RESEARCH HIGHLIGHT

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

Rainscreen wall and window assemblies are now being used in coastal British Columbia because they provide improved water penetration control properties and acceptable long-term performance. A recent trend has seen builders and the design community increasingly utilize lower cost poured-in-place concrete wall assemblies, without rainscreen, in combination with rainscreen windows to provide acceptable long-term envelope performance. In contrast to the acceptable performance history of uninsulated mass masonry walls, there is very little information regarding the performance history of insulated poured-in-place concrete wall assemblies. There is little significant guidance available with respect to the best design and construction practice for them. In order to better understand the performance of this form of construction, Canada Mortgage and Housing Corporation (CMHC) and Homeowner Protection Office (HPO) commissioned a study to analyze and document potential performance questions associated with poured-in-place concrete wall assemblies, as well as develop a guideline for appropriate design and construction practices. The primary objectives of the study are as follows.

- Identify and investigate key performance questions associated with components and materials utilized with poured-in-place concrete wall assemblies in multi-unit residential construction. In all, four existing buildings and five new projects were reviewed.
- Analyze heat, air and moisture control requirements of Part 5 of the building code for poured-in-place concrete wall assemblies, including water penetration control, air leakage, vapour diffusion, thermal performance and durability of materials.
- Examine several specific aspects of construction practices (including exterior coatings, concrete mix, crack control and joint detailing) that impact the performance characteristics of poured-in-place concrete wall assemblies.
- 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.

WALL ASSEMBLIES

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 poured-in-place wall assemblies, as shown in Figure 1, are examined and analyzed with respect to various performance issues in this study.

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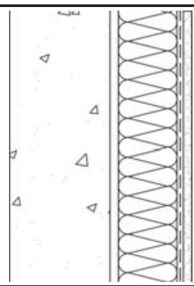
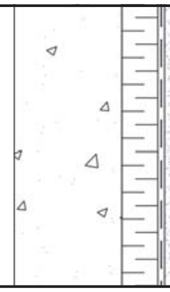
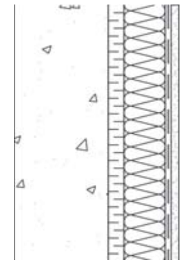
 **W1**	 **W2**	 **W3**
Exterior 150 mm concrete (with or without coating) 13 mm airspace 92 mm steel studs and batt insulation 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior	Exterior 150 mm concrete (with or without coating) 50 mm Extruded Polystyrene (XPS) with integral T-shaped steel supports (Alternate assembly of this type would utilize spray-in-place polyurethane foam instead of XPS) 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior	Exterior 150 mm concrete (with or without coating) 25 mm XPS 64 mm steel studs and batt insulation 0.15 mm polyethylene film 13 mm gypsum board and interior finishes Interior

Figure 1: Commonly Constructed Poured-in-Place Wall Assemblies

FIELD INVESTIGATION OF PERFORMANCE

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 1, without prioritizing, summarizes these 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

Table 1: Summary of Performance Issues

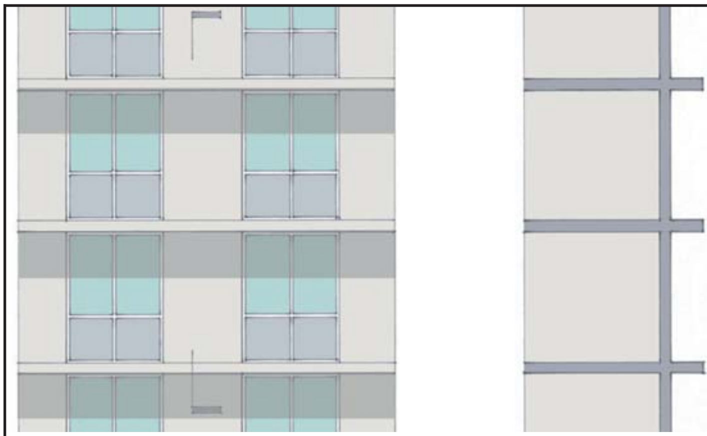
PERFORMANCE OBJECTIVES AND PRIORITIES

The successful long-term performance of a poured-in-place concrete wall clearly involves achieving many performance objectives. The control of heat, air and moisture flows (both vapour and rain) are important but the wall assembly must also be durable, constructible and maintainable.

Rain penetration control should be considered a priority performance criterion since achieving this objective is not easy in the B.C. 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.

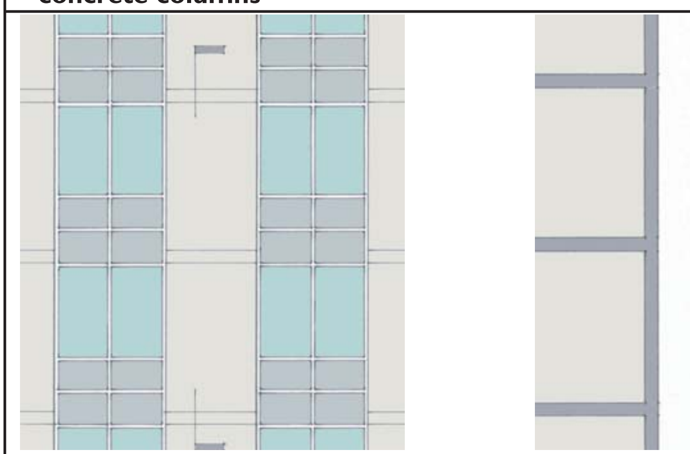
BUILDING FORM

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. 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 (Figure 2). 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.



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 AND 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.

Figure 2: Alternate arrangements of projections and poured-in-place concrete wall configurations create differing levels of risk of water penetration

RAIN PENETRATION CONTROL

Poured-in-place concrete walls by their nature are unable to provide redundancy in the same way that rainscreen walls provide redundancy in the prevention and remediation of water penetration. This suggests a need to understand the implications of design and construction practice on risk of water penetration in environments where the wall is subjected to regular wetting.

The first line of water penetration resistance for the monolithic concrete wall area 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 it 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 a second line of resistance 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 to the building interior.

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

- 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 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 joints or have crystalline grout installed from the interior.

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.

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. 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.

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 air movement through intersecting partition walls, electrical outlets and other penetrations through the stud wall assembly and possibly through a dropped ceiling assembly.

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 and 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 and provides a relatively continuous thermal insulation layer within the wall to reduce the impact of the highly conductive steel studs.

Rain which penetrates the poured-in-place concrete to accumulate within the wall will generally overwhelm the ability of any wall assembly to dry to the interior through vapour diffusion. Furthermore, excess water which is allowed to diffuse as a vapour to the inside can, in the absence of controlled ventilation, present the risk of excessive dampness indoors. Excessive dampness indoors contributes to problematic health exposures[1]. Thus, 'drying to the inside' is not a realistic strategy to manage moisture in poured-in-place concrete wall assemblies. Vapour retarders restrict the movement of vapour through the wall. Polyethylene as a vapour retarder limits the inward migration of moisture so that mold growth on the gypsum board next to the occupied space is less likely to occur.

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. Issues such as thermal bridging and condensation risk pose design challenges in poured-in-place walls. 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.

It is clearly beneficial to design wall assemblies to ensure 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.

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 was performed to assess the effect of the window recess on condensation potential. 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. One such 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.

Thermal Performance at Intersecting Partitions

A series of thermal simulations conducted for a partition wall intersecting an exterior concrete wall showed that 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

[1] "Damp Indoor Spaces and Health," Institute of Medicine, National Academy of Sciences, 25 May 2004

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.

Thermal Performance at Intersecting Floor Slabs

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. It was found that the thermal bridging that occurs at these eyebrow areas generally created very little difference in interior surface temperatures when compared to a wall without an eyebrow projection. Insulating flooring such as carpeting or raised hardwood will lower the surface temperature of the concrete and thus increase the risk of condensation. Control of the interior operating conditions (temperature, relative humidity through mechanical ventilation) is imperative in managing condensation risk in poured-in-place concrete buildings.

Ventilation and Heating System Considerations

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 10 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.

SUMMARY OF HYGROTHERMAL AND THERMAL ANALYSIS

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 2 summarizes conclusions reached following the analysis of these assemblies.

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.	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.
5.	Polyethylene or other interior vapour retarders help control winter wetting in W1 but prevent drying in the summer.
6.	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.
7.	Wall assembly types W2 and 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.
8.	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.

Table 2: Summary of Observations From Hygrothermal and Thermal Analysis

CONCRETE CONSTRUCTION PRACTICES

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

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 detailed in Chapter 21 of CSA-A23.1 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.

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 water-cement 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.

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.

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

- 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

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 onto which the coating can bond. 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.

CONCLUSIONS

Poured-in-place concrete walls have historically provided an acceptable level of performance in multi-unit residential buildings where performance issues have been addressed using appropriate design and construction practices. The 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 water leakage at cracks and joints is an important source of performance problems in poured-in-place concrete wall construction.

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Research Report: Study of Poured-in-Place Concrete Wall Assemblies in Coastal British Columbia

Research Consultant: RDH Building Engineers Limited

CMHC undertook this study in partnership with the Homeowner Protection Office.

Housing Research at CMHC

Under Part IX of the *National Housing Act*, the Government of Canada provides funds to CMHC to conduct research into the social, economic and technical aspects of housing and related fields, and to undertake the publishing and distribution of the results of this research.

This fact sheet is one of a series intended to inform you of the nature and scope of CMHC's research.

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