Hygric performance of Portland cement and cement-lime plasters (stucco) for frame-wall construction

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ABSTRACT

Rainscreen walls are typically recommended for all regions of North America with humid climates. This approach was accepted by the Exterior Insulation and Finish Systems (EIFS) industry and drainable air gaps were introduced behind the insulation after well-publicized failures of wall-window interface in the North Carolina state. One may also expect that the same solution used for stucco cladding would improve the moisture protection provided for those walls. Questions arise if this approach is necessary for less severe climates than in coastal areas. Are there other options for providing sufficient moisture protection in continental climates, e.g., in Minnesota or Alberta? If so, such approaches should be examined.

The authors claim that properly detailed stucco cladding with adequate design of material when placed on two layers of water resistive barrier (WRB) is able to provide sufficient moisture protection in most of North American climates. Yet, this statement is conditional on good detailing of the wall assembly and the provision of hygric properties that are appropriate for the climatic and service conditions. This paper reviews the use of Portland cement and cement-lime plaster (stucco) for frame-wall constructions highlighting the difference hygric performance of traditional lime-cement and modern polymer-modified cement stucco.

1. INTRODUCTION

There are many excellent compilations of field evaluations related to performance of stucco. Ribar and Scanlon (1984) wrote perhaps one of the best deficiency reviews, not only dealing with performance of Portland cement plaster but also providing advice on how to avoid deficiencies. Scandinavian publications e.g., NBRI (1980) dealing with adhesion failures of plaster on concrete; Svendsen (1954 and 1962) reporting damage of renderings in Norway , NBRI (1961, translated into English), Saretok (1957) provided a literature review on rendering (in Swedish) and Kvande and Waldum (2002) provided an update that gives a very detailed picture of the field performance of stucco.

Tibbets (1954) reviewed research on stucco cracking that occurred between 1911 and 1952 which complemented the NBS (1951) review on lime-stucco failures. This list of several publications from cold climate countries demonstrates that stucco systems have been developed primarily on the basis of tradition.

Today, however, traditional exterior walls with traditional stucco are seldom being constructed in North American housing. Today, stucco systems are built on substrates with much lower stiffness or are placed on an elastic exterior insulation. This has increased requirements for stucco strength and introduced a shift towards cement-based stucco products. To counteract the propensity for increased shrinkage several polymeric admixtures have been used. In this development process, the hygric properties of the modified stucco are often disregarded.

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In the USA, application of stucco on to external thermal insulation has been a popular practice in the West and the South West, i.e. warm and predominantly dry regions. In the North East (mostly cooler and often humid) stucco is rarely used. In Western Canada stucco is a cladding of choice but it constitutes a rare practice in the Eastern part of the country, where the traditional stucco systems have been replaced by other cladding systems.

Research on traditional and modern 3- coat, 2-coat (or 1-coat applied in two layers) stucco systems is very limited. In central Canada efforts have been directed to examine the field appearance (visible cracking) of two coat stucco in relation to its counterpart 3 coat stucco with thickness being the discrimination factor (CMHC, 2004).

Yet, traditional (3- coat, 2-coat or 1-coat applied in two layers) stucco offer several advantages and should not be written off. Stucco, with the metal lath used for mechanical reinforcement can provide much better cracking resistance than typical EIFS lamina. The most effective traditional reinforcement – expanded metal lath had an effective cross-sectional area varying from 0.075 square inch to 0.6 square inch per ft of width (Kidder-Parker, 1954) and an elastic limit 60% higher than commercial steel. It provided reinforcement with distribution of in all directions.

The 15th edition of the 1894 Kidder-Parker handbook (1954) stated:

> "The general function of metal lath is to serve as a plaster base, but in addition it reinforces the plaster, distributes stresses and precludes the possibilities of cracking… It tends to eliminate streaking and staining when condensation of moisture occurs….Its superiority from a fire protection point of view depends in large measure on its ability to hold the softened and claimed plasters and mortars in place by mechanical bond."

Traditional stucco was often placed on outside of furring to prevent passage of moisture. This practice, more recently, was replaced by some by the use of a two water resistive barrier (WRB) layers that may provide an "adequate" capacity for water removal[2] (Bomberg et al 2005b). Thus one may postulate that stucco systems can have substantial moisture storage and capability for moisture removal that would mitigate the effects of intermittent moisture loading by rain.

A cogent question that should be asked is this: why has traditional stucco on masonry lasted for centuries while modern stucco on wood frame walls has, in some regions, experienced an unsatisfactory record of performance, often during the first decade of service[3]? Researchers have discovered that in spite of hundreds of years of documented stucco usage all over the world, a methodology to evaluate long-term performance of stucco systems does not exist! To address this issue we start with a review of historic use.

2. TRADITIONAL THREE-COAT STUCCO.

Traditional[4] stucco consists of a base, scratch or brown and finish coats. The cementitious components are Portland cement and hydrated lime in volume proportions indicated in Table 1.

[2] The need for 2 layers of WRB stems from the requirement of imperfect hydraulic contact that combined with frequent reversal of thermal gradient (solar and night sky radiation) accelerates the process of removal of moisture by water vapor diffusion aided by gravity. (See coming 2nd edition of ASTM moisture manual)
[3] See Energy Design Update, "Report form Minnesota", EDU vol.26, No5, May 2006
[4] Actually, the old stucco (in the Roman empire time) was based on natural cement, what we call "traditional" in this paper would relate to 19th and the beginning of the 20th century.

The volume of the aggregate is proportional to the total volume of the cementitious volumes. In a typical application over a solid base the base coat thickness varies between 9 and 12 mm (3/8" to ½'). The scratch coat is approximately 9 mm (3/8" in) thick and the finish coat varies from a paint layer to a 3 to 6 mm (⅛" to ¼") thick stucco layer with additional granular materials.

Table 1: Composition of 3 coat stucco (Portland Cement-based Plaster), Gorman et al., (1988)

Coat	**Volume cement**	**Volume Lime**	**Volume Aggregate**	**Min thickness**	**Minimum moist cure**	**Min. interval between coats**
Scratch	1	¼ to 1	2½ to 4 5	9 mm	2 days	2 days
Brown	1	¾ to 1½	3 or 5	9 mm	2 days	7 days
Finish		¾ to 1½	1½ to 3	3 - 6 mm		

Table 1 presents a range of volumes of cement, lime and aggregate which potentially can result in a significant difference in hygrothermal performance of the stucco. The varying proportions of cement, lime and aggregate in a stucco mix will modify its hygric properties of the cured stucco including the equilibrium moisture content or water and vapor permeability. These properties are important because they influence the quantity of moisture that can be stored (retained) in the material and the rate at which that moisture can dry out.

Mechanical properties are also influenced by the cement and lime ratio. Specification for masonry mortar (CSA 179) provides a good template to describe this relationship. The cement and lime mortar types M, S, N, O and K represent a decrease in cement and increase in lime, a decrease in compressive strength, and more importantly, an increase in ductility. Table 2 provides a summary of the volume proportions and typical 28-day compressive strength data. Morstead and Morstead (1988) highlight the development of cracking in non-load bearing brick veneer with the increase in compressive strength requirements for mortars:

> **"**Type "N" is now the most commonly used. 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. It appears that to offset cracking one must increase the frequency of control joints in masonry and that this happens in direct relation with the increased fraction of Portland cement in mortar.

Morstead and Morstead (1988) recommended the use of mortar types N and O mortars noting that:

> "Tests have shown that high lime mortars cure at a rate that is more compatible with rate of building and unit movement."

Table 2, quoted from the same paper, shows compressive strength gains from the 28th day to that at one year were averaged from tests conducted at five laboratories that were located in temperate to severe weather zones.

Table 2: Typical proportions of mortar types M, N, S, O, K and compressive strength gains between that at 28 days to that at one year after mixing.

Mortar Type	Volume cement	Volume Lime	Volume Aggregate	Typical 28 day strength, MPa	Percent Increase
M	1	0	3	23	28
S	2	1	9	20	36

N	1	1	6	17	60
O	1	2	9	10	95
K	1	3	12	5	252

Significantly, type K, a high-lime mortar shows a dramatic increase in compressive strength (in excess of 200%) between 28 days and a year. The type N mortar shows less of an increase in strength (60%). The hardening mechanisms of cement and lime are different (Thomson et al., 2004). Cement hardens quickly by a hydration reaction of the calcium silicate and calcium aluminate minerals to calcium silica hydrate. Lime hardens slowly by the diffusion reaction of calcium hydroxide with dissolved CO_2 (carbonic acid) to form calcium carbonate.

Table 2 indicates that lime-cement mortar offers an advantage over a cement mortar because micro-cracks can develop freely during the initial period of mortar strength development while rapid growth of strength in cement mortar counteracts micro-crack development. It is not the absolute strength development (as mortars M and S will be stronger than O) but the time when the strength is developed that may be of significance. Cracking in mortar (stucco) is an inevitable phenomenon that is sure to occur. While macro cracks may lead to moisture damage of the stucco, the presence of micro-cracks does not significantly affect stucco performance providing that the later strength growth prevents their growth to macro size.

3. CHARACTERIZATION OF HYGROTHERMAL PERFORMANCE OF STUCCO

Four physical characteristics are used to quantify hygrothermal behavior of stucco under variable wetting and drying conditions:

- *Water absorption coefficient* or A-coefficient (also called capillarity or capillary-rise test), relates the cumulative water inflow and the square root of time as measured during a free water intake process. The test is performed with specimens whose lower boundary is in contact with a free water surface (typically the specimen is immersed 3 mm (1/8 inch) and water intake is expressed in $kg/(m^2s^{1/2})$.

- *Water vapor permeance* (WVP) is measured by the dry cup test (with conditions corresponding to 50 %RH and near 0% RH on the opposite boundaries of the specimen) or the wet cup[5] test (with conditions corresponding to 100% RH and 50 % RH on the opposite boundaries). These tests, specified by ASTM or ISO, define the water vapor diffusion through the porous material. Results are reported in permeance (perms or ng/m^2sPa) in North America, but in Europe either as mi-values or Z-values". The latter are a 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.

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

[5] In the dry cup test water vapor diffusion is the dominant transport mechanism while in the other cup tests there is always an unknown combination of vapor and liquid transport mechanisms.

- *Total open porosity (vacuum saturation)* describes 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 into the material matrix is not constricted or blocked by the entrapped air.

The environmental significance of the water absorption coefficient (A-coefficient) relates to the rate that rain can enter the exterior stucco surface. On the other hand, the rate of vapor diffusion from the center of the material to its surface is governed by the water vapor permeability. Significance of two last concepts is less apparent. They define the fraction of porosity that can be used to store moisture, or the rain buffering capacity of the cladding.

Kruger and Eriksson (1925, see Bomberg, 1974), showed that lime-cement mortar containing coarse sand permits water to move much faster than the same lime-cement mix containing finer sand particles. Figure 1, quoted from this paper, shows cumulative water intake plotted as a function of square root of time measured with similar composites. The lime-based stucco transports water faster than cement-based stucco. Both curve 1 and curve 2 exhibits a change in the water absorption rate, which is associated with the effect of the second stucco layer. This is particularly significant for curve 2 where lime-based stucco is placed against the cement-based stucco (rendering) layer.

The change in the slope indicates that both layers affect the hygric performance of the stucco. In other words, the stucco can be designed so that the interior layer may control ingress of moisture to the substrate even when the outer layer is very permeable. This is a very important observation because, in later discussion, we postulate that many stucco failures are the result of use of a finish layer (outer surface of the stucco) that is selected to prevent water entry but effectively prevents also drying of the stucco.

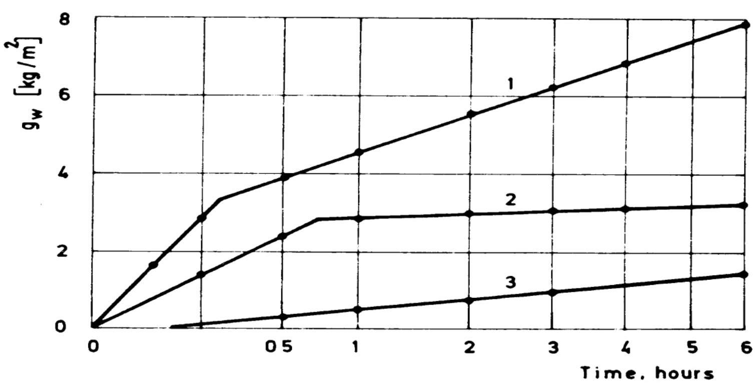

Figure 1 Cumulative water flow, g_w, to clay brick through stucco, plotted against time. Curve 1 represents lime stucco (A_o = 0.07 kg/m^{2}s$^{1/2}$), curve 2 is lime on a cement-splattered surface, and curve 3 is a cement stucco (A_o = 0.01 kg/m^{2}s$^{1/2}$). Kruger and Eriksson (1925, see Bomberg, 1974)

Today's material technology (Ohama, 1967; Marie-Victoire and. Bromblet, 1999; Thomson et al, 2004; Veiga et al, 2004) permits to design stucco mixes with the water absorption coefficient of the material being almost independent of material porosity. Yet, before discussing the design of multilayered system such as modern stucco, we will examine variations in wetting and drying properties of a few basic stucco material formulations.

4. HYGROTHERMAL PROPERTIES OF SELECTED STUCCO MIXES

Chemical Lime Corporation prepared test specimens that represented both traditional and modern stucco for test at Syracuse University. All tests were performed in laboratory chamber or room with a controlled environment having a temperature of 24 + 1 °C, relative humidity of 50 + 2% RH and a circulating air velocity of less than 0.3 m/s.

Our reference material was denoted as code A and represents a strong lime-cement mix 1:1:4.5 (scratch coat), while type B was similar but with significantly reduced lime content to 1: ¼: 4.5. Three other mixes included fly ash and other proprietary admixtures. All materials were produced with strict volumetric proportions correcting for density and moisture content of the sand.

4.1. Results of wetting and drying tests

Figures 2, 3 and 4 show the initial wetting rate of five stucco mixes coded as A, B, C, D and E.

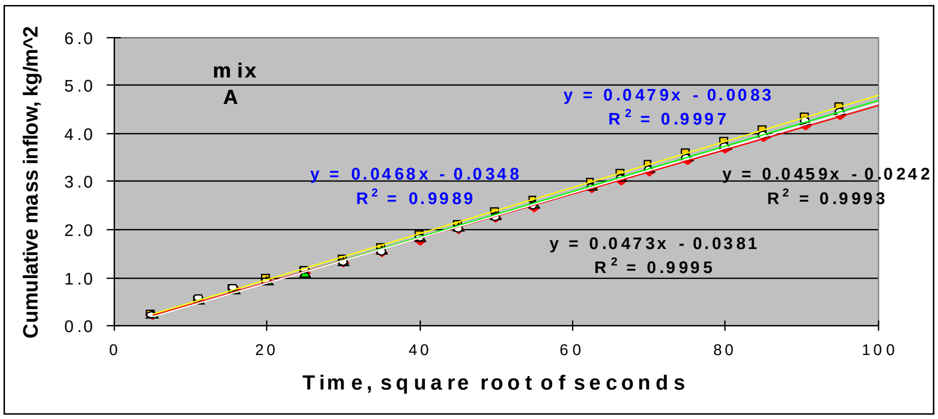

Figure 2 Initial water absorption process, measured at SU on stucco mix A.

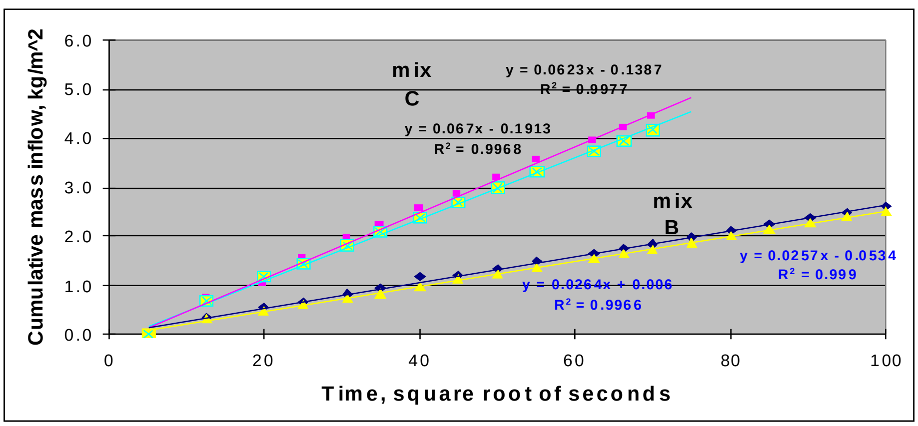

Figure 3 Initial water absorption process, measured at SU on stucco mixes B and C.

Our reference material coded A shows good measurement reproducibility and an average water absorption coefficient $A_o = 0.047\ kg/m^2s^{1/2}$. Next in the series, mix B, is the only one having much lower water absorption coefficient namely $A_o = 0.026\ kg/m^2s^{1/2}$. This reinforces observation of Kruger and Eriksson (1925) reproduced in Figure 1, that cement-based mortars are much less absorptive than cement-lime or lime mortars.

Mixes C and E have similar rates of water absorption ranging from $A_o = 0.059$ to $0.067\ kg/m^2s^{1/2}$. The highest rate of water absorption was measured for mix D, namely $A_o = 0.096\ kg/m^2s^{1/2}$. Thus in comparison to the reference mix, the cement-based stucco had half the rate of water absorption and the modified stucco had double the rate of water intake compared with the reference material.

Figure 5 shows drying rates of stucco specimens B through D. While there is a general trend that specimens with a higher water absorption display a faster drying rate, the differences in drying rate are not as obvious as found for the absorption results.

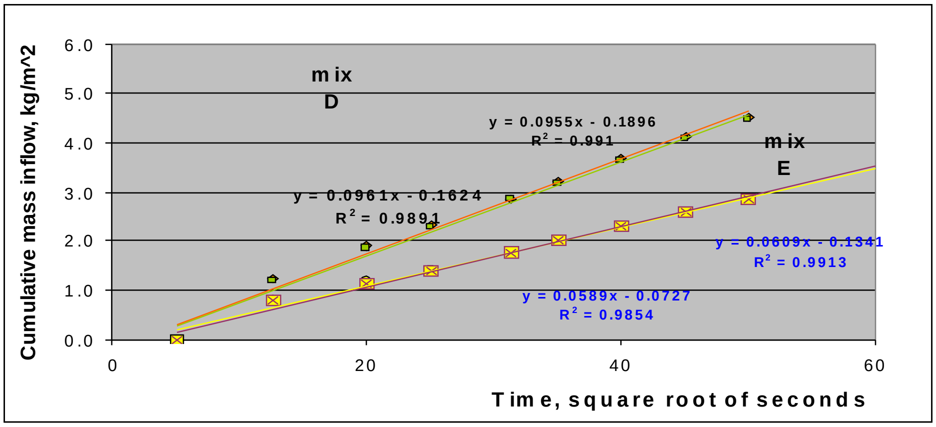

Figure 4: Initial water absorption process, measured at SU on the stucco mixes D and E.

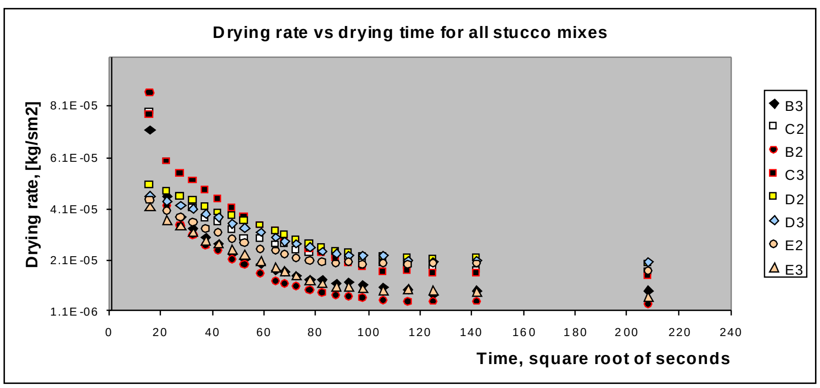

Figure 5: Drying rate versus drying time measured at SU on all stucco mixes. (The same scale is used only for comparison with wetting)

4.3 Effect of hydrophobic admixtures on properties of a lime stucco

Table 3 presents results from Cerny et al (2004) who examined lime plasters with pozzolanic admixtures. Metakaolin (P1), ground brick (P2) and enamel glass (P3) were used as the pozzolana materials in lime-pozzolana plaster mixtures and zinc stearate was used as a hydrophobic admixture to reduce water absorption coefficient of the mix (Table 4). An additional characteristic they measured was the hygric expansion coefficient.

Table 3: Hygric properties of basic plasters without hydrophobic admixtures

Material	WV diffusion resistance	Water absorption coeff., $kg/m^2s^{1/2}$	Liquid diffusivity, m^2/s	Hygric expansion coef. 10^{-5} [% wt]
Lime plaster S	15	0.241	6.9E-7	3.3
Lime- pozzolana P1	18	0.108	7.6E-8	6.1
Lime- pozzolana P2	8.3	0.183	3.6E-7	7.2
Lime- pozzolana P3	9.4	0.161	3.7E-7	7.6

Table 4: Hygric properties of basic plasters with 0.4% zinc stearate admixture

Material	WV diffusion resistance [-]	Water absorption coeff., $kg/m^2s^{1/2}$	Liquid diffusivity, m^2/s	Hygric expansion coef. 10^{-5} [% wt]
Lime- pozzolana P1	15.6	0.039	1.2E-8	4.7
Lime- pozzolana P2	13.9	0.015	1.1E-8	1.4
Lime- pozzolana P3	12	0.012	0.9E-8	1.1

The results shown in Tables 3 and 4 show the effect of having a hydrophobic admixture. It reduced water absorption coefficient for all mixes but its effect on other properties varied. Water vapor transport was increased in P1 mix while it was reduced in the other two cases (P2 and P3). The water cement ratio was reduced which resulted in reduced moisture expansion.

4.4 Discussion on variability of hygric properties of different stucco products

In addition to laboratory tests reported in sections 4.2 and 4.3 some test samples were obtained in the field. Typically these samples included 20 – 25 mm thick stucco. They were made by the contractor renovating a building.

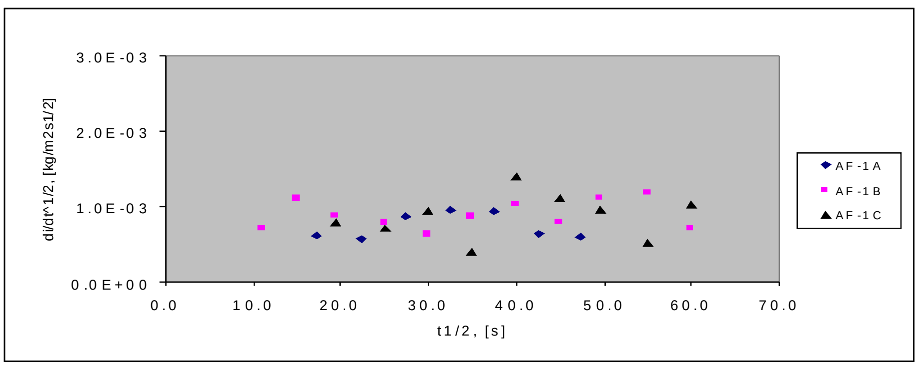

Figure 6 Water absorption coefficient measured on a field sample of acrylic-modified stucco

The field samples showed a variation in A_o-coefficient from 0.0006 to 0.04 $kg/m^2s^{1/2}$. The upper level of A_o-coefficient agrees well with laboratory results shown in Figures 3 and 4. Yet, the lower level of A_o-coefficient measured on these samples was unexpectedly low. The result for one sample, identified by the contractor as acrylic stucco, is shown in Figure 6. The test gave a value of A_o = 0.00092 $kg/m^2s^{1/2}$ i.e., the low end of the measured field samples. Figure 6 presents results differently from that used in Figures 3-5. The slope of the cumulative water intake is plotted against the square root of time. This manner of presentation is sometimes used to visualize the period when the approximation of the A-coefficient is valid and displays the stability of the measurements (see Bomberg et al 2005c).

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While Figure 6 shows a very low A-coefficient, another sample identified by the contractor to be 1:1 mix with sand between 5 and 6 parts (on the building site the proportion is somewhat uncertain) gave A_o = 0.16 $kg/m^2s^{1/2}$. Thus, the spread of A-coefficient is large, from A_o= 0.001 $kg/m^2s^{1/2}$ to A_o = 0.160 $kg/m^2s^{1/2}$

4.5 Example of commercial insulating stucco

Insulating stucco manufactured in Beijing[6] was tested and results are shown in Figures 7 and 8

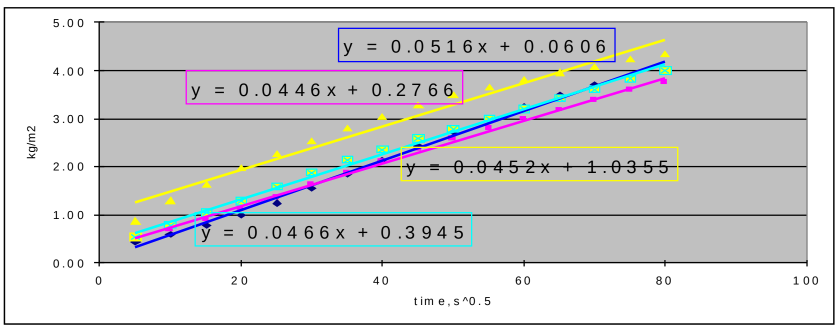
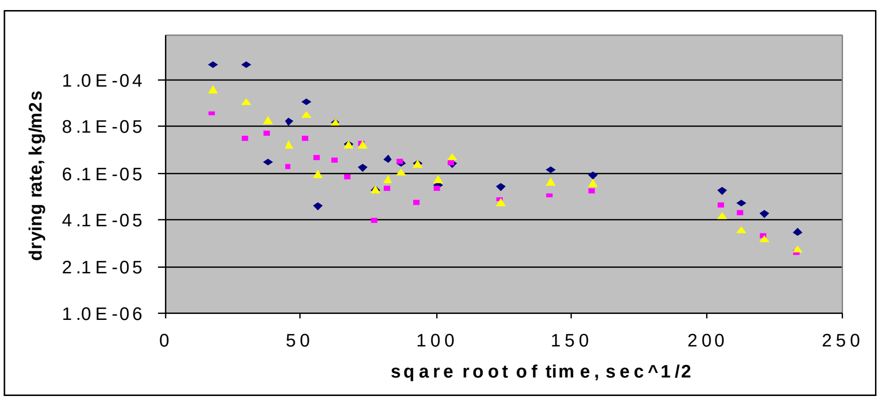


Figure 7: Water absorption coefficient measured on insulated stucco made in Beijing



[6] This product was manufactured by Zhen Li High Technology company in Beijing and delivered to SU

Figure 8 Drying rate of the insulating stucco from Beijing

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 (Figure 3).

4.6 Example of some lab produced hand-mixed insulating stucco

Pilot tests were made on some hand-mixed lime-cements with polystyrene beads classed as thermal insulating mortars, with two or three different polymer admixtures (for bonding, workability and dispersion of the polystyrene beads). The results are shown in Table 5.

Table 5: Observed range of variation in the water absorption coefficient of insulating stucco

Mix	Mix - density kg/m^3	A-coefficient $kg/m^2s^{1/2}$	Initial drying rate[7] kg/m^2h
A	1550 kg/m^3	0.041	0.118
B	1500 kg/m^3	0.082	0.164
C	1630 kg/m^3	0.046	0.129
D	800 kg/m^3	0.004	0.154

These results reinforce our previous statement that today's technology permits designing a stucco mix in a manner that hygric properties can be almost independent of material density (porosity).

5. DISCUSSION AND CONCLUDING REMARKS

For comparison, we also reviewed the results for some stucco products tested at the Technical University of Dresden8 (TUD). The highest A-coefficient value measured, 0.17 kg/m2s1/2, was for a stucco with a density of about 610 kg/m3, while the lowest value of A_o =0.013 kg/m2s1/2 was measured for a rendering with a bulk density of about 500 kg/m3. Another product with density of 1450 kg/m3 gave A_o=0.074 kg/m2s1/2.

Effectively, this review of the hygric properties of different stucco mixes revealed a large variability. The A_o-coefficient ranged from 0.0006 to 0.16 $kg/m^2s^{1/2}$ i.e., showing more than a 1000-fold variation. The upper level of A_o-coefficient agrees well with the characteristics of traditional stucco and reference lime-cement stucco as shown in Figure 3 and 5, the lower level appears to be much lower than that of traditional North American or modern climatic stucco manufactured in Germany. It is important because there appears to be a degree of correlation between the drying rate and water absorption of tested materials, so that materials with lower water absorption coefficient will dry much slower than the traditional stucco products.

Why is A_o-coefficient lower in NA than in Germany? Does the "waterproofing" (very low water absorption coefficient) of the stucco surface reduces water ingress into the wall? The answer is:" NO" because wetting of stucco clad walls takes place mostly through cracks and stucco terminations. Cracks exert a large capillary force and suck rain water into the cladding. In contrast, drying of the wall takes place through the plane of the stucco. Now with the drying rate 10 times slower than for traditional stucco we have reduced the moisture tolerance that the old wall systems possessed.

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[7] An arbitrary comparison using an initial slope of drying rate as a function of square root of time
[8] Private communication with Dr. Rudolph Plagge, TUD

We have not changed the wetting conditions and the wall can become as wet as walls 50 years ago but we have reduced the drying ability of stucco cladding by factor of between 10 and 100 times. The stucco will become wetter and stay wet over prolonged periods of time. Add to that the fact that some new polymer-based WRB products have much higher permeance than old asphalt impregnated Kraft paper The high water vapor permeance of these WRB products under certain environmental conditions increases the rat e of moisture transport from wet stucco to the OSB In exposures with prevailing solar radiation in the winter time and only one layer of polymeric WRB (plastic wrap) having permeance of 80 to 100 perms the OSB sheathing may became wet and may rot (as it happened in some houses in Minnesota and Alberta). Effectively, using a "waterproofed" finishing layer in stucco may be detrimental to durability of walls.

This paper was written to show that designing adequate hygric properties of stucco is possible for all types of stucco and that the current trend of using tight finishing layers should be abandoned for certain assemblies. Conversely, very permeable inorganic mineral paints (Reinartz, 2005) may be the preferred option for finishing stucco surfaces. The correct traditional design requires reducing the layer stiffness and increasing the WV permeance of each layer towards the outside. While traditionally this was achieved with changes in porosity, modern science allows us to do it for any material mix.

In a nutshell, a correct hygrothermal design for stucco mixes is the first step needed to ensure durable performance of stucco-clad walls.

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