APPLYING LESSONS FROM CLAY-BRICK VENEER TO DESIGN A STUCCO MIX

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Abstract

A number of reported moisture-originated failures in stucco-clad walls, attributed in most cases to poor detail design, highlight some misconceptions about moisture control of exterior stucco (other names are plaster or rendering) systems. The authors believe that different type of stucco, installed on an adequate substrate layer, and integrated with proven architectural details can be one of the most economical and ecologically-justified cladding systems that will perform well in most climates. However, the approach to moisture management of this system and to building enclosures in general, must be changed. The new paradigm should be based on moisture balance of the cladding system in combination with moisture management that relates to climatic and service conditions.

Key words: rendering, exterior stucco**,** plaster cladding system, moisture-originated damage, durability

1. HISTORIC AND CURRENT MATERIALS

In this paper terms “exterior stucco” or “stucco” are equivalent to “Portland cement plaster” or “rendering”. We distinguish, however, between the traditional 2 or 3 coat stuccos reinforced with metal lath and lamina in the Exterior Insulation Finish System (EIFS) consists of a polymer modified material reinforced with a flexible polymeric mesh installed on a rigid polystyrene insulation.

The traditional stucco was based on lime-sand base (Millar, 1987; Millar and Bankart, 2009), later cement-lime stucco was successfully used in many different applications (Saretok 1957). Obviously there were some failures (Tibbets, 1954; Svendsen 1961) but the solutions typically related to the material (NBS, 1951; NBRI, 1980; Ribar and Scanlon, 1984) but generally positive experiences were reported (Svendsen, 1954; Kvande and Waldum, 2002).

Since 1970’s however, significant number of moisture-originated failures in the building enclosure have been associated with cement-based stucco or EIFS lamina (also called “stucco”). Moisture problems have been reported and discussed by Merrill and TenWolde (1989); (Williams et al, 1998). Desjairlais et al, (2001), and particularly for coastal regions: Gulf of Mexico (Trechsel (1987), British Columbia (MH, 1989; Chouinard and Lawton, 2001), Washington State and North Carolina (Brown et al 1997, 1997a, Crandell and Kenney, 1996), as well as in the cold, dry climates of Northwest (Tsongas,1990, 1992), Minnesota or Alberta (BEE, 2000).

The authors do not favor lime-based over cement-base stucco. From the hygrothermal standpoint cement-based mortar can be designed to function as well as lime-based products (see Marie-Victoire and Bromblet, 1999). We simply postulate that achieving low shrinkage, crack-free stuccos suitable for significant moisture loads occurring in coastal regions requires a more complex mix design. It appears that often proprietary materials are not optimized in different aspects of performance. Doing it with a material having equal volume fractions of lime and cement may be much easier because of properties of lime (see Baronio et al 1999; Balksten and Magnusson, 2004).

In this paper we focus on moisture and to assist in understanding moisture performance of stucco under field conditions first review the critical hygric properties and their use in material comparisons.

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4.1 1.1 The hygrothermal properties of rendering materials

Four physical characteristics are used to quantify hygric behavior of rendering under variable wetting and drying conditions (Bomberg et al 2002):

- *Water absorption coefficient* or A-coefficient is a relation between the cumulative water flow from the free water surface and the square root of time from the water intake test. It is typically expressed in kg/($m^2s^{1/2}$). (Bomberg et al. 2005**;** Veiga et al., 2004)

- *Water vapor permeance (WVP)* is typically measured by the dry cup test (between 50 %RH and desiccant). This test, ASTM E96, determines the water vapor diffusion through a porous material. Results are reported in permeance (perms or ng/m^2sPa) in North America, but in "mi-values or Z-values" in Europe. The mi-value is a relation between water vapor diffusion resistances through the material and through a layer of still air at the same temperature and pressure conditions, and the Z-value is an equivalent thickness of an air layer with the same resistance to water vapor diffusion.

- *Capillary moisture content* is the maximum moisture content that can be reached by a material during the first stage of free water intake test. This value is often 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 (also approximated by boiling test for clay bricks).

The significance of the water absorption coefficient (A-coefficient) and WVP is self-evident. The former indicates the rate at which water enters the pore system of the material; and the latter governs the rate of vapor diffusion through the material. The use of other two concepts is less apparent and they relate the fraction of porosity that can be used for storage of moisture; in other words they describe the moisture buffering capacity of the cladding material and the ratio of water and air filled volume of the pores.

When the cement based mortar appeared in the market place 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 exhibit significantly slower water movement than clay brick alone. Figure 1 shows cumulative water intake plotted as a function of the square root of time for three materials; lime rendering (curve 1), lime rendering on a cement splatter substrate (curve 2) and cement rendering (curve 3). The lime-based rendering transports water much faster than the cement-based rendering. Figure 1 shows differences in water absorption rates for the three materials. The decrease in liquid inflow (curve 2) might be associated with the effect of the cement substrate. The change in slope indicates that both layers affect the hygric performance of the rendering. In other words, the rendering as a multilayer system may control ingress of moisture to the substrate even when the first layer has higher water absorption rate. As discussed below, an opposite situation is also possible as the current use of acrylic based finishing layer is tighter than cement-based products.

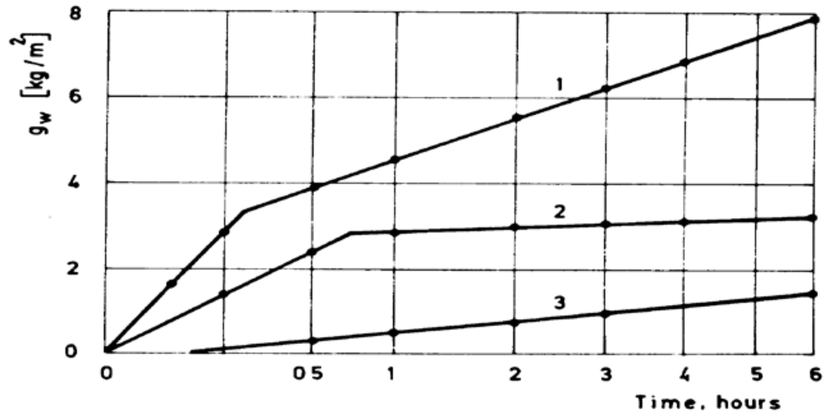

Figure 1: Cumulative water flow, g_w, to clay brick through rendering, plotted against the square root of time in hours (drawn in year 1925). We recalculate values to the current units and curve 1 represents lime rendering (A = 0.07 $kg/m^2s^{1/2}$), curve 2 is lime rendering on a cement-splattered surface, and curve 3 is a cement rendering (A = 0.01 $kg/m^2s^{1/2}$).

4.2 1.2 Current materials

Use of plasticizers, bonding admixtures and dispersive polymers in stuccos changes the relation between the material density, composition and hygrothermal characteristics. Figure 2 shows A-coefficients for five stucco specimens taken from existing houses in a Pacific-coast location.

Figure 2 shows the variability between stucco specimens obtained from one region of the country. The variability may be introduced by varying fraction of polymeric modifiers, use of different grades of sand or different water cement ratios, or difference in curing conditions showing that defining a typical product for a given location is not a straight forward task.

Therefore, as the reference we will use the hygric properties of a laboratory-prepared specimen. Figure 3 shows the water absorption coefficient of brown coat of cement-lime stucco with cement: lime: sand ratio of (1: 1: 5.5) taken by the authors to be the reference stucco mix. In contrast to this, Figure 4 shows the water absorption coefficient of an acrylic-modified proprietary product used for the finish coat in a typical Northeast application. The difference between A=0.16 and A=0.0009 $kg/m^2s^{1/2}$ tells the whole story.

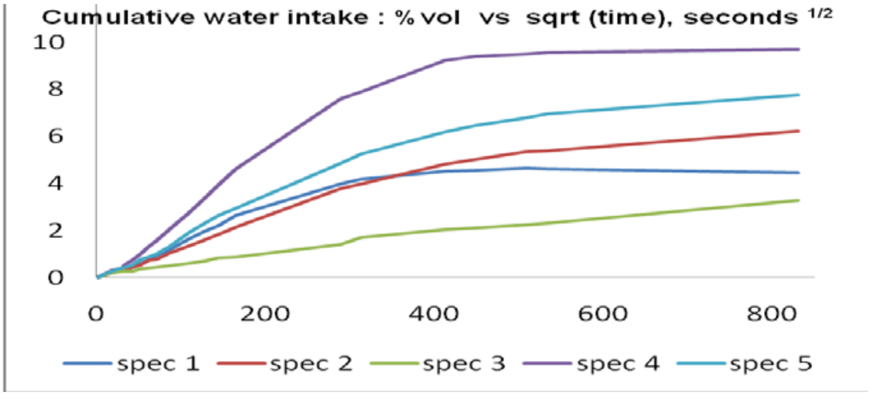

Figure 2: Variation in free water intake test between 5 random samples taken from the existing stucco-clad buildings in the same region

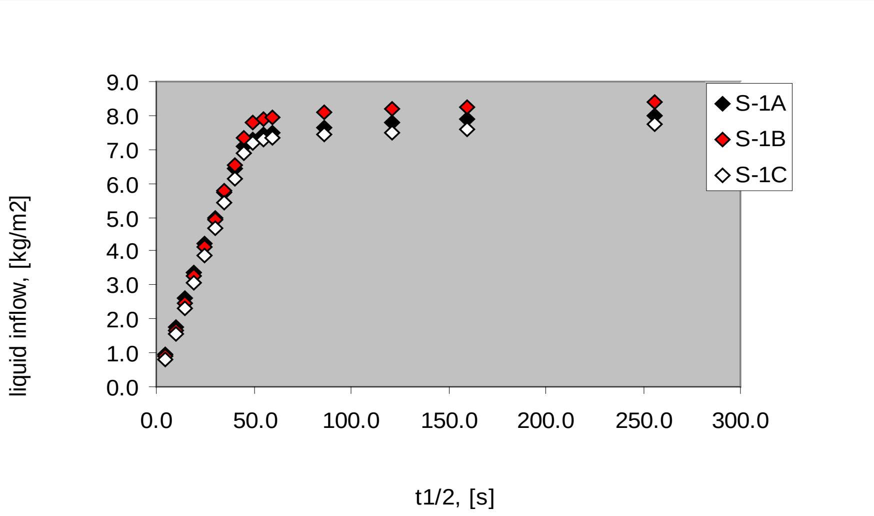

Figure 3: Cumulative water flow into specimens (50x50x50 mm) made on the building site from a brown coat of lime-cement rendering (1: 1: 5.5). Tests performed at Syracuse U gave a mean value of A = 0.16 kg/m^{2}s$^{1/2}$.

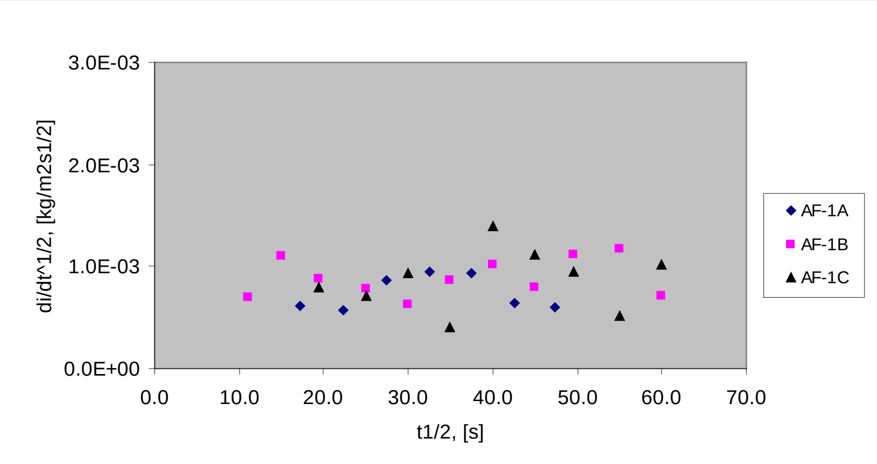

Figure 4: Water absorption coefficient (slope of the line in Figure 3) of an acrylic-modified finish coat used in a Northeast rendering. Tests performed at Syracuse U gave a mean value A = 0.00092 kg/m^{2}s$^{1/2}$.

Let us compare these measured values with materials used in Germany. Technical University of Dresden (TUD)[3] test results show also a variation in A-coefficient of commercial premixed products. The highest A-coefficient value, 0.17 kg/m^{2}s$^{1/2}$, was measured for a rendering having a density of about 610 kg/m^3, while the lowest value of A = 0.013 kg/m^{2}s$^{1/2}$ was measured for a rendering with bulk density of about 500 kg/m^3. On the other hand an interim value of 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 3). Yet, the lowest values measured on American products are one magnitude lower than those from the

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[3] Private communication with Dr. Rudolph Plagge, Technical University of Dresden

TUD series (Figure 3). The significance of this difference becomes evident when one realizes that drying rates are correlated with the wetting rates.

Bruckmayer (Nevander, 1968[4]) 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). While the external stucco used in German buildings cover the range of drying rate between clay brick and concrete; the drying rate of finishing coat in Figure 4 appears one magnitude slower than concrete.

Putting these data in a plain language one may say that the finishing coat shown in Figure 4 does not dry fast enough. Wetting of the wall takes place through junctions and penetrations and drying must take place through the field of the material – if we do not dry incidental moisture we get the moisture damage as discussed in the introduction.

4.3 1.3 Historic perspective on mortars

Ideally, mortar should possess the following characteristics:

1) The mortar must be workable to ensure complete joint filling without separating or "tearing".
2) It should be sufficiently strong to carry imposed loads but yet elastic enough to follow movements of the structure.
3) It should completely and permanently bond into the surface of the unit.
4) It should in itself be durable and have the capability to fill small cracks and fissures by chemical reconstitution.
5) It should have minimal cyclic dimensional changes after being incorporated into the wall.
6) It should possess high water retention capabilities to resist rapid moisture loss to the units.

Obviously, there is no mortar suitable for all applications and a designer must make a choice that takes into consideration the particular characteristics of the mortar and the materials required for the construction. For instance, types "M" and "S" are selected for the strength but their rating in all other rate attributes listed above is low. The weaker mortars, type N, O or even K show much better capability to cope with movements and deformations. Yet, there is a significant difference between the rates of the strength gain that relates to the use of lime. Morstead and Morstead (1988) noted that: “Tests have shown that high lime content mortars cure at a rate that is more compatible with rate of building and unit movement. Table 1 shows averaged compressive strength gain from the 28th day to one year[5]:

Table 1: Classification of typical mortar mixes with Portland cement and compressive strength gains from the 28th day to one year, Morstead & Morstead (1988)

Mortar		**Parts by Volume**			
Type	**Portland Cement**	**Hydrated Lime or Lime Putty**	**Aggregate***	**Compressive strength (CS, psi)**	**% increase in CS**
M	**1**	**1/4**	**31/2**	**2500**	**28**
S	**1**	**½**	**41/2**	**1800**	**36**
N	**1**	**1**	**6**	**750**	**60**
O	**1**	**2**	**9**	**350**	**95**
K, or	**1**	**3**	**12**	**--**	**148**
K	**--**	**1**	**3**	**--**	**252**

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[4] Lectures in the course of Building Physics 1968 at Lund Inst. of Technology

[5] Currently the rate of lime curing is believed to depend on the type of other binders used in combination with hydraulic lime – private communication with Dr. Margaret Thompson, Chemical Lime Corp

Tate (2005) reviewed attributes of lime and lime-cement stucco highlighting three aspects that are particular to presence of lime, namely: elasticity, autogenous healing and water tightness.

(1) Slow-hardening of high lime content mortars “accommodates stresses caused by building movement and cyclical changes without excessive cracking. An example of the flexibility of lime-based mortars is its use in the construction of tall industrial masonry chimneys” Boynton (1980) indicated 1:1:5 being a typical formulation used for chimneys.

(2) When hairline cracks develop in the mortar, the combination of hydrated lime, moisture and carbon dioxide from the air can help to seal the crack by the formation of limestone (calcium carbonate). The crystals formed by this process help to plug the hairline cracks. This process is called autogenous healing.

(3) Evidence of the use of lime in masonry applications dates back to 500 BC. Conner (1948) published an empirical study of 100 buildings with a wide range of mortar types, all of which were owned by the New Jersey Bell Telephone Company. The buildings varied from 6 to 23 years old. One of the four factors he found to be present in water-tight construction was the use of a lime-cement mortar of a 1:1:5 or 1:1:6 mix design.

Mortar functions to protect the masonry unit and interact with it to transfer loads to the backup wall. Specific performance aspects of lime such as slow curing and t allowable elasticity during initial period of construction brought back the trend to use 1:1 volumetric ratio between cement and lime.

2. PERFORMANCE ANALYSIS FOR EXTERIOR STUCCO

To answer the question – Can two-coat stucco perform as well as three-coat stucco we need to review the functions of all layers.

2.1 Functions of different layers

The primary requirements for a base coat material are:

- Good adhesion to the substrate (Hoegberg,1967), a difficult task when stucco is bonding to an insulation material, typically adhesive bond must be stronger than the cohesive bond of material)
- Relatively fast strength development (the actual requirement depends on construction stiffness and permissible degree of cracking, typically at 28 days minimum 350psi).
- Limited shrinkage deformation (typically linear shrinkage below 0.7%)
- Limited macro-crack development during drying (no test method exists in public domain)
- Limited capillary water transport (water absorption coefficient between 0.01 to 0.1 kg/m^{2}s$^{1/2}$)
- Some drying capability i.e., water vapor permeance 2 to 10 perms (2E-10 to 6 E-10 kg/(m^{2}sPa)

The primary requirements for the brown stucco coat 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^{2}s$^{1/2}$)
- Medium to high water vapor permeance 10 to 30 perms (6E-10 to 2 E-09 kg/(m^{2}sPa).

The brown stucco coat needs to be much more permeable and it appears that a cement-lime mix 1: 1 ratio with addition of polymeric admixtures would provide increased permeability. Ohama (1976) showed that shrinkage of the Portland cement mortars was reduced by factor of 3 with 20% admixture containing natural rubber and by factor of 2 with 20% admixture containing styrene-butadiene and significant fraction of coarse sand. A surface finish on the brown coat may be necessary to control surface staining due to dirt settlement and discoloration.

Since the most critical consideration in the mix design is shrinkage, the lime-strong mixture offers a better shrinkage control as well as a chemical re-constitution of soluble salts (see 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 cement mix requires RH near 100% to avoid early macroscopic shrinkage cracks). In stucco system the layers must have reduced strength such that the scratch coat has the highest strength and the finish coat is the weakest layer. This sequence is necessary to preventing warping of the rendering system and ensuring an increasing rate of vapor diffusion towards the exterior surface.

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 typically do not exhibit large shrinkage cracks. Conversely, to establish bond between a cement-rich mortar and a dry substrate, the substrate may need to be pre-wetted.

Typically, stucco shows 4 – 5 % water absorption in 6 hours and 11 to 13% after 2 days exposure i.e., capillary saturation between11 and 13% while its total porosity varies from 22 to 31 percent by volume.

Bruckmayer[6] showed that lime mortar has drying rates similar to that of clay brick, while cement mortar dries at the rate similar to that of concrete (i.e., about 10 times slower). Kruger (1925) showed that lime-cement mortar containing coarse sand dried out faster that mortar with fine sand, though both are significantly slower than the clay brick alone.

2.2 Moisture management strategy

An important aspect of rendering (stucco) performance is related to the development and crack propagation. Figure 5 illustrates the effect of a crack on water spread.

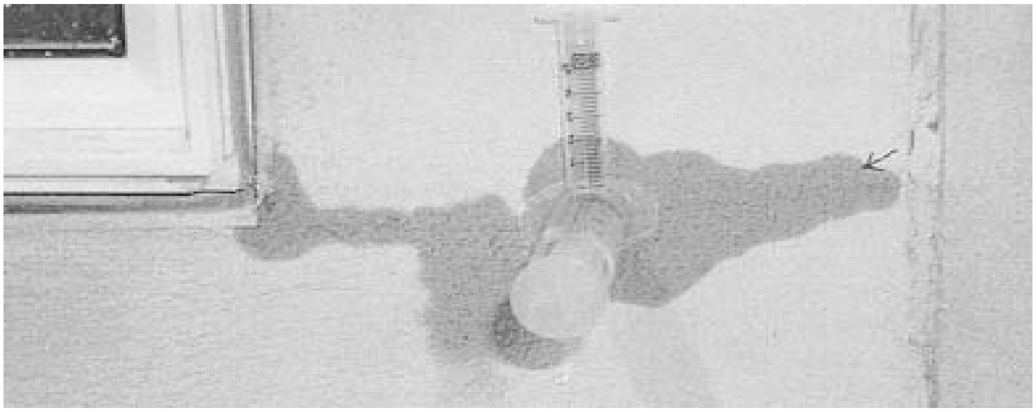

Figure 5: Effect of a crack - water spread along the crack

Cracks are primarily caused by shrinkage during drying of the construction moisture from the material. While unrestrained deformation is possible only at rendering edges, one should wait until the primary shrinkage has been completed before the appropriate sealing be applied to terminations and around windows.

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[6] Private communication by Lars Eric Nevander (1972) based on Bruckmayer lectures at Institute in Vienna,

Given 0.3% shrinkage one may expect a crack with width 0.3 mm at the corner of the window located 3 to 4 ft above termination (similar to the one shown above). This explains why one needs a second layer of stucco. It needs to bridge the cracks in the first layer (scratch coat) and to this end it must be more elastic (weaker) and less affected by moisture accumulation i.e. be more permeable.

The performance of the third (finishing) layer is actually prone to misconceptions. It is typically assumed that it functions to "protect stucco from the rain ingress". This is completely incorrect. If the second layer is to be weaker and more permeable than the first so the third layer (exposed to the weather) must be ever more permeable. This reduces the capillary suction of water and increases the drying capability.

2.3. Principles of stucco design

It is now generally believed that there are three probable causes of the moisture problems:

(1) A significant water penetration occurs around windows and doors, allowing excessive amounts of bulk water to enter into the wall assembly.
(2) The stucco is not adequately separated from the wall sheathing allowing the transfer of moisture from stucco to the inner part of the wall as WV diffusion under solar induced gradients.
(3) The exterior wall has limited drying ability both to the exterior and interior, which compounds the water entrapment and worsens the effect of the other two problems.

Wetting of the building assembly occurs through joints, junctions, terminations and cracks. Manufactures of stucco systems cannot control workmanship in the field and even with well developed moisture management strategies certain quantity of bulk moisture is bound to penetrate the lamina. However, the manufacturer can design lamina with properties that optimize the drying capability of the material.

Is there a difference between 2 and 3 -coat stucco with respect to wetting and drying? CMHC (2004) sponsored a study that included 184 facades on 47 buildings in Alberta, 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 lamina thickness on the remaining buildings was less than 15 mm. The results are shown in Table 2.

Table 2: Results from CMHC (2004) study in Alberta

Description	**3-coat stucco**	**2 coat stucco**
No deterioration		1
Normal deterioration	15	67
Minor distress	8	76
Significant deterioration		9
Needs immediate repair		8

As expected, most damage was found at flashing locations, windows and door perimeters and corners. The most important conclusions from this study were as follows:

- There is a lack of standard procedures to evaluate 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 from being wicked towards the building interior.
- Cracking must be considered in evaluating water management performance.
- Need to educate builders and stucco applicators in best practices and need to improve stucco materials as well as practices in constructing building enclosure.

Table 2 highlights the current situation – poor rating of 5 to 10 year old stucco in cold and dry climate region while one of the authors lives in 40 year old stucco clad house in cold and humid climate that has no cracks or sign of deterioration – obviously the problem appears to be a loss of construction know-how leading to lack of understanding how does the stucco function.

3: A BUILDING PHYSICS BASED STUCCO DESIGN

The concept of lime-based, breathable stucco was presented by Bomberg at al (2005) and further expanded in Pazera and Bomberg (2007). They postulated the need to bridge the traditional and modern trends in renderings. Since research in this field is scarce, the authors decided to undertake this work on their own.

We intend to develop two-coat light-weight stucco that includes a mixture of different recycling and post-consumer materials. The recycling materials are selected with a view to:

(a) Improving a freeze-thaw resistance (in lieu of the air entrainment) – that requires control of the fraction of capillary pores between 1 and 10 microns
(b) Reduce fatigue based damage by provision of pores with a diameter large enough stop to the crack propagation
(c) Different charring/ melting behavior in fire to achieve fire-resistance with a minimum of fire retarding chemicals
(d) Reducing density by 30-40% of that of a typical Portland cement plaster

The binding mix will material will comprise lime, Portland, and natural cements. The primary material is hydraulic lime. Yet, as lime develops strength over prolonged period of time, sufficient fraction of Portland cement is added to achieve the 28 day required strength**.** As discussed before**,** lime rich mortars were used successfully in construction of many large size structures in the early part of the 20th century. The famous Chrysler Building in NY City constructed with a steel frame and masonry infill consisted of mortar with 1: 3: 7 (cement /lime/sand) ratio. A high chimney stack in Montana was built in 1918 with mortar having 1: 2: 5 ratio and required only minor repairs in 1952. Lime rich mortars cure much slower than cement rich mortars – concrete columns may have shrunk a lot before the full strength is developed (e.g. in a year)

A paper from the Lime Association[7] reports several studies and concludes that type S hydrated lime provides improved bonding. It is caused by the high water retention due to the high surface area and micro-fineness of Type S hydrated lime fineness (50% less than one micron in size). This results in increased water holding capacity and in turn improves workability of the mortar. Secondly, lime can reconstitute itself through re-carbonation. Carbon dioxide from the atmosphere combines with lime to form new calcium carbonate that tends to plug the voids or hairline cracks. Two studies have demonstrated that walls containing lime tend to resist moisture penetration better after six months of outdoor curing.

Based on the experience of masons one can recommend type N Portland cement – lime mortar (1:1:6) as a mix providing a good balance between compressive strength and water retention capability. Looking from the side of historic restoration, there was shortage of lime in 1970 and its replacement with N-type (1:1:6) and O-type (1:2:9) mortars as typical solutions over these decades until lime reappeared in the historic applications. Effectively, our design will be focused on achieving performance between types N and O. The requirement for 28 days minimum compressive strength was set at 400-500 psi (2.8 -3.5 MPa) with tolerance of ±10%.

Natural cement, sand, organic and inorganic fillers will be used to design the required degree of pore connectivity and to achieve the required level of hygrothermal properties. Littman (1960) evaluated the addition of the bark extracts of trees in the Mayan area and found that its use caused less cracking and a smoother surface postulating that these additions stabilizing the lime plaster during drying. We also know **(**Bomberg at al, 2003) that bark/ wood extracts dramatically reduce the viscosity of water and reduce the amount of water need for good workability. This, after all is 21st century and we may replace the ground bones, hair and blood of animals used in the medieval lime mortars by their modern chemical equivalent – silica, stone fibers, viscosity modifiers and dispersive polymers.

As pozzolanes can also be obtained from burning agricultural waste and mixed with lime create a very good binder, Middendorf et al (2005) advocate a substitution of Portland cement by this combination. They show that 60% of cement can easily be replaced and 28-days strength is still within the reach. Reda Taha and Shrive (2001) highlights that use of pozzolans will improve bond and bond strength.
The main consideration in design of the mix is the shrinkage-originated cracking. The hygroscopic effect of Portland cement is reduced by the use of natural cements to permit use of the elastic mesh instead of metal lath one must differentiate between the base and finishing coat mixes. The base coat can be designed to accelerate the shrinkage related macro-cracking and have it completed at an early stage of drying[8], the second coat can be designed for slow rate of strength development (Morstead and Morstead, 1988) that offers significant advantages in design of material mix as long as the finishing paint (coating) has adequate elasticity and permeability. This makes a permeable, finishing coat from EIFS technology welcomed here.

Water retentively is one of the most important physical masonry mortar properties that affect bond (Goodwin and West, 1982). This aspect of performance will also be included in the scientifically designed stucco.

4. EFFECT OF COMPOSITION ON HYGRIC PROPERTIES OF THE STUCCO

First we need to look at 'classic" mixes made without any polymeric modifiers.

4.1 Wetting and drying performance of traditional stucco formulations

For comparison sake we have prepared 5 types of the stucco mixes prepared in a lab:

A = 1: 1: 4.5 (strong scratch coat in lime cement stucco)
B= 1: ¼: 4 (strong scratch coat in cement stucco)
C= 1: 1: 1: 6 (fly ash modified lime-cement stucco)
D= 1: ½: 6 (weaker traditional coat)
E= 1: 1: 5

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[8] Moeller, G., 1954, unpublished report in Swedish, Chalmers Tech. University, Sweden, p.30)

Wetting and drying rates of these mixes are shown in Table 3 and Figure 6.

Table 3: Water absprtion coeffcient in kg/($m^2s^{1/2}$) of six mixes

A	B	C	D	E
0.0459	0.0257	0.067	0.0961	0.0589
0.0479	0.0264	0.0623	0.0955	0.0609
0.047	**0.026**	**0.065**	**0.096**	**0.060**

Table 3 shows that cement-strong mixes A and B show lower A-coefficient than other three mixes. Mixes C and D are displaying higher water absorption coefficient that is in our mind a better hygric performance. Figure 6 confirms this judgment. Initially mixes B and C show the best drying ability while at the later stage only mix C (where part of cement is replaced with fly ash) stays on the top of drying rate curves.

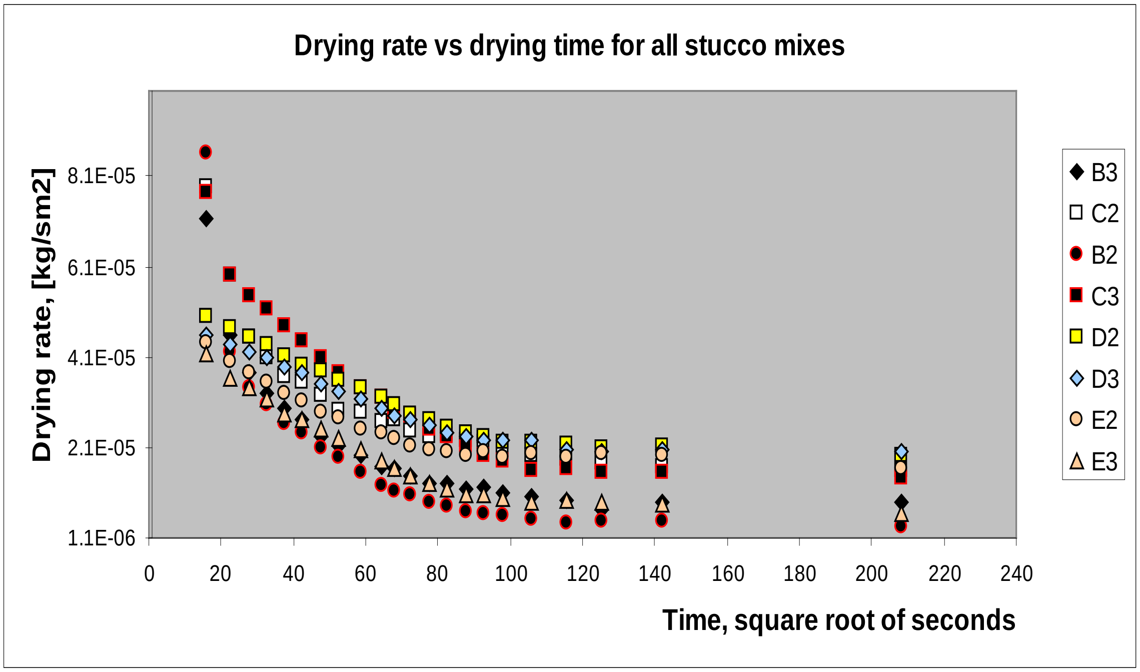

Figure 6: Drying rate versus drying time measured at SU on all stucco mixes

4.2 Wetting and drying performance of thermal insulating stucco formulations

Insulating stucco manufactured in Beijing[9] was tested and results are shown in Figures 7 and 8. Figure 7 shows the mean value of water absorption coefficient 0.047 kg/m^2*$s^{1/2}$ i.e., identical to that measured on the reference mix A but the drying rate is somewhat faster than the traditional mixes. This indicates that use of polymeric admixtures permit more freedom in designing hygric performance of stucco.

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* This product was manufactured by Zhen Li High Technology Co in Beijing but tested at SU

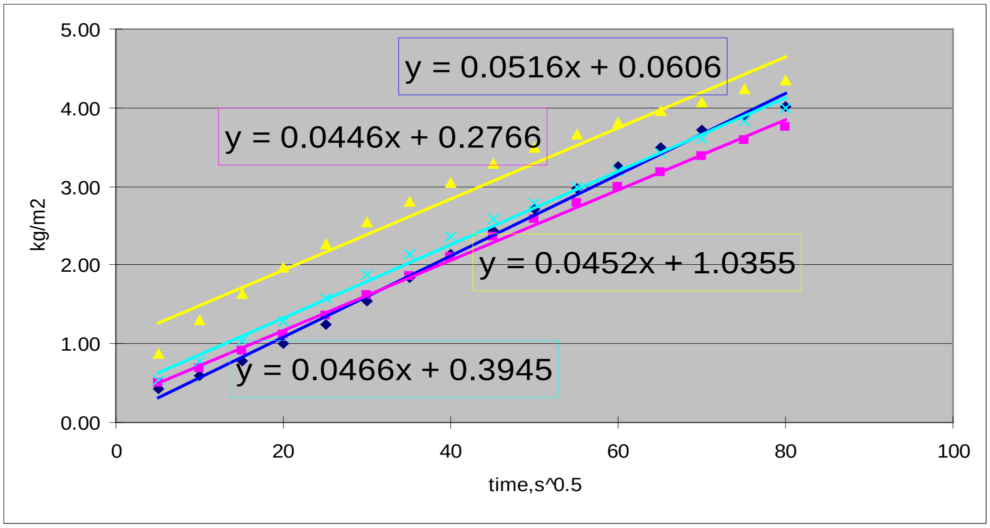

Figure 7: Water absorption coefficient in *(kg/m^{2}s$^{1/2}$)* slope of the lines measured on insulated stucco made in Beijing*

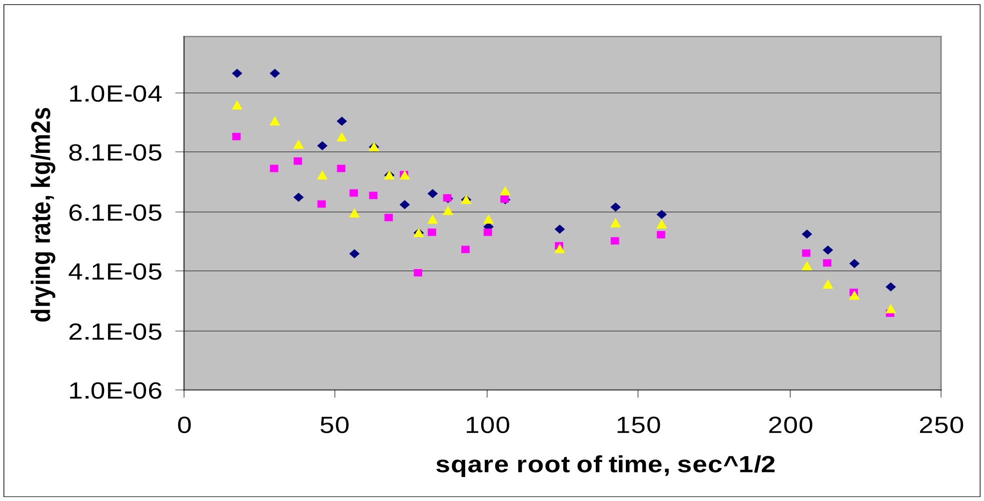

Figure 8 Drying rate of the insulating stucco from Beijing*

4.3 In search of a low density stucco mix

The authors propose light weight stucco based on recycled aggregates and binder with lime - cement - natural cement to be placed on thermal insulation substrate (wood fiber boards and close cell spray polyurethane foams are selected for this purpose) as the system needed for both new and rehabilitation of old houses. Why?

Traditional polymer-based lamina is typically 2.5 to 3 mm thick. This is sufficient when the surface of a new building is smooth and tolerances are small. Yet, many old building have rough or uneven surface. Furthermore the enclosure lacks air barrier system. One would like to use close cell polyurethane foam for heat, air and moisture control but applying a 3 mm thick lamina requires removal of the surface skin and planning the material surface. Experience of several years[10] indicates that this is possible but effort in foam planning and waste of material would be reduced with a thicker stucco layer. A thicker layer would allow larger irregularity of the surface.

Wood fiber materials are used in Europe for direct application of lamina for number of years. They also benefit from a 10-12 mm thick stucco layer. Such a stucco layer must be as elastic as the current EIFS lamina. Here we are finding a dilemma, stucco is reinforced with metal and metal mesh is not compatible with the requirement of elasticity introduced by low stiffness of wood or metal frame walls.

5. SOME EXPERIMENTAL RESULTS DURING THE R-STUCCO® DESIGN

Figure 9 shows wetting rate in free water intake process on two experimental mixes from new system trade-marked R-stucco® for use of recycled aggregates and eliminating 60% of cement content. The latter is only used for generating initial strength of the mix. These samples have identical binder formulation (lime, natural and Portland cement) and two contain two reground recycled aggregates (newsprint and cellular plastic). The difference is that material S1 has only the traditional polymeric admixtures (0.01% of the total mass) while S2 has an additional (1% by mass) additional water retaining admixture. The purpose of this admixture is two-fold: (1) increasing tightness of the cured material and (2) allowing slow drying in hot climate application. The selection of the used fraction of the admixture was such that it delayed time of specimens de-molding from 1 day for mix S1 to 3 days for S2.

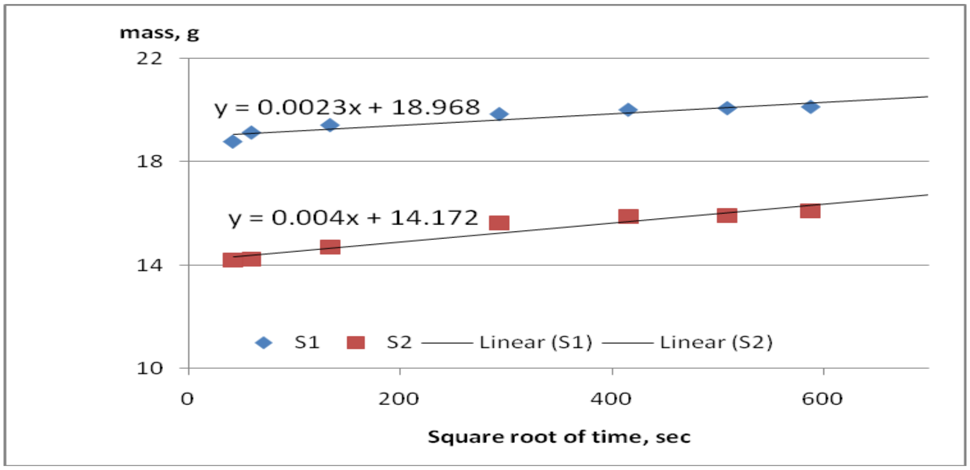

Figure 9: The same experimental R-stucco® mix with (S2) and without (S1) water retention admixture (see text)

One can observe that the water retaining additive modified the pore structure of the cured product (see Thomson et al, 2004). The total water absorption of the mix is reduced (from 18.97 to 14.18 i.e., 25%) but the water absorption coefficient is increased from 0.0023 to 0.0040 (i.e., 74%). A-coefficient of S2 is still 3 times lower than typical cement-based stucco or the lowest German stucco but it is 1 magnitude higher than the tight acrylic stucco shown in Figure 4. Other properties of mix S1 and S2 are shown in Table 4.

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[10] Spray Foam Stucco, a small company operating in Boston, MA have used extensive surface cutting of cc foams and successfully applied EIFS lamina since 1997.

Table 4: Critical properties of R-stucco® mixes from series S

Description	Shrinkage, 14 (28) day in percent	Density, kg/m^3 - lb/ft^3	Compressive strength 14 day, psi - MPa
Design criterion	Max 0.25(0.30)	Max 1100 – 69	Min 400 – 2.8
Mix S1	0.23	1100 – 69	972 - 6.7
Mix S2	0.14	1200 – 75 fail	841 - 5.8

As seen in Table 4 mix 2 failed only on density while passed the required control of shrinkage and with strength exceeding 200% of the minimum, one can increase the fraction of aggregate to reduce both the density and compressive strength. Let us compare a few stucco mixes from the series S5 and S6 where the low end of the design range was studied.

Table 5: Selected properties of some R-stucco®

Description	Shrinkage, 14 (28) day in percent	Compressive strength 14d psi - MPa	Initial A-coefficient kg/m^{2}s$^{1/2}$	drying rate at 24 h kg/m2s
Design criterion	0.25 (0.30)	Min 350 – 2.5	--	
Mix S51	0.29 (0.30)	392 - 2.7	0.040	1.11E-05
Mix S60	0.37 (0.39)	392 - 2.7	0.076	0.95E-06

Table 5 shows the lower end of the property range selected as the development limits. One can observe that use of chemical and fibrous admixtures to the mixes allows uncoupling the water absorption coefficient from the drying rate. Water absorption coefficient of the tested mixes S-series is within the optimal range of 0.04 to 0.08 kg/m^{2}s$^{1/2}$ but water vapor permeance measured with wet cup method is very high namely in the range of 14 to 30 perms.

Effectively we have achieved our goals: low shrinkage, slow water intake and high drying rate of the stucco.

CLOSING REMARKS

In is well known that cladding that lacks air tightness and moisture storage cannot be used in exposed location on a face-sealed system. Yet, it is also known that except for high exposure areas with driving rain and prevailing periods with high humidity a standard masonry walls has shown successful hygric performance over years. Thus, it is logic to assume that for majority of the climatic regions of North America one could use an adhered system if it included three components of moisture management, namely air tightness, moisture storage and water resistive barrier (WRB). In building science this approach is identified as a dual barrier system see: Bomberg and Trechsel (2009).

The stress is placed on effective moisture management strategy, not on the drainage principle. It is also known that drainage of water out of masonry walls happens very seldom, if any (note that most brick veneer walls function very well with cavities plugged by mortar layer as long as the diffusion-based drying is accelerated by some air exchange).

In this project, we found the definition of exterior plaster (stucco) is obsolete. Use of a metal reinforcing lath is required in stucco to control shrinkage and cracking induced by hygrothermal movements. Yet, designing modern stucco one can avoid cracking using different mix composition altering curing pattern. For instance, by using post-consumer, recycled elastic aggregates we modify the nature of the stucco. Furthermore, we are using a double reinforcement system (glass fiber mesh and reinforcing fibers. Therefore, we decided to call this material R-stucco® so that the issue of terminology is eliminated.

The traditional stucco is supposed to have 18-19 mm (¾ inch) thickness and is built with 3 layers. In Germany stucco placed on semi-rigid, water retaining boards has typically thickness of 10 mm. 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 R-stucco® is proposed to have thickness about 10 mm and contain 2 layers applied with 2 - 7 days delay between each other plus a finishing layer typically about 1 mm (1/25“) so there is not much of a difference from the current practice.

This paper does not present a specific mix of R- stucco® but presents a feasibility of a new technology. We wanted to demonstrate that by using recycled wood or newsprint together with regrind of foam insulation not only we can reduce 40% weight and 50% thickness of the traditional stucco but we can reduce its shrinkage, improve its cracking resistance and allow use of alternative reinforcing.

Elsewhere in this conference we introduced bio-fiber batts and boards technology. Therefore, the next step in our research will be to address hygrothermal performance of an exterior insulation system when R-stucco is placed on bio-fiber exterior insulation**.**

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[11] WRB is a most frequently used term denoting a membrane placed to the exterior of sheathing material and used to control flow of moisture. While the explanation of the abbreviated term WRB (weather or water resistive barrier) may technically be incorrect (most of the barriers are permeable to water vapour) we use the term WRB mainly because of its convenience and the spread in use.

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