International Building Lime Symposium 2005
Orlando, Florida, March 9 -11, 2005

3E WALL FOR ALL CLIMATES: PART 1. THE PROBLEM [*]

Mark Bomberg[1], Marcin Pazera[2], and Paul Ellringer[3]

Abstract

Moisture-originated failures in stucco-clad walls have been reported in the coastal climate of the Canadian Province of British Columbia as well as in the cold climates of Alberta and Minnesota. Damages are often attributed to poor design and water penetration at windows, balconies and walkways. Yet, there is a misconception about moisture control of exterior stucco (rendering) systems. Despite the recent failures, the authors postulate that wood-framed walls with stucco cladding placed on an exterior insulation over oriented strand board (OSB) protected by water-resistive barrier (WRB), and with cellulose fiber insulation within the wall framing can be one of the most economical and ecologically-justified systems that will perform well in most climates. This 3E wall system is designed for energy efficiency, environmental control and ecological responsibility. However, the approach in which building envelopes (BE) are currently designed must be changed.

Key words: portland cement plaster, rendering, exterior stucco**,** moisture-originated damage, durability

---

[1] Syracuse University, Syracuse, NY, mbomberg@syr.edu
[3] Syracuse University, Syracuse, NY
[4] Air Tamarack, St. Paul, MN, paul@airtamarack.com

1 Introduction

Recently, moisture-originated structural failures of exterior rendering on houses were reported in coastal climates such as Maritimes, British Columbia and states of Washington and North Carolina, as well as in the cold climates of Alberta and Minnesota. Exterior rendering on masonry buildings has an excellent history of performance in Europe. In North America, 30-year-old wood-frame houses also perform satisfactorily. So, perhaps something slowly, but systematically, occurred that changed many of the service conditions so that the current multitude of failures resulted.

This paper postulates that a wood or steel frame wall with rendering placed on exterior insulation and water resistive barrier (WRB), with the framing cavity filled with thermal insulation having sufficient moisture storage (e.g., cellulose fiber), can be one of the most economic and ecologically-justified systems. Furthermore, a system with an appropriately selected type of WRB (selected in relation to climate and service conditions) will exhibit adequate performance. This claim is made despite the list of field damages and failures discussed below.

To prove their point, the authors will review several areas of technical considerations:

- Typical exterior rendering on oriented strand board (OSB) sheathing on wood-framed walls
- Moisture management strategy and hygrothermal properties of rendering materials
- Probable causes of current moisture-originated damage and reported failures
- Historic mortars and renderings as the blueprint for modern exterior rendering
- Typical design mistakes and ways to eliminate them
- A conceptual proposal for 3E wall design that also includes architectural design and “required” technical parameters for the exterior rendering

The paper comes in two parts: the first part reviews the state-of-the-art; the second part proposes specific solutions.

2 Exterior rendering (stucco) on wood frame walls

Portland cement plaster (PCP), exterior stucco and rendering are terms that are used interchangeably. The following section of this paper describes a generic rendering system and, in particular, its application on wood-based sheathing in framed wall construction.

2.1 Substrate

Wood-based sheathing, exterior grade gypsum or other sheathing materials can be used. To reduce shrinkage and deformations, the moisture content of wood-based products should be 19 percent or less. Furthermore, plywood and OSB boards (1/2 or 5/8 inch) should be positioned with their long axis along the studs and a 3-mm (1/8 in) gap at the vertical and the horizontal joints to allow for moisture-originated movements. Often, sheathing boards of a thinner grade (3/8 in) are positioned horizontally to increase stiffness. In the latter case, horizontal gaps between sheathing sheets will reduce air-tightness of the wall and may result in deficient moisture performance, unless adhered air barrier strips or an appropriate air barrier membrane is used.

2.2 Water resistive barrier (WRB)

To provide an additional protective measure (redundancy in the assembly), a WRB is required behind the rendering system. The WRB can be one of the following classes:

- class C (asphalt-impregnated cellulose fibers), known as building paper
- class P (polymeric fibers), traditionally known as building wrap
- class PP (perforated polymeric sheets), known only under various trade marks
- class M (micro-porous films), new type of material (see Bomberg et al 2003a)
- class ML (multilayered polymeric films), new type of material
- class LA (liquid-applied), new type of material.

Typically, the WRB layer retards the passage of water. Some products will perform as a vapor barrier, but most are breathable. The required degree of vapor permeance depends on the climate. Research (Bomberg et al, 2003) and practical experience highlight the advantages of using two layers of WRB next to each other, rather than being guided by their laboratory test rating. (Note that the specification for building paper, or #15 felt, was introduced to National Building Code of Canada in 1941).

2.3 Metal-lath

This reinforcement should always be used with non-masonry substrates that do not provide satisfactory bond or crack-bridging ability of the rendering. A number of metal-lath types are used: expanded-metal lath (diamond mesh), woven-wire mesh, self-furring lath, or welded-wire lath. Flat and self-furring expanded metal laths are the oldest and most proven types of rendering reinforcement. The second type, rib metal lath, can be used either flat or with two sizes of ribs (9 and 19 mm or $^3/_8$" and ¾"). These types of metal lath are cut and expanded from steel sheets, then coated with rust-inhibiting paint following the fabrication process. Plain wire fabric lath (with or without self-furring arrangement) is usually fabricated from galvanized wire positioned at 50-mm (2") spacing. The normal woven wire lath that is used in the Western part of the U.S. has 1-½ inch openings and 17 gauge wire. One-coat rendering products normally use 1-inch opening with 20-gauge wire for the lath.

2.4 Rendering materials

In a typical application of the base coat, the thickness of the scratch coat varies between 9 and 12 mm (3/8" to ½'). The second coat (brown coat) is approximately 9 mm (3/8" in) thick. In a fire-rated assembly, the minimum thickness of the base coat must be 20 mm (3/4"), or 23 mm (7/8") if an acrylic finish coat is used.

Table 1. Typical composition of portland cement plaster – 3 coat system

Coat	Volume cement*	Lime Options*	Volume sand	Min thickness	Min. moist cure	Min interval between coats
Scratch	1	¼ or 1	4 or 3	9 mm	48 hours	48 hours
Brown	1	¼ or 1	5 or 4	9 mm	48 hours	7 days
Finish**				3 or 6 mm		

NOTES:

* Hydrated lime (or equivalent lime putty) can be used as a plasticizing agent (¼) or as the binder (1). A mix of ½ masonry cement and ½ regular portland cement (either type I or type II) can be used to increase compressive strength development and minimize cracking.

** In the Southern and Western parts of the U.S., the finish coat is comprised of 1/8" (3 mm) of a non-polymer-modified portland cement-based finish. Some believe that a coat as thin as 3 mm requires the use of polymeric cement and approx. 6 mm is preferred for the lime-cement plaster.

In some regions, the amount of lime in the scratch coat is reduced to 50% of its recommended proportion, and about 1 kg of 13-mm long fibers (fiberglass, polypropylene, nylon etc) are added. Polymer-modified rendering is then used as the brown coat, and polymer-modified or polymer-based (acrylic) rendering is used as the finish coat. This, however, is not a normal practice in the Western and Southwestern U.S., where polymer addition is rarely used.

2.5 Sand in the plaster

Because of exposure, the sand cannot have more than: 8% of its particles smaller than 0.05 mm, 1% of sulfates (when recalculated to $S0_3$), a trace of organic pollution but none if color is used, and 20% of its grains larger than 2 mm. For manufactured finishes, the sand grain size is seldom larger than 2 mm.

2.6 Aggregate in the plaster

When made from a job site mix, the aggregate should have minimum compressive strength of 4 MPa, average grain size of 2 mm for a fine finish, 3 mm for a middle finish, and 8 mm for a coarse texture.

2.7 Lime

Lime (without sulfates or chlorides) is completely slaked; the lime must be without any grains. The use of hydrated lime is preferred.

2.8 Sequence of rendering layers

Rendering is always applied from the strongest (scratch coat) to the weakest (finish coat). This sequence is necessary to ensure an increasing rate of vapor diffusion towards the exterior surface and to prevent warping of the rendering.

Shrinkage of the rendering, when measured between day 1 and day 28, varies between 0.3 and 0.5% and, to some extent, depends on the type of substrate used. Rendering made of lime or weak lime-cement mortars do not normally experience large shrinkage cracks. To establish bond between a cement-rich mortar and a dry substrate, the substrate may need to be wetted.

2.9 Framing members

Typically, wood framing members that are nominal 2x4 in (39 mm x 89 mm) or 2x6 in (39 mm x 140 mm) are used. Similar sized metal framing is used, with a minimum base metal thickness of 0.8 mm (0.033 in), or 20 gauge. Plastering practice is based on a maximum wall deflection of L/ 360 (typically L/240). Wood or steel joist systems are expected to have a solid rim joist around the perimeter.

3 Moisture management of exterior stucco systems

Control joints are normally tied or attached to the lath while the WRB runs continuously (with proper overlaps) behind the lath. Therefore, any water reaching the WRB would drain to the base of the wall and out the drip screed. One may question however, if water would run downwards for more than a few feet before being re-absorbed into the stucco. Therefore, the wall with exterior stucco is normally classified as having a concealed barrier (dual barrier).

3.1 General considerations

Rendering itself provides significant resistance to the ingress of water. The amount of water passing through the rendering layer and coming into contact with the WRB is very small. The WRB, placed between the exterior plaster and sheathing board, is tested and classified according to the duration of time that it resists water penetration. However, this concept is vague and the actual classification depends on the test method used. Incidental water that penetrates through cracks or discontinuities in the cladding, e.g. through the wall /window interface, may either be absorbed by the rendering or directed along the WRB down to the flashing. In their 1936 publication, Metal Lath Manufacturers Association of Chicago required that:

> "*Before application of metal lath for stucco work metal flashing shall be applied at water tables, over all door and window openings, wherever projecting wood trim occurs, at ends of sills, and at all horizontal courses and elsewhere wherever water might remain on or get behind stucco."*

This statement is as important today as it was 70 years ago.

Another important property of the rendering is its drying ability, which traditionally has been estimated by its water vapor permeance. However, this criterion alone is not sufficient. Drying rate of a stucco system, which consists of material layers, depends on both permeance and moisture storage of each layer. Furthermore, drying rate depends on the forces driving the moisture out of the rendering, i.e. boundary conditions (temperature, air movement, relative humidity). Therefore, the following material characteristics must be considered: (1) wetting ability of the rendering, (2) drainage ability of the rendering, (3) water vapor permeance of each layer in the rendering system, and (4) moisture storage in the rendering system.

These characteristics can either be considered individually or lumped into parameters that affect rate of wetting or drying. Independently of how the moisture characteristics are selected, they are affected by a number of construction-related variables. These variables include the type of rendering (number of coats), the dry mix composition (portland or mortar cement, lime, type of sand etc.), the type and amount of fiber reinforcement (if used), water-cement ratio, temperature and humidity during curing, and other construction-related effects.

3.2 The hygrothermal properties of rendering materials

Four physical characteristics will be used to quantify hygrothermal behavior of rendering under variable wetting and drying conditions:

- *Water absorption coefficient* or A-coefficient (also called capillarity or capillary rise test), is a relation between the cumulative water flow from the free water surface and the square root of time of the free water intake test. It is typically expressed in kg/($m^2s^{1/2}$).

- *Water vapor permeance* is measured by the so-called dry cup test (between 50% RH and desiccant). This test, which is specified in ASTM or CEN, defines the water vapor diffusion through the porous material. Results are reported in permeance (perms or ng/m^2sPa) in North America, but in "mu-values or Z-values" in Europe. The latter are the relation of the material's resistance to water vapor diffusion to the air layer at the same temperature and pressure conditions, or the equivalent thickness of an air layer with the same resistance to water vapor diffusion. This test is often confused with so-called wet cup test method, where a combination of liquid and vapor flows are measured to give an apparent rate of moisture diffusion that is valid only under the actual test conditions.

- *Capillary moisture content* is the maximum moisture content that can be reached in a material under a free water intake test. This value is compared with the total open porosity.

- *Total open porosity (vacuum saturation)* is the moisture content that can be reached in a material subjected to water saturation under vacuum, that is, when air is evacuated from the material and water entry is not blocked by entrapped air.

The significance of the water absorption coefficient (A-coefficient) is self-evident, since it relates to the amount of rain entering the rendering surface. On the other hand, the rate of vapor diffusion from the middle of the material to its surface is governed by the water vapor permeance. The other two concepts are less apparent. They relate to the fraction of porosity that can be used for storage of moisture; or the moisture buffering capacity of the cladding surface. Their values will become more apparent in the last part of this paper, where calculations of moisture profiles in the walls are reported.

Kruger and Eriksson (1925, see Bomberg, 1974), showed that lime-cement mortar containing coarse sand permits water to move faster than the same lime-cement mix containing finer sand particles. However, both permit significantly slower water movement than clay brick alone.

Figure 1 shows cumulative water intake for similar composites plotted as a function of the square root of time. The lime-based rendering transports water much faster than the cement-based rendering. Figure 1 shows changes in water absorption rate for curves 1 and 2, which might be associated with the effect of the second layer in the tested composite. The change in slope indicates that both layers affect the hygric performance of the rendering. In other words, the rendering may control ingress of moisture to the substrate even when the first layer is not tight. This is an important observation because rendering failure is often a result of the assumption that the outer surface of rendering must prevent water entry.

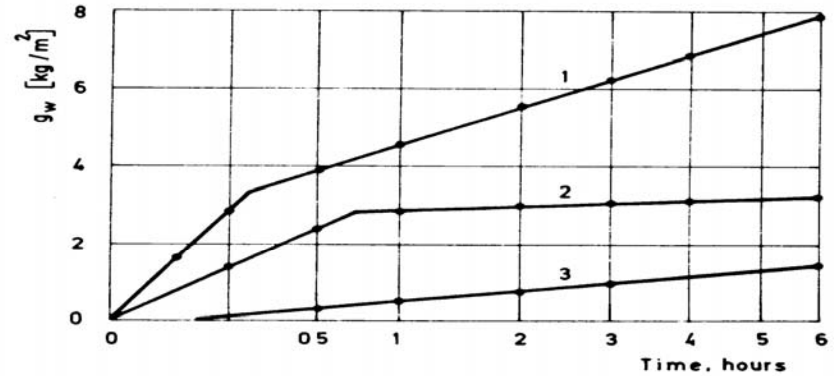

Figure 1. Cumulative water flow, g_w, to clay brick through rendering, plotted against the square root of time in hours. Curve 1 represents lime rendering ($A = 0.07\ kg/m^2s^{1/2}$), curve 2 is lime rendering on a cement-splattered surface, and curve 3 is a cement rendering ($A = 0.01\ kg/m^2s^{1/2}$).

Today's technology permits the ability to design the water absorption coefficient of the material almost independently from its porosity. At the Technical University of Dresden (TUD) (Plagge), test results for several types of renderings show a significant variation in A-coefficient of commercial premixed products. The highest A-coefficient value measured, $0.17\ kg/m^2s^{1/2}$, was for a rendering having a density of about $610\ kg/m^3$, while the lowest value of $A = 0.013\ kg/m^2s^{1/2}$ was measured for a rendering with bulk density of about 500 kg/m^3. On the other hand, A = 0.074 kg/m^{2}s$^{1/2}$ was measured with a material having a density of 1450 kg/m^3.

The highest value measured at TUD agrees well with the lime-cement stucco measured at SU (Figure 2). Yet, the lowest values measured on American products are one magnitude lower than those from the TUD series (Figure 3). Bruckmayer (see Nevander, 1968) showed that lime mortar has a drying rate similar to that of clay brick, while cement mortar dries at a rate similar to that of concrete (about 10 times slower). The stucco used in repairs of German buildings cover the range of drying rate between clay brick and concrete; the tested American finishing coat rate appears one magnitude slower than concrete.

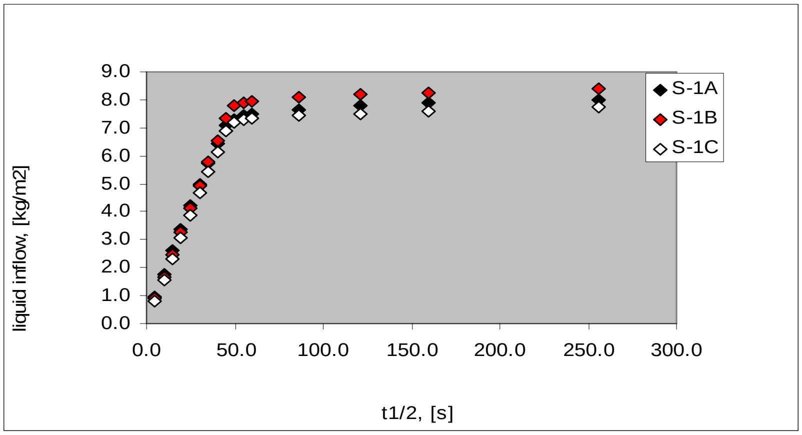

Figure 2. Cumulative water flow into specimens (50x50x50 mm) made on the building site from a brown coat of lime-cement rendering (1: 1: 5.5). Tests performed at Syracuse U gave a mean value of A = 0.16 kg/m^{2}s$^{1/2}$.

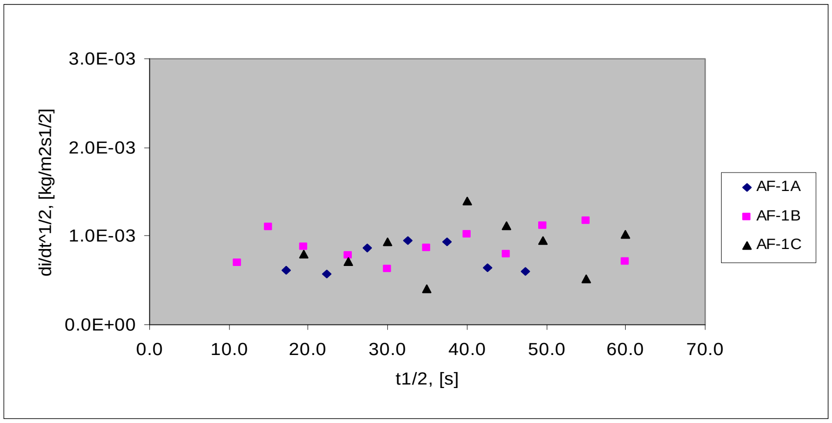

Figure 3. Water absorption coefficient of a proprietary product (acrylic-modified) used for the finish coat in a typical northeast rendering. Tests performed at Syracuse U gave a mean value A = 0.00092 kg/m^{2}s$^{1/2}$. (Note: this does not represent southwest stucco practices).

Results of water vapor permeability testing show a similar picture. The water vapor permeability measured on approximately 19 mm (¾ inch) thick Pacific coast rendering with density between 1550 and 1750 kg/m^3 was approximately 2.45 E-12 kg/(m s Pa) (Karagiozis), corresponding to a permeance of 130E-12 kg/(m^2 s Pa), or 2.3 perms. For comparison, a typical rendering tested at TUD with a mu -value ranging from 5.45 to 14.7 has a permeability value ranging from 13 E-12 to 36 E-12 kg/(m^2 s Pa), or values from 5 to 15 times higher than the Pacific coast rendering.

3.2 Effect of cracks and terminations

One particular aspect of rendering performance is related to the development and propagation of cracks. Our concern is limited to macro-cracks, since micro-cracks have little effect on the rendering performance. Figure 4 illustrates the effect of a crack on water spread.

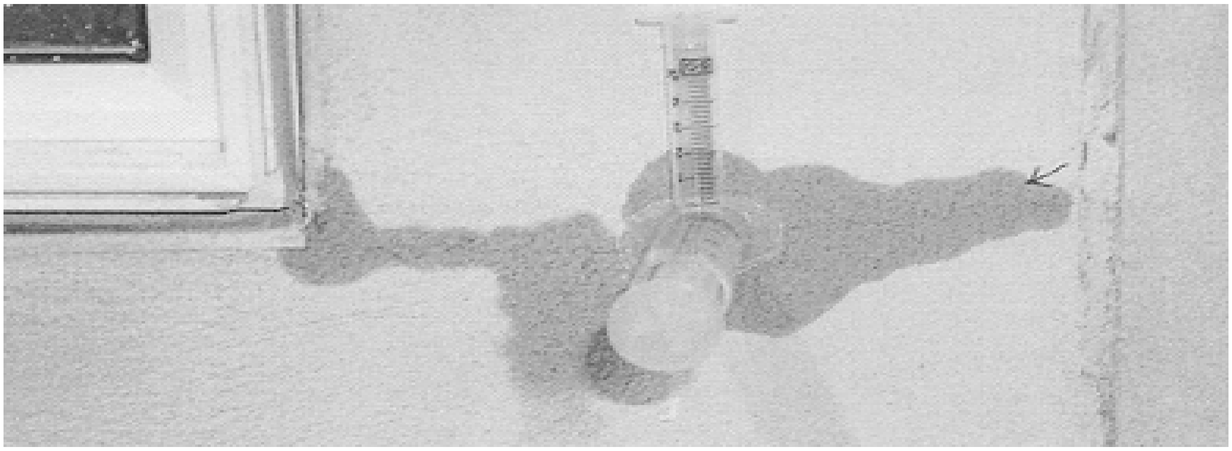

Figure 4. Effect of a crack - water spread along the crack

Cracks are primarily caused by cement plaster shrinkage during initial drying of the material. To minimize shrinkage cracking, conditions of slow and uniform drying and unrestrained deformation must be accommodated. While unrestrained deformation is possible only at rendering edges, this condition should be optimized by detailing rendering terminations in the appropriate fashion. A typical example is rendering termination around windows. The appropriate sealing (caulking on the backer rod, gasket, bead-applied foam and surface finish) should be applied only after primary shrinkage has been completed (see the second part of the paper).

4 Examples of moisture-originated damage on EIFS and stucco clad buildings

Moisture-originated problems in the building envelope (BE) have been a relatively new, but rapidly growing, problem in North American buildings. Instances of failures in coastal and mainland regions of North America have been well documented. In Wilmington, North Carolina, failures in exterior insulation and finish systems (EIFS) were examined by many (Crandell and Kenney, 1996; Brown et al., 1997; 1997a; Williams and Williams, 1998; Williams et al., 1998). Problems in Seattle were discussed by Desjarlais (Desjarlais et. al., 2000). In Vancouver, British Columbia, the stucco (rendering) clad building failures ultimately became known as the “leaky condominium syndrome”. Technical publications indicated that the frequency of damage in stucco-clad buildings was above the average failure rate of other types of multi-unit buildings (Morrison Hersfield Ltd, 1998). In BC, unfavorably wet climate conditions, lack of understanding of the significance of moisture control principles, and inadequate design and construction of BE details have contributed to the failures. In extreme cases, a total rotting of wood frame components was reported to have occurred as early as six months following construction (building commissioning) (Ricketts, 1997).

Other coastal areas, such as Nova Scotia (Chouinard & Lawton, 2001) and Pensacola, Florida (Trechsel et al., 1987) also have shown some moisture-originated problems, although at a much lower frequency and severity than those documented in BC. Mainland North American locations, including Ontario (Chouinard & Lawton, 2001), Alberta (Building Envelope Engineering, 2000), Wisconsin (Merrill & TenWolde, 1989), Cleveland, Ohio (Lstiburek, 1987), and Montana (Tsongas, 1990; 1992) also have documented cases of moisture-related problems.

A number of detailed field studies were commissioned to assess the extent of damage, determine the reason for this occurrence, and identify the components of the BE envelope that are most affected. The BC survey (Morrison Hershfield Ltd, 1998) highlighted the finding that rendering-clad walls showed a higher frequency of defects than walls with other cladding systems. 84% of all window-related problems occur on rendering-clad walls, although only 60% of walls have rendering cladding. A higher percentage of deck/balcony/walkway problems are on rendering walls. Inappropriate sequencing of construction (where rendering is installed on the walls prior to installation of the waterproofing deck membrane) is suspected to have had a significant contribution to the problems.

The survey of building envelope failures in the coastal climate of BC identified:

- 25 % of the problems were related to windows and their interface with the wall (mitered corners in window frames and wall/window interfaces were not sealed, wall/window head or sill interface was inadequately flashed, and building paper was inappropriately installed).
- 25 % of the problems were attributed to inadequate flashing on horizontal surfaces, including parapet cap flashing, or the interfaces between horizontal members and vertical surfaces, such as the guardrail/wall interface with saddle flashing.
- 17% of the problems were attributed to decks/balconies/walkways. The interfaces between the waterproof membrane and the wall, or joints with penetrations comprised the primary paths for water entry.
- The remaining 33% of problems were attributed to inadequate roof/wall flashing, insufficient eave, and vents, etc.

The survey reported on deficiencies in installation of the WRB paper, including discontinuities and no existing or reversed laps, which accounted for 40% of the water penetration problems. Table 2 lists the WRB deficiencies that permitted water penetration to reach the sheathing board and/or structure in exterior walls.

Table 2. Sources of water penetration through WRB (Morrison Hershfield Ltd., 1998)

No exterior sheathing	14 %
Discontinuities	30 %
Material degradation	11%
No or reversed lap	10%
At flashing	16%
At penetration	16%
Other	3%

The same survey observed that the frequency of damage is lower with increased width of the overhangs. Typically, buildings clad with rendering had narrower overhangs. Yet, there are regional differences in the use of renderings. Renderings are not popular in the Eastern part of North America. In western regions, its use accounts for 50% to 70% of all cladding systems.

Similar findings were reported in Seattle, Washington and Wilmington, North Carolina. The New Hanover County Building Inspectors have reported that as many as 3200 homes might have possible moisture problems. In a follow-up study of 300 randomly-selected homes in Wilmington, Charlotte, Greensboro, Raleigh, Fayetteville, and the Outer Banks, 98% showed moisture problems in external walls. Problems were attributed to inadequate joint sealing around openings and at interfaces such as doors and windows, lack of slope in horizontal surfaces, and lack of proper flashing at roof lines and decks.

One can ask why are EIFS and stucco clad buildings discussed together? The answer is that these two cladding systems are airtight. If venting is not provided behind the cladding, entrapped moisture behind the cladding must escape by diffusing across the material. Therefore, these cladding systems must also be evaluated for their drying ability. It is not a surprise that airtight systems in coastal areas appear to be prone to moisture damage. However, other reports indicate that similar moisture problems occur in less moist, but colder climates, including the provinces of Alberta (Building Envelope Engineering, 2000) and Ontario (Chouinard & Lawton, 2001).

A survey of 25 polymer-modified EIFS-clad buildings located in Toronto, Calgary, Edmonton and Vancouver revealed that none of the installations was defect-free. In 30% of the cases, the observed problems were serious enough to jeopardize service life of the building. Ingress of moisture into the system was a result of failed joints, surface cracking, thin application, softening, erosion and delamination of the finish layer, inadequate attachment, and reduced aesthetics, including algae growth.

The Alberta study reported that design, material selection, installation, and maintenance have contributed to the encountered moisture problems (Building Envelope Engineering, 2000). However, construction deficiencies reported in 42 out of 45 dwellings that were inspected appear to be significant (Table 3).

Table 3. Number of problems encountered in 45 homes in Alberta (Building Envelope Engineering, 2000)

Cause ascribed to	**Problems in**
Design	20/45
Construction	42/45
Maintenance	3/45
Operation	5/45

The sources and paths of moisture penetration through the face of the wall were expressed in terms of percentages. Direct penetration of rain through the second line of defense (the WRB) was the major cause of moisture penetration through the wall (Table 4 and Tables 5a and 5b).

Table 4. Moisture sources in 45 homes inspected in Alberta (Building Envelope Engineering, 2000)

Moisture sources	**Frequency**
Direct rain penetration	76%
Run-off	7%
Ponding	5%
Snow melt	9%

Minnesota's climate is very similar to that of Alberta and a pattern of moisture penetration similarities is observed. Statistics of buildings currently diagnosed with moisture problems in Minnesota are listed in Table 6.

Moisture-originated problems have already existed in coastal areas (Marshall et al., 1983). Yet, what is new is the spread of this problem into areas of severe cold climate, such as Minnesota or Alberta, and increased frequency of damage for airtight cladding systems such as exterior stucco or EIFS. Therefore, examination of what changes took place over the last few decades to cause such a dramatic shift is important.

Table 5a. Frequency of moisture paths through the WRB in the same study (Building Envelope Engineering, 2000)

Paths through the WRB	**Frequency**
Laps	44%
Flashing	22%
Discontinuities	22%
No barrier	6%
Penetrations	3%
Degradation	1%
Other	2%

Table 5a. Frequency of moisture paths through the wall in the same study (Building Envelope Engineering, 2000)

Path through the face of wall	
Window/door sill	13%
Deck base	11%
Inherent pores and joints	30%
Window/door head	11%
Roof/wall	6%
Exterior deck edge	11%
Other	18%

Table 6. Moisture problems in Minnesota were observed by Air Tamarack in 477 commercial and 347 residential buildings from 2000 to August 2004*

90% (135 out of 150) rendering-clad residential buildings investigated by Air Tamarack, which were built after 1990, were found to have major moisture problems (repair costs over $200,000 dollars).
The City of Woodbury (a suburb of St. Paul, MN) found 174 rendering-clad homes with moisture problems out of 670 (26%) rendering-clad homes inspected in 1999
By the middle of 2004, 41% of the rendering-clad homes built in Woodbury have been rebuilt; the cost of most repairs exceeded $100,000 dollars

*Note that Air Tamarack is a very small company – there are at least 12 other companies doing the same type of work in Minnesota.

5 Why a 30-year-old stucco house performs better than one built today

One of the authors compiled data on 70 stucco houses inspected prior to 2003. Sixty five of these houses were built after 1990, one was built in 1982, and four were built prior to 1950. The majority of the houses built since 1990 had major problems with rotting exterior walls, primarily caused by moisture being retained in the exterior walls. The old houses did not have problems with moisture in their exterior walls even though all houses were air-conditioned and had insulated exterior walls. Furthermore, several stucco-clad houses built between 1920 and 1945 and reinsulated were also inspected, and no mold problems were found.

All four of the pre 1950s stucco houses had similar construction. The 1982 stucco house had a similar design to 65 of the newer stucco houses with a couple of key differences. Twelve of the newer houses were similar to the other 65, also with the exception of a couple of key differences. Each of these houses will be discussed in the next sections. All above-grade walls in newer stucco houses have a similar design (see Figure 5).

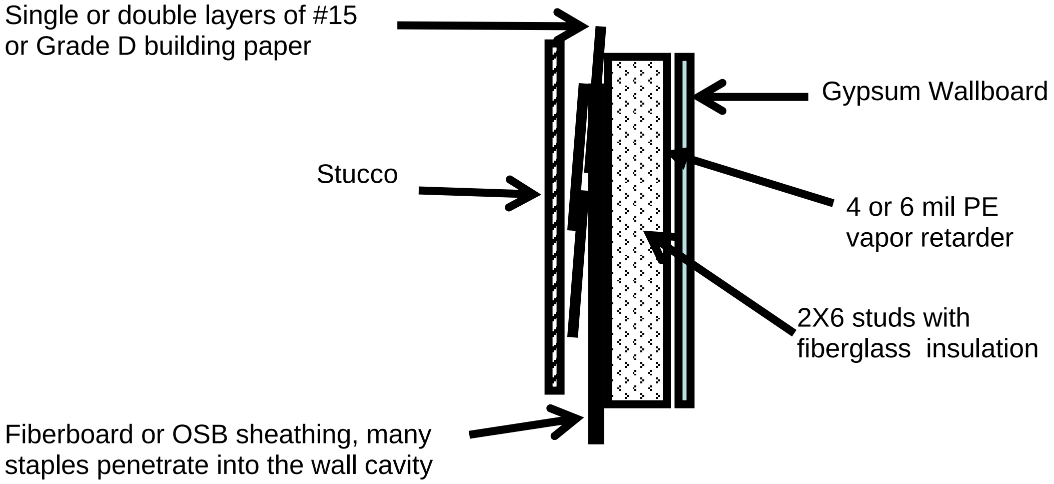

Figure 5. Stucco wall design typical of Minnesota houses built after 1980

The above-grade wall construction is comprised of stucco, wire mesh, one or two layers of #15 building paper or grade D building paper, fiberboard or OSB sheathing, 2 x 6 wooden studs with 5-½ inches of fibrous glass insulation, 4 or 6 mil polyethylene vapor retarder, and gypsum wallboard. In most of the houses, some of the stucco was installed below grade on concrete block or poured concrete.

Fifty-three of the newer houses had a single layer of 15# building paper, 5 of them had two layers of 15# felt, and 7 had two layers of Grade D building paper. Three of the seven houses with two layers of Grade D paper also had weep screeds and the stucco terminated more than four inches above grade (one house is 9 months old and two are two years old). One of the houses, with two layers of Grade D paper and with no weep screeds, was two years old and had extensive amounts of brick in the lower level below the stucco. Metal flashing was used between the stucco and the brick to weep out water behind the stucco and down the exterior of the brick. Four of the seven houses with two layers of Grade D paper had some stucco located below grade and did not have weep screeds (these houses were 2 to 6 years old). All 53 of the post-1990 houses with a single layer of building paper had stucco located below grade and did not have weep screeds.

Sheathing on all of the post-1990 houses and the 1982 house was either OSB or fiberboard. Several houses had small areas of the plywood sheathing, frequently around the rim joist area, large windows, or around fireplaces. Usually, less than 20% of the sheathing was plywood. Other houses used only OSB sheathing. No houses used just fiberboard sheathing. Houses with fiberboard sheathing would commonly use either plywood or OSB sheathing at the rim joist areas and around large windows.

The stucco houses that visually appeared the worst typically used OSB sheathing on the entire exterior wall system. The ones that visually appeared the best primarily used fiberboard sheathing. Although the houses using fiberboard sheathing visually looked better than houses with OSB sheathing, they really were not any better in preventing mold growth. Where OSB was used, stucco exhibited larger cracks that were visually obvious. This likely occurs as a result of OSB expansion and delamination when wet, which increases the cracking (increased stresses) in stucco. The fiberboard doesn't expand as much; it just rots away. Very little plywood sheathing was observed on these newer houses. Where it was observed, it was rotten, but not as extensively as the OSB or fiberboard sheathing materials immediately adjacent to it.

One major difference between the current (1990 to the present) houses and those built between 1980 and 1990 is the manner of vapor retarder application. Prior to 1990, the seams of the 4 or 6 mil polyethylene were neither taped nor sealed with adhesives. The latter method became popular after 1990, when the vapor barrier was also used as the air barrier system.

The second difference was the more liberal use of staples that penetrate the exterior sheathing. This was most pronounced when fiberboard sheathing was used. Many of these houses averaged 5 to 15 staples per square foot of surface, all of which penetrate the shielding ½ to ¾ inch beyond the inside face. Excessive use of staples and nails that penetrate the sheathing at locations remote from a supporting stud is a problem seen in many new homes.

The four stucco houses that were built pre 1950 all had similar construction. They used a single layer of #30 building paper, shiplap sheathing (3/4 inch tongue and groove pine board), 2 x 4 wooden studs with mineral wool, fibrous glass or cellulose insulation, or a combination of these. The stucco did not extend below grade at any of these houses. However, no weep screeds were present at the base of any of the exterior walls. Two of the houses had a Kraft paper vapor retarder on the warm side of the insulation. All of the houses likely had at least one coat of oil-based paint on the plaster walls. No rotting or mold-infested materials, related to exterior moisture, were observed or tested and found in these walls.

In summary, newer stucco houses located in the metropolitan area of the Twin Cities (Minnesota), especially those built since 1990, are having serious problems with their exterior walls. The primary problem with these structures is the manner in which exterior moisture is controlled by the exterior wall design and materials. There appears to be three primary causes of this problem, each having almost equal weight.

- First, there is significant water penetration around windows and doors, allowing excessive amounts of bulk water to enter into the wall assembly.
- Secondly, the stucco cladding, which is a major reservoir of moisture, is not properly isolated from the wall sheathing to prevent the transfer of exterior moisture to the inner part of the wall assembly.
- Thirdly, the exterior wall has limited drying ability to the exterior and interior, which compounds the effect of water entrapment and worsens the effect of the other two problems.

Water penetration issues were addressed by organizations like the Minnesota Lath and Plaster Bureau, Energy and Environmental Building Association, APA - the Engineered Wood Association and the Northwest Wall and Ceiling Bureau. However, no one has addressed the issue of drying ability of the stucco-clad walls.

6 Is there any performance difference observed in the market place?

While Section 5 of this paper dealt with the wall construction, this section will examine whether field observations highlight any performance difference between so called 1-coat, 2- coat and 3-coat stucco systems. The three-coat stucco system was described in Section 2. The two-coat stucco system is identical, but instead of the third finishing layer, a trawled surface finish or paint is applied. A one coat stucco system implies a two stage operation, but using the same material in both stages. Typically, the material includes reinforcing fibers or/and other proprietary admixtures.

CMHC (2004) sponsored a study to assess the impact of stucco thickness reduction from 19 to 15 mm for 2-coat stuccos in Alberta. The field sample included 184 facades on 47 buildings, where 60% of the buildings were 5 to 10 years old. Only 6 buildings had 3-coat stuccos. The remaining 41 buildings had 2-coat stuccos, with about 50% having thickness of 15 mm while the other 50% had less than 15 mm stucco thickness.

The ratings contained two categories: water management and serviceability, described in Table 7. The rating scale and results are shown in Table 8.

Table 7. Conditions included in evaluation of stucco performance

Water management	**Serviceability**
Staining	Cracks
Efflorescence	Material loss
Fungi/algae	Impact damage
Erosion	Accessories
Freeze-thaw	Repairs
Measured moisture content	

Table 8. Distress ratings and overall results

Rating	**Description**	**3-coat stucco**	**2 coat stucco**
Excellent	No deterioration		1
Good	Normal deterioration	15	67
Fair	Minor distress	8	76
Poor	Significant deterioration		9
Defective	Needs immediate repair		8

Since more than 50% of 2-coat stucco systems were rated fair or lower, the industry decided against the acceptance of 2-coat stucco as equivalent to 3-coat stucco. As expected, most damage was found at flashing locations, windows, door perimeters and corners.

The most important conclusions from this study were:

- There are no standard procedures for evaluating the water management and serviceability of stucco cladding.
- Serviceability depends on the whole building envelope system; changes to the mix, base coat thickness, and curing conditions must be included as well as consideration of a capillary break layer to prevent water being sucked into the interior of the wall.
- Cracking must be considered in evaluating water management performance.
- There is a need for educating builders and stucco applicators in best practices and for improving stucco materials as well as practices for the building envelope.

7 Closing remarks

There are a number of excellent compilations of case studies and field evaluations related to performance of renderings. Ribar and Scanlon (1984) wrote one of the best deficiency reviews dealing with portland cement plaster and providing advice on how to avoid them. Norwegian publications, such as NBRI (1980), which reviews adhesion failures of plaster on concrete, and Svendsen (1954 and 1962), who published two reports on damage of renderings (in Norway), or the NBRI (1961) report on plaster damages, which was translated into English, must be listed. Saretok (1957) wrote a critical literature review on rendering and rendering work (in Swedish). A recent review by Kvande and Waldum (2002) updates the state-of-the-art relative to the current Norwegian situation. An internal NRCC note by Tibbets (1954) reviews research on stucco cracking between 1911 and 1952, and makes a good complement to the NBS (1951) review on lime stucco failures.

This list highlights several publications from various countries to demonstrate that stucco systems have been developed primarily on the basis of tradition. However, the traditional exterior walls are no longer being constructed in today's North American housing. Therefore, the authors postulate that there is a need to review the performance requirements for modern energy-efficient and environmentally-responsive stucco-clad wall systems.

References

Bomberg M., M. Pazera, J. Zhang, T. Mungo and F. Haghighat, 2003, Weather resistive barriers: New methodology for their evaluation, AIVC/BETEC Conf. Oct 12-14, 2003, Washington, DC

Bomberg M., M. Pazera and F. Haghighat, 2003a, Weather resistive barriers: assessment of their laboratory and field performance, , 2nd Int. Building Physics Conf., Leuven, Sept 14-16

Bomberg, 1974, Moisture flow through porous media, Bldg Technology, Lund University

Building Envelope Engineering Inc, 2000, Wall moisture problems in Alberta dwellings, Canadian Housing Information Center (CHMC), Technical Series 2000-112.

Brown, W., Adams, P., Tonyan, T. & Ullett, J., 1997, Water management in exterior wall claddings, Journal of Thermal Insulation and Building Envelopes, vol. 21, (pp. 23-45).

Brown, W., J. Ullett. & A. Karagiozis, 1997a. Barrier EIFS clad walls: results form a moisture engineering study. J. Thermal Insulation and Building Envelopes, vol. 20, (pp. 206-226).

Chouinard, K. L. and Lawton, M. D., 2001, "Rotting wood framed apartments – not just a Vancouver problem".

Canadian Housing and Mortgage Corporation, 1993, Exterior insulation finish systems (EIFS) field performance evaluation

Crandell, J. & Kenney, T., 1996, Investigation of moisture damage in single-family detached houses sided with exterior insulation finish system in Wilmington, NC. NAHB Research Center, Inc. Upper Marlboro, MD

Desjarlais, O.A., Karagiozis, A.N., and Aohi-Kramer, M.A., 2001, The role of building envelope professional in Aftermath of Vancouver's Leaky Condominium Crisis. Proceedings for Performance of Exterior Enveloped and Whole Buildings VIII: Integration of Building Envelopes, December 2-7, Clearwater Beach Florida

Karagiozis, Dr. Achilles, Manager of hygrothermal program of ORNL, private communitcation

Kruger & Eriksson, (1925) see Bomberg, 1974, Moisture flow through porous media, Bldg Techn., Lund University

Kvande T, and A.M. Waldum, Experience with plaster in rain-exposure (In Norwegian) Norwegian Building Research, Rep. 320-2002, pp.1-65

Lstiburek, J., 1987, "Insulation Induced Paint and Siding Failures," Proceedings, Energy Efficient Buildings Association Conference, Minneapolis, MN.

Marshall, Macklin, Monaghan, 1983, "Moisture-Induced Problems in NHA Housing, CMHC

Merrill, J.L. & TenWolde, A., 1989, "Overview of Moisture Related Damage in One group of Wisconsin Mfg Homes," ASHRAE Transaction, Vol.95, 1, pp. 405-414.

Morrison Hershfield Ltd., 1998, "Survey of building envelope failures in the coastal climate of British Columbia", *Canadian Housing Information Center (CHIC)*, Technical Series 98-102.

NBS, 1951, Plaster failures resolved, Building research Summary Report 76, pp 1-.5

NBRI information sheet, 1980, Adhesion failures of plaster on concrete, NBRI of CSIR, Pretoria

Nevander L.E., 1968, Notes from lectures at Institute in Vienna (private communications)

Plagge, Dr. R., Leader of Technical University of Dresden testing laboratory, private communication

Ribar J.W. and J.M. Scanlon, 1984, How to avoid deficiencies in Portland-Cement Plaster constructions, Tech. rep. SL-84-10, US Army Corps of Engineers, Washington, BC

Ricketts, D., 1997, Building envelope construction in the lower mainland. Proceedings of the Eighteenth Annual General Meeting of the Canadian Wood Preservation Ass. (pp. 31-51).

Tibbets D.C., 1954, Stucco cracking on wood-frame structures, DBR:NRCC Technical Note 188, (internal use)

Saretok V., 1957, Plater and plastering, critical literature-review, (In Swedish) Transactions 29, Swedish Bldg Res. Council, translated entirely into English by Building Research Station as Library Communication No, 791

Svenden S.D., 1954, Plaster in Norewgian Climate (in Norwegian) NBI, J. Gundt Tanum Press, Oslo pp 1-149

Svenden S.D., 1961, Damage on plaster, (in Norwegian), NBI, report 57, published Bygg 1961 pp 5-7 -17 English translation 5742 from NRC Canada)

Trechsel, H.R., 1987, "Field study on Moisture Problems in Exterior Walls of Masonry Housing Development on the Coast of the Gulf Mexico," Thermal Insulation: Materials and Systems, ASTM STP 922, F.J.Powell and S.L. Mathews, Eds., ASTM, Philadelphia, pp 371-393.

Tsongas, G.A., 1990, "The Northwest Wall Moisture Study: A Field Study of Excess Moisture in Walls and Moisture Problems and Damage in New Northwest Homes," U.S. Department of Energy/Bonneville Power Administration, DOE/BP-91489-1.

Tsongas, G.A., 1992, "A Field Study of Moisture Problems and Damage Inside New Pacific Northwest Homes", Proceedings, ASHRAE/DOE/BTECC conference on the Thermal Performance of the Exterior Envelopes of Buildings V, Clearwater, FL.

URL: http://alcor.concordia.ca/raojw/refbyconcept.html

Williams, M.F. & B.L. Williams, 1998, An overview of water leakage problems in single family residences clad with exterior insulation finish system (EIFS). In Kudder and Erdly (Eds.), ASTM Special Technical Publication no. 1314: Water leakage through building facades (pp 277-287), West Conshohocken, PA

Williams, M.F., Williams, B.L. & L.J. Hamilton, 1998, In situ assessment of moisture levels in exterior walls of a single family residences clad with exterior insulation and finish system (EIFS). In Kudder and Erdly (Eds.), ASTM Special Technical Pub. 1314: Water leakage through building facades (pp 52-69), West Conshohocken, PA