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3E WALL FOR ALL CLIMATES:
PART 2: A PROPOSED SOLUTION[*]

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Abstract

Recent failures of exterior stucco on walls were discussed in the first part of this paper. After assessing those problems, the authors postulate that providing stucco with a capillary breaking layer combined with exterior thermal insulation and improved ability of the wall to dry both outwards and inwards will restore the excellent track record for which exterior stucco walls were known forcenturies. This 3E wall system is designed for energy efficiency, environmental control, and ecological responsibility.

The authors highlight that exterior stucco should be applied on exterior insulation in both hot and cold climates. The system should incorporate water resistive barriers (WRB) and cellulose fiber insulation in the framing cavities. Such a wall can be one of the most economical and ecologically-justified systems that will perform well in most climates. However, such a wall should also be designed with a different paradigm for heat, air and moisture control of the building envelope (BE). A new paradigm should be based on moisture balance in relation to climatic and service conditions. In this context, modern lime-cement rendering placed on thermal insulation and provided with proper architectural detailing may successfully compete with all other cladding systems.

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1. Introduction

Moisture-originated damage in EIFS-clad houses was widely publicized. Yet, a survey of recently built stucco-clad houses in Minnesota and field examinations in Alberta (see Part 1 of this paper) also highlighted a number of premature failures. This was in strong contrast to the older houses that functioned well and exhibited no moisture problems.

The major differences between the old and new stucco constructions relate to their moisture management strategies. 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 appear to be three primary causes of this moisture-control problem, each having almost equal impact.

- First, there is significant water penetration around windows and doors, allowing excessive amounts of bulk water to enter the wall assembly.
- Secondly, the stucco cladding, which is a major reservoir of moisture, is not properly separated from the wall sheathing to prevent 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. This fact increases the effect of water entrapment and further compounds the effects of first two problems. Factors contributing to reduced drying rates in current wall systems include: the use of less permeable finishing layers on the exterior, the use of less permeable vapor retarders on inside (even when polyethylene was introduced it was not air-tight until 1990s), and complete elimination of the capillary break between the stucco and the substrate (wood strapping was placed behind the stucco layer in older houses).

Various organizations have made efforts to address most of the water penetration issues. No one, however, has addressed the issue of drying ability of the stucco-clad walls. Therefore, the following paper starts with a comparison between the current and historic renderings.

2. Historic mortars as a blueprint for modern renderings

Significant research effort toward understanding historic mortars is currently being undertaken by the European community. This work is fascinating, not only for those actively involved in conservation of buildings that have passed the test of time, but also for those of us who are passively watching from the sidelines. The selection of “new” replacement materials for historic construction involves the current knowledge of material science and an attempt to replicate the original mortar systems as closely as possible. In doing so, the understanding of modern materials is blended with the need for preserving old-fashioned solutions.

The scientific bystanders are watching the research on historic mortars, since this might be the only source of public information in which critical properties of mortars are evaluated in a systematic and holistic manner. In North America, more projects are performed by consultants who would compare field performance of two- and three-coat renderings than scientists who would analyze performance of exterior rendering systems in different climates and different service conditions. The selection of mortars for historic buildings must address a number of issues including chemical, mineralogical, and physical aspects (shrinkage, adhesion, rate of water absorption, capillary moisture content and water vapor permeability) in addition to durability considerations (sulphate resistance, freeze-thaw and salt spalling resistance) as well as compatibility with existing construction (Raupach et al., 2004; and Hughes and Valek, 2003). To design an optimally-performing material, researchers must compare several different mortar types.

To understand moisture transport and frost durability, Balken (2004) analyzed the pore structure of lime plasters using test methods described by a Swedish building physics handbook. Lime rendering requires completion of the carbonation process before testing and, therefore, curing is typically performed at 65% RH (Hughes, 2004* private communication) or 6 weeks at 75 % RH (Balken, 2004). Balken (2004) tested 11 mixes, two of which included cement (10 % and 60% respectively). All lime-based mortars showed similar sorption curves. Only one mix, with a significant fraction of cement, had higher hygroscopic moisture content in the middle range of RH. This indicates a larger fraction of micropores with a size below 0.4 microns.

Alesiani et al (2004) used NMR (nuclear magnetic resonance) technique to examine the water absorption coefficient of surface-treated and untreated materials. The tested materials included marble stones and lime with quartz in a 0.5: 0.25 ratio by volume. Specimens were in contact with wet filter paper. The lime mortar specimens were approximately 10 mm thick. The untreated lime mortar specimens reached the capillary moisture content in 10 min and 45 minutes respectively, yielding a water absorption coefficient of 0.013 $kg/m^2s^{1/2}$ for the mortar with less quartz sand and 0.0063 $kg/m^2s^{1/2}$ for the lime-sand mortar in a 1: 1 ratio, or about half the coefficient for the mortar with less sand.

Baronio et al. (1999) presents hygric properties of some historic mortars. Water absorption coefficient varied from 0.20 to 0.35 $kg/m^2s^{1/2}$, or about twice of that of the mortars with the same porosity studied at the Technical University of Dresden (TUD). Marie-Victoire and Bromblet (1999) examined several new cement-based renderings with performance similar to that of historic lime renderings. The test series included three one-coat cement-based materials (P1, P2, P3), lime putty (T1), hydraulic lime (T2), mixed lime rendering (T3), and other materials. The water absorption coefficient for the P materials varied from 0.025 to 0.12 $kg/m^2s^{1/2}$ and from 0.1 to 0.6 $kg/m^2s^{1/2}$ for the T materials. Despite these differences, the water vapor permeability was similar for all materials and varied from 1 to 1.8 E-9 kg/m^2 s Pa, or 17 to 32 perms.

Completing this short review of historic mortars with work on porosity (see Thomson et al., 2004; and Veiga et al., 2004), historic mortars were observed to have a broad range of hygric properties. At the lower end, they were on the same level as the current renderings; on the upper end, they were about one magnitude more permeable than the modern renderings studied at TUD. On the other hand, the North American renderings are one magnitude less permeable than the modern renderings tested at TUD and, perhaps, as much as two magnitudes tighter than the historic renderings.

3. Historic perspective of Morstead and Morstead (1988)

Changes in stucco took a parallel path to those taking place in mortars. Morstead and Morstead (1988) observed a gradual increase in strength requirements for mortars: Type N is now the most commonly used mortar. Type S was rarely used prior to the 1970's, but now it is specified more frequently for brick veneer and non-load-bearing block-work. This is not appropriate because of the inherent rigidity of this mortar structure. To prevent cracking, one must increase the frequency of control joints in masonry in direct relation to the increased fraction of portland cement in the mortar.

Morstead and Morstead (1988) stated: "*While values for drying shrinkage, brick growth, coefficients of thermal and moisture expansions for locally available masonry units are presently unavailable, it would be premature to state that we may be able to return to completely control joint-free masonry construction. Though the potential for the control of movement through resilient mortar exists, even to the extent of coping with building movement, additional research is badly needed."*

The designer must choose a suitable mortar, but the attributes of mortars for specific purposes are not prescribed. The codes and standards do not prescribe requirements other than structural requirements (compressive strength) for load-bearing masonry. Ideally, mortar should possess the following characteristics:

1) workable to ensure complete joint filling without separating or "tearing",
2) sufficiently strong to carry imposed loads,
3) able to completely and permanently bond into the surface of the unit,
4) be durable and have the capability to fill small cracks and fissures by chemical reconstitution,
5) have minimal cyclic volume changes after being incorporated into the wall,
6) have the ability to resist stress without excessive rigidity, and
7) possess high water-retention capabilities to resist rapid moisture loss to the units.

Obviously, mortar cannot possess a full measure of all of these qualities and still be suitable for all applications. Choices must be made, taking into consideration the particular characteristics of the mortar and the materials required for the construction. Generally, mortar Types M and S rate low in most of these attributes with the exception of the second, the requirement for strength to carry imposed loads.

<u>Type N Mortar (1: 1: 6)</u> - Recommended for load-bearing work, with lightweight block, and conforming to Clause 5.3.2 of CAN3-S304-M84 Prism Tests. When used with lightweight, non-moisture-controlled concrete brick, control joint spacing should be 5m. Control joints should be spaced at 18 m when Type N mortar is used with well cured, dry, normal weight block. For clay masonry on masonry foundations and wall heights over 2m, control joint spacing may be 25m, and for clay masonry supported on steel and wall heights under 2m, space control joints at 18m.

<u>Type 0 Mortar (1: 2: 9)</u> - Recommended for brick and block veneer, nonbearing block-work, interior block walls and partitions. Control joint spacing for clay masonry under 2m high and bearing on steel should be 25m. Clay masonry over 2m high should not need control joints. For lightweight brick and block veneer (well-cured), space control joints at 12m; if cure is not assured, reduce joint spacing to 7 to 10m.

Morstead and Morstead (1988) noted that: "*Tests have shown that high lime mortars cure at a rate that is more compatible with rate of building and unit movement*." Table 1, which shows compressive strength gains from the 28th day to one year, were averaged from tests conducted at five laboratories that were located in temperate to severe weather zones.

Table 1. Compressive strength gains from the 28th day to one year

Mortar Type	% Increase in Compressive Strength
M	28
S	36
N	60
O	95
K (1:3) Lime/Sand	252

4. A need for a paradigm change for environmental design

For many years, students in general building technology (later named Building Physics, it remains a mandatory course in most civil engineering and architecture faculties in universities of central, eastern and northern Europe) have been told that each wall must breathe. This statement implied that the wall must allow transfer of vapor to both interior and exterior sides. Masonry walls have enough moisture capacity to get wet and dry with changing weather In addition, masonry walls provide the required degree of overall air-tightness. This is not the case with American frame walls (wood or steel frame), as they do not have sufficient moisture storage. From the beginning of the discipline called building science (see Bomberg and Onysko, 2002), our approach focused on prevention of moisture entry by installation of various barriers. As long as both the level of thermal insulation and the quality of these barriers was poor (Ojnanen and Kumaran, 1996), typical frame walls had a sufficient *moisture tolerance* to withstand occasional and incidental wetting.

Recently, however, the increased levels of thermal insulation reduced the thermal drive of moisture. Air-tightness of the building envelope was improved with the introduction of new polymeric materials and the capability to pass air to remove interstitial moisture was reduced. Changes in the neutral plane of air pressure by improvements in furnace efficiency (in cold climate) or even complete elimination of chimneys from many houses (caused by adoption of hot water or electrical resistance heating), changes in window technology that introduced incompatibility at the wall-window interface (e.g. flange windows), shifting trends in building styles (more balconies, terraces), changes in occupancy activities related to increased comfort (humidification, air conditioning), and washable wall finishes all point toward a completely different picture of service conditions in a modern residential house. There are dramatically increased loads and little or no moisture tolerance in the wall. Unless the fundamentals of moisture management are reexamined, more moisture-related damages might be inevitable in harsh (cold or costal) North American climates.

5. The concept of air-tight but vapor semi-permeable wall

The phrase “airtight, vapor permeable building envelope” was introduced by Simonson et al (2004), who reported results of numerical simulations and field measurements in the research house in Finland (Simonson et al 2004a, 2004b). The researchers stated:

> ”*The results show that the diffusion resistance of the internal surface should be greater than the diffusion resistance of the external surface (typically recommended ratio of 3:1 or 5:1). The vapor resistance of the vapor retarder can be significantly below that provided by polyethylene and still will result in a safe structure, even in a cold climate.*

> *An airtight layer (a part of air barrier system) reduces air leakage through the building envelope, thereby improving the moisture performance, energy consumption and thermal comfort. Even with an airtight building envelope, the diffusion of water vapor may be significant and therefore it is important to have a layer that is resistant to vapor diffusion on the warm side of an insulated envelope in cold climates. This layer (often called vapor barrier or vapor retarder) functions to reduce the diffusion of moisture from indoor air into the building envelope to a level that does not result in moisture related problems. Naturally, in cold climates for an airtight envelope, a very high vapor resistance is safer (i.e., reduces diffusion moisture transfer more) than a very low resistance, and often polyethylene vapor retarder is applied. However, since a vapor permeable and hygroscopic building envelope can reduce the peak indoor air humidity (Simonson et al., 2004 a, 2004b), it may actually be safer than a vapor tight envelope when there are small air leakages through construction defects. There is no official definition of a vapor permeable building envelope, but in this paper it means that there is such moisture flow between indoor air and the structures that it can have a significant effect on the peak values of the diurnal variation of the indoor air relative humidity. This does not necessarily mean that the vapor permeance of the inside sheathing should be very high, because the vapor resistance layer could be assembled also at the exterior side of the vapor open, hygroscopic interior sheathing layer."*
>
> *"Polyethylene also has a very low air permeance and therefore functions as both an air and vapor barrier when it is installed without penetrations. Because of its dual function, polyethylene is often specified and the safety of envelopes with air and vapor barriers other than polyethylene is often questioned. Therefore, the purpose of this paper is to present research that illustrates the level of vapor resistance required to keep water vapor diffusion from causing a moisture problem in a cold climate such as Finland. In this paper, mold growth will be considered to be the most critical moisture concern, where the risk of mold growth depends on the temperature, humidity and time of exposure. The mold growth analysis is based on laboratory measurements and a numerical model developed from these results".*

As stated previously, there is a growing realization that moisture performance of portland cement plasters (stucco) needs to be re-examined. One can use a water-resistive barrier (WRB) that is applied in liquid form to the OSB surface (this is one of newly-emerging technologies). Moisture management strategy based on multiple defense lines is now widely used. These strategies typically involve inclusion of a drainage mat on the WRB or an air gap created by strapping and two layers of WRB, one on each side of the air gap.

A layer of thermal insulation can also be placed between the sheathing board and the stucco. The thermal insulation layer can be provided with groves and other means for water vapor pressure equalization to increase the drying rate for moisture contained in the inner wall.

The actual design of details depends on a number of factors including the type of insulation and the manner in which the joints of the insulation are treated. Furthermore, one must consider what material is used and where the principal plane of airtightness is located. Only one aspect of design will be discussed here, namely material selection relative to wetting and drying.

6. Conceptual design and selection of materials for stucco in a 3E wall

Generally speaking, research in construction materials takes place within proprietary technologies. Yet, there must be a defined set of performance requirements for building envelopes that would allow the private sector to respond by development of appropriate materials. The path from such a set of performance requirements to practice includes a stringent cost benefit analysis. Yet, at this stage, one cannot present the set of performance requirements. The building codes give us only a few selected, minimum requirements. Today, one can only discuss some performance-oriented considerations and exemplify them with possible material selections.

The required performance for exterior stucco can be achieved with either a one coat or three coat system. From the building science point of view, one needs two layers of stucco and a surface treatment. So, each of these two stucco systems can function well, though each may have a different range of applications and require different considerations. While reviewing historic mortars, one may notice that the same performance could be achieved with different combinations of raw materials and the polymer-modified cement-based mortars could be performing in a manner similar to lime-based mortars (Marie-Victoire and Bromblet, 1999). Therefore, use of cement- or lime-based mortar in the forthcoming discussion relates to performance traits typically associated with each of these types rather than an absolute demand of the material type.

The primary difference between lime- and cement-based materials is the curing mechanism. Cement requires the presence of free water and protection from drying to maintain nearly 100 % RH for curing, while lime gains strength through carbonation and the required RH range is between 65 and 75%. Lime curing provides a great advantage in the current construction pace. Secondly, the slow rate of strength development (Morstead and Morstead, 1988) offers significant advantages in the design of the material mix for the second coat. Furthermore, shrinkage-related macro-cracking is completed at an early stage of drying (Moeller, 1954)

The primary requirements for a base coat material are:

- Good adhesion to the substrate (Hoegberg, 1967), which is an even more difficult task when the substrate is insulation material
- Relatively fast strength development (The actual values depend on construction stiffness and permissible degree of cracking. The latter may vary depending on possible use of an interstitial spray).
- Limited shrinkage deformation
- Medium to small and predicable macro-crack development during drying (no test method or criterion exists in the public domain)
- Medium to small capability for capillary water transport (water absorption coefficient in the range between 0.01 to 0.1 $kg/m^2s^{1/2}$)
- Medium capability for water vapor transport (from 2E-10 to 6 E-10 $kg/(m^2sPa)$ or 2 to 10 perms)

Realizing that relatively fast strength development is needed, a 1:1 mix of masonry cement and lime may be a starting point for material development.

The primary requirements for the brown (second) coat material are:

- Good adhesion to the first coat and bond durability under hygrothermal cycling
- Good crack-bridging ability

- Relatively slow strength development to accommodate initial movements in construction
- Limited shrinkage deformation and little or no macro-crack development during drying
- Little or no irreversible moisture deformation
- Medium to high capability for capillary water transport (water absorption coefficient in the range between 0.2 to 0.6 $kg/m^2s^{1/2}$)
- Medium to high capability for water vapor transport (from 6E-10 to 2 E-09 $kg/(m^2sPa)$ or 10 to 30 perms)

The second coat needs to be much more permeable than the first cost. The cement-to-lime ratio could be 1: 1.5 or 1:1 with polymeric admixtures and a significant fraction of coarse sand. Ohama (1976) showed that shrinkage of the portland cement mortars was reduced by a factor of 3 with a 20% admixture of natural rubber, and by factor of 2 with a 20% admixture of styrene-butadiene. A surface finish on the second coat may be necessary to control staining because the large water transport capability may lead to differential dirt settlement and discoloration.

Generally speaking, the most critical consideration in the mix design is shrinkage, and the lime-rich mixture offers better control of shrinkage as well as a chemical reconstitution of soluble salts (Hughes and Valek, 2003). Lime curing, through the process of carbonation, results in a more permeable structure than one using a cement-based mix (curing a cement mix requires RH near 100% to avoid early macroscopic shrinkage cracks). Nevertheless, as stated previously, optimization of the mix should be left to experts from the private sector. Other aspects of the system design need to be reviewed.

The second aspect of the design is selection of the mechanical properties of the insulation. Expanded polystyrene (EPS) or low density, air-filled, extruded polystyrene (XPS) would likely be used as thermal insulation. Primary consideration must be given to the following aspects of polystyrene performance:

- Surface preparation to ensure sufficient adhesion, with consideration of differential thermal and hygric movements between the base coat of the rendering and the polystyrene
- Contribution of the polystyrene elasticity modulus to impact resistance of the stucco
- Contribution of the polystyrene to local drainage and vapor pressure equalization in the wall system
- Effect of mechanical fasteners passing through the polystyrene layer

Finally the review must include an analysis of the minimum overall stucco thickness with regard to shrinkage and hygrothermal movements, cracking and durability. In all the above discussions, the stucco application method was assumed to remain unchanged.

The concept of exterior stucco on thermal insulation is not new; and it is becoming widely used in the southwest U.S. What is new, however, is that the authors postulate a change in design paradigm. A 3E wall system is designed for energy efficiency, environmental control, and ecological responsibility. The design of the 3E wall shall be such that both wetting and drying can occur though both surfaces of the wall. The hygrothermal properties of those surfaces must be optimized with a view to moisture balance. This balance must be checked for periods of seasons and days. The moisture balance requirements lead to design of the stucco mix based on drying rate. This is a critical parameter, because even if the stucco absorbs more water during a rain period, the overall moisture balance and durability of the wall will be improved.

7. Design of critical details in the 3E wall

Primary consideration must be given to the following details:

- Stucco termination and design of horizontal flashing and drainage holes at the floor level
- Stucco termination and design of a wall/window interface with two stage joints (water penetration-controlled joints)
- Stucco termination at roof and foundation wall

The main problem with termination details in directly-applied stucco is the limited space (3/4 inch) for design of the wall/window interface or other junctions. While the use of thermal insulation is justified by a reduction of heat loss (in cold climates) or heat gains (in warm climates), and by an improvement in thermal mass performance (in mixed climates), its presence brings the possibility of two-stage joint design. Traditional terminations of stucco at windows always leak water because the shrinkage and thermal movement of the window frame make it impossible to maintain contact between the stucco and the frame. This leakage may not have much effect if water drains and dries quickly, but as recent failures have demonstrated, the drainage and drying ability is rarely sufficient to avoid local water accumulation.

This is also the main reason that medium capabilities for capillary action in the base coat (water absorption coefficient in the range between 0.01 to 0.1 $kg/m^2s^{1/2}$) and good capillary action in the finishing coat (water absorption coefficient in the range between 0.2 to 0.6 $kg/m^2s^{1/2}$) are required. These recommendations agree with the traditional stucco systems, but contradict most of the current systems in the market place.

8. Example of hygrothermal calculations and discussion

To highlight the effect of moisture storage, Figures 1 and 2 show calculations performed using hourly weather data for New York City and the hypothetical case of no vapor retarder, but a reasonably low RH in the indoor space (30% in winter and 50% in summer). Figure 1 shows moisture content in the OSB on the side facing the WRB (exterior surface).

The calculations are performed without exterior insulation and with the wall cavity filled either with mineral fiber batt (MFI) or with spray-applied cellulose fiber insulation (CFI). To avoid making 2-dimensional calculations but to examine the effect of moisture being entrapped in the wall, the OSB was assumed to be wet at the start. OSB sheathing has density of 630 kg/m^3, open porosity equal to 22% volume, and initial moisture content (MC) corresponding to equilibrium MC attained at 90% RH.

There is only a small difference in moisture content in the first winter because moisture is readily available in the OSB sheet and the prevailing thermal gradient transports it to the outer surface of the OSB. The difference in summer is much larger because the inverse thermal gradient may move some of this moisture back into the cavity of the frame. Since CFI has a hygroscopic character, it binds and stores part of this moisture. At the ending point (January 1), the amount of moisture in the OSB is much lower for the cellulose wall than that for MFI-filled wall. It appears that CFI allowed an inward drying during the summer, but the OSB in the wall with MFI is at the same moisture level as was introduced into the system.

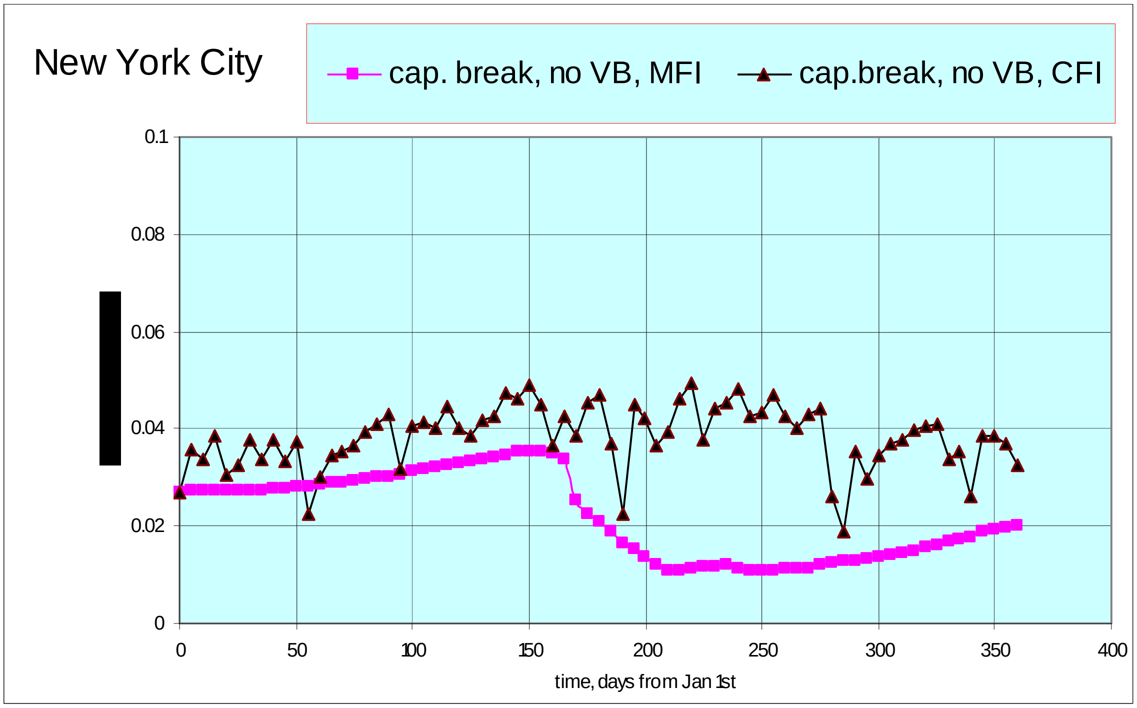

Figure 1. Moisture content at the ***exterior*** *face of the OSB (adjacent to WRB) with high initial moisture content.*

Figure 1 permits deriving a few conclusions. Firstly, we can observe a significant difference between moisture content levels in walls with MFI and CFI in the first year of the cycle as a result of the hygroscopic nature of the CFI. One should remember that the outcome of this calculation depends on the indoor climate conditions that are input into the computer model. Figure 1 presents the extreme case (exclusion of vapor barrier). The actual inward drying during the summer will be reduced in relation to the resistance of the vapor retarder that is used.

Even though Figure 1 showed that the required resistance to flow of vapor depends on moisture properties of different layers in the assembly as well as the indoor temperature and relative humidity conditions, selection of the vapor retarder is made without consideration of these variables. The exterior climate is the only variable considered. Vapor barriers used in the 3E walls will be that of Class 3, as recently proposed by Lstiburek (2002) and shown in Table 2.

Table 2. Proposed classification of vapor barriers (Lstiburek, 2004)

Class	Range of permeance	Name and primary use
1	Less than 0.1	Impermeable, industrial freezers
2	0.1 to 1 perm	semi-impermeable, severe cold
3	1 to 10 perm	semi-permeable, most climates
4	More than 10	permeable, to facilitate drying

The Class 3 (semi-permeable) vapor retarder has been used in walls with traditional stucco. Providing that an air barrier system is in place, a semi-permeable water vapor barrier should remain as the primary choice for construction in most of the North American climates. Research from Finland (Ojnanen 1993, Uvslokk, 1996, Simonson et al 2004, 2004a, 2004b) and Canada

(Karagiosis and Kumaran, 1993; Ojnanen & Kumaran, 1996) supports this choice. Currently, a Class 1 vapor barrier is typically used. In Minnesota, use of 6 mil polyethylene with sealed joints forms a practically impermeable layer.

Figure 2 shows calculations identical to those shown in Figure 1, but reports moisture content on the other side of the OSB (at the interior face adjacent to the frame cavity). The same conclusion, pertaining to the lower overall moisture content in the CFI-filled wall, can be reached. The difference between MFI and CFI appears to be much more significant.

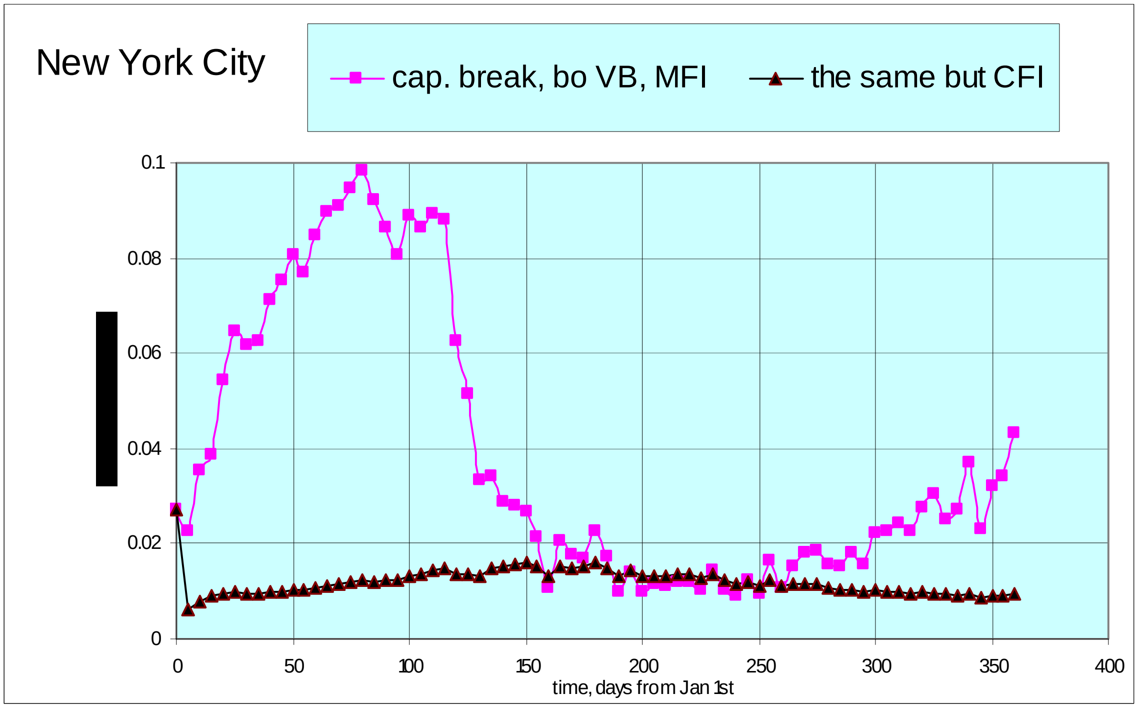

Figure 2. Moisture content at the ***interior*** *face of the OSB (adjacent to frame cavity), conditions same as in Figure 1.*

The main purpose of showing these two figures is to highlight the following:

- Since hygrothermal calculations depend on a large number of variables, they have to be interpreted with caution.
- Transport properties (liquid and vapor diffusivities) are not the only factors that affect hygrothermal performance of the wall; the moisture storage of each component of the wall assembly also affects performance.
- Since moisture is typically redistributed between the upper and lower parts of the wall, typical calculations have a great value as a sensitivity (parametric) analysis, but should not be considered as real time results.
- As discussed in the context of other projects such as MEWS (2002) or ASHRAE standard 160 (TenWolde, 2004), the need for moisture tolerance relates to probable ingress of moisture from faulty windows or other unpredictable deficiencies in the building envelope. As long as realistic loads representing wall deficiency cannot be defined, showing "realistic" calculations of one or another stucco system could be questionable.

Finally, there was another reason for showing the calculations in Figures 1 and 2. These calculations show that if moisture content in the OSB reaches a level as high as the equilibrium moisture content at 90% RH for any reason (because of deficiency or construction moisture content), serious mold growth will result. To alleviate the situation, drying ability both inwards and outwards must be provided – but this is not done in today's construction. In this respect, the 3E wall is based on a different design paradigm.

9. Conclusions

This paper analyzed the performance of exterior stucco (one coat or three coats) from a few different points of view. First, in looking at changes in material technology, we have found that many North American stuccos tend to have a much lower water absorption coefficient than historic stucco or modern stucco tested at TUD. Although different causes led to this difference, including strength considerations or lack of moisture storage leading to higher protection requirements, this trend has reduced the outward drying ability of a wall. Since water typically enters stucco through cracks, crevices, terminations and penetrations, this trend resulted in entrapment of moisture in walls clad with the stucco systems.

Moisture entrapment, combined with increased levels of airtightness and thermal insulation (further reducing the thermal drive for moisture), resulted in a significant reduction of drying capability. Furthermore, misinterpretation of vapor diffusion and the concept of combining air and vapor barriers together (such as sealing vapor barriers in Minnesota practice) have led to complete elimination of inwards drying. To make the situation worse, two field studies reported in this paper indicated that stucco contractors seldom understand the significance of details involved in moisture management.

The paper also shows that moisture management includes many interacting phenomena such as heat, air and moisture flows; and that transient moisture flow prevails in building envelopes and depends not only on transport properties but also on the moisture storage of various materials (for example, cellulose fiber affects wall performance in a different manner than mineral fiber insulation).

Placing these different parts of the puzzle together, the authors maintain that exterior stucco provided with a capillary breaking layer and combined with exterior thermal insulation in a system with improved drying ability, both outwards and inwards, will restore the excellent track record for which exterior stucco walls were known for centuries. The concept of exterior stucco on thermal insulation is not new; it is popular in the southwest U.S. What is new, however, is deliberate design of the wall with wetting and drying ability on both surfaces and design of hygrothermal properties of those surfaces with a view to seasonal and daily balance. This leads to the requirement for optimization of the stucco mix design with the drying rate in mind, even if this involves more water absorption during rain periods, because the overall moisture balance and durability of the wall will be improved.

The authors believe that systematic public-private consortium research should be undertaken for optimization of properties for a modern stucco system that combines high energy efficiency with other environmental considerations.

References

Alesiani, M., Capuari, S., Pirazoli, I., and B. Maraviglia, 2004, Stone structure properties determination by nuclear magnetic resonance imagining and relaxation, Kwiatkowski, D. and Lofvendahl, R., (eds), Proceedings of the 10th International Congress on Deterioration and Conservation of Stone, Stockholm June 27th- July 2, 2004, Vol.2, pp 587-594

Balksten K and S. Magnusson, 2004, The pore structure in lime plaster as a key to understanding moisture transportation properties and frost damages, Kwiatkowski, D. and Lofvendahl, R., (eds), Proceedings of the 10th International Congress on Deterioration and Conservation of Stone, Stockholm June 27th- July 2, 2004, Vol.2, pp 1033-1040

Baronio G., L. Binda and A. Saisi, 1999, Mechanical and physical behaviour of lime mortars reproduced after characterization of historic mortar, P. Bartos, C. Groot and J.J. Hughes,(eds), Int. RILEM workshop on Historic Mortars: Characteristis and Tests, Pailey, Scotland, pp 307-326

Bomberg M. and D. Onysko, 2002, Heat, air and moisture control in walls of Canadian houses: a review of the historic basis for current practice, Journal of Thermal Envelope and Building Science, Vol. 26, pp 3-31

Bonelou E, Y. Doganis, A. Galanos and I. Katsiskis, 2004, The selection of compatible mortars for the preservation of a dense sedimentation limestone, Kwiatkowski, D. and Lofvendahl, R., (eds), Proceedings of the 10th International Congress on Deterioration and Conservation of Stone, Stockholm June 27th- July 2, 2004, Vol.2, pp 993-999

Hoegberg, E., 1967, Mortar bond, Rep.40, Nat. Swedish Inst. For Building Research, Stockolm, pp.1-90

Hughes, J.J. and Valek J., 2003, “Mortars in historic buildings. A review of the scientific and conservation literature,” Historic Scotland, ISBN 1903570 82 4, pp. 79.

Karagiozis, A. and Kumaran, M.K., 1993, Computer model calculations on the perform of vapour barriers in Canadian residential buildings, *ASHRAE Trans.*, **99** (1), 991-1003.

Lstiburek J.W., 2002, Moisture control for buildings, ASHRAE Journal, pp 36-41, or WWW search: moisture control URL: www.eere.energy.gov/buildings/building_america/pdfs/db/33288.pdf

Lstiburek J.W., 2004, presentation on vapor barrier seminar, Building America, Westford, June

MEWS, 2002, Beaulieu P., Bomberg M, Cornick S., Dalgliesh A., Desmarais G, Djebbar R., Kumaran K. Lacasse M, lackey J, Maref W, Mukhopadhyahaa P, Nofal M, Normandin N, Nicholls M, O’Connor T, Quirt D, Rousseau M, Said N, Swinton M, Tariku F, van Reenen D , IRC RR-112

URL: http://irc.nrc-cnrc.gc.ca/fulltext/rr112/

Ohama, Y. 1967, Comparison of properties with various polymer-modified mortars, Colloquium, Building Research Institute, Tokyo, Japan

Ojanen, T., 1993, Criteria for the hygrothermal performance of wind barrier structures, *Proceedings of the 3rd Symposium of Building Physics in the Nordic Countries*, (edited by B. Saxhof), Thermal Insulation Laboratory, Technical University of Denmark, 643–652.

Ojanen, T. and Kumaran, K., 1996, Effect of exfiltration on the hygrothermal behaviour of a residential wall assembly, *J. Thermal Insul. and Bldg. Envs.*, **19** (1), 215-227

Onysko D. and M. Bomberg, 2004, The functional requirements for WRB exposed to incidental water leakage, Part 3: Evaluation of Wall Systems Involving WRB Materials, submitted to ASTM, J. Testing and Evaluation

Marie-Victoire E. and P. Bromblet, 1999, A new generation of cement based renderings: an alternative to traditional lime-based mortars, P. Bartos, C. Groot and J.J. Hughes (eds.), Int. RILEM workshop on Historic Mortars: Characteristis and Tests, Pailey, Scotland, pp 371-394

Moeller, G., 1954, unpublished report in Swedish, Chalmers Tech. University, Sweden, p.30

Morstead and Morstead, 1988, lecture in the Building Science Seminar organized by Alberta Building Envelope Council

Raupach M,. R. Rankers L. Wolff, and M. Gargoundi, 2004; Analysis of the existing mortars and development of new mortar for the historic masonry of Carls cathedral in Aachen, , Kwaiatkowski, D. and Lofvendahl, R., (eds), Proceedings of the 10th International Congress on Deterioration and Conservation of Stone, Stockholm June 27th- July 2, 2004, Vol.2, pp 1089-1096

Research Highlight, 2004, Assessing the impact of thickness on the performance of stucco cladding, CHHC technical Series 04-123

Simonson, C.J., Salonvaara, M. and Ojanen, T., 2004a. Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope, Part I – Field measurements, *Journal of Thermal Envelope and Building Science*, in print

Simonson, C.J., Salonvaara, M. and Ojanen, T., 2004b. Heat and mass transfer between indoor air and a permeable and hygroscopic building envelope, Part II – Verification and numerical studies, *Journal of Thermal Envelope and Building Science*, in print.

Simonson C. J., T. Ojanen, and M. Salonvaara, 2004, Moisture performance of an airtight, vapor permeable building envelope in a cold climate *Journal of Thermal Envelope and Building Science*, in print

TenWolde A, 2004, presentation on vapor barrier seminar, Building America, Westford, June

Thomson M. L., J-E Lindqvist , J.Elsen, C.J.W.P. Groot, 2004, Porosity of historic mortars, 13th International Brick and Block Masonry Conference Amsterdam, July 4-7, 2004

Veiga M.R.; A. C. Magalhães; V. Bokan-Bosilikov, 2004, Capillarity tests on historic mortar samples extracted from site, methodology and compared results, 13th International Brick and Block Masonry Conference Amsterdam, July 4-7, 2004

Uvslokk, 1996, The importance of wind barriers for insulated timber frame constructions, *J. Thermal Insul. and Bldg. Envs.*, **20**, July, 40–62.