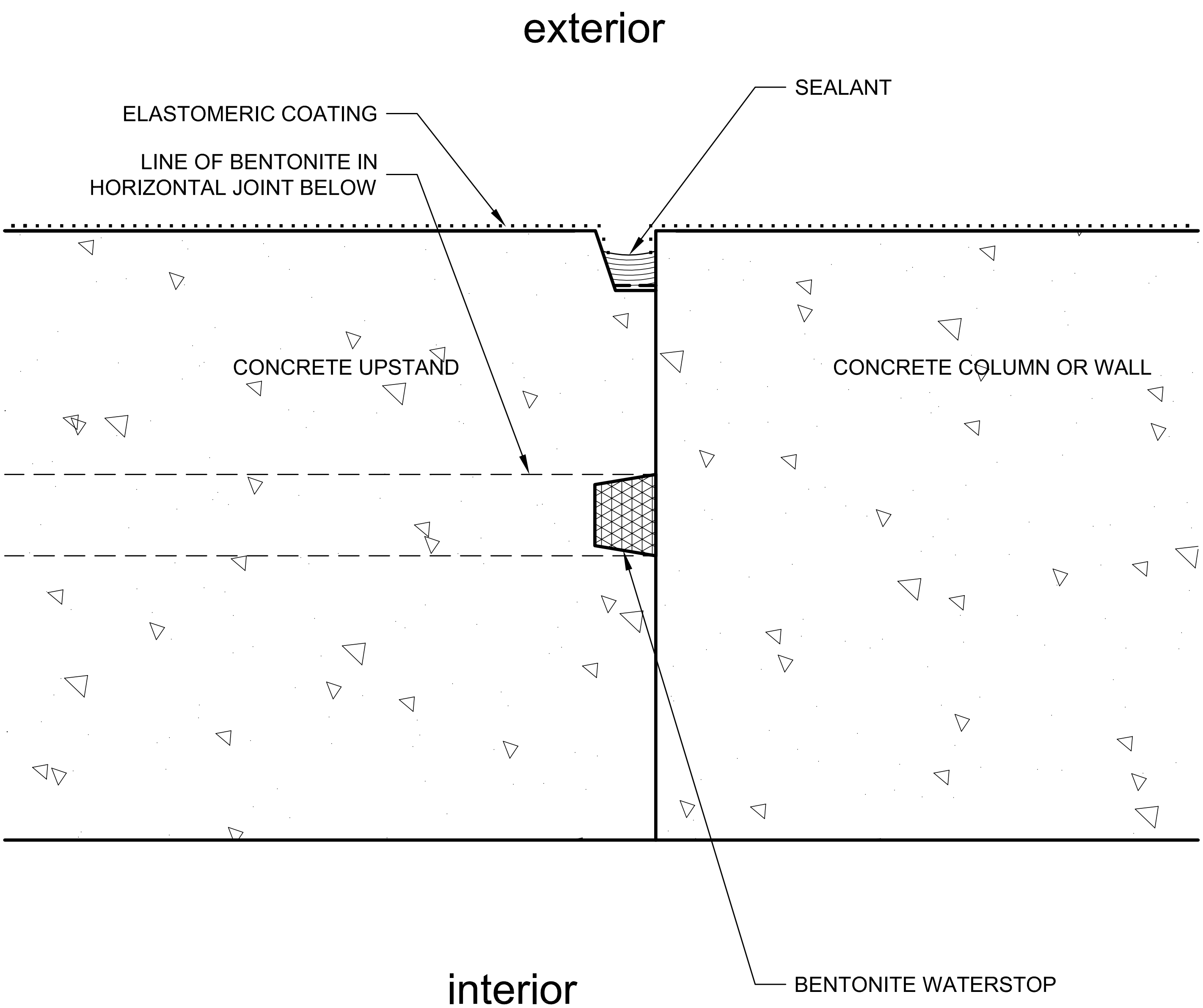


Description	Colour Isotherm	T_{out} (°C)	T_{Frame} (°C)	RH_{allow} (%)	RH_{max} (%)
Typical Sill with no insulation between frame and the concrete.		-6	2.0	29	44
		0	6.2	39	54
Typical sill with heat sink angle installed providing contact between sill angle and steel stud supports.		-6	4.1	34	45
		0	7.8	44	54
Typical sill with heat sink angle installed and insulation between the sill frame and the concrete.		-6	5.3	36	45
		0	8.7	46	54



SECTION

RDH Building Engineering Ltd. 224 WEST 8TH AVENUE VANCOUVER BC V5Y 1N5 TEL 604 873 1181 FAX 604 873 0933 VAN@RDHBE.COM WWW.RDHBE.COM	DRAWING TITLE: HORIZONTAL CONSTRUCTION JOINT	DRAWING NO.: SK1
	DETAIL IS PROVIDED TO ILLUSTRATE CONCEPTS OF EFFECTIVE WATER PENETRATION CONTROL. IT IS NOT INTENDED FOR USE ON ACTUAL PROJECTS WITHOUT DUE CONSIDERATION OF ALL RELAVENT DESIGN FACTORS.	



SOME WALL ASSEMBLY MATERIALS
NOT SHOWN FOR CLARITY

PLAN

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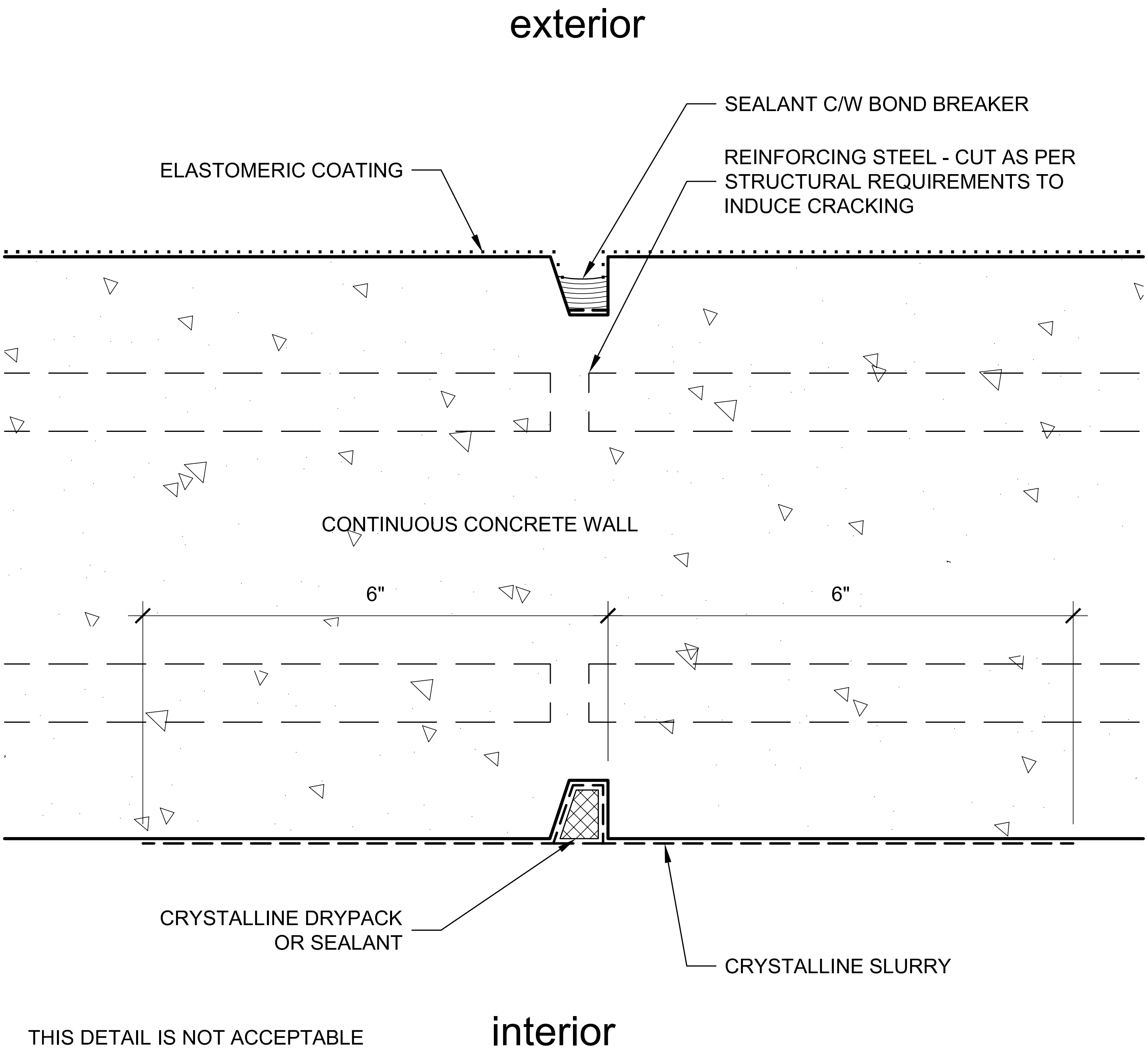
DRAWING TITLE: VERTICAL CONSTRUCTION JOINT

DRAWING NO.: SK2



THIS DETAIL IS NOT ACCEPTABLE FOR TRANSITIONS BETWEEN FULL HEIGHT WALLS AND UPSTANDS

SOME WALL ASSEMBLY MATERIALS NOT SHOWN FOR CLARITY

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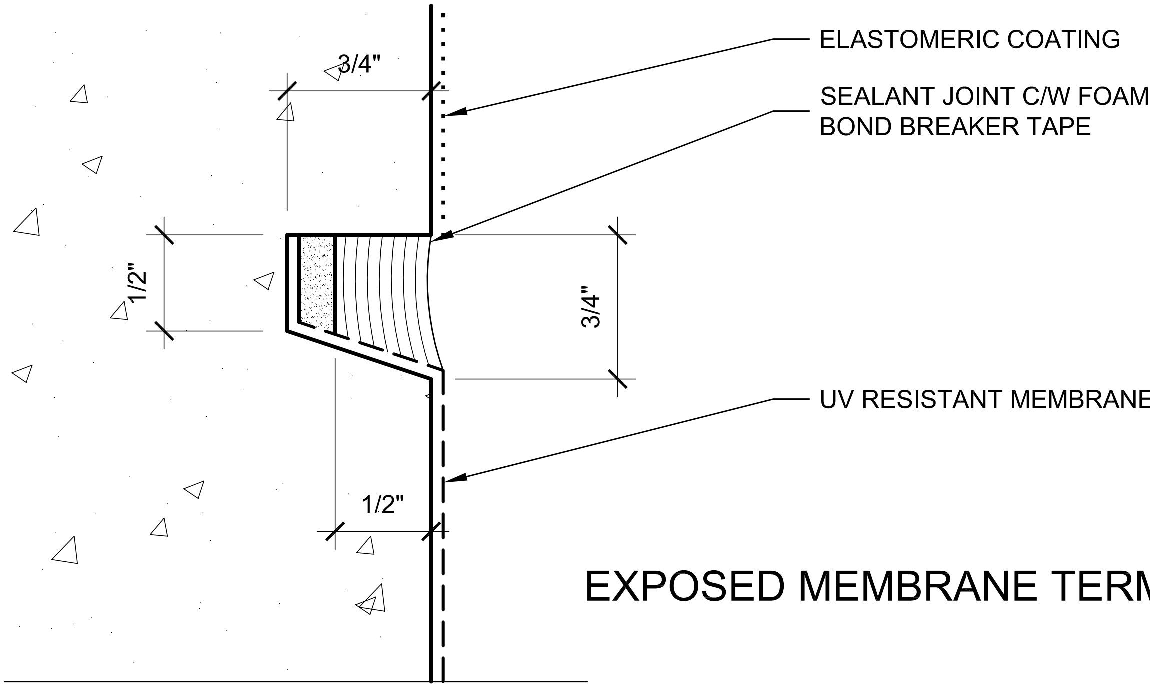
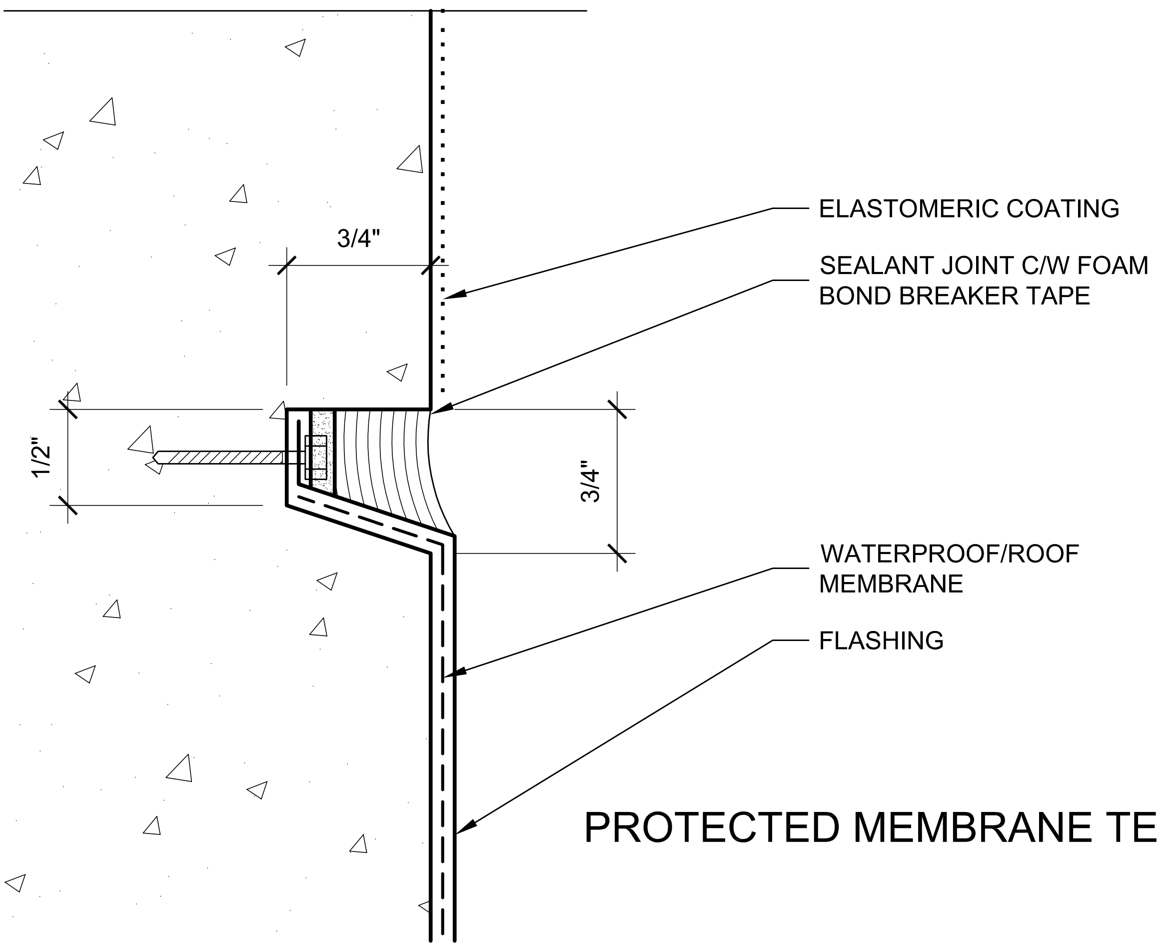
DRAWING TITLE: VERTICAL CONTROL JOINT

DRAWING NO.: SK3



EXPOSED MEMBRANE TERMINATION



PROTECTED MEMBRANE TERMINATION

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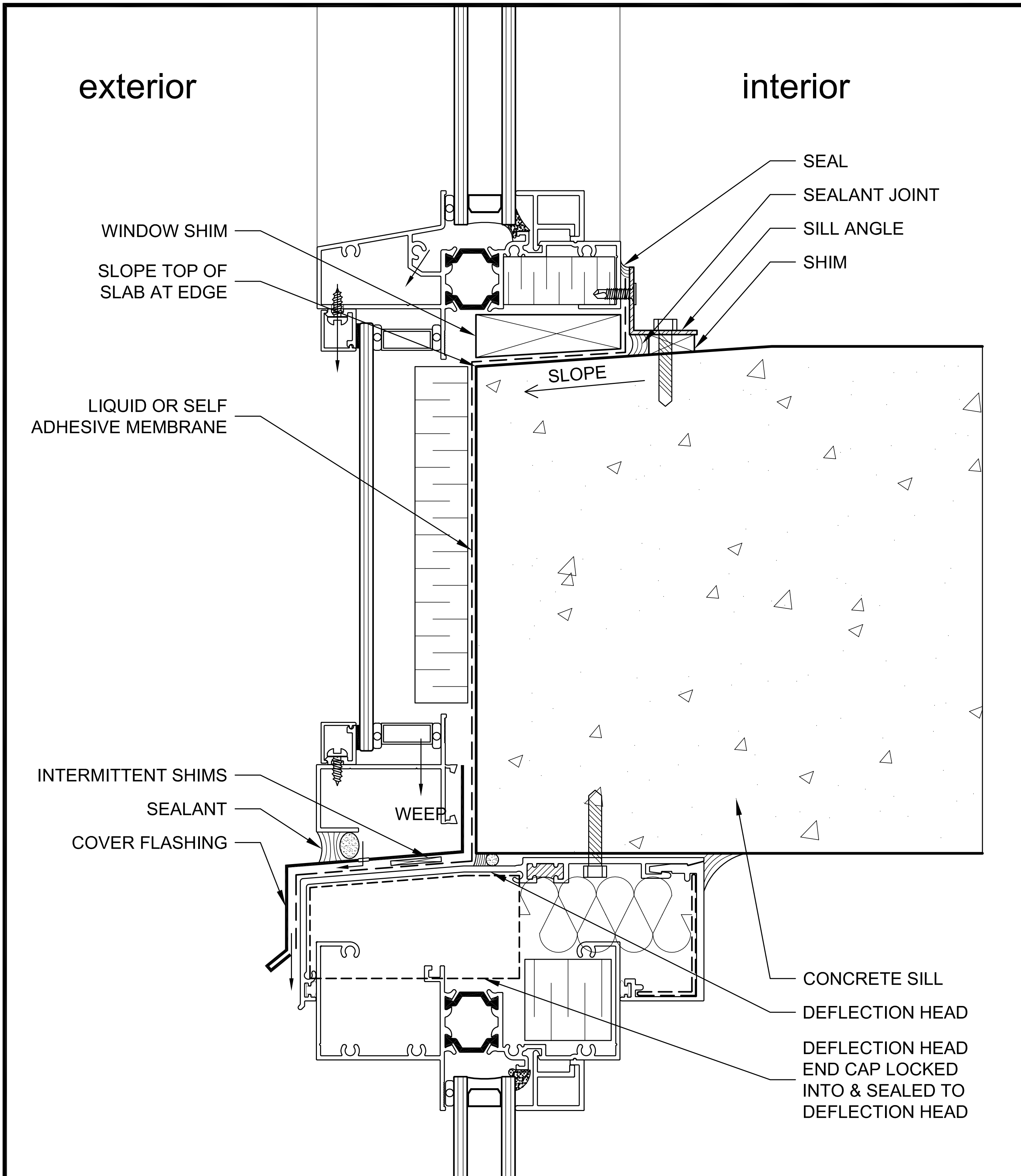
DRAWING TITLE: TYPICAL MEMBRANE TERMINATIONS

DRAWING NO.: SK4

DETAIL IS PROVIDED TO ILLUSTRATE CONCEPTS OF EFFECTIVE WATER PENETRATION CONTROL. IT IS NOT INTENDED FOR USE ON ACTUAL PROJECTS WITHOUT DUE CONSIDERATION OF ALL RELAVENT DESIGN FACTORS.



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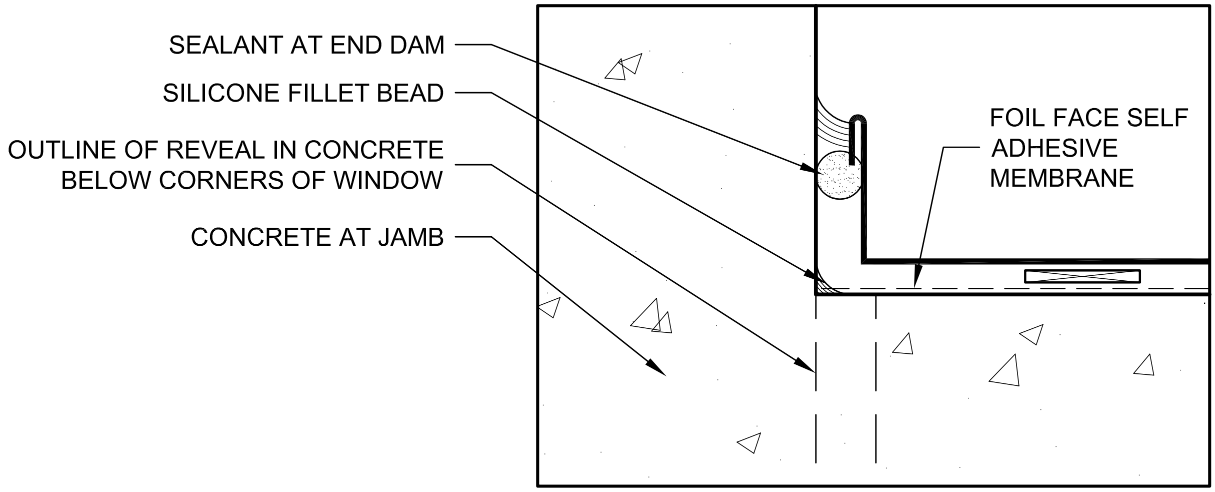
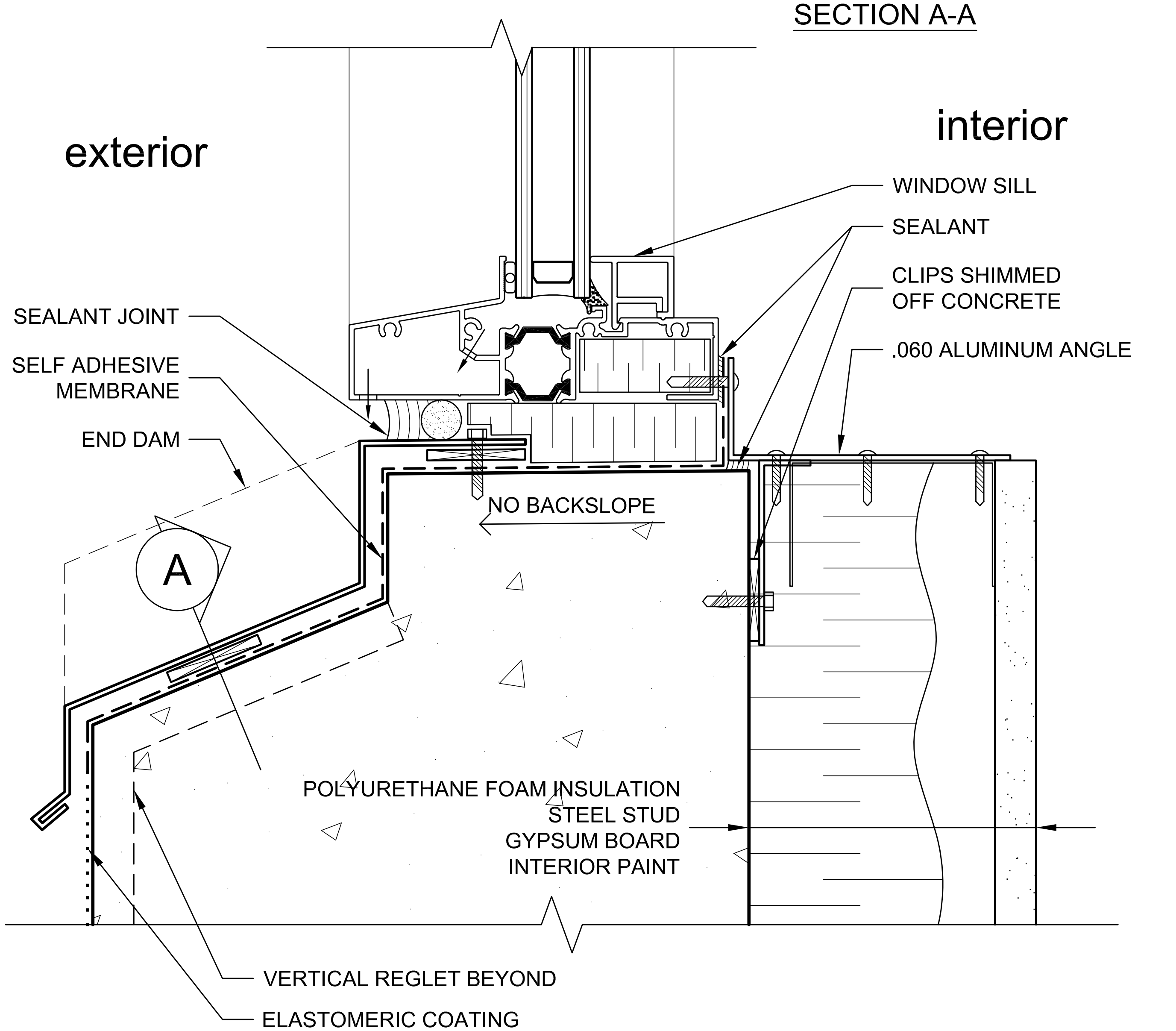
DRAWING TITLE: WINDOW-WALL BYPASS

DRAWING NO.: SK5



SECTION A-A



SECTION

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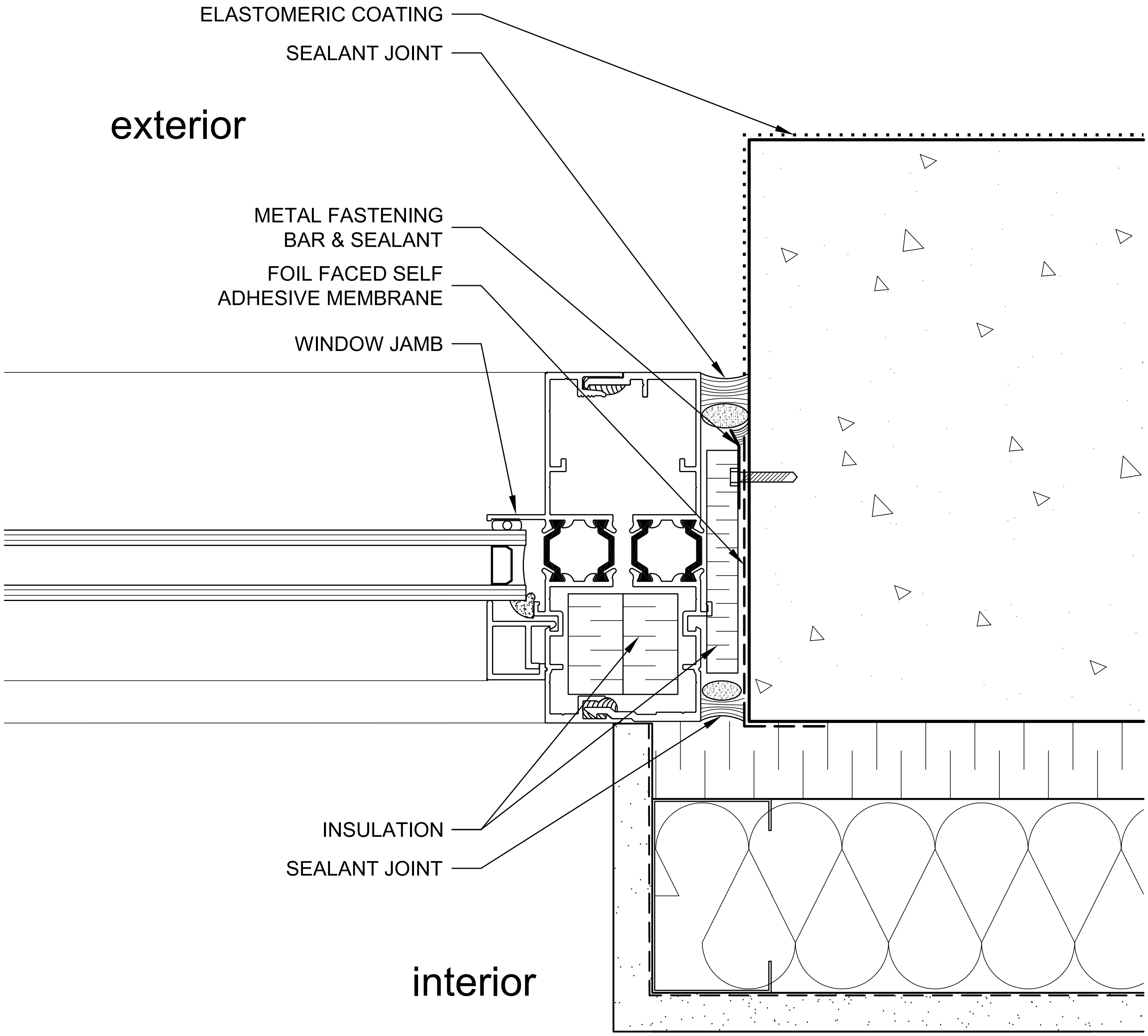
DRAWING TITLE: WINDOW SILL

DRAWING NO.: SK6

DETAIL IS PROVIDED TO ILLUSTRATE CONCEPTS OF EFFECTIVE WATER PENETRATION CONTROL. IT IS NOT INTENDED FOR USE ON ACTUAL PROJECTS WITHOUT DUE CONSIDERATION OF ALL RELAVENT DESIGN FACTORS.



PLAN

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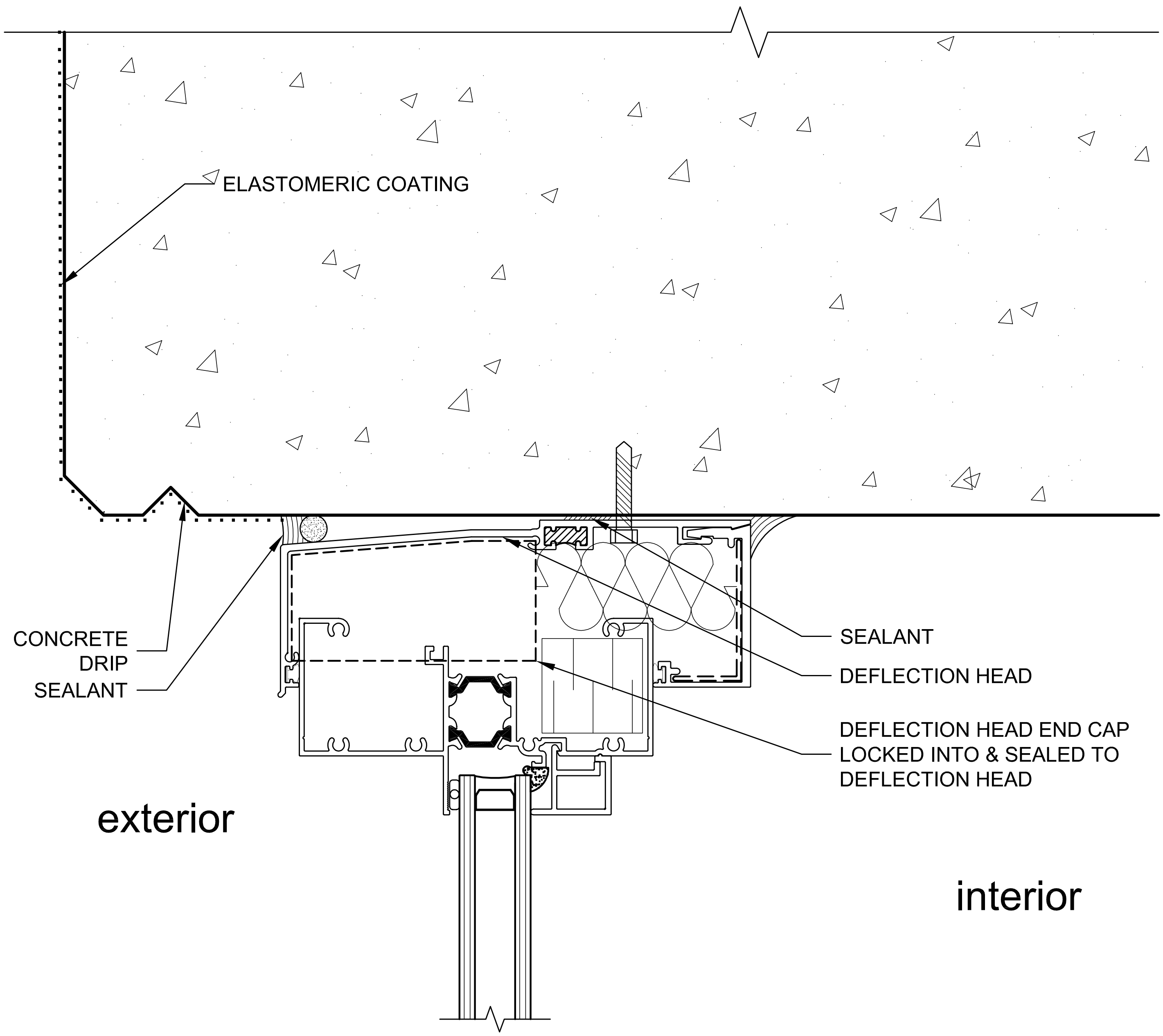
DRAWING TITLE:	DRAWING NO.:
WINDOW JAMB	SK7

DETAIL IS PROVIDED TO ILLUSTRATE CONCEPTS OF EFFECTIVE WATER PENETRATION CONTROL. IT IS NOT INTENDED FOR USE ON ACTUAL PROJECTS WITHOUT DUE CONSIDERATION OF ALL RELAVENT DESIGN FACTORS.



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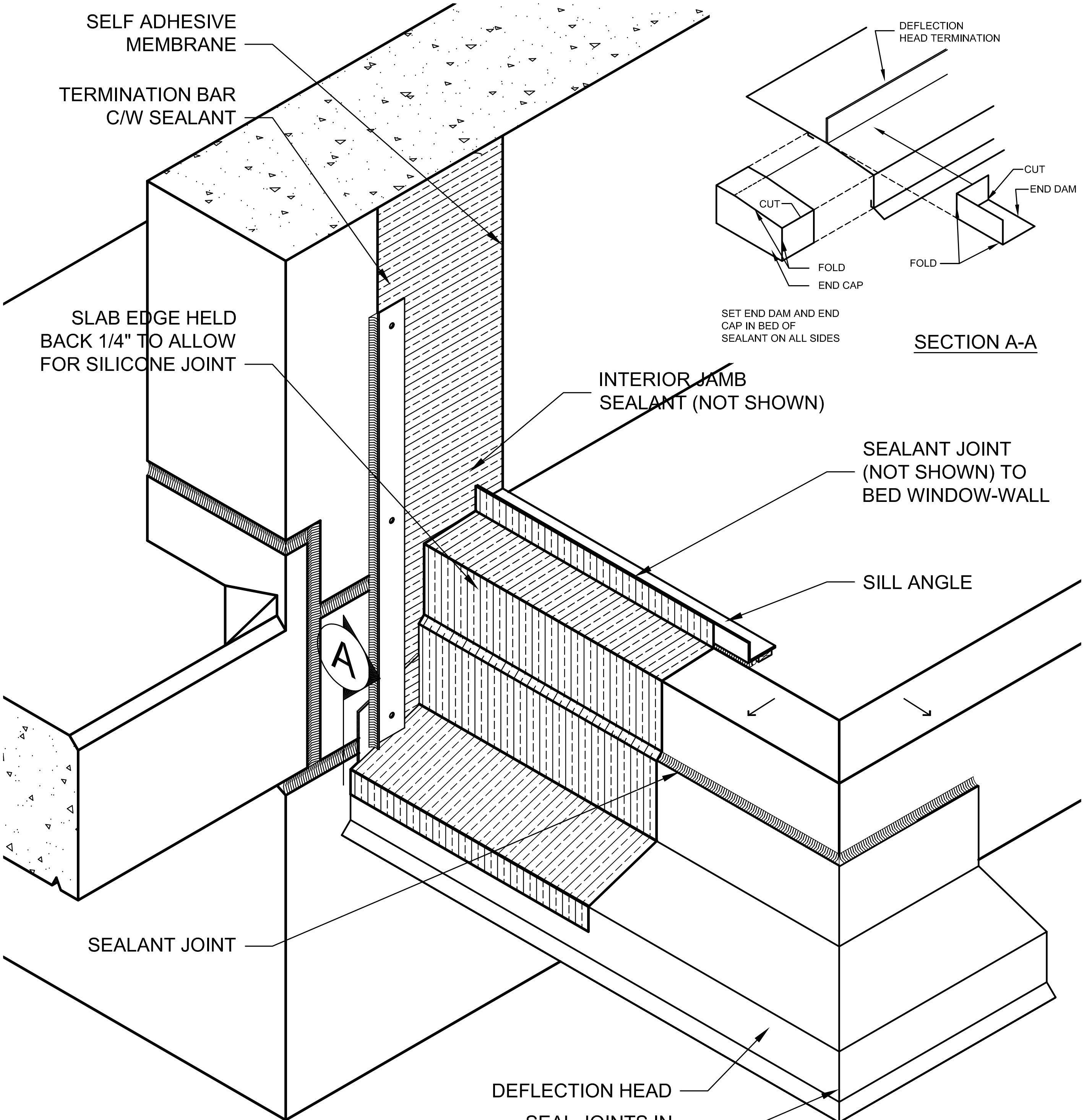
DRAWING TITLE:	DRAWING NO.:
WINDOW HEAD	SK8

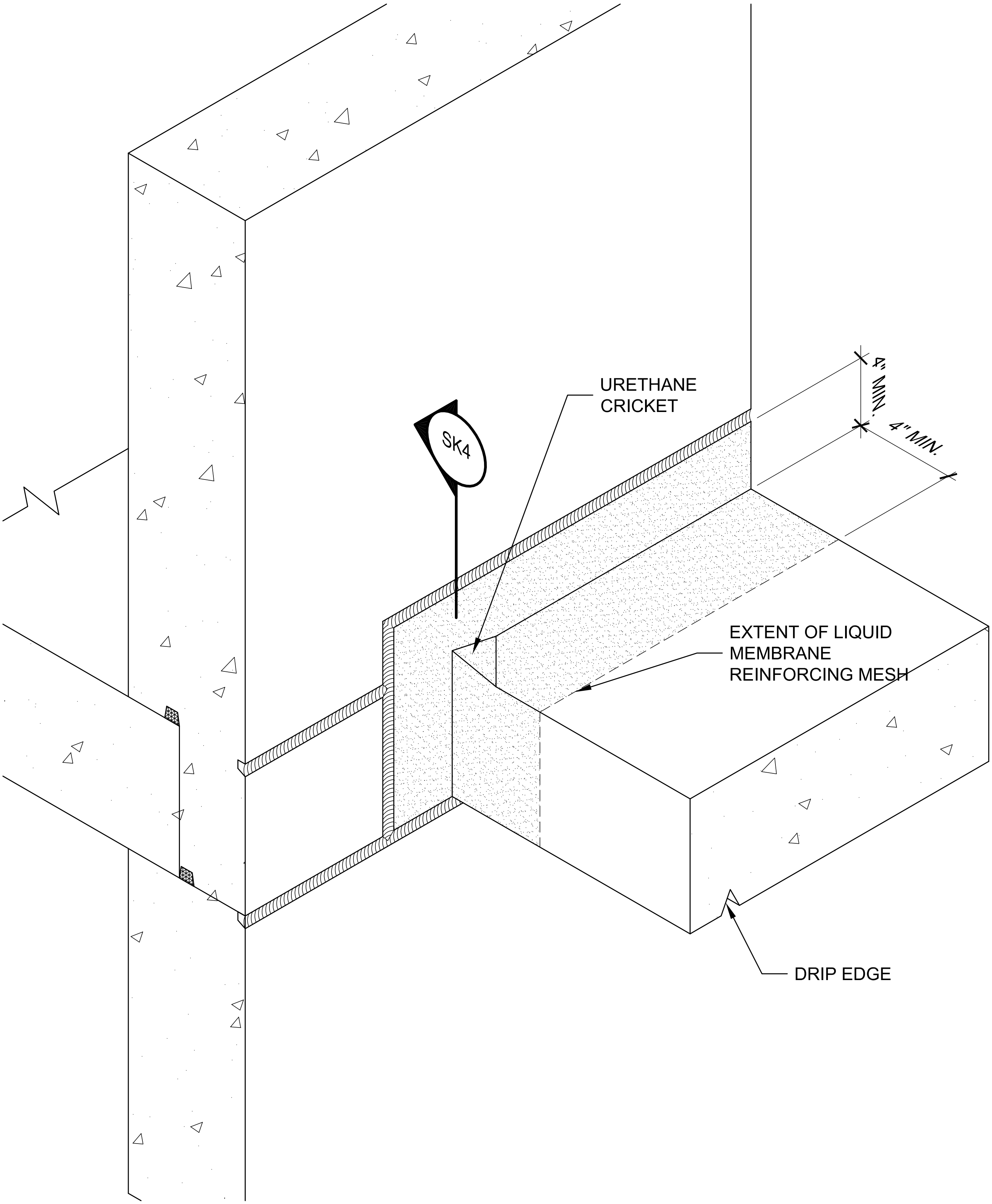
DETAIL IS PROVIDED TO ILLUSTRATE CONCEPTS OF EFFECTIVE WATER PENETRATION CONTROL. IT IS NOT INTENDED FOR USE ON ACTUAL PROJECTS WITHOUT DUE CONSIDERATION OF ALL RELAVENT DESIGN FACTORS.



NOTE:
EXTERIOR SEALANTS NOT SHOWN FOR CLARITY

ISOMETRIC

RDH Building Engineering Ltd. 224 WEST 8TH AVENUE TEL 604 873 1181 VAN@RDHBE.COM VANCOUVER BC V5Y 1N5 FAX 604 873 0933 WWW.RDHBE.COM	DRAWING TITLE: WINDOW-WALL BYPASS TERMINATION AT WALL	DRAWING NO.: SK9
	DETAIL IS PROVIDED TO ILLUSTRATE CONCEPTS OF EFFECTIVE WATER PENETRATION CONTROL. IT IS NOT INTENDED FOR USE ON ACTUAL PROJECTS WITHOUT DUE CONSIDERATION OF ALL RELAVENT DESIGN FACTORS.	



ISOMETRIC

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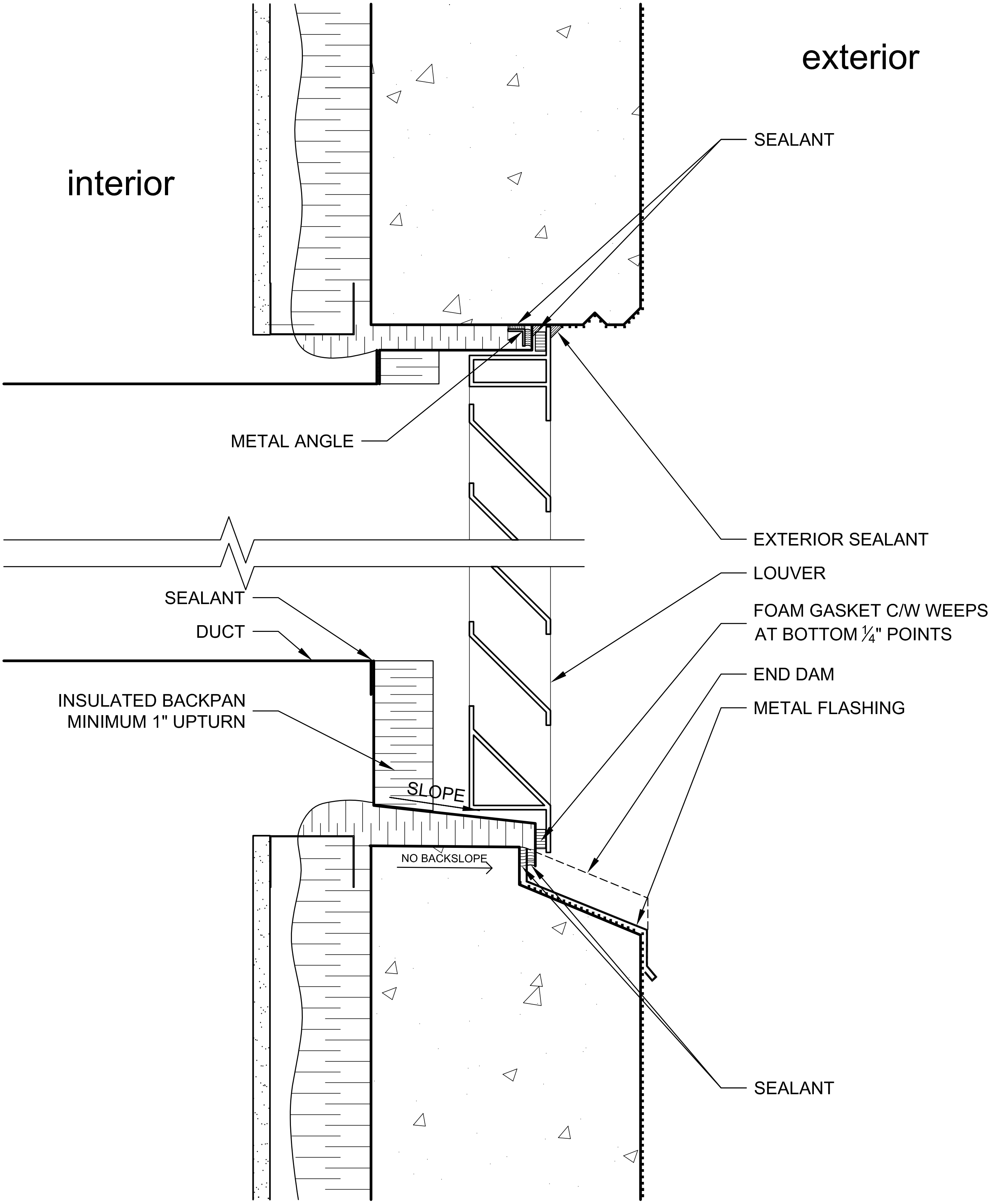
DRAWING TITLE: BALCONY MEMBRANE TERMINATION

DRAWING NO.: SK10



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DRAWING TITLE: LOUVER PENETRATION

DRAWING NO.: SK11

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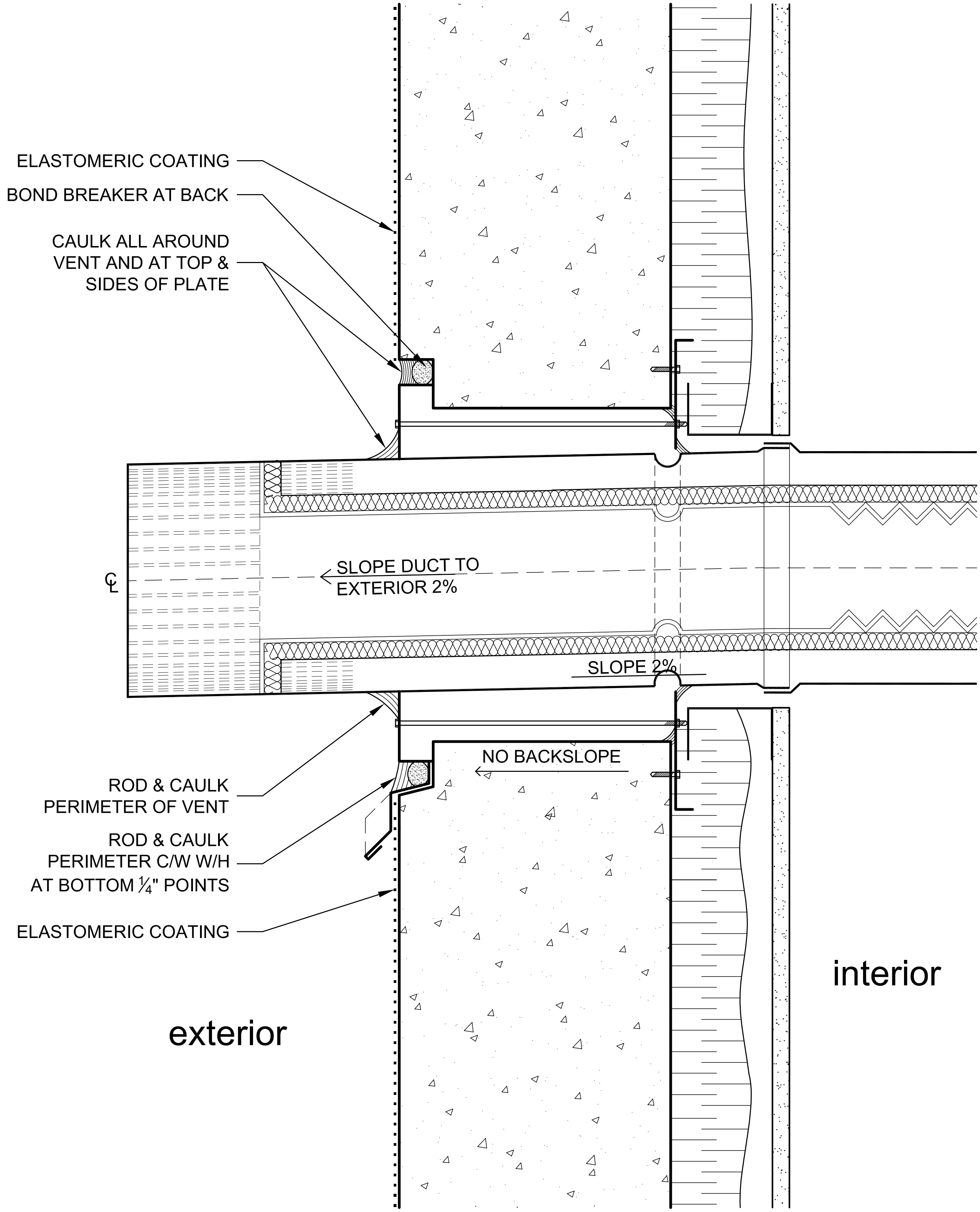

SECTION

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DRAWING TITLE: FIREPLACE VENT PENETRATION

DRAWING NO.: SK12

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