Note:
This Document is a Draft

Moisture Properties of Plaster and Stucco for Strawbale Buildings

1 Introduction

Strawbale walls for houses have been used since the introduction of the mechanical baler in the early 1900's. Although strawbale (SB) houses were popular for a short while in a local area of Nebraska, they lost favour for nearly half a century. There has recently been a rebirth in SB construction and interest. In many cases the interest stems from the highly insulating, simple, and sustainable nature of SB walls.

The classic and time-proven strawbale wall assembly consists of strawbales with 25 to 50 mm thick mineral-based stucco skins applied to both faces. In modern times, the stucco skin is often made of steel mesh reinforced cement stucco skins applied directly to the strawbales. This coating provides a finish, a weather barrier, an air barrier, fire protection, rodent and insect control. As the stiffest part of the wall assembly, the skins also often act as structural elements, whether intentionally or not.

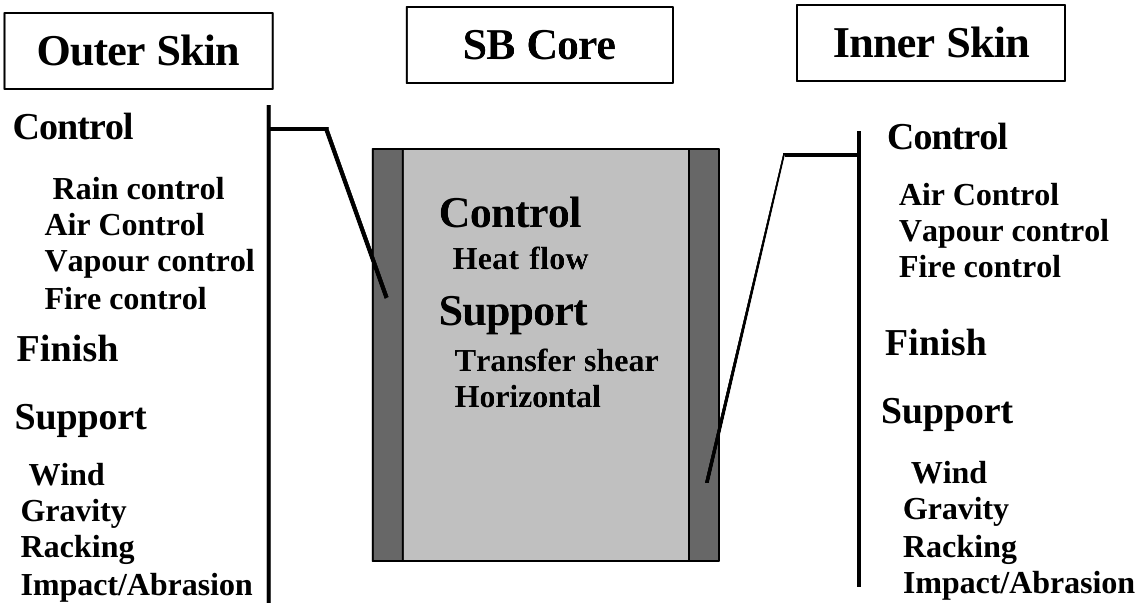

Figure 1: Typical Strawbale Wall Section

Straw, like wood, degrades when exposed to a sufficient amount of moisture for a sufficient amount of time at above-freezing temperatures. Therefore, one of the major performance-related concerns of strawbale enclosure walls is moisture control. Moisture control in enclosure walls is best achieved by selecting materials and assemblies that ensure a balance of wetting and drying potentials, with an appropriate amount of safe storage capacity. Understanding and predicting wetting and drying is therefore of fundamental importance to predicting and improving performance, particularly durability, of strawbale enclosure walls.

To allow for the prediction of heat and moisture performance, material properties are needed. In strawbales walls, the most important materials are the plaster and stucco skins.

A very low vapour permeance layer, called a vapour barrier, is usually required by codes on the inside of modern framed house walls in cold climates. A sheet of 0.15 mm (6 mil) poly, with a permeance of 3.4 metric perms (0.05 US perms)[†], is typical. Many proponents of strawbale building maintain that a very impermeable vapour barrier (e.g., Type I in the National Building Code of Canada with a vapour permeance less than or 15 metric perms/ 0.25 US perms) is not required for good performance. In fact, a Type I vapour barrier may be detrimental to performance.

Measured vapour permeance values of stucco and some analysis of the level of vapour permeance required for good performance are needed to assure code officials that sufficient vapour control is provided by interior plaster finishes to meet the intent of building codes. Drying of walls is predominately a vapour diffusion driven phenomenom. To predict the drying rate of water stored in straw bale walls, the vapour permeance of both the interior and exterior skins must be known.

Air leakage and rain penetration are usually the two largest sources of moisture in enclosure walls. Strawbales are very vapour and water permeable and hence rely on the skins to control the entry of these sources of moisture. While almost all finishes are sufficiently air impermeable to control air flow, their liquid water absorption and vapour permeance properties are highly variable and poorly known. The ability of an exterior stucco to absorb and store water is critical since this water can then be transported inward to the strawbales by vapour diffusion (and potentially by capillarity).

Finally, to aid in the control of rain penetration and absorption, water repellents and sealers have been proposed as simple and relatively inexpensive solutions. Manufacturer's and designers often do not understand the effect of such products on liquid and vapour transport of moisture across the outer skin because of a lack of material

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[†] One US perm = 57.4 metric perms = 57.4 ng / Pa s m^2

property information. Such information would be very useful to guide strawbale builders in their choice of a climate-appropriate finish.

For all of these reasons, CMHC sponsored a project to measure the liquid water absorption and water vapour permeability of cement skins. The author provided his labour without charge and did not charge for the use of existing equipment.

2 Known Material Properties

As discussed above, most strawbale walls are made of plaster skins and a core of strawbales. The properties of these individual materials will be briefly reviewed below.

2.1 Strawbales

The strawbale core acts primarily as thermal insulation while transferring structural loads between the skins. The thermal resistance of strawbales is dependent on straw type and density, straw orientation, and thickness. Values of RSI3 (R17) to over RSI6 (R35) have been reported, although for the common 450 mm (18”) thick strawbale of 110 to 190 kg/m^3 (7 to 12 pcf) density, a value of at least RSI4 (R23) can be expected.

The vapour permeance of strawbales have not been measured (as far as the author is aware) but estimates can be made. Based on published data for the vapour permeance of highly porous natural materials such as cellulose insulation (ρ = 25-50 kg/m^3, μ=110-130), wood fibreboard (ρ=340 kg/m^3, μ=20-60), and wood wool cement board (ρ=400 kg/m^3, μ=30-40), the vapour permeability is expected to be quite high, in the order of μ=50 to 100 ng/Pa•s•m. This means that a 1 meter thick layer of strawbale is expected to have a vapour permeance of 50 to 150 ng/Pa •s•m^2, and that a 450 mm thick strawbale should have a permeance of approximately 110 to 330 ng/ Pa•s•m^2. [†]

The capillary transport properties of strawbale have also not been measured. While the walls of the stalks will wick liquid water (because of the nature of the small cellulosic walls), the bale itself is composed of mostly large pores which will not wick water. Therefore, the water uptake of a strawbale will be slow, and should quickly reach equilibrium with drying.

[†] Vapour permeability is a material property, expressed independently of material thickness, in units of ng/Pa s m, and given the symbol, μ. Vapour permeance is a measure of the ease of vapour flow through a specific layer, in units of perms (equal to 1 ng/Pa s m^2), and given the symbol M. Permeability and permeace are analogous to thermal conductivity and thermal conductance respectively.

2.2 Plaster / Stucco Skins

Stucco or exterior plaster, defined as a hardened mix of fine aggregate and inorganic binders, is a highly desirable finish for walls and ceilings. Stucco that uses sand aggregate and cementitous binders is and has been widely used throughout the world for many years. In modern times, the stucco skin is often made of steel mesh reinforced cement stucco skins applied directly to the strawbales.

The stucco used in strawbale walls can range from high-strength gunite or shotcrete to cement-lime mixtures to earth-based plasters with and without lime or cement stabilizers. Common practise describes stucco mixes as a volumetric ratio in the form C:L:S, where C is the cement component, L is the lime component, and S is the sand component. In many strawbale buildings typical stucco mixes are 1:3 cement stucco or 1:1:6 cement-lime stucco. Table 1 lists some of the common mixes and letter definitions from the Portland Cement Association's Portland Cement Stucco Manual. The use of masonry cement is intended to replace the plasticizer function of lime. Pure lime plasters are typically made with a ratio of about 1:3.

Mesh reinforced cement-lime based stucco with typically have compressive strengths of 15 to 35 MPa (2000 to 5000 psi) and equivalent tensile strengths of 0.2 to 0.7 MPa (20 to 100 psi), depending on the quality and quantity of wire mesh reinforcing. The stiffness of such stucco is in the range of 10 000 to 25 000 MPa (1.4 to 3.6 x 10^6 psi).

Type (mortar or stucco)	Portland Cement	Hydrated Lime	Masonry Cement	Sand First Coat	Sand Second Coat	Minimum compressive strength (Mpa)
C/S	1	$^1/_2$		5 – 8	6 - 10	12
CM/N	1		1	5 – 8	6 – 10	5
L	1	$^1/_2$ - 1 $^1/_4$		5 – 8	6 – 10	5
M			1	5 – 8	6 – 10	?
O	1	2		5 – 8	6 – 10	2.4
K		1		5 – 8	6 - 10	0.5

Table 1: Recommended Stucco/Mortar Mixes, by volume of cement

The most widely used reference in North America, the ASHRAE Handbook of Fundamentals, lists values for (presumably) 19 mm thick gypsum plaster of 630 to 1140 ng/Pa s m^2. Coatings will likely reduce the vapour permeance from these values. European data also indicates that the addition of lime tends to increase the vapour permeance, sometimes significantly.

The water-to-cementitious component ratio (w/c) is known to greatly affect the pore structure of concrete and plaster. The higher the w/c ratio, the greater the number of open pores in the finished product and the higher its vapour permeability and liquid water absorption. Similarly, the degree of compaction of a concrete or stucco product will affect the pore structure. The density, and hence the pore structure, of plasters and stuccoes will be sensitive to how they are applied. In fact, the use of steel trowels versus wood floats will result in significantly more surface compaction. While the effect of water-cement ratio, density, finishing technique on moisture transport properties may be significant it has not been studied in any depth.

These complexities were not part of the scope of this study, but should be borne in mind when interpreting the results and guiding future research.

3 Test Program

The test program involved:

1. applying a range of different stucco mixes directly to strawbales,
2. removing the samples from the bales
3. applying various coatings (paints and water repellent coatings) to some of the samples
4. conducting vapour permeance tests under a realistic relative humidity gradient
5. conducting water uptake (capillary absorption tests) tests.

The test procedures, apparatus, and samples will be described in greater detail below.

3.1 Samples

After discussion with many people on the Internet-based CREST Strawbale building list, the following set of samples was chosen. This covers the range of realistic stucco mixes that can be used. All samples were mixed using volume proportions.

3.2 Mix Designs

A. 1:3 Cement: Sand

B. 1:1:6 Cement: Lime: Sand

C. 1:2:9 Cement: Lime: Sand

D.	1:3 Type S slaked Lime: Sand
E.	Clay: Sand "earth plaster"

Variations

A1	As A with an elastomeric paint
A2	As A with siloxane treatment
B1	As B with linseed oil treatment
B2	As B with an elastomeric paint
B3	As B with a siloxane penetrating repellent treatment
B4	As B with calcium stearate (2% by weight of cementitous components)
B6	As B with alkyd (oil) primer and paint
B5	As B with latex primer and paint
B6	As B with oil paint and primer
C1	As C with linseed oil treatment treatment
D1	As D but with slaked Type S quicklime

3.3 Sample Preparation

Samples of both interior plaster and exterior stucco were prepared on indivdual strawbale substrates in areas of at least 250 by 600 mm. Bales were loosely stacked against a wall to allow for the vertical application. All stucco samples comprised a three-coat application, but the thickness varied from about 32 to 54 mm. The second coat was applied 9 days after the first. The walls were kept damp and inside (no wind or sun) during this period. The finish coat was applied 3 weeks after the second coat.

Water was added as necessary to reach the required level of workability and plasticity. In general, 500 to 600 ml of water needed to be added to 1000 g of cement and *moist* sand (Note: the moisture content of the sand was not measured. In future tests the oven dry density of the sand and the density of the sand as used should be recorded). Thus, the water-to-cement ratio was in the order of 0.6 to 0.7, but might have been higher for some samples. Little or no water needed to be added to the pure lime mixes since the slaking process and the moist sand provided almost all the water required.

Although the mix design should normally progress from rich to lean for stucco (e.g., more to less sand in the mix), the ratio was kept constant for this study so that simple, uniform samples would be created.

The stucco was allowed to cure at 10 to 20 °C for at least 90 days before being cut from the strawbales. Square samples, approximately 150 mm x 150 mm, were cut from the bales using an abrasive blade. Sets of two or three samples were cut from the same bales.

3.4 Material Description

The cement was a standard bagged Type 10 Portland Cement (by St Lawrence Cement). The lime was a standard Type S hydrated lime (tradename: MortaSeal) purchased at a local supply store and slaked for two weeks before being used in the base coat application. The sand used was plastering sand produced by a local aggregate producer. For sample D1, the lime was a quicklime, tradename Niagara, produced and donated by GenLime (contact Mr Mike Tate). The quicklime used had been slaked for more than a year.

The elastomeric coating was an acrylic based product, (Maxicyrl, by Sto Industries, www.stocorp.com). The product has an advertised vapour permeance of over 700 ng/Pa s m^2 (12 US perms). The siloxane (Sikagard 70 by Sika) was a 5% by weight solvent-based product. The calcium stearate was provided by a local chemical supply company. Finding a source for this chemical required considerbale effort and may make its use in plasters difficult.

The paints were of average quality interior grade (tradename: CIL Dulux), purchased at Canadian Tire. The linseed oil was a double-boiled product (by Recochem).

3.5 Observations

The differences in the workability of the mixes were pronounced and obvious. The 1:3 slaked Niagara quicklime mix was exceptionally smooth and plastic. The slaked (for 2 weeks) Type S MortaSeal lime was almost as smooth and workable, but the difference was noticeable. The 1:3 cement plaster behaved almost like concrete, but this did not make it much more difficult to apply.

The clay and sand for the earth plasters were sourced from a local farm. It was difficult to characterize the nature of the soil, and more difficult to produce a workable mix. Although several attempts were made, the plaster on the strawbale never resulted in a satisfactory stucco. The final one-coat plaster that appeared to be acceptable crumbled when it came time to cut the sample from the bale. It is recommended that an earth plaster in place be identified and a sample removed for testing.

4 Test Setup and Procedure

4.1 Vapour Permeance

Vapour permeability is the material property that defines the ease at which water vapour diffuses through it. As described in the introduction, most drying of SB walls will be through diffusion of water vapour from the straw and stucco to the interior and exterior environment. Thus, the vapour permeability of stucco and plaster skins is important.

One of the complexities involved in the measurement and interpretation of vapour permeance data is the variation of vapour permeance with relative humidity. The vapour permeance of many natural materials varies significantly with relative humidity as shown in Figure 2. To use test data for a 25 mm thick cement-lime stucco as a reference, the permeance varies from about 100 perms (2 US perms) at 10 to 20%RH to over 400 perms (6.5 US perms) at 90%RH.

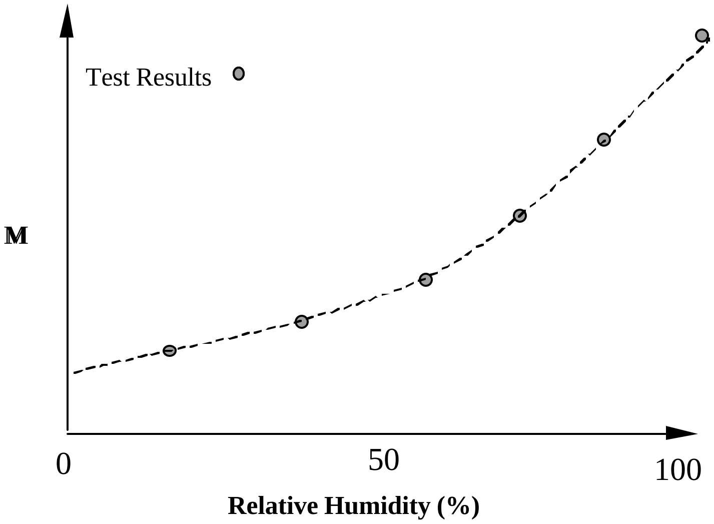

Figure 2: Typical Vapour Permeance of Stucco as Function of Relative Humidity

4.1.1 Standard Test Procedures

Standard test methods, such as the ASTM E96 standard, provide a number of means to capture this RH dependency. The wet-cup measure (ASTM E96 Procedure B) measures the vapour permeance of a specimen exposed to 100%RH on one side and 50%RH on the other. The dry-cup method (ASTM E96 Procedure A) measures the vapour permeance of a specimen exposed to 50%RH on one side and 0% on the other.

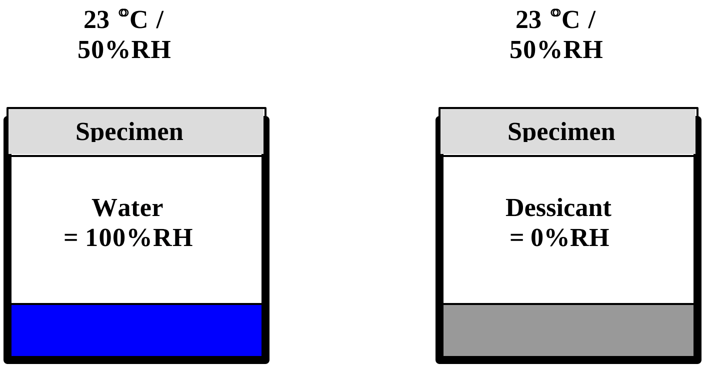

Figure 3: Wet Cup and Dry Cup Vapour Permeance Tests

In practise, the dry cup method is used for materials that will be in service under dry conditions (since the average test RH is 25%), and the wet cup method is used for materials expected to be used in humid conditions (since the average test RH is 75%).

For stucco over strawbales, the interior winter time RH is likely to be about 25 to 40%, and thus the humidity on both sides of the interior stucco will be 25 to 40% on the inside and 15 to 30% on the outer face. Thus, the dry cup vapour permeance test is likely a reasonably accurate representation of the vapour permeance in performance.

In a wet climate, the outer stucco is more likely to be exposed to conditions ranging from 75 to 100% RH (in the case of rain wetting stucco or condensation). The wet-cup vapour permeance is a reasonable test value to use, but the average RH (75%) of this test is likely too low for most cold weather conditions in SB walls.

The present test program measures the vapour permeance of a sample with 75%RH on the outside and 100% on the inside (an average humidity of 87.5%). These conditions simulate the situtation of wet straw on the exterior of a SB wall drying to the exterior in a humid climate. Most cold climates have an outdoor humidity of 70 to 80% during the winter

4.1.2 Vapour Permeance Test Setup

The vapour permeance test setup was similar to a normal ASTM E96 test. The samples were placed over a sealed, vapour impermeable plastic container. The samples were sealed around their edges and to the container with aluminum (vapour impermeable) foil tape. Because of the rough edges and thick size of the samples, it was necessary to grind the edges smooth and flat. A template was used to shape an opening of foil tape on the top of the specimens of a predetermined and similar size. The same template was used to create an opening in the bottom (between the water in the container and the sample).

The container was filled with about 20 mm of water (to create constant 100%RH conditions). Great care was taken to ensure that no liquid water splashed in contact with sample during handling. The complete container-sample assemblage was placed in a large container (80 liters volume) on wooden racks over a salt (NaCL) saturated water solution. This solution creates a constant 75%RH. The large container was sealed, although not airtight, since the source of 75%RH was strong enough to overcome a small amount of air or vapour leakage. The conditions within the large chamber were monitored with a small portable data logger. These measurements showed a temperature of approximately 17 °C and an average vapour pressure difference across the specimens of about 500 Pa. Actual measured values were used to calculate the vapour permeance.

4.1.3 Vapour Permeance Test Procedure

The sample-container assemblages were weighed each week with an AHD electronic balance, capable of measuring the weight to within 0.1 grams.

The vapour permeance and permeability values were calculated by measuring the weight loss of the container-sample assemblage once this weight loss reached equilibrium. The permeance of the sample was then calculated from:

Permeance in ng/Pa s m^2 = (weight loss in nanograms[†]) / [(7 days x 24 hrs x 3600 sec) x (sample area in m^2) x (average vapour pressure difference in Pa)].

And permeability was calculated simply as:

Permeability in ng / Pa s m = permeance / average sample thickness in m.

It is important to recognize that the permeability can only be calculated from measured permeance values if the test sample is a single homogenous material. In the case of coatings, permeability is not a valid measure. The total permeance of a two-layer system (e.g., plaster and coating) can be found from:

$$M_{total} = 1 / (1/M_1 + 1/M_2).$$

The permeability was therefore only calculated for the single layer specimens, not the samples with coatings.

[†] one nanogram equals one billionth of a gram, e.g., 1 $x10^{-9}$ grams.

4.2 Capillary Suction

Porous hydrophylic materials tend to absorb liquid water (or “wick” water). During a rain event, water that is deposited on the surface of the exterior skin will therefore be wicked into the stucco. This water can be stored in the stucco and may contact the straw at the bonded interface. The stored water can also be dried to the exterior or interior when heated by the sun.

4.2.1 Standard Capillary Suction Tests

Capillary suction can most simply be measured from water uptake tests. Standard tests include the EuroNorm TC 89/WG10 N95 and the German DIN 52617. These tests place the sample in contact with water to a depth of 1 to 2mm. The weight gain is measured at several points over a 24 hour period. The total weight gain per unit area is then plotted versus the square root of time. The resulting plot usually exhibits a straight line, and the water absorption coefficient is defined as the slope of this line in units of $kg/(m^2\ hr^{1/2})$ or $kg/(m^2\ s^{1/2})$. If the line exhibits an initial slope that is different from the final slope, the initial straight portion is used. If there is no significant change, the total water uptake at 24 hours is used to define the water absorption coefficient.

4.2.2 Capillary Suction Test Set-up and Procedure

Several large containers were filled with about 8 mm of water. The samples were weighed initially and then placed face down in contact with 1 to 2 mm of water. The samples were removed and weighed at 1, 4, 10, and 24 hours. The samples were quickly removed, surface water was removed by wiping with a damp cloth, weighed, and returned to the test containers within 2 or 3 minutes.

The weight gain (in kg/m^2) was plotted against the square root of time (in seconds). Portions of the plot with straight lines were judged, and the slope calculated.

5 Results

The results for the water absorption and vapour permeance testing are covered below.

5.1 Vapour Permeance and Permeability

The samples required some time to reach equilibrium with their environment since vapour first had to diffuse into the sample and adsorb to the sides of all of the pores. This took a few weeks in the case of the pure lime-sand plasters and much longer for the pure cement-sand plasters. Figure 4 provides a typical response for a lime plaster.

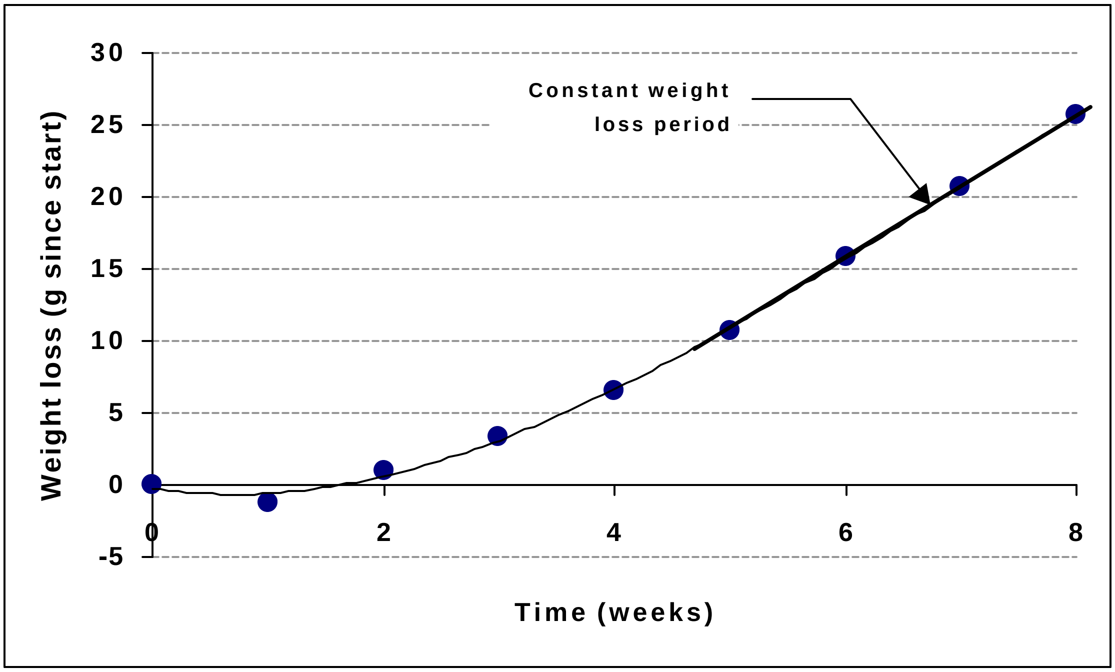

Figure 4: Cumulative Weight Loss/Gain versus Time During Permeance Test

The initial period of response indicates a weight gain. This occurred because vapour diffused into the sample (which was initially very dry) from the exterior (75%RH) climate. As the sample equilibrated with the two different environments, the weight loss increased until it reached a steady state. Table 2 provides a summary of the results.

It is clear that the datum cement sand stucco mix was the least impermeable, with a permeance of about 40 metric perms for the 40 mm thickness. The addition of lime in the 1:1:6 datum mix resulted in a much higher vapour permeance, almost 300 metric perms for a 35 mm thickness. The 1:2:9 mix was even more permeable and the pure lime mixes the most permeable. The permeability of the different datum mixes are compared in Figure 5. The quicklime appeared to have a sightly lower, but still high, vapour permeance than the hydrated lime. Both are very vapour permeable.

Sample	t [mm]	Permeance [ng/Pa s m2]	Permeability [ng/Pa s m]	US Perms
Cement :Sand				
1:3 datum	43.5	39	1.7	0.68
1:3 elastomeric	39.5	40	--	0.70
1:3 siloxane	41.0	40	1.7	0.70
Cement:Lime:Sand				
1:1:6 datum	35	295	10.3	5.13
1:1:6 linseed	36	223	8.0	3.89
1:1:6 elastomeric	32.5	244	--	4.25
1:1:6 siloxane	41	203	8.3	3.54
1:1:6 calcium stearate	53.5	81	4.3	1.42
1:1:6 calcium stearate	44	142	6.2	2.47
1:1:6 calcium stearate	53.5	41	2.2	0.71
1:1:6 latex paint	36.5	203	--	3.54
1:1:6 oil paint	40	41	--	0.71
Cement:Lime:Sand				
1:2:9 datum	50.5	295	14.9	5.13
1:2:9 linseed	50.5	259	13.1	4.52
Lime:Sand				
1:3 Datum	33.5	565	18.9	9.85
1:3 Datum	35.5	529	18.8	9.22
1:3 Quicklime	32	459	14.7	8.00

Table 2: summarizes the values for the test samples.

Different coatings resulted in different responses. The elastomeric and siloxane had little effect on the vapour permeability of the cement samples. The same two treatments appeared to reduce the permeability of the more permeable 1:1:6 mix, although the permeability was still about 8 for both products. The linseed oil had little effect on the permeance of either the 1:1:6 or 1:2:9 mixes. The latex paint reduced the permeance of the 1:1:6 mix to about 200 metric perms (almost 4 US perms) as expected. The oil paint also performed as expected, lowering the permeance to around 40 metric perms (0.6 US perms). Thus, the oil paint can act as a vapour barrier by most code definitions.

The addition of the calcium stearate caused a reduction in permeance, sometimes sizable, but the 1:1:6 stucco remained more permeable than the cement.

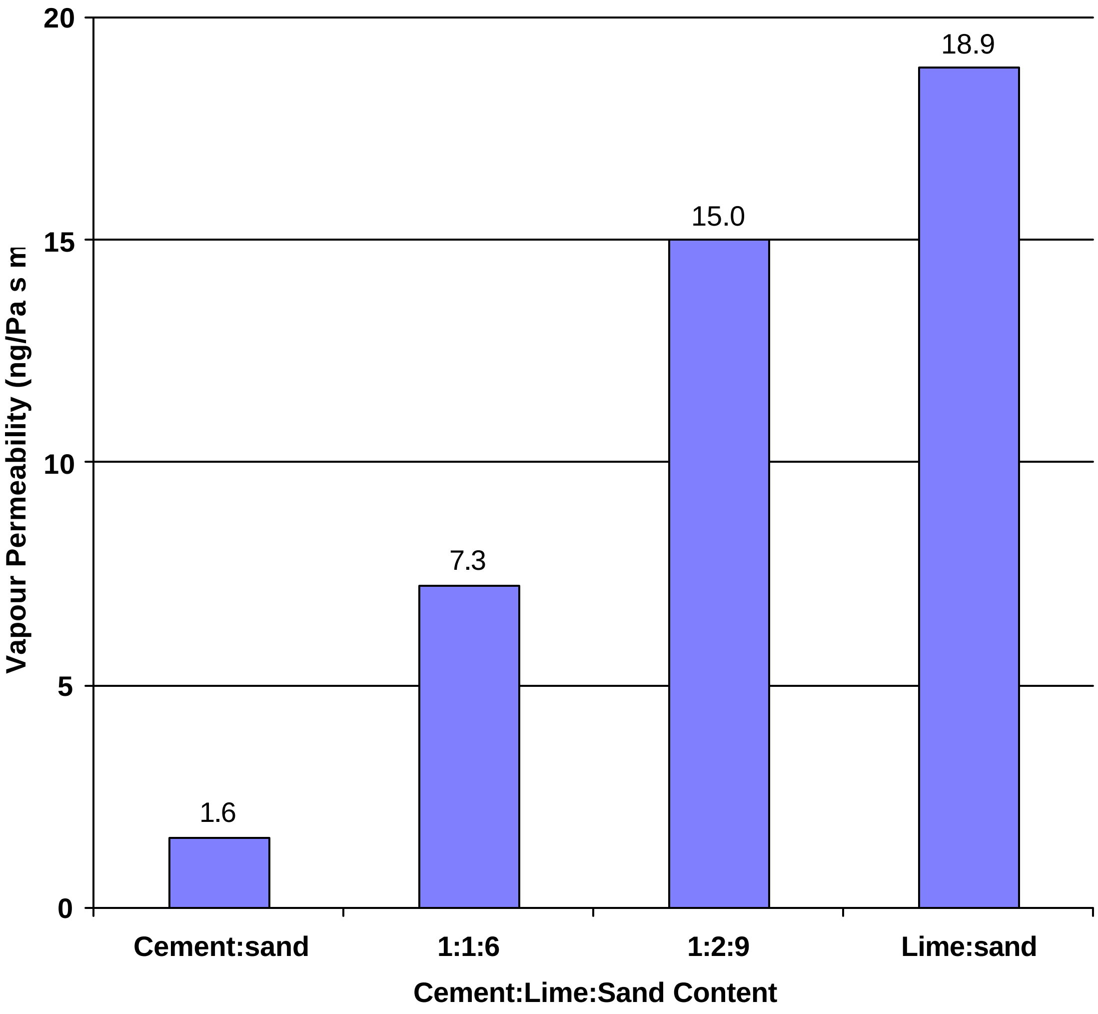

Figure 5: The Influence of Lime Content on Vapour Permeability

5.2 Capillary Suction

The results of the capillary suction testing are shown in Figure 6 and summarized in Table 3.

Sample	Suction (kg/(m2 $s^{1/2}$)
Cement	
1:3 datum	0.0378
1:3 elastomeric	0.0085
1:3 siloxane	0.0004
Cement:Lime	
1:1:6 datum	0.0917
1:1:6 linseed	0.0665
1:1:6 elastomeric	0.0146
1:1:6 siloxane	0.0006
1:1:6 calcium stearate	0.1005
1:1:6 calcium stearate	0.0833
1:1:6 calcium stearate	0.0934
1:1:6 latex paint	0.0197
1:1:6 oil paint	0.0140
Cement:Lime	
1:2:9 datum	0.1100
1:2:9 linseed	0.1052
Lime	
1:3 Datum	0.1273
1:3 Datum	0.1725
1:3 Quicklime	0.1608

Table 3: Water Absorption Coefficient

The more lime content, the more absorbent the stucco was. The cement stucco was ¼ as absorptive as the lime stucco. The coatings were tested to assess their ability to reduce absorption. The siloxane was remarkably effective, practically eliminating absorption. The elastomeric coating was almost as effective, but not as effective as might be expected. The paints did reduce absorption, but since this is not their function, no better performance could be expected.

Linseed oil appears to have a small but beneficial effect on the water uptake of the 1:2:9 and 1:1:6 samples. The improvement was so small, and the number of samples so limited, that no strong conclusions can be drawn. Tests with heavier linseed oil coverage might be appropriate.

The addition of calcium stearate changed the nature of the absorption but did not have much, if any effect on the water uptake of the 1:1:6 samples.

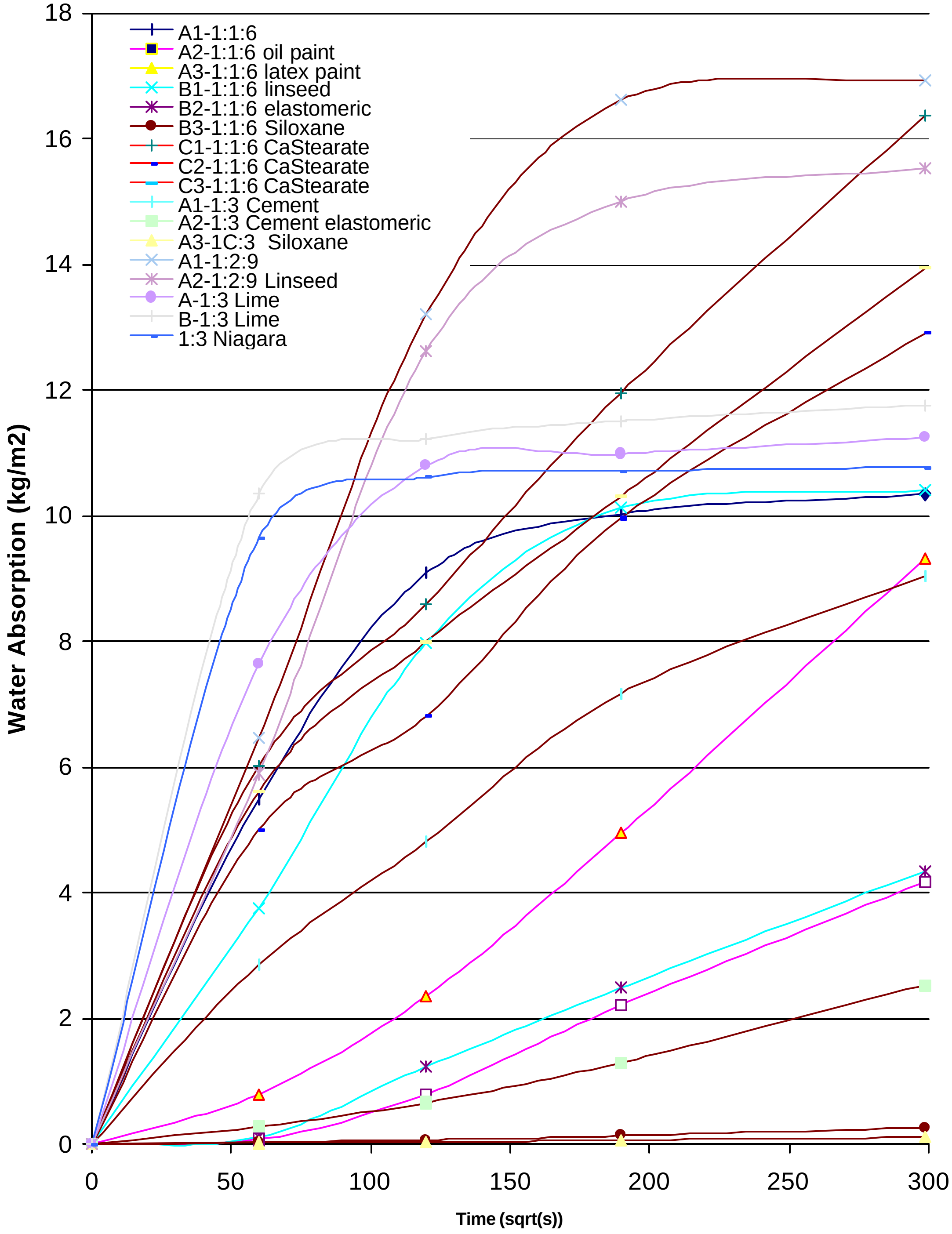

Figure 6: Water Absorption versus Time

6 Conclusions

Based on the test data, several conclusions can be drawn:

1. Cement : sand stuccos are relatively vapour impermeable, in fact a 40 mm thick cement stucco will act as a vapour barrier.
2. The addition of lime has a dramatic effect on vapour permeance. The pure lime samples are very vapour permeable.
3. Applying an oil paint to a moderately permeable 1:1:6 stucco will provide a permeance of less than 60 metric perms (1 US perms) and thus meet the code requirements of a vapour barrier.
4. Applying latex paint to a 1:1:6 stucco reduces the permeance to about 200 metric perms (3.5 US Perms).
5. There was no large differences in behaviour between quicklime and hydrated lime, although they behaved differently during application.
6. Quality elastomerics appear to high vapour permeance and low water absorption. The performance of these products after a year or two of exposure should be investigated. The use of vapour permeable elastomerics can be recommended based on these tests.
7. Siloxane appears to have no effect on the vapour permeance of cement and cement:lime stucco while almost eliminating absorption. The use of siloxane can be recommended based on these tests.
8. Linseed oil is not a very effective water repellent and does not restrict vapour permeance. Thicker layers, and more coats should be investigated.
9. Calcium stearate as a cement additive reduces the vapour permeance and has little effect on water absorption. Its use is not recommended based on these tests.