Moisture Properties of Plaster and Stucco for Strawbale Buildings

John Straube

1 Introduction

Straw, as a fiber, has been used as part of building materials for several thousand years. With the invention of the mechanical baler in the early 1900's it became possible for compressed straw to be used as the primary building block of exterior building walls. Although strawbale (SB) houses were popular for a short while in a local area of Nebraska, they lost favor for nearly half a century. There has recently been a rebirth in SB house construction and interest. In many cases the interest stems from the highly insulating, simple, and sustainable nature of SB walls.

Although there is a large and growing body of empirical evidence that strawbale buildings can be used very successfully, the scientific justification and explanation is lacking, and hence accepted engineering approaches to design, testing, and inspection have not been well developed.

To support the growing volume of rice straw agricultural waste the State of California supported a research program to improve the level of scientific knowledge of strawbale wall behavior and performance.

This report is a draft summary of the results of the moisture property testing of a range of plaster types that might be installed over strawbale walls. It reviews the literature for previous data, describes the test protocols, and summarizes the results.

1.1 Plaster -- Strawbale Skins

The most common and time-proven strawbale wall assembly consists of strawbales with 1 to 3" (25 to 75 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. For reasons of performance, cost, sustainability, health, and ease of construction the use of non-cement mineral binders such as lime, earth and gypsum has grown. Regardless of what it is made, the plaster skins provide a finish, a weather barrier, an air barrier, fire protection, rodent and insect control. Since they are usually the stiffest part of a wall assembly, the skins also often act as structural elements, whether intentionally or not.

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 is a complex subject that requires an understanding of climate, micro-climate, building details, enclosure assembly, and interior conditions. The material properties of straw and plaster are critical to the understanding of the enclosure assembly part of moisture control.

Building enclosure strawbale walls with appropriate moisture tolerance 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, given the conditions the walls are expected to separate. Understanding and predicting wetting and drying is therefore of fundamental importance to predicting and improving performance, and particularly durability, of strawbale enclosure walls.

1.2 Project Scope and Objectives

To allow for the prediction of heat and moisture performance, material properties are needed. In strawbales walls, the strawbale core and plaster skins are usually the only materials whose properties are of interest. However, there is a wide variety of plaster types, additives, and coatings.

The most important properties to measure are the vapor and liquid diffusivity and moisture storage function of the skins, and the thermal resistance, vapor diffusivity, and moisture storage function of the straw.

Measured vapor permeance values of stucco and some analysis of the level of vapor permeance required for good performance are needed to assess if sufficient vapor resistance is provided by interior plaster finishes to resist diffusive vapour flow into walls in cold weather (and to meet the intent of some building codes). Drying of walls is predominately a vapour diffusion driven phenomenon. To predict the drying rate of water stored in straw bale walls, the vapor 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 vapor and water permeable and hence rely on the skins to control the entry of these sources of moisture. While almost all wet-applied monolithic plaster finishes are sufficiently air impermeable to control air flow, their liquid water absorption are highly variable and poorly known. The ability of an exterior plaster to absorb and store rainwater is critical since this water can then be transported inward to the strawbales by vapor diffusion and capillarity.

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 vapor transport of moisture across the outer skin because of a lack of material property information. Such information would be very useful to guide strawbale builders in their choice of a climate-appropriate finish.

The thermal resistance of the strawbales are important for the insulating function required of modern enclosure wall systems. The thermal resistance also affects the temperatures experienced by the skins when exposed to varying temperatures over the day, and this greatly influences the flow of water vapor. Thermal resistance has been measured by others, is similar to other cellulosic materials of similar density, and the literature is being reviewed as part of another EBNet project. Hence, the work reported here did not involve thermal resistance testing.

Given the material properties described above interior and exterior environmental conditions computer models can predict, with reasonable accuracy, the temperature and moisture conditions within a wall system.

1.3 Technical Background

The material properties described in this report are fundamental building science properties that may not be familiar to all readers. Hence, the terminology is reviewed in this section.

1.3.1 Thermal Conductivity

Thermal conductivity (symbol k or λ) is a fundamental material property that describes the rate of heat flow across a unit area, through a unit thickness for a temperature gradient of one degree. The symbol λ is often used in Europe instead of k.

Units: SI W / m ·K

Imperial Btu ·in / (hr ·ft^2 ·°F)

Conversion 0.144 Btu · in / (hr ·ft^2 ·°F) = W / m ·K

Thermal conductivity often varies with the mean temperature and the magnitude of the temperature differential. Standards normally specify these values so that different materials can be compared.

Units: SI W / m^2 ·K

Imperial Btu / (hr ·ft^2 ·°F)

Conversion 5.678 Btu / (hr · ft^2 ·°F) = W / m^2 ·K or

Btu / (hr ·ft^2 ·°F) = 0.176 W / m^2 ·K

Thermal resistance is the reciprocal of conductance.

Resistance = 1/C = thickness / conductivity = l/k.

Units: SI (m^2 ·K) / W (RSI)

Imperial hr ·ft^2 ·°F / Btu

Conversion R = 5.678 ·RSI or RSI = 0.176 R

Hence, R-value is valid for a specific wall thickness, temperature difference, and temperature across the specimen. It is not uncommon for R-values to be reported as R-values per inch, so that users can simply multiply the given value by the thickness of the material to assess the total R-value.

It should be emphasized that the heat flow decreases with the inverse of R-value, that is:

Heat flow = 1 / R-value * Temperature difference

Hence, the reduction in heat flow as the a walls R-value increases from 20 to 25 (a reduction of 0.01 in heat flow) is small compared to the increase in R-value from R10 to R15 (a reduction of 0.033), the R-value increase achieved by moving from a typical 2x4 wall to a 2x6 wall in many modern homes. Debates over the difference in R-value of 25 or 29 are essentially academic, since the heat flow is so small that little benefit would be gained by the increase.

1.3.2 Vapor Permeability

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 material layer, in units of perms (equal to 1 ng/Pa s m^2 or 1 grain/(hr ·in Hg · ft^2)) and given the symbol M. Permeability and permeance are analogous to thermal conductivity and thermal conductance respectively. Imperial US perms can be converted to metric perms by multiplying by 57.1.

Many codes define a vapor barrier as any material or system that has a permeance of less than 1 US perm. This is an arbitrary value based on a limited and questionable study conducted in the 1940's. Vapor diffusion flow through a wall may need to be controlled with vapor resistant layer in some special cases, but plastered strawbale alls usually don't need them, and often appear to perform much better without them.

1.3.3 Liquid Uptake

The water absorption coefficient is a measure of a materials ability to transport capillary water. It is determined experimentally by measuring the rate of water absorption when a sample is placed in contact with liquid water. The water absorption coefficient so determined can then be used to estimate the liquid diffusivity, the fundamental measure of liquid water movement within porous bodies.

There are no material property standard requirements for it in North America although German stucco standards provide upper limits if a stucco is to be called "water repellent".

In general, water absorption is measured in units of kg/m^2 $s^{0.5}$ and given the symbol A.

Units:	SI	$kg/m^2\ s^{0.5}$ (or $kg/m^2\ h^{0.5}$)
	Imperial	$ounces/ft^2\ s^{0.5}$
	Conversion	$0.334\ ounces/ft^2\ s^{0.5} = 1\ kg/m^2\ s^{0.5}$

1.3.4 Moisture Storage

Surfaces in contact with water vapour molecules have the tendency to capture and hold water molecules because of the polar nature of the water molecule; this process is called *adsorption*. Most building materials are porous and have very large internal surface areas. For example, brick typically has an internal surface area of from 1 to 10 m^2 /g, cement paste from 10 to 100 m^2/g, and wood, straw, or cellulose can have even larger surface areas. Therefore, as water vapour molecules adsorb to the internal surfaces of these materials, the materials' water content increases significantly, and the materials are then described as *hygroscopic* . Materials such as plastic and steel do not have internal pores and therefore are not hygroscopic -- they do not pick up moisture from water vapour in the air.

As the relative humidity increases, the moisture content of porous materials increases because more of the vapor in the air adheres to the materials’ pore walls. When the RH exceeds about 80 to 90%, liquid water begins to form in the smallest pores, and eventually in the larger pores.

The relationship of air relative humidity to moisture content is called the *sorption isotherm* and is unique for each material (Figure 1.1). It may take weeks or months for a thick solid material to reach equilibrium with its relative humidity environment.

When a material has adsorbed all the vapor it can from the air (e.g., the moisture that a material will adsorb when left in a 100%RH room for long enough), further moisture will be stored in the pores and cracks within the material by capillary suction, or by absorption. Only when all pores are filled with water is a material capillary saturated. For example, wood (and likely straw) will adsorb vapour from the air up to approximately 25% moisture content at 98% relative humidity, but fully capillary saturated wood may hold two to four times this amount of water. Once a material is capillary saturated it will generally not be able to store any more moisture. Hence, when this moisture content is exceeded, a material is called over-saturated, and drainage, if possible, will begin to remove the excess moisture.

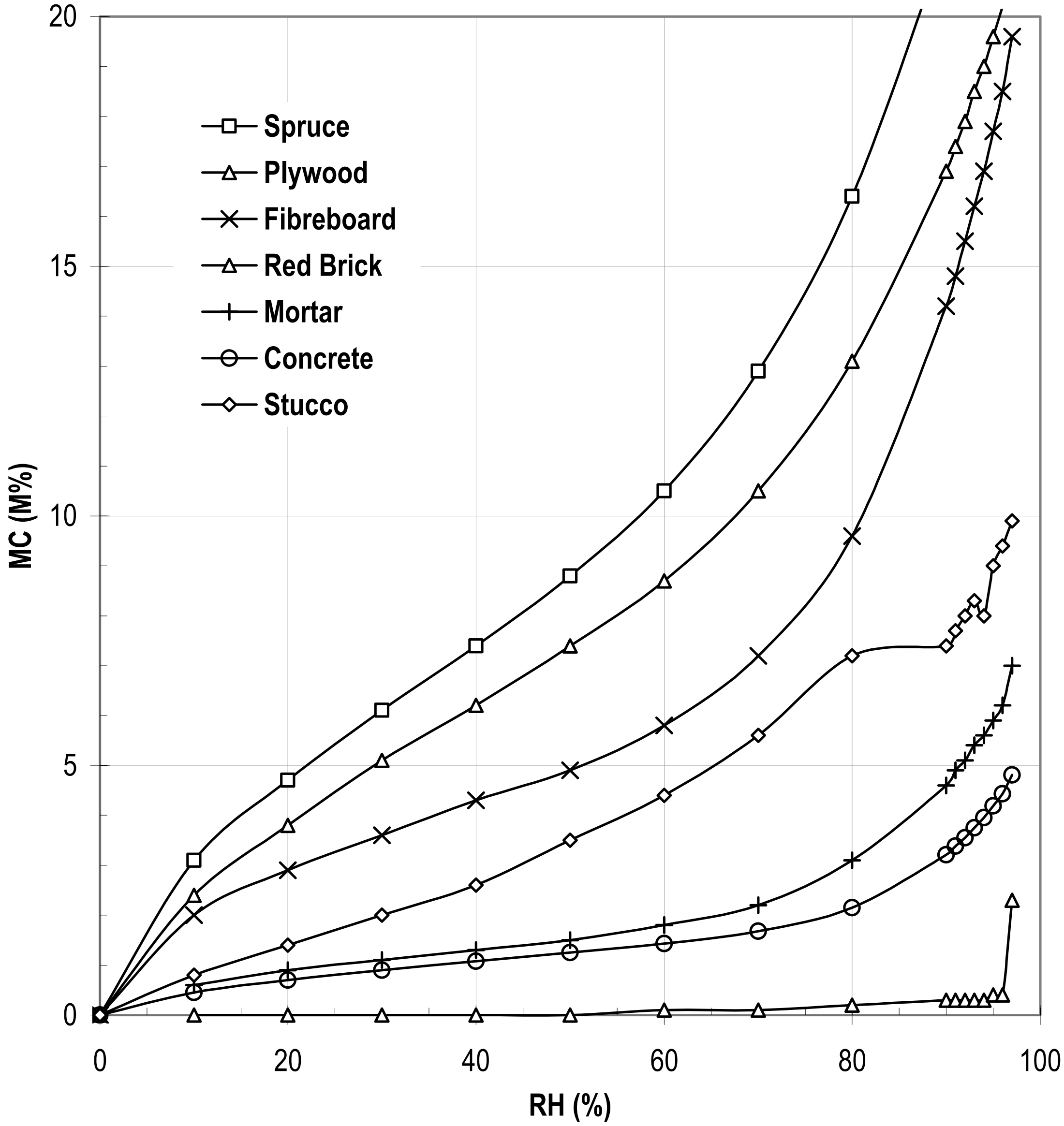

Figure 1.1: Sorption Isotherms for Several Common Building Materials

2 Literature Review

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

2.1 Strawbales

The strawbale core acts primarily as thermal insulation while transferring structural loads between the skins. Strawbales come in two main sizes, two-string and three-string, and a wide range of density. The density, which typically varies from below 7 pcf to over 12 pcf (110 to 190 kg/m^3) is the most important variable to assess – it strongly affects R-value, stiffness, strength, and air permeability.

2.1.1 Strawbale Thermal Conductivity

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.

Recent Danish [Andersen, 2000] research on full-scale wall samples found thermal conductivity values that ranged from R2.4 to almost R2.8 per inch. The bales were of an unknown straw species (not rice) and were of relatively low density. Great care was taken to prevent air movement within the walls. The group also studied highly compacted bales (37.4 pcf!) and found that despite the high density, a R-value of about 1.3 per inch was still achieved.

Heat Flow Relative to Straw Direction	Density (pcf)	R-value/inch	R-value / 18 inch
Perpendicular	4.8	2.77	50
Perpendicular	5.9	2.58	46
Parallel	4.8	2.53	46
Parallel	5.7	2.40	43
Compacted	37.4	1.31	

Table 2.1: Thermal Resistance measured for Danish Strawbale

2.1.2 Vapor and Liquid Permeability

The vapor permeance of strawbales have not been measured (as far as the author is aware) but good estimates can be made. Based on published data for the vapor permeance of highly porous natural materials such as cellulose insulation (density= 25-50 kg/m^3 / 1.6 to 3.2 pcf, μ=110-130), wood fiberboard (density = 340 kg/m^3 /21 pcf, μ=20-60), wood wool cement board (density = 400 kg/m^3/ 25 pcf μ=30-40), and light straw clay (density = 450 kg/m^3 /28 pcf, μ=80) 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 vapor permeance of 50 to 100 ng/Pa •s•m^2, and that a 450 mm thick strawbale should have a permeance of approximately 110 to 220 ng/ Pa•s•m^2 (2 to 4 US perms).

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. In general, liquid transfer of the straw has no practical importance since liquid water should not be allowed to contact strawbales.

2.1.3 Moisture Storage

The moisture storage (sorption isotherm) of grasses and straws is of some interest to agricultural engineers. It has been studied by many. Plots of some of the data from Lamond and Graham [1993] are presented in Figure 2.1.

It can be seen that the sorption isothem is little affected by temperature (hence the term isotherm) and that the curve is similar to that of wood. That the response of straw, grass, and wood are similar is expected because of their similar cellulose and lignin microstructure.

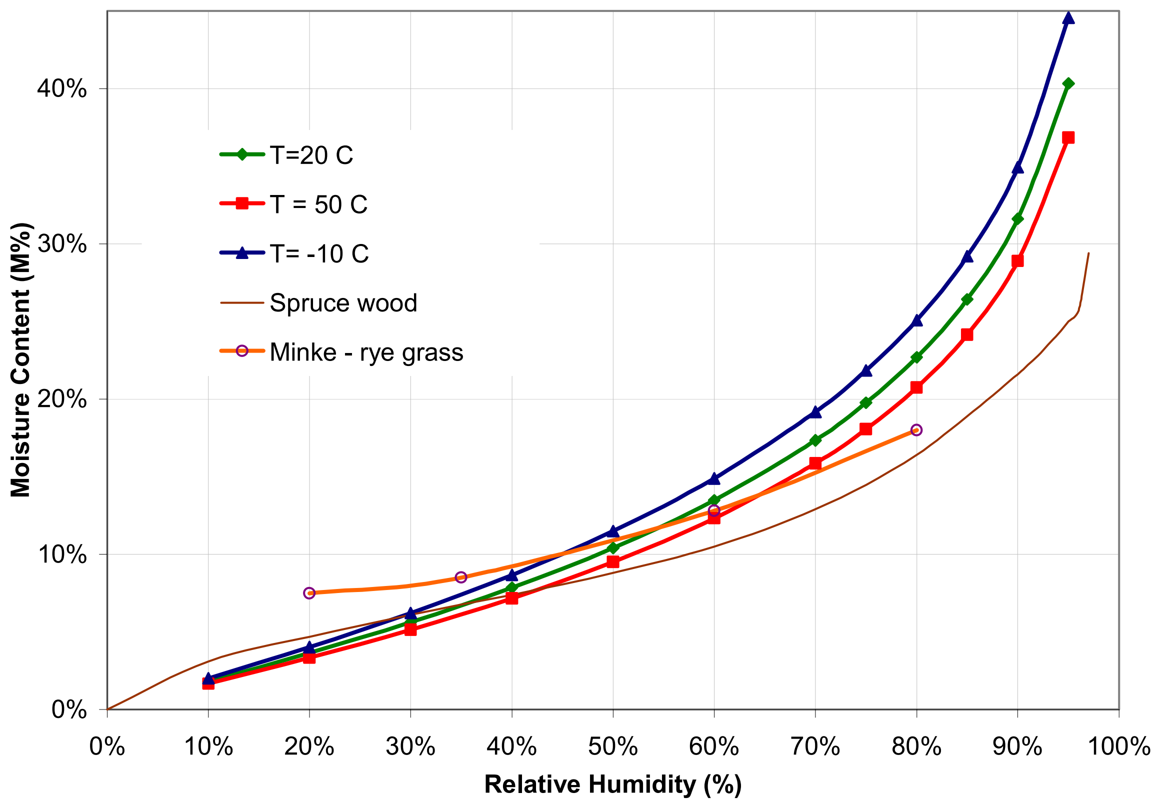

Figure 2.1: Sorption Isotherms for Grasses [Lamond & Graham 1993]

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 practice 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 2.1 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.

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 2.2: Recommended Stucco/Mortar Mixes, by volume of cement

Straube [2000] conducted a series of vapor permeance and water uptake tests on a range of plaster finishes that had been applied to strawbales. The samples were all lime or cement bonded, and investigated the influence of various coatings on the moisture properties. Since this study is very similar and relevant to the current study, it is reviewed in some depth here.

The samples tested included

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

A wide range of coatings and additives were tested on these basic stucco samples. The samples and results are summarized in Table 2.3.

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 coating	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 2.3: Results of Vapor Permeance Test Results [Straube, 2000]

The most remarkable result of the study was the influence of lime on stucco mixes. Increasing the lime content of stucco mixes (maintaining the typical 3:1 ratio of aggregate to cementitious binders) caused a large increase in permeance (Figure 2.2). Pure lime:sand stuccos were the most permeable tested. It is also clear that pure cement:sand stuccos are quite vapor resistant, meeting the definition of a vapor barrier in many cases.

Different coatings generated quite different results. The elastomeric and siloxane had little effect on the vapor 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 of a 1:1:6 mix to around 40 metric perms (0.6 US perms). Thus, oil paint can render a typical stucco a vapor 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.

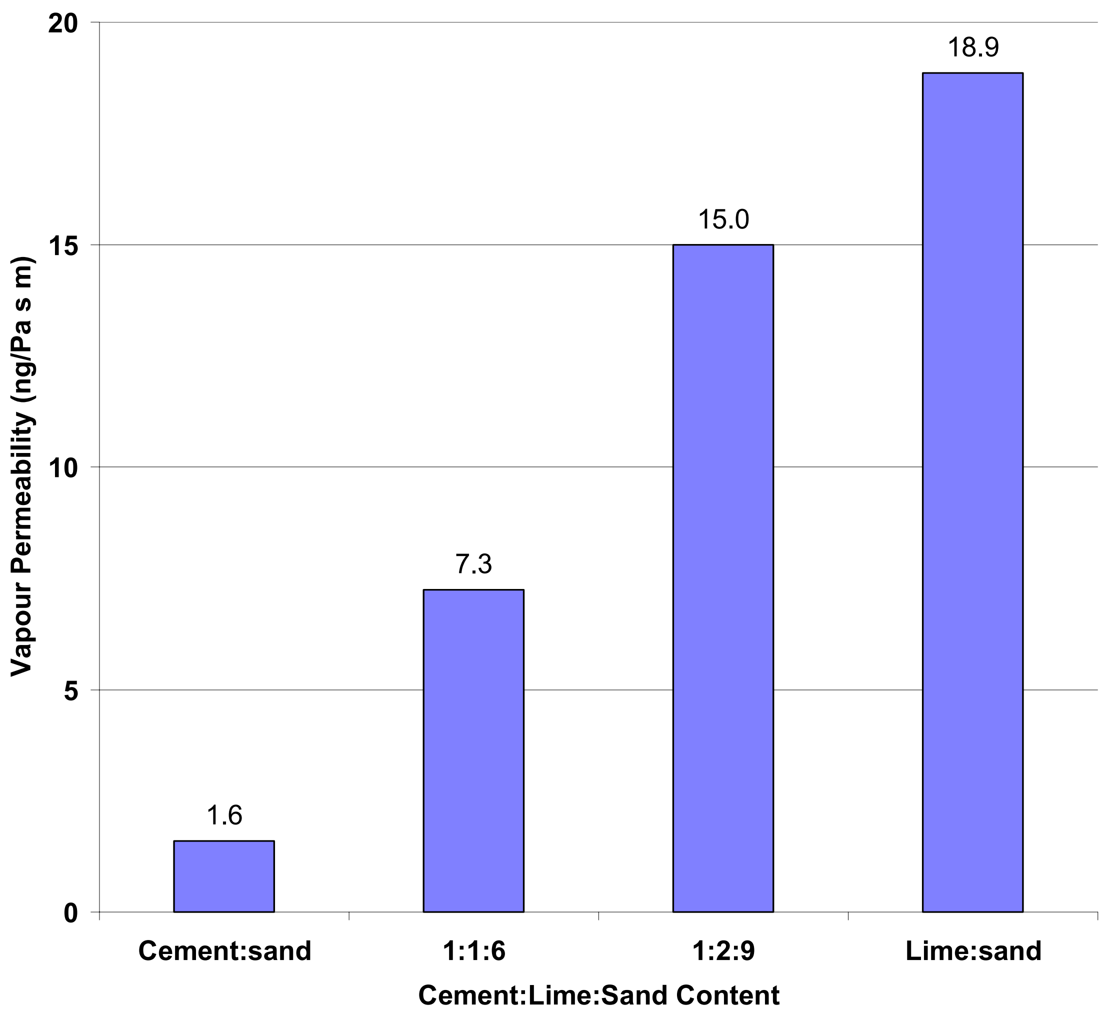

Figure 2.2 : Lime Content and Vapour Permeability [Straube, 2000]

Minke [2001] has produced several widely respected books on earth building, as well as conducting and assembling technical information from around Europe. His vapor permeability results are summarized in Table 2.4. His results essentially match Straube's work for the common lime:sand stucco tested, but offer also offer values fo earth plasters, and earth-straw mixtues.

Material Description	Permeability ng/Pa s m	Permeance for 38 mm/1.5 in ng/Pa s m^2	Permeability US Perm-inch
Clay soil	25.7	675	17.6
Silty soil	31.0	816	21.3
Sandy soil	24.8	653	17.0
Strawclay (1250 kg/m^3)	41.3	1088	28.4
Strawclay (950 kg/m^3)	62.0	1632	42.6
Strawclay (750 kg/m^3)	64.1	1688	44.1
Strawclay (450 kg/m^3)	82.7	2175	56.8
Clay earth plaster	23.3	612	16.0
Silty earth plaster	19.1	502	13.1
Cowdung-earth-lime plaster (12/4/3/20)	23.5	620	16.2
Lime Plaster	16.9	445	11.6
Lime-Casein-plaster (10:1)	14.3	377	9.8
Lime-linseed oil-Plaster (20:1)	13.2	347	9.1

Table 2.4: Vapor Permeability Values of Soil and Soil-straw [Minke]

2.2.1 Moisture Storage

The Institute for Research in Construction / National Research Council of Canada (IRC/NRCC) has recently completed a campaign of building material property testing, including sorption isotherms. Some of this data is plotted in Figure 2.3 for mortar, cement stucco, concrete, and for comparison, spruce wood.

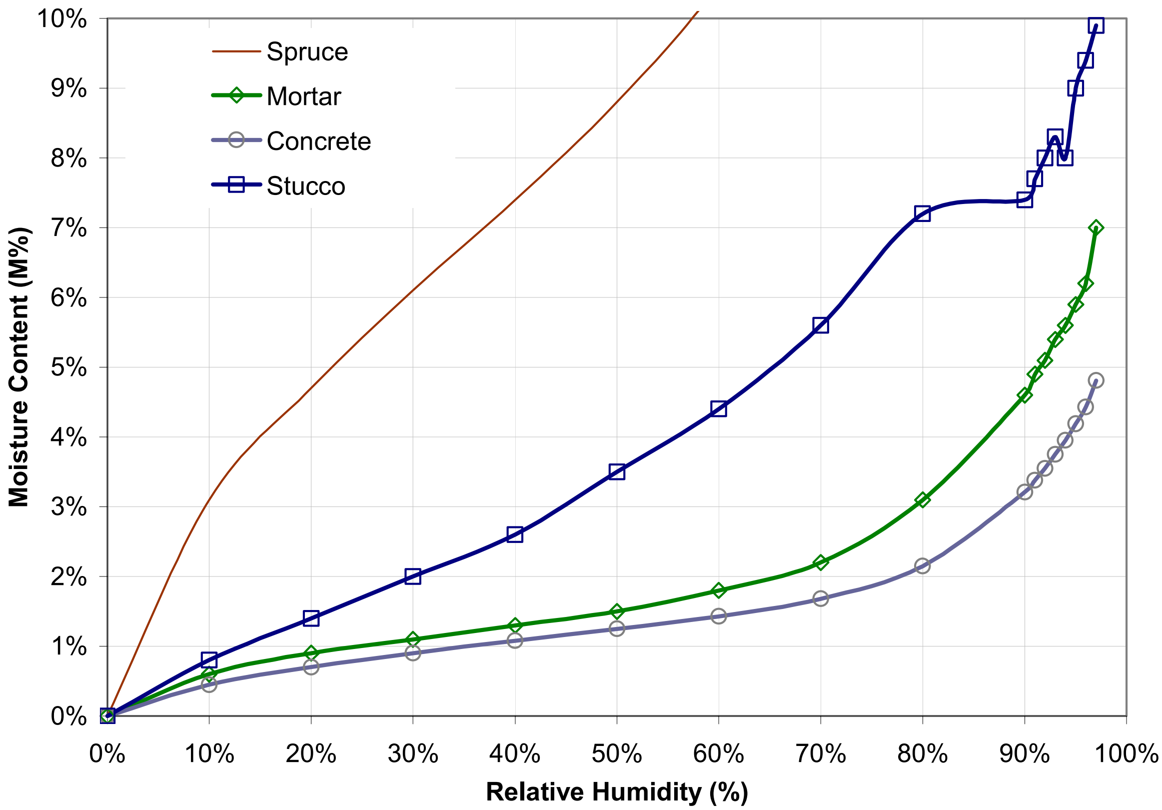

Figure 2.3: Representative Values of Sorption Isotherms for Cement-based Concrete, Mortar, and Stucco

2.2.2 Water Uptake

The results of Straube's water absorption coefficient testing on the test samples already described above are shown in Table 2.5. Increasing the lime content of the stucco mix resulted in increased water absorption. The siloxane and elastomeric coatings dramatically reduced water absorption, with the siloxane being especially effective. Linseed oil, of the type and rate applied, was not very effective.

Minke [2001] found that various silanes and siloxanes applied to earth plasters were very effective at reducing water absorption. The siloxanes performed best with no increase in vapor resistance. His results also showed that a linseed oil coating, applied at 400 g/m^2 (about a pint per square yard) was also effective at reducing water absorption, but did add a significant amount of vapor resistance (about 128 metric perms, or 2 US perms).

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 2.5: Water Absorption Coefficient Results [Straube 2000]

Material	Suction (kg/(m^2 $s^{1/2}$)
Earth plaster	0.152
Earth plaster w/siloxane (BS15 Wacker)	0.00170
Earth plaster w/2 coasts lime: casein (1:8)	0.0117
Strawclay (1150 kg/m^3)	0.052
Strawclay (450 kg/m^3)	0.040

Table 2.6: Water Absorption Coefficient Results [Minke 2001]

3 Test Program

The test program involved:

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

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

3.1 Mix Designs and Sample Preparation

The following mixes were chosen by EBNet and produced by Vital Systems. The majority of the samples were earth and lime based plasters. This is due to the fact that significant data already exists for cement based stuccos.

The samples were in two groups. The first group of six test mixes was the official sample set, of which triplicates were made. These are described, based on the information sent with the samples and received from Tim Owen Kennedy, in Table 3.1. The measured density is also included to allow for a quantitative comparison.

The lime plaster appeared to be poorly consolidated, and one of the three samples was broken on delivery.

A wide range of additional samples were sent, with different mix additives and coatings. These samples, of which only one each were provided, are summarized in Table 3.2.

Mix #	Description	Avg. Density [kg/m^3]
1	Portland cement plaster (1:0.2:3)	1,997
2	Cement lime plaster (1:1:6)	1,942
3	Lime plaster (1:3)	1,748
4	Earth Plaster -1	1,531
5	Earth Plaster -2	1,759
6	Earth Plaster -3	1,844

Table 3.1: Plaster Test Samples (triplicate)

The samples were shipped from California in carefully padded boxes, with each sample surrounded in a plywood case (Figure 3.1).

Label	Description	Density [kg/m^3]
1/2 D	Mix D with Sodium Silicate 100%	1,643
3-4 D	3/4" Mix D with ¼" Lime Plaster & 3 Coats of Lime Wash	1,419
D	Mix D with Sodium Silicate 50%	1,698
1-1/4 D	Mix D with Lime Wash (5 Coats)	1,408
OIL ON	2% Raw Linseed Oil in Mix D	1,643
ALIZ	Mix D with Wheat Stabilized Interior Clay Paint Finish	1,666
L1	10% Lime by Volume in Clay Plaster Mix	1,621
L2	50% Lime by Volume in Clay Plaster Mix	1,741

Table 3.2: Other Plaster Samples Tested (one each)

Figure 3.1: Samples, as received

4 Vapor Permeability

Vapor permeability is important for the assessment of strawbale wall drying. Each of the samples described in Section 3 was tested for permeance. This section describes the test equipment, protocol, results and interpretation.

4.1 Vapor Permeance Test Protocol

ASTM E96 is used as a basis but some modifications were required to accommodate the materials. Instead of a wet-cup test (100%-50%), we employed conditions of 75-100%RH. These later conditions more accurately mimic the condition of interest, namely that of drying wet material (at 100%RH) to outdoor air in moderately humid conditions (75%).

4.2 Test Equipment and Setup

Samples were placed horizontally over a sealed, vapor impermeable container of plastic (Figure 4.1). They were sealed around their vertical edges and to the container in a vapor tight manner using aluminum tape and paraffin wax. The area of sample exposed to the exterior was carefully taped off to an area of 125 x 125 mm and measured to an accuracy of better than 1%. The area of sample exposed to the interior of the container was kept the same as that exposed to the exterior by using a machined PVC plate. The two areas were essentially perpendicular (within ±2 degrees or ±1.5 mm, whichever is less restrictive).

To reduce the initial weight, EPS foam inserts were used to displace some water in the deep plastic reservoirs. A plastic grill about 12mm (½”) deep with grids spaced at about 15 mm (5/8”) was used to prevent the foam from floating up and to control sloshing during measurement. Sloshing of water can cause contact with the sample and result in high readings.

An electronic Sartorius balance capable of accurately measuring up to 12 kg with an accuracy of ±0.01 g was used for all of the mass measurements.

The samples were placed in an insulated controlled temperature and humidity chamber. The humidity was controlled using a saturated salt solution, air was circulated using fans, and a thermostat controlled an electric heater to maintain the chamber temperature at 25 C (77 F) with a control of better than +/- 1 C (+/- 1.8F).

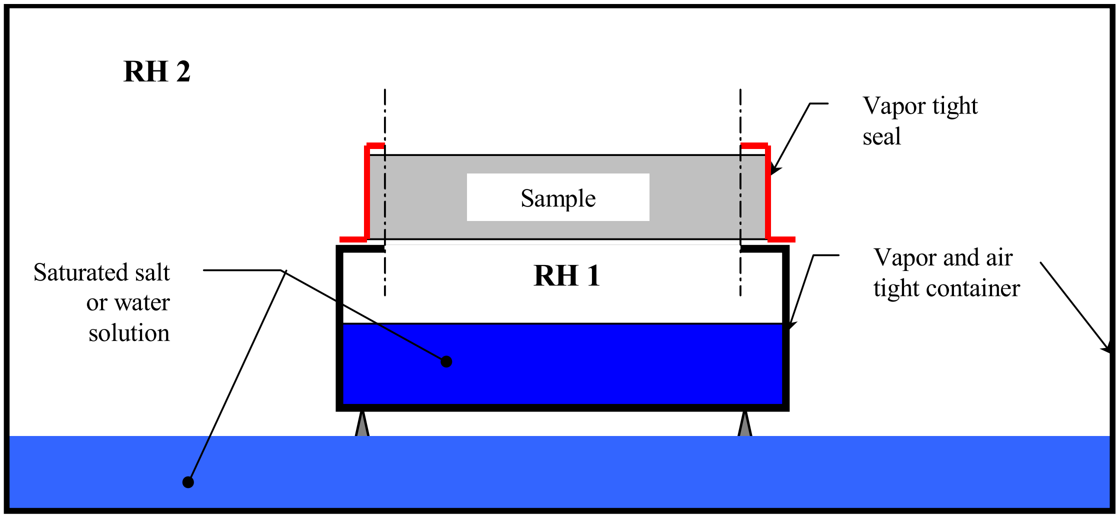

Figure 4.1: Test Apparatus Schematic for Measuring Vapor Permeance

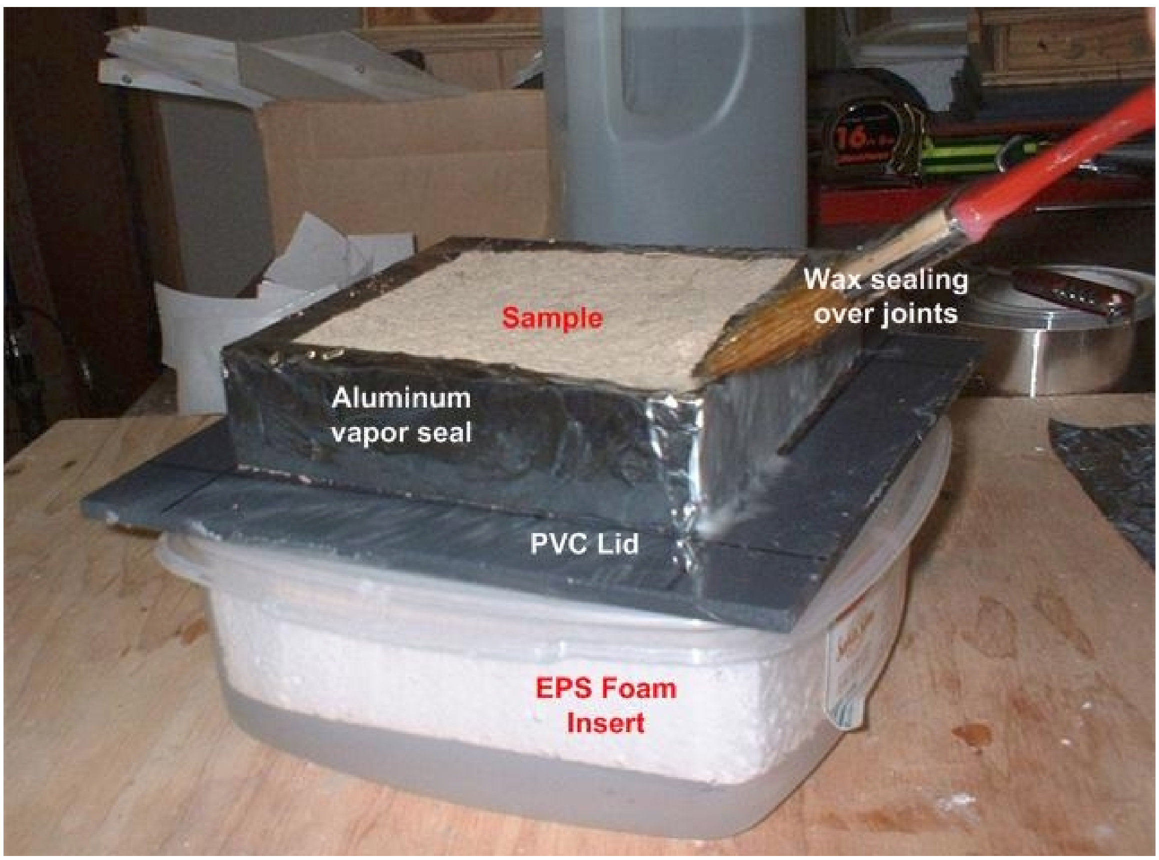

Figure 4.2: Photograph of Sample Assembly

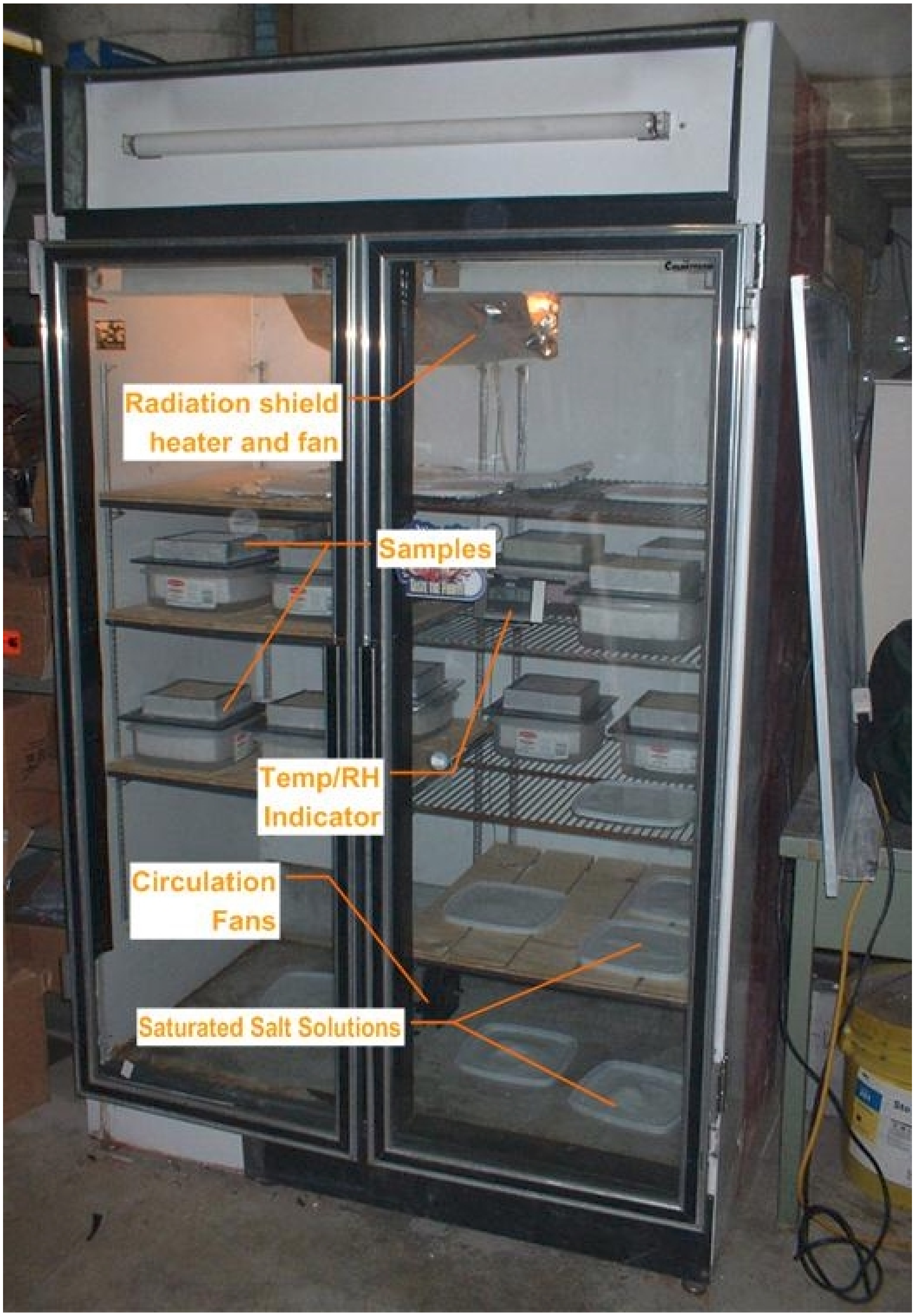

Figure 4.3: Temperature and Humidity Controlled Chamber

4.3 Procedure

The sample-container assemblages were weighed before being placed in the constant temperature/humidity chamber. The weight of the container-sample assembly was then weighed at equally spaced intervals (typically a few weeks). Tests can require several months.

When the rate of weight change over at least three intervals have the same rate (typically within 2%) equilibrium can be assumed to have taken place, and the permeance of the sample can be calculated (Figure 4.4). We chose to plot the data, and stop the tests when the slope of the graph (permeance) was consistent over several measurement periods.

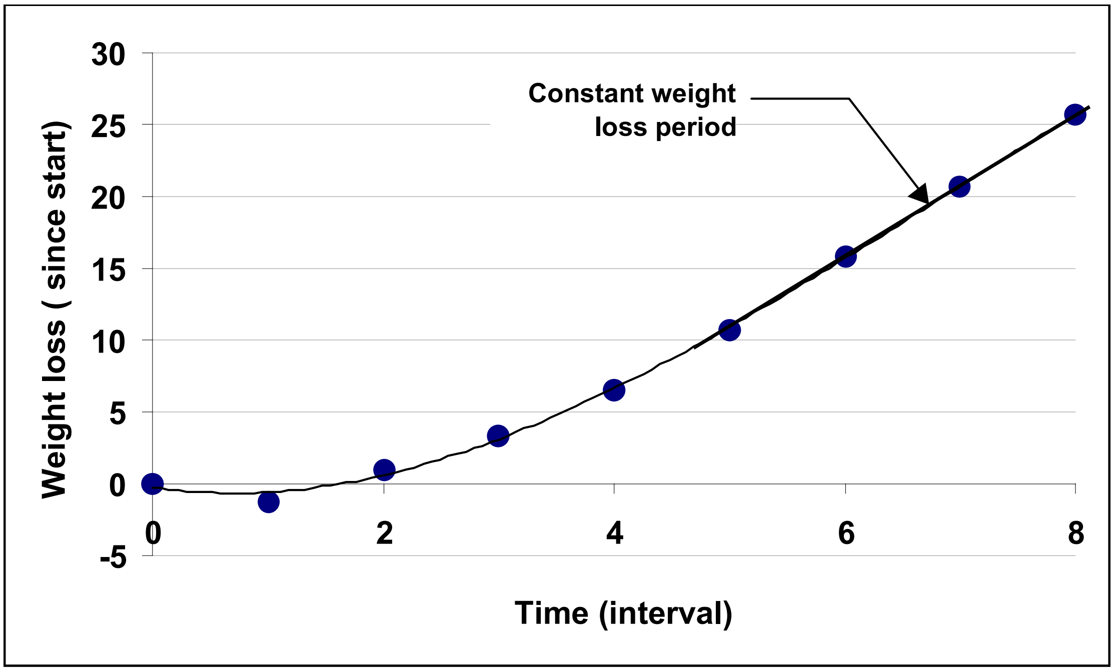

Figure 4.4: Example Vapor Permeance Test Data

4.4 Interpretation

The vapor permeance and permeability values can be calculated from the measured, steady-state weight loss (or gain). The permeance of the sample is calculated from:

Permeance in ng/Pa s m^2 = (weight loss in nanograms†) / [(duration of time interval in seconds) x (sample area in m^2) x (average vapour pressure difference in Pa)].

And permeability is calculated as:

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

4.5 Results

The results for the two series of plaster samples are summarized in Table 4.1 and Table 4.2. The results are plotted in Appendix A.

Mix #	Description	Permeance (ng/Pa m^2 s)	Permeability (ng/Pa m s)	US Perms
1	Portland cement plaster (1:0.2:3)	355	13.7	6.2
2	Cement lime plaster (1:1:6)	514	19.0	9.0
3	Lime plaster (1:3)	804	30.1	14.0
4	Earth Plaster - 1	1,259	45.7	21.9
5	Earth Plaster -2	1,133	41.2	19.7
6	Earth Plaster -3	1,073	40.1	18.7

Table 4.1: Vapor Permeance and Permeability (avg of triplicates)
Permeance for 38 +/- 1 mm (1.5" thick) samples

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

Label	Description	Permeance ($ng/Pa\ m^2\ s$)	Permeability (ng/Pa m s)	Permeance (US Perms)
1/2 D	Mix D with Sodium Silicate 100%	1,408	52.1	24.5
3-4 D	3/4" Mix D with 1/4" Lime Plaster & 3 Coats of Lime Wash	919	34.0	16.0
D	Mix D with Sodium Silicate 50%	1,162	41.8	20.3
1-1/4 D	Mix D with Lime Wash (5 Coats)	1,102	40.8	19.2
OIL ON	2% Raw Linseed Oil in Mix D	872	32.3	15.2
ALIZ	Mix D with Wheat Stabilized Interior Clay Paint Finish	1,201	44.5	20.9
L1	10% Lime by Volume in Clay Plaster Mix	1,097	41.7	19.1
L2	50% Lime by Volume in Clay Plaster Mix	1,092	40.4	19.0

Table 4.2: Vapor Permeance of Other Plaster Samples (one each)
Permeance for 38 +/- 1 mm (1.5" thick) samples

4.6 Discussion

Several interesting results can be seen from the tabulated data. The EBNet cement stucco sample was much more permeable than values for pure 1:3 cement stuccos in the literature (permeability of 13.7 versus 1.7 by Straube). This is almost certainly due to the fact that the EBNet sample contained 0.2 parts lime or masonry cement. While this may be common practice, it does result in different results because of the powerful vapor diffusion enhancement effect of lime additives.

The 1:1:6 plasters were more comparable, with an EBNet permeability of 19 versus 10 in the earlier Straube study. The results for the lime plaster also show an increase in permeance, with the EBNet sample returning a value of 30, whereas Straube and Minke reported results of 15 to 19 and 17 respectively. It is possible that the samples were of a lower density, or where applied differently (in a casting box instead of on a bale), or where cured differently. All of these factors are known to play a significant role.

The earth plasters tested are the most permeable samples we have tested. They appear to have a decreasing permeability with increasing density. This is expected and the data is consistent. In any event, the range of permeance is low, with the nine 38 mm (1.5 inch) plaster samples with an average density 1700 kg/m^3 of exhibiting a permeance of 1017 to 1290 (17.8 to 22.5 US Perms). These results match those of Minke's more extensive testing for strawclay mixtures. It is worth noting that this level of vapor permeance is about the same or greater than many housewraps and building paper products. Hence, as suspected, earth plasters clearly have the ability to allow fast drying.

The second series of singular samples were all based on earth plaster. The results were all grouped tightly together. The D mix with 100% sodium silicate may have been an aberration, since this showed a very high permeance which slowly increased during the test. The vapor permeance of the sample with linseed oil exhibited reduced vapor permeability of about 32 ng/Pa s m, or 20% less than the average of the earth samples. The earth sample with the lime plaster and lime wash was also slightly less permeable than the untreated earth plaster. The sample with 5 coats of lime wash was essentially as permeable as the bare earth, although it is likely some small reduction occurred that was not large enough to be measurable.

The addition of sodium silicate did not appear to impact the vapor permeance noticeably, although a slight reduction was noted.

Importantly, the addition of 10% and 50% lime to the clay plaster mix did not reduce the permeance significantly.

5 Water Uptake Testing

As described earlier, water uptake testing is very useful for assessing the ease with which material will allow liquid water movement.

5.1 Test Protocol

The test protocol followed the EuroNorm TC 89/WG10 N95 and German DIN 52617.

5.2 Test Equipment and Setup

Samples were placed horizontally in a water tight container on two supports (Figure 5.1). To prevent the surface of the earth plaster from becoming dissolved in the water, the samples were supported by a plastic grill about 12mm (½") deep with grids spaced at about 15 mm (5/8"). This grill supported a fine plastic screen under a filter paper. This apparatus allowed water to wick easily through while giving good support to the sample. This approach was also used by Hansen et al [2001] in their testing of natural materials. The lid of the container was covered to prevent excess evaporation.

An electronic Sartorius balance capable of accurately measuring up to 12 kg with an accuracy of ±0.01 g was used for all of the mass measurements.

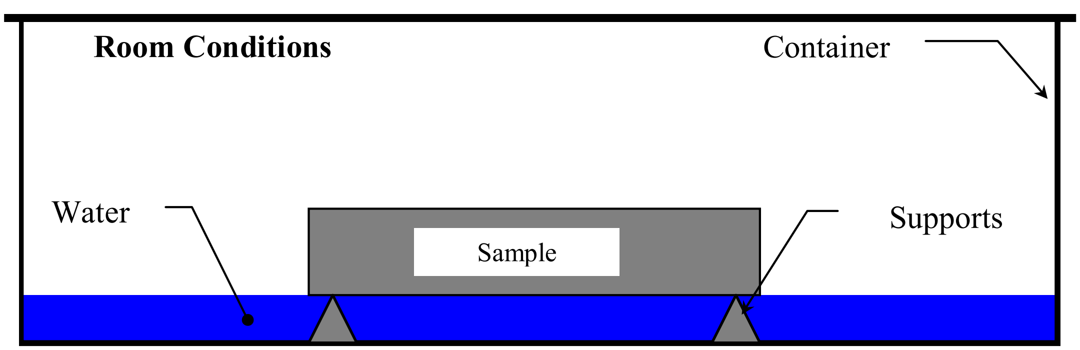

Figure 5.1: Test Apparatus for Measuring Water Absorption

Figure 5.2: Sample preparation for water absorption test

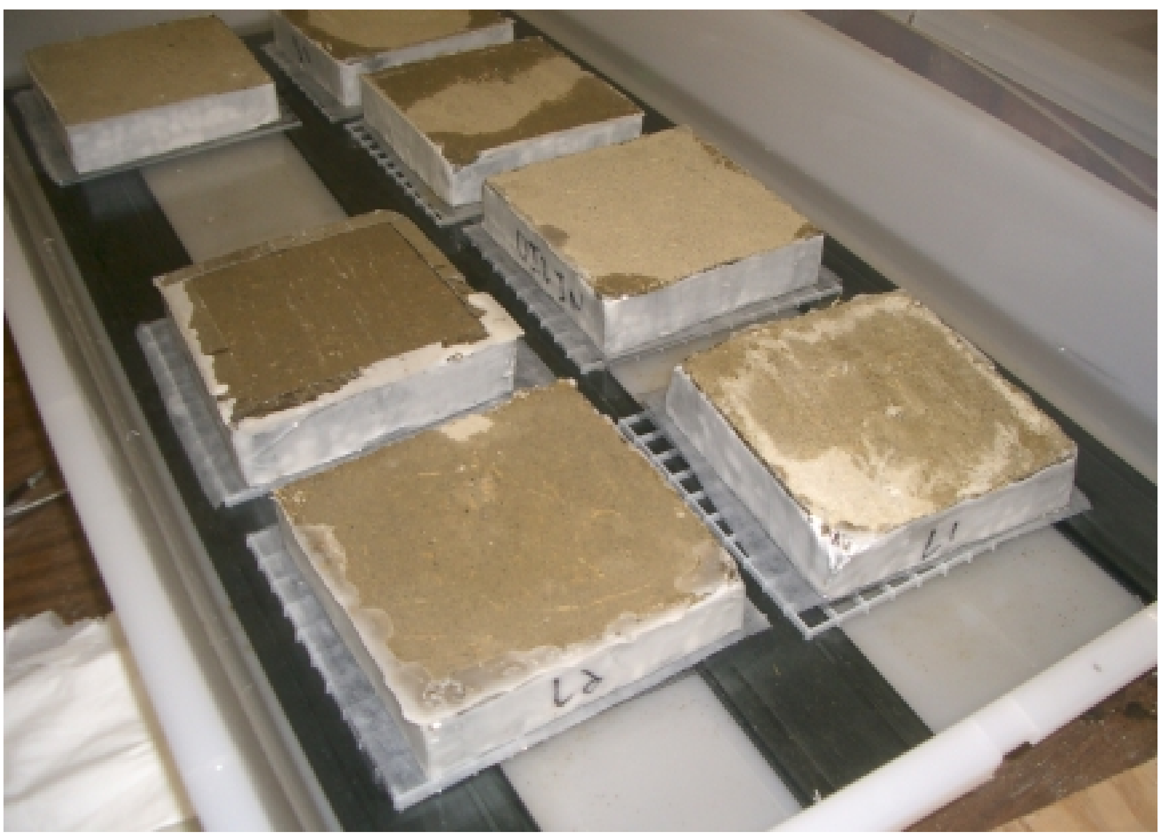

Figure 5.3: Plaster Samples in test chamber (note grid and filter cloth)

5.3 Procedure

Samples were dried until in equilibrium with laboratory conditions (50%RH). They were weighed, and then placed in contact with water to a depth of 1 to 2 mm (1/16"). The specimen area (of the face to be tested) and thickness was also measured and recorded. The area of the sample was measured to an accuracy of 1% of total dimension or better. The weight gain was measured at several points over a 24 hour period (typically 1, 2, 4, 8, and 24 hrs).

5.4 Interpretation

The total weight gain (measured weight less dry weight) per unit area is 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 in slope, the total water uptake at 24 hours is used to define the water absorption coefficient, A.

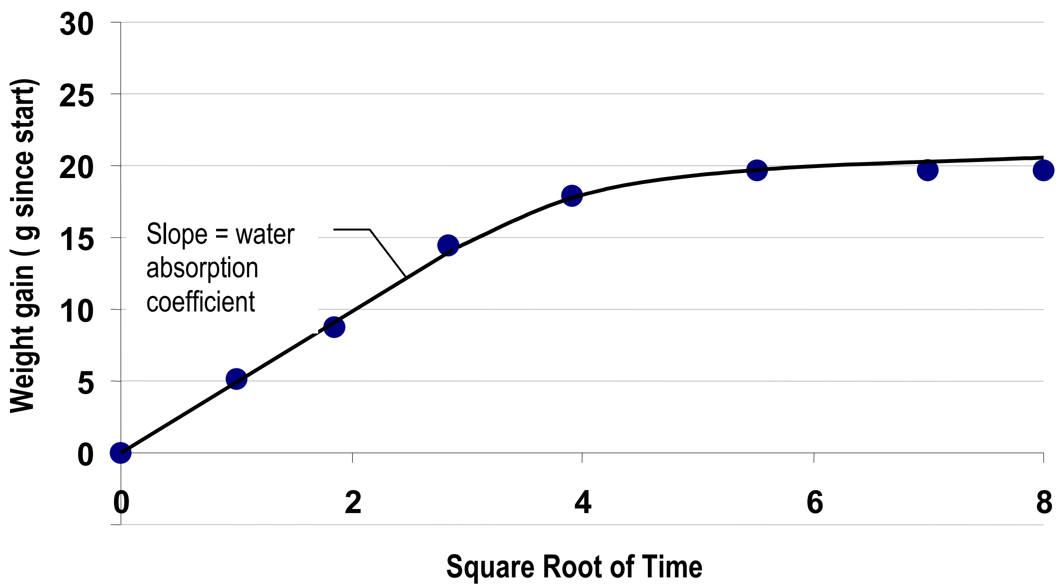

Figure 5.4: Example Water Uptake Test Data

5.5 Results

The water absorption coefficients for all of the samples are summarized in Table 5.1 and Table 5.2 below. The results are also plotted in Appendix A.

It can be seen that the curves do not always exhibit a well defined slope as is typical of most porous materials. This is especially true of some of the lime and cement samples. This is likely because of the different surface treatments, e.g., a trowel smooth surface has a low absorption coefficient because the surface has closed cells.

Mix #	Description	Water Absorption ($kg/m^2s^{1/2}$)
1	Portland cement plaster (1:0.2:3)	0.059
2	Cement lime plaster (1:1:6)	0.083
3	Lime plaster (1:3)	0.164
4	Earth Plaster - 1	0.075
5	Earth Plaster -2	0.068
6	Earth Plaster -3	0.067

Table 5.1: Water Absorption Coefficients (avg of triplicates)

It was observed that the earth plaster samples developed a wet, muddy, skin soon after contacting the water (within 30 minutes). The samples were remarkably tolerant of wetting however, and the effort taken with the grid and mesh was probably not necessary. The lime washed earth plasters remained firm even after 24 hours in contact with water.

Label	Description	Water Absorption ($kg/m^2s^{1/2}$)
1/2 D	Mix D with Sodium Silicate 100%	0.061
3/4 D	3/4" Mix D w/ 1/4" Lime Plaster & 3 Coats of Lime Wash	0.046
D	Mix D with Sodium Silicate 50%	0.052
1-1/4 D	Mix D with Lime Wash (5 Coats)	0.047
OIL ON	2% Raw Linseed Oil in Mix D	0.066
ALIZ	Mix D with Wheat Stabilized Interior Clay Paint Finish	0.087
L1	10% Lime by Volume in Clay Plaster Mix	0.106
L2	50% Lime by Volume in Clay Plaster Mix	0.092

Table 5.2: Water Absorption of other Plaster Samples (one each)

5.6 Discussion

The results of the uptake tests were not very consistent or repeatable in the case of the lime and cement stuccos. The earth plasters were remarkably consistent, exhibiting a coefficient of variation of only 3 to 6%. The earth plaster samples were remarkably consistent, and low absorption. Minke found his earth plasters to be twice as absorptive (0.152) although this range of material property must be considered normal in earthen materials. There was a slight trend toward lower absorption with increasing earth plaster density.

The results covered a relatively narrow range. The cement, and cement : lime stuccos responded in a very similar manner as the earth plasters. The lime plaster samples were by far the most absorbent, although the rough and poorly consolidated state of the samples should be borne in mind.

Sample 2-1 was tested with the cast side down, i.e., the face that was cast against the wood was placed in contact with the water. In all other cases, the face finished with a trowel was placed in contact with the water. This difference may be the reason that the Sample 2-1 exhibited very high water absorption values. Sample 1-1 also exhibited aberrant behavior because the surface finish was quite different.

In general, none of the coatings reduce water absorption to the remarkable degree that siloxane did in both Straube and Minke's previous test. The best results were achieved by samples with coats of lime wash (which also exhibited high vapor permeance).

The addition of lime to the earth plasters seemed to increase the water absorption. Perhaps the addition of several coats of lime wash would reduce the absorption.

Although we sealed around the edges of the samples with a poured in place hot wax seal, water did appear to wick preferentially up along this edge (Figure 5.5). This could be due to the nature of the sample preparation (cast in a wood mold) or shrinkage and swelling at the edge seal area.

Figure 5.5: Water wicking at edges

6 Conclusions

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

1. A 450 mm (18") thick strawbale should have a vapor permeance of approximately 110 to 220 ng/ Pa•s•m^2 (2 to 4 US perms).

2. Cement:sand stuccos are relatively vapour impermeable. In fact a 38 mm (1.5") thick cement : sand stucco may act as a vapor barrier (i.e., have a permeance of less than 1 US Perm).

3. The addition of lime to a cement stucco mix increases permeance. As the proportion of lime is increased, the permeance increases. Pure lime:sand stuccos are very vapor permeable. The permeance of a 38 mm (1.5") thick cement : sand stucco can be increased to 5 or 10 US Perms by replacing half the cement with lime and to 15 to 30 US Perms by using a pure lime : sand stucco. The addition of even a small amount of lime (0.2 parts) may increase the permeance of cement stucco dramatically (e.g.,from under 1 to 3 to 6 US Perms).

4. Earth plasters are generally more permeable than even lime plasters. The addition of straw increases the permeability further. A 38 mm (1.5") thick earth plaster can have a permeance of over 1200 metric perms (over 20 US Perms), in the same order as building papers and housewraps.

5. 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.

6. Earth plasters were not found to have significantly different water absorption than cement and lime stuccos. The earth plasters, regardless of density and straw content, resisted 24 hour of constant wetting easily, although the topmost 1/8" of surface became quite "muddy". In a real rainstorm this behavior may cause erosion.

7. Lime washes appear to be somewhat useful for reducing water absorption while not reducing vapor permeance. The lime wash over earth plaster did not dramatically lower water absorption but will increase the mechanical strength of the plaster after wetting, i.e., they will increase the resistance to rain erosion.

8. Based on Minke's and Straube's earlier tests, siloxane appears to have little or no effect on the vapor permeance of cement, cement:lime, lime, and

earth plasters while almost eliminating water absorption. The use of siloxane can be recommended based on these earlier tests.

9. Sodium silicate did not seem to have much impact on water uptake or vapor permeance. This additive may hold earth plaster together, or increase its erosion resistance, but as tested it had no noticeable impact on moisture properties.
10. Linseed oil at 2% in an earth plaster mix is not a very effective water repellent and does act to restrict vapor permeance somewhat. It may add some strength to an earth plaster in the wet state. Heavy applications of linseed oil to the surface of finished earth plaster will, based on Minke's tests, reduce the water absorption to almost zero, but will markedly decrease vapor permeance.
11. The test methods described here appear to provide repeatable results, and in general compare well to previous tests on different samples by both the same (Straube) and different researchers (Minke).

7 Acknowledgements

Most of the experimental test work was conducted by Frank McCarthy, who deserves thanks for the care he took in the work. Patrick Roppel, Randy van Straaten, and Chris Schumacher all helped during the development of the test program and in the construction of the test apparatus. Tim Owen Kennedy and the Vital Systems team produced the samples and made sure they were safely delivered.

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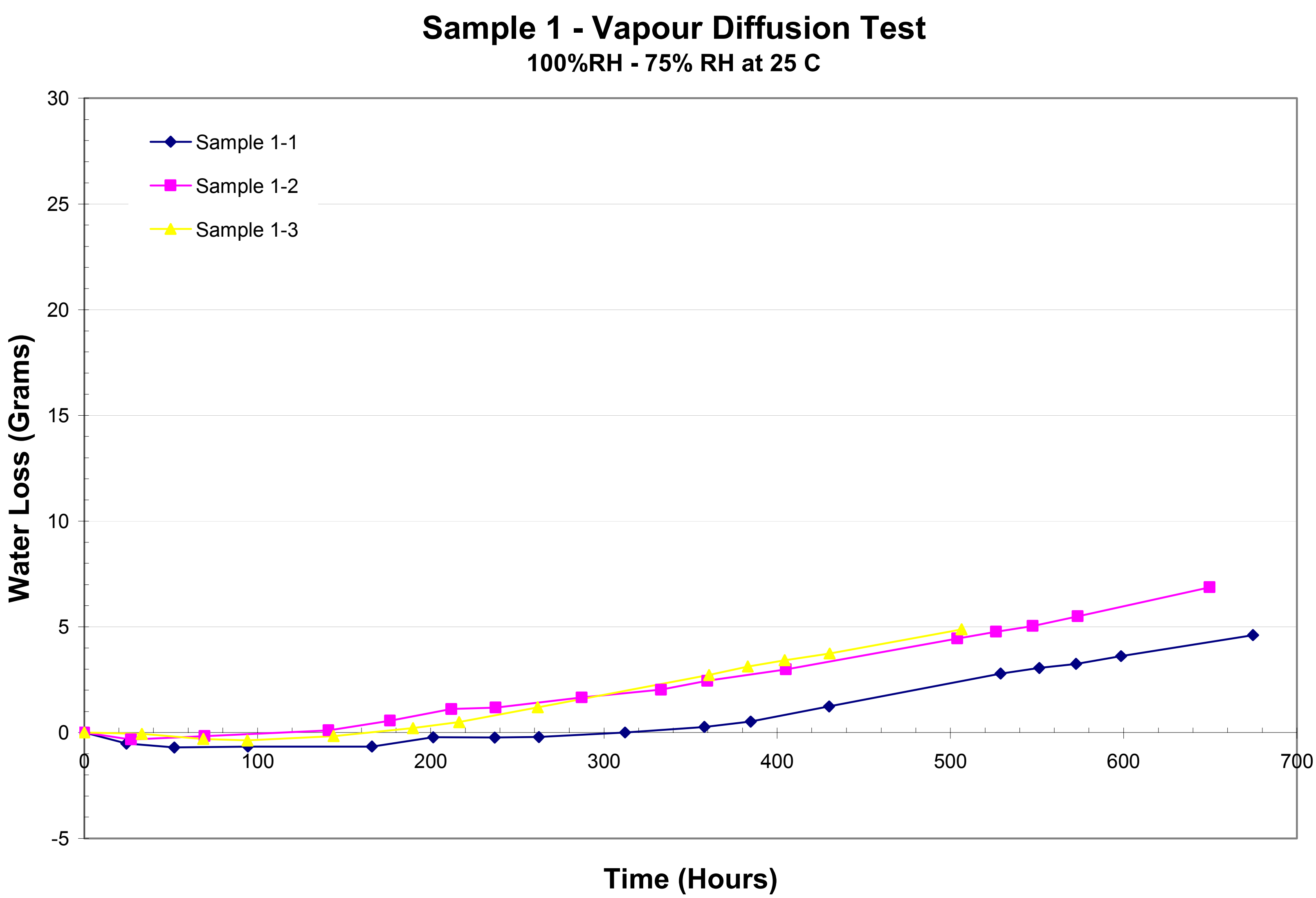
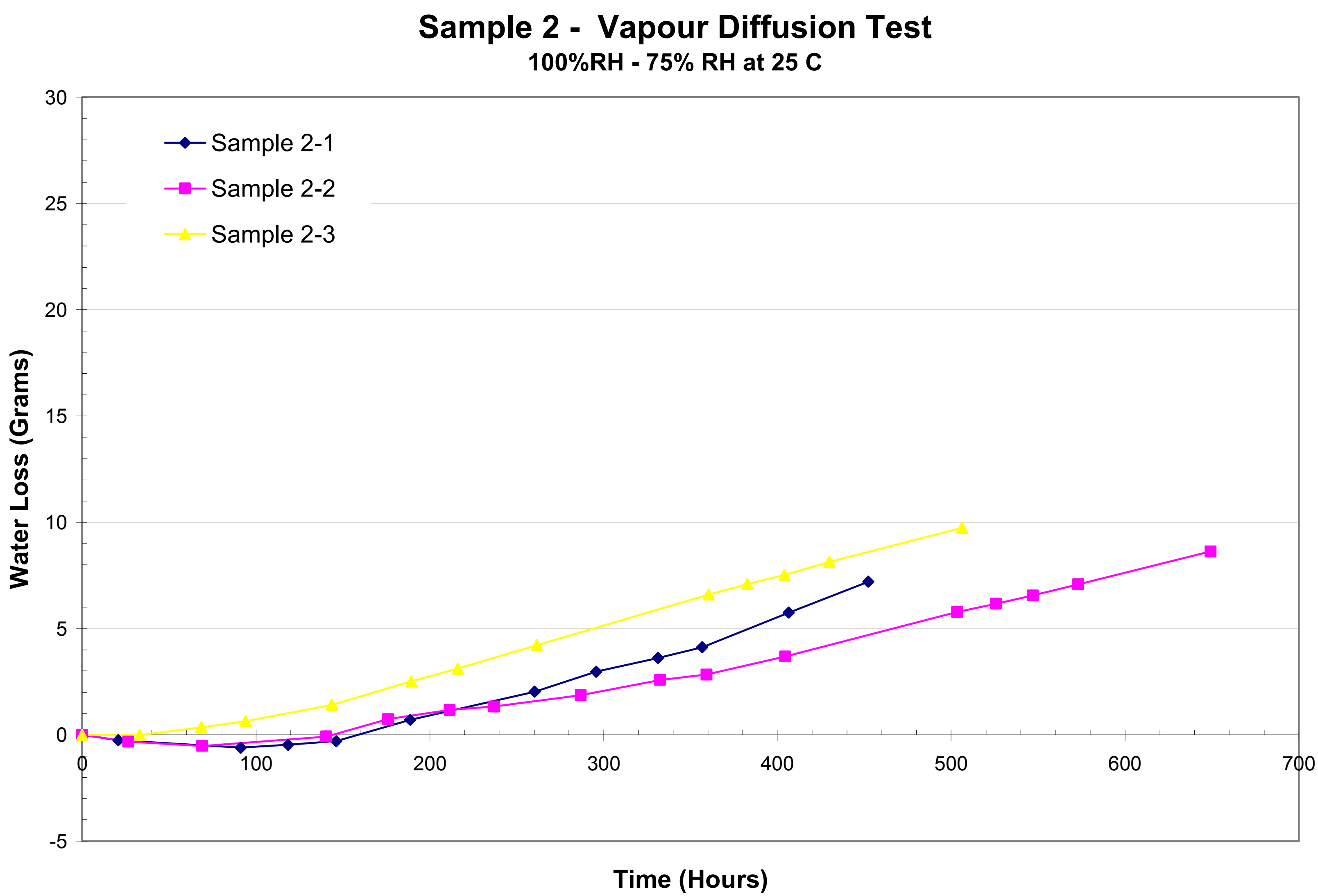
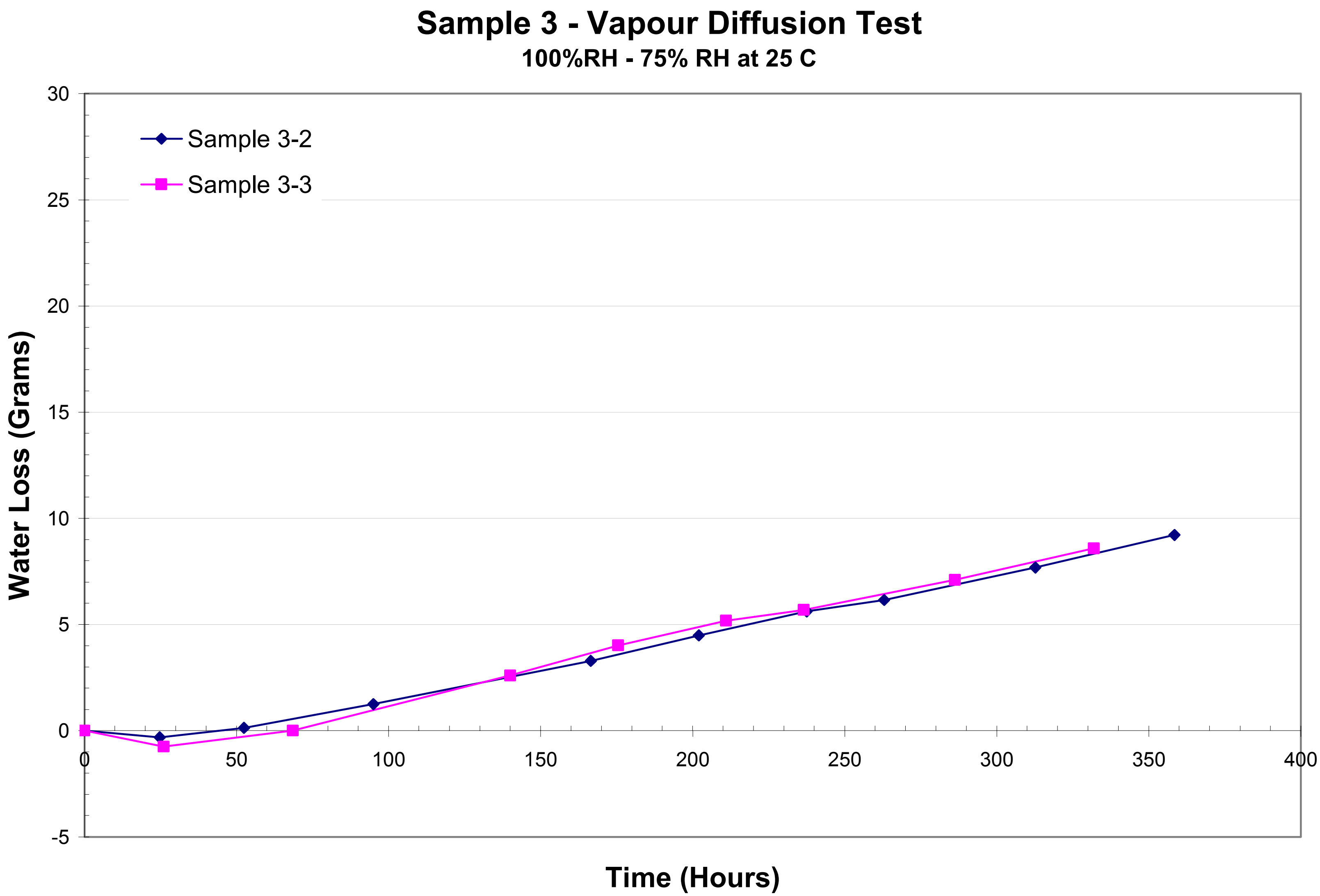
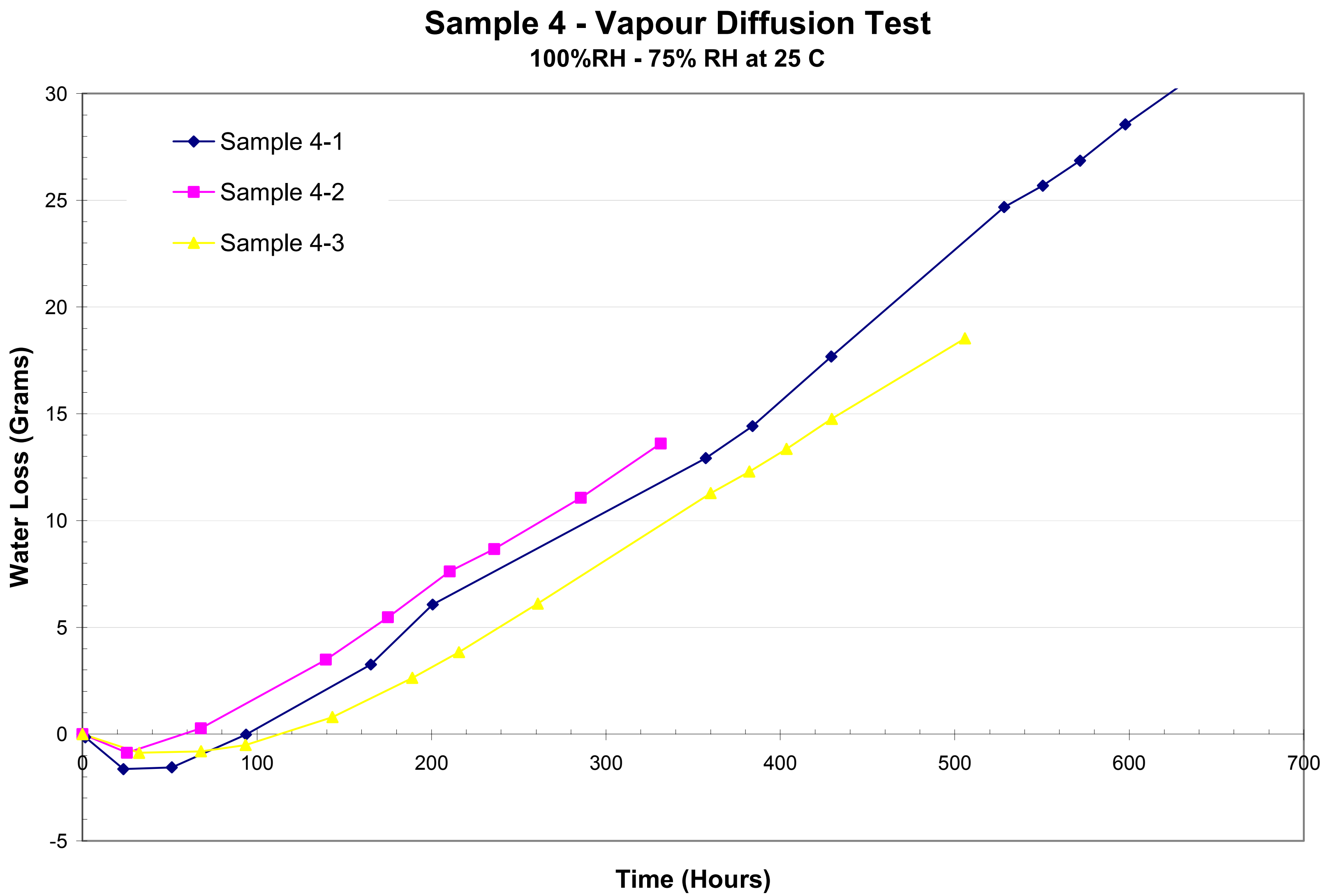
Appendix A
Sample Descriptions and Raw Data

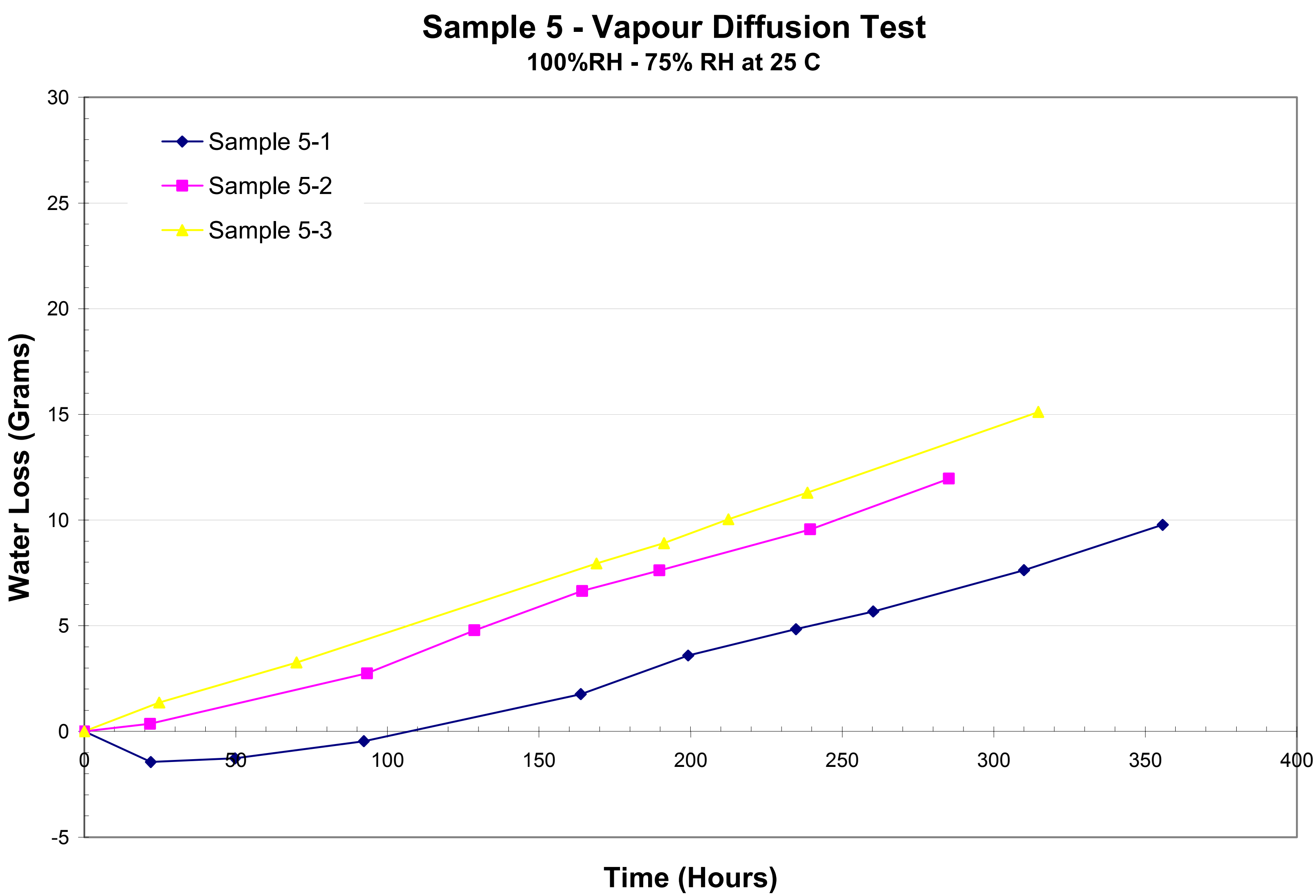
Sample	Height (mm)	Width (mm)	Depth (mm)	Volume (mm^3)	Weight (g)	Density (kg/m^3)
1-1	40	152	153	930,240	1,810.36	1,946
1-2	38	148	152	854,848	1,732.97	2,027
1-3	38	151	152	872,176	1,758.86	2,017
2-2	38	147	151	843,486	1,643.46	1,948
2-3	36	153	152	837,216	1,619.67	1,935
3-1	Sample	broken	on	arrival		
3-2	38	148	153	860,472	1,524.44	1,772
3-3	37	153	152	860,472	1,483.75	1,724
4-1	37	149	148	815,924	1,215.27	1,489
4-2	36	146	145	762,120	1,184.13	1,554
4-3	36	147	149	788,508	1,221.26	1,549
5-1	36	145	152	793,440	1,377.92	1,737
5-2	37	148	148	810,448	1,417.08	1,749
5-3	36	148	150	799,200	1,431.89	1,792
6-1	38	150	150	855,000	1,509.20	1,765
6-2	37	149	149	821,437	1,561.19	1,901
6-3	37	146	150	810,300	1,512.40	1,866
1/2 D	37	149	147	810,411	1,331.83	1,643
3/4 D	37	155	154	883,190	1,252.82	1,419
D	36	151	146	793,656	1,347.26	1,698
1-1/4 D	37	151	152	849,224	1,196.03	1,408
OILIN	37	149	152	837,976	1,376.46	1,643
ALIZ	37	150	148	821,400	1,368.39	1,666
L1	38	150	150	855,000	1,386.28	1,621
L2	37	150	146	810,300	1,410.74	1,741

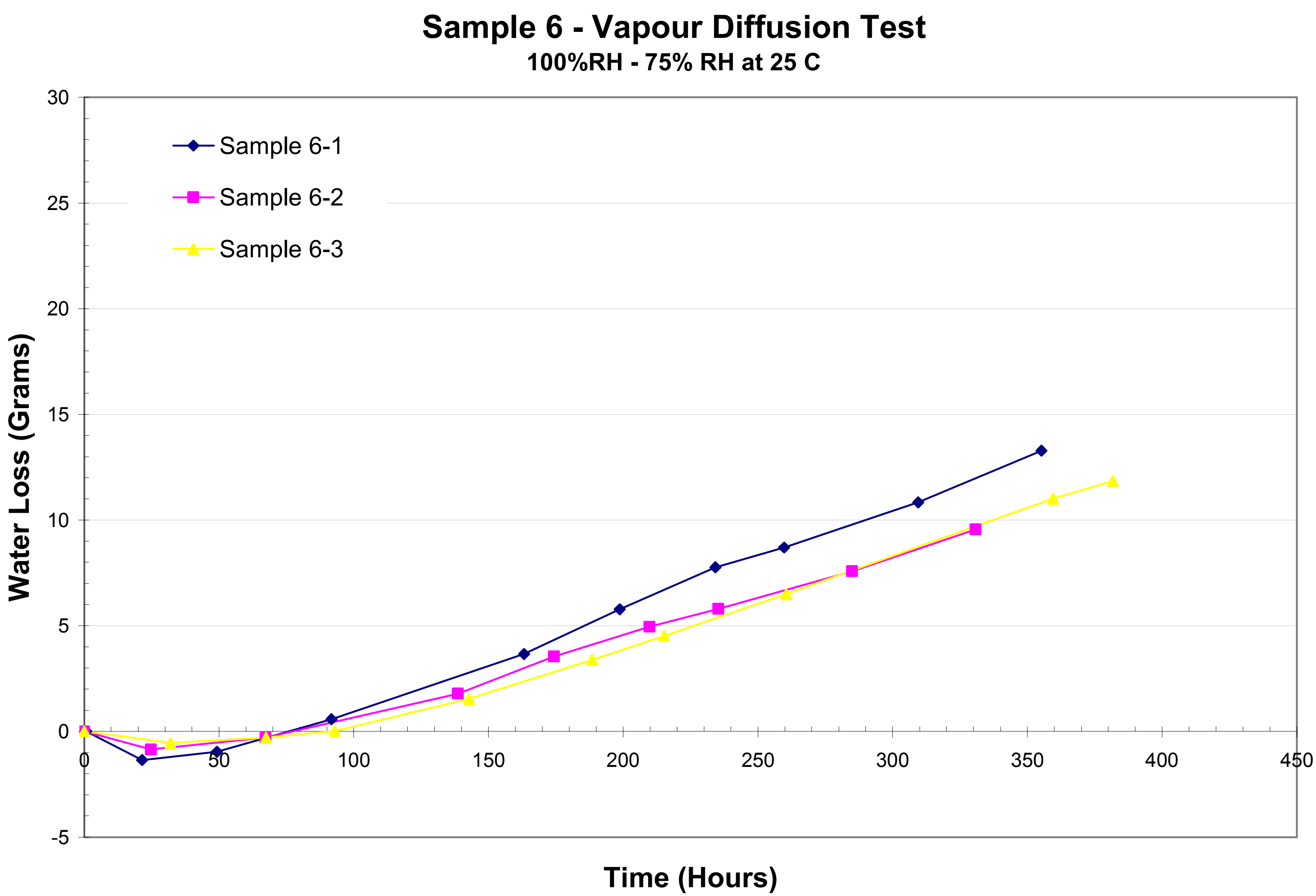

Sample 1 - Vapour Diffusion Test
100%RH - 75% RH at 25 C
Water Loss (Grams)
Time (Hours)
Sample 1-1
Sample 1-2
Sample 1-3
30
25
20
15
10
5
0
-5
0
100
200
300
400
500
600
700

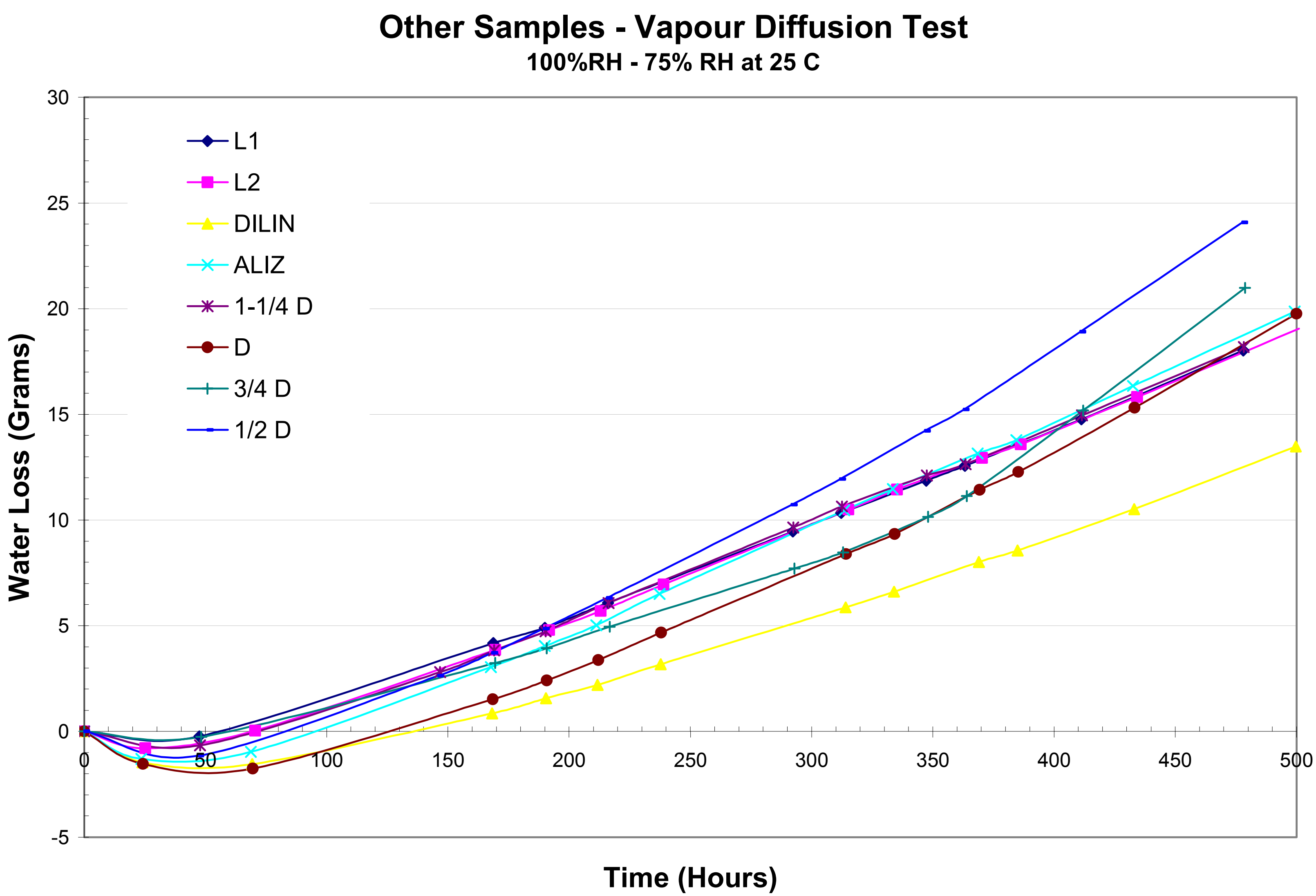

Sample 2 - Vapour Diffusion Test
100%RH - 75% RH at 25 C
Sample 2-1
Sample 2-2
Sample 2-3
Water Loss (Grams)
Time (Hours)
30
25
20
15
10
5
0
-5
0
100
200
300
400
500
600
700

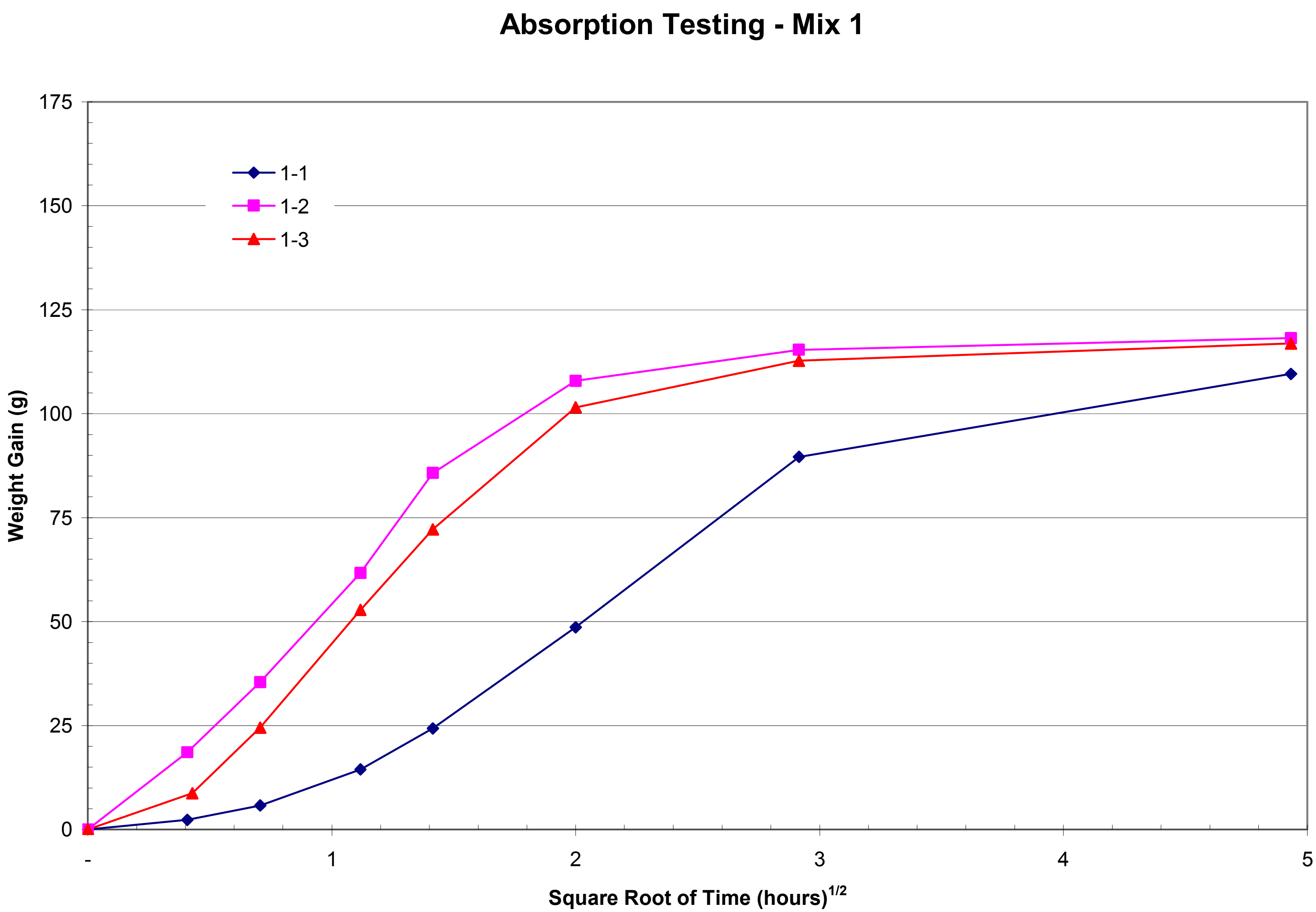

Sample 3 - Vapour Diffusion Test
100%RH - 75% RH at 25 C
Sample 3-2
Sample 3-3
Water Loss (Grams)
Time (Hours)
30
25
20
15
10
5
0
-5
0
50
100
150
200
250
300
350
400

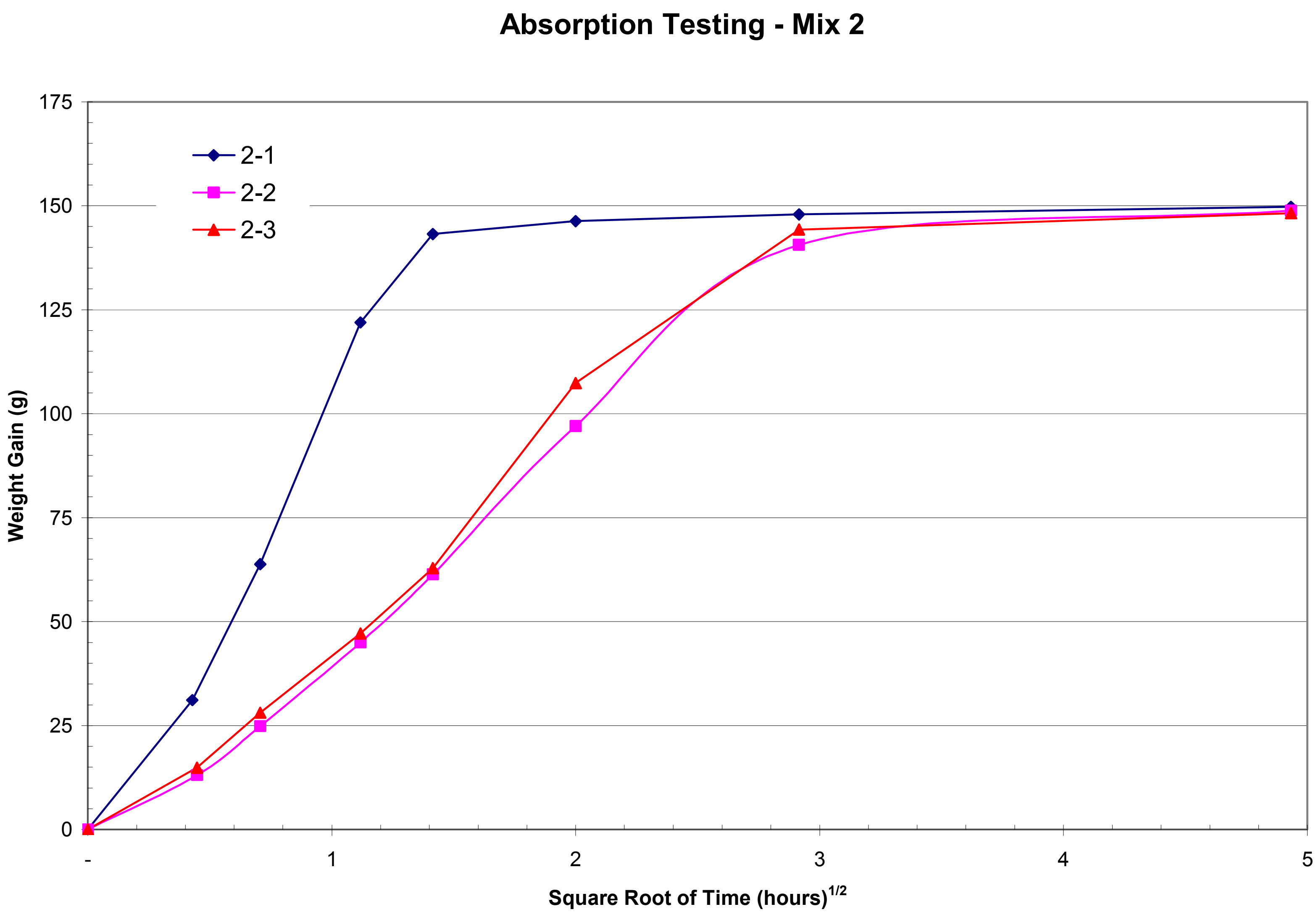

Sample 4 - Vapour Diffusion Test
100%RH - 75% RH at 25 C
Sample 4-1
Sample 4-2
Sample 4-3
Water Loss (Grams)
Time (Hours)
30
25
20
15
10
5
0
-5
0
100
200
300
400
500
600
700


Sample 5 - Vapour Diffusion Test
100%RH - 75% RH at 25 C
Sample 5-1
Sample 5-2
Sample 5-3
Water Loss (Grams)
Time (Hours)
30
25
20
15
10
5
0
-5
0
50
100
150
200
250
300
350
400

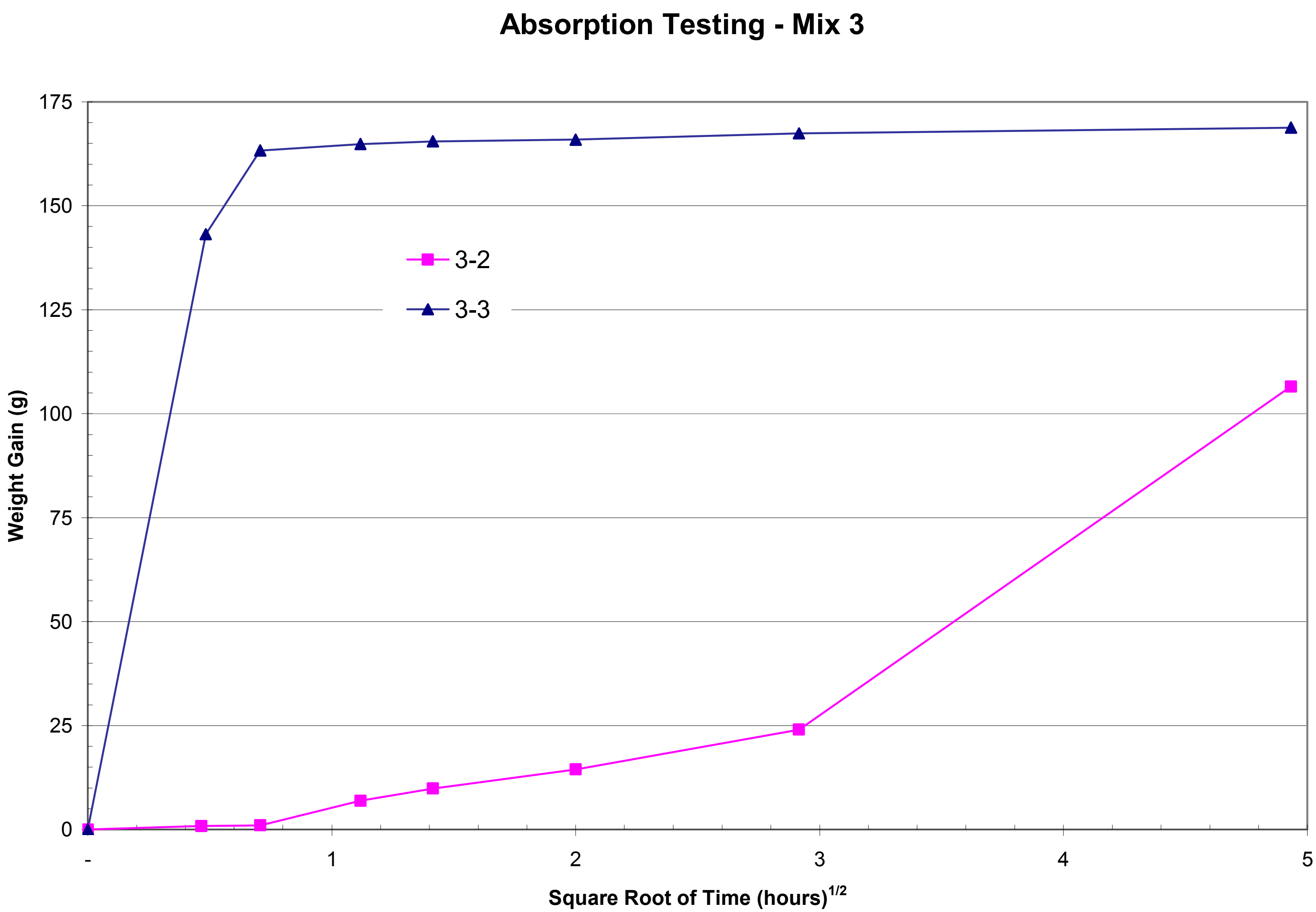

Sample 6 - Vapour Diffusion Test
100%RH - 75% RH at 25 C
Sample 6-1
Sample 6-2
Sample 6-3
Water Loss (Grams)
30
25
20
15
10
5
0
-5
0
50
100
150
200
250
300
350
400
450
Time (Hours)

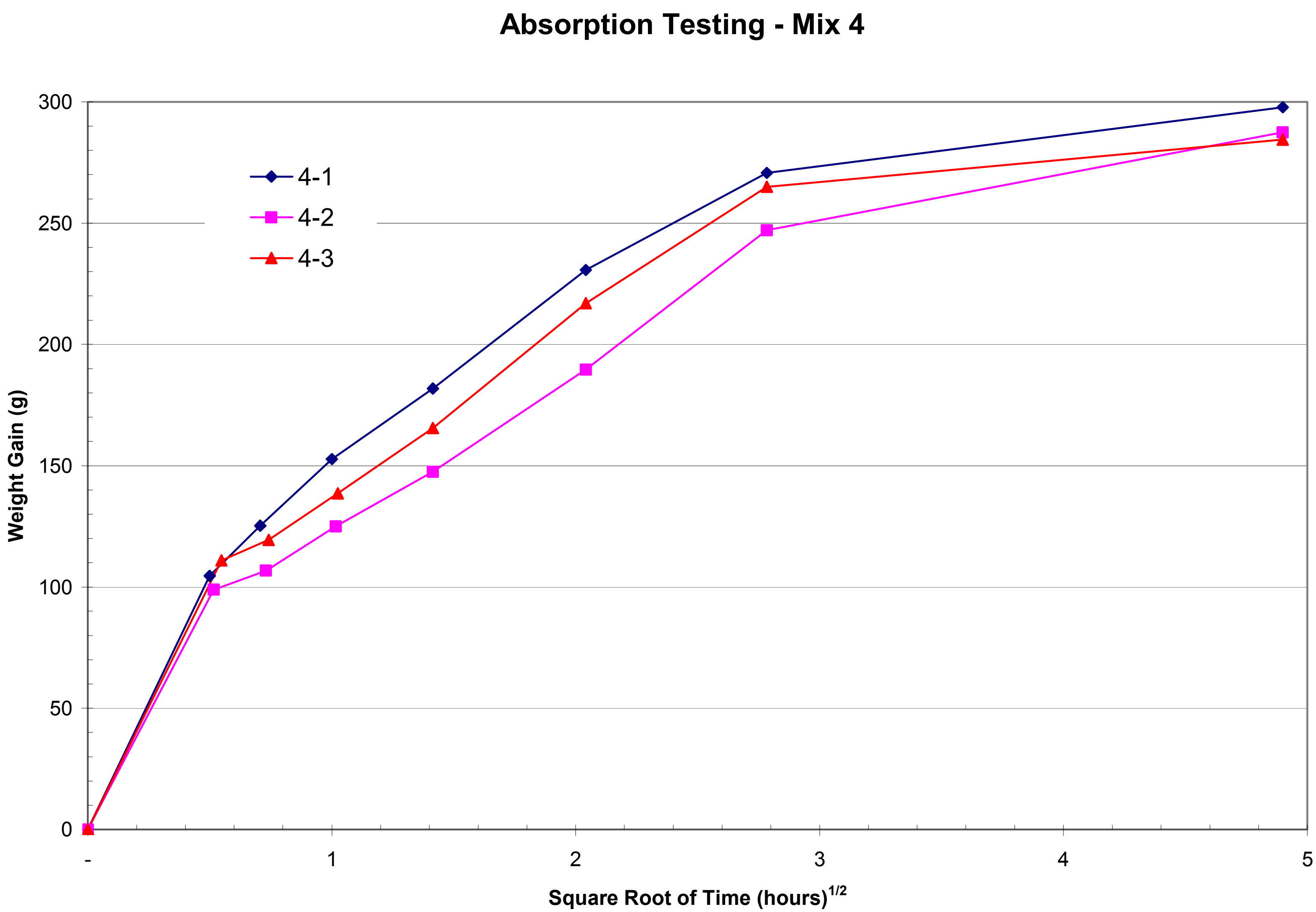

Other Samples - Vapour Diffusion Test
100%RH - 75% RH at 25 C
Water Loss (Grams)
Time (Hours)
L1
L2
DILIN
ALIZ
1-1/4 D
D
3/4 D
1/2 D
30
25
20
15
10
5
0
-5
0
50
100
150
200
250
300
350
400
450
500

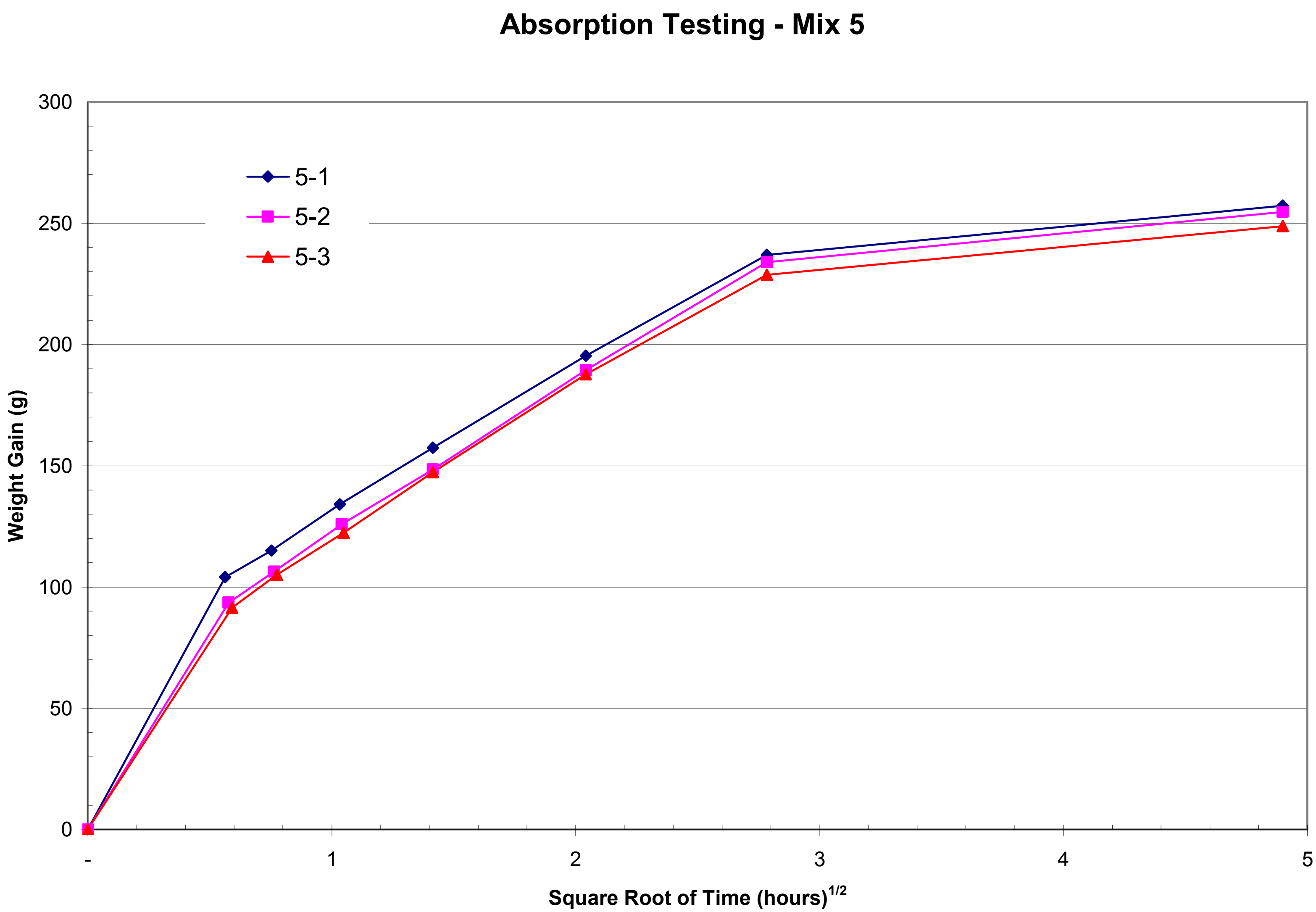

Absorption Testing - Mix 1
175
150
125
100
75
50
25
0
Weight Gain (g)
1-1
1-2
1-3
-
1
2
3
4
5
Square Root of Time (hours)^1/2



Absorption Testing - Mix 2
2-1
2-2
2-3
Weight Gain (g)
0
25
50
75
100
125
150
175
-
1
2
3
4
5
Square Root of Time (hours)1/2


Absorption Testing - Mix 3
175
150
125
100
75
50
25
0
-
1
2
3
4
5
Weight Gain (g)
Square Root of Time (hours)1/2
3-2
3-3


Absorption Testing - Mix 4
300
250
200
150
100
50
0
4-1
4-2
4-3
Weight Gain (g)
-
1
2
3
4
5
Square Root of Time (hours)1/2


Absorption Testing - Mix 5
5-1
5-2
5-3
Weight Gain (g)
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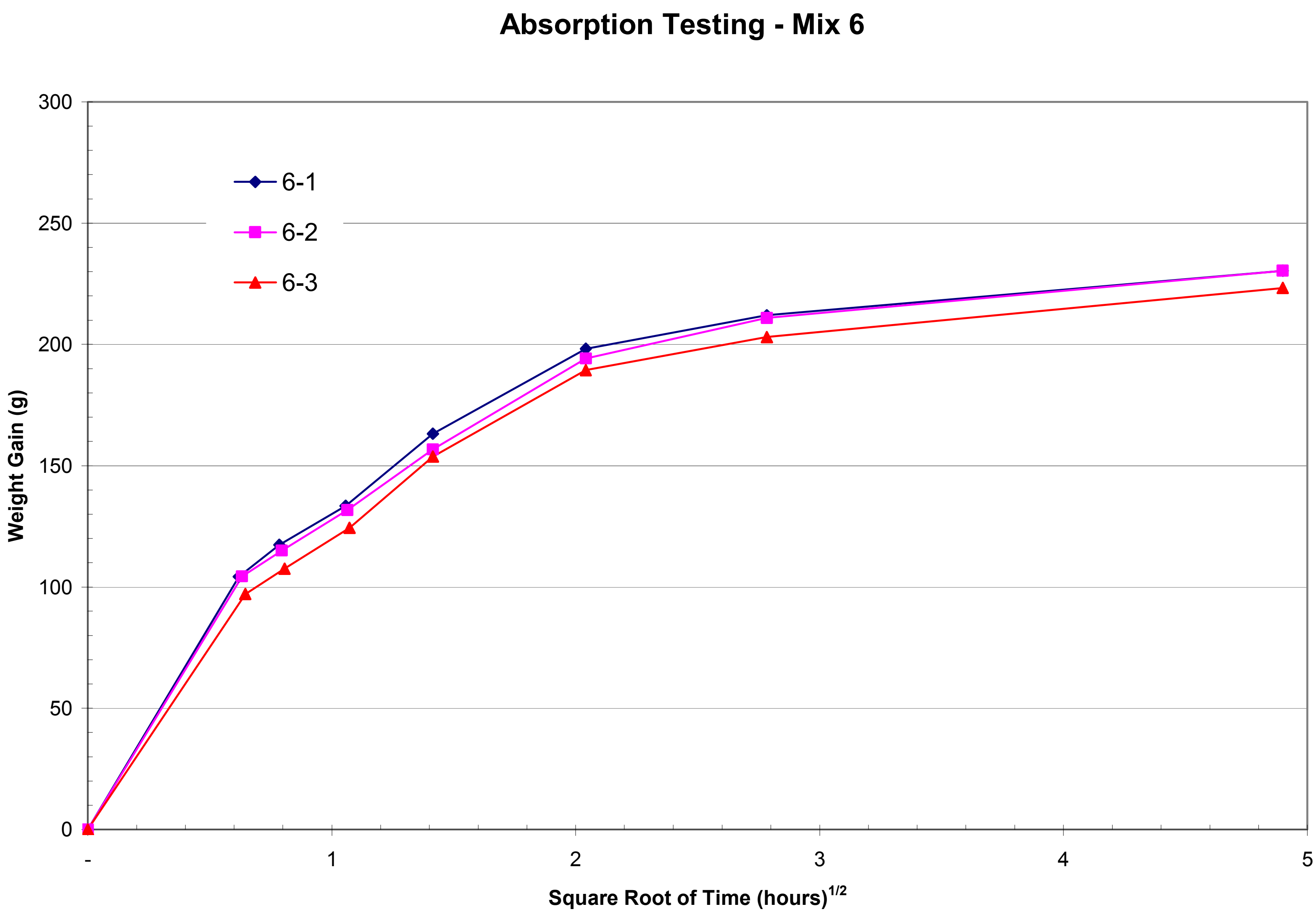
250
200
150
100
50
0
-
1
2
3
4
5
Square Root of Time (hours)1/2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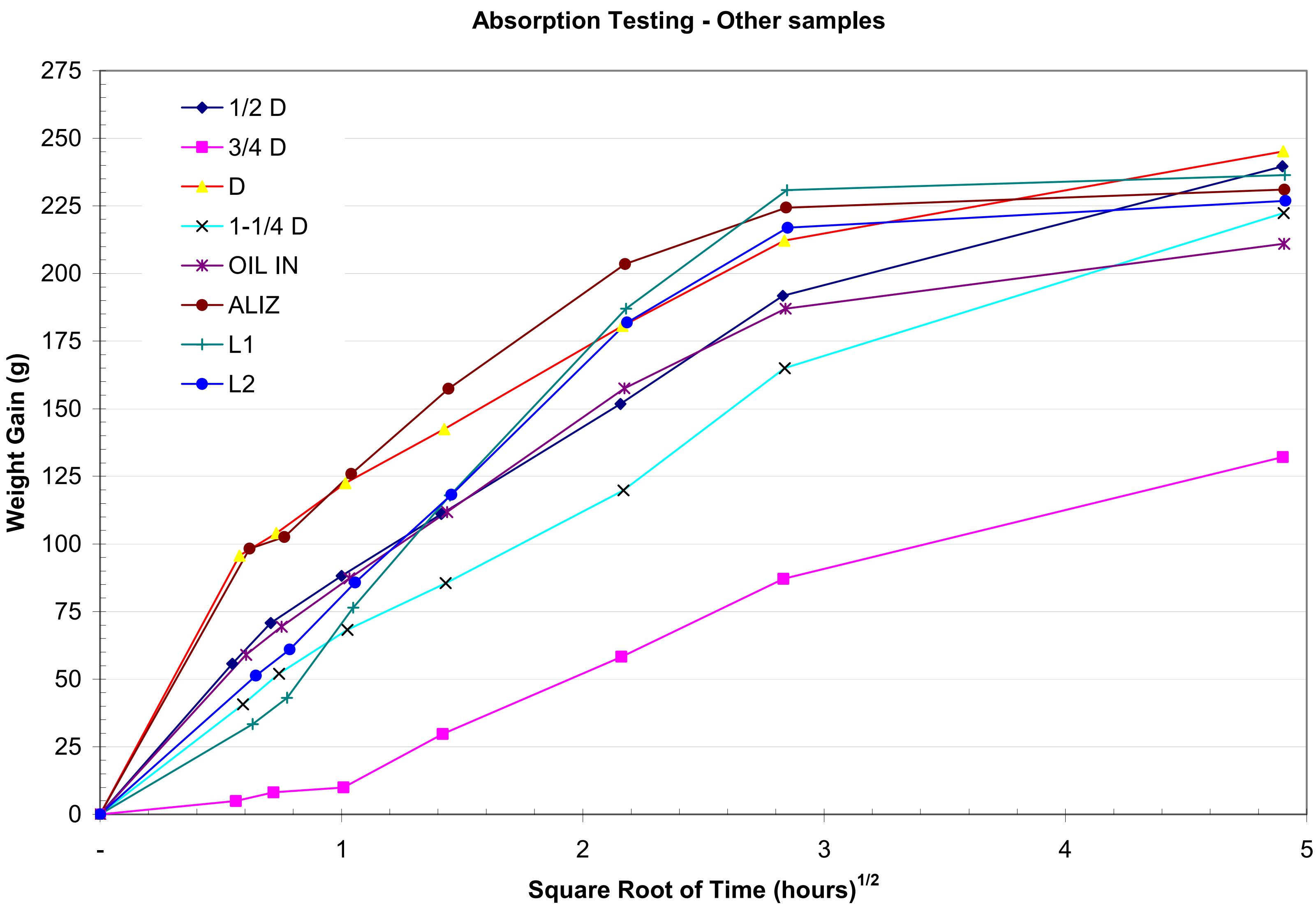
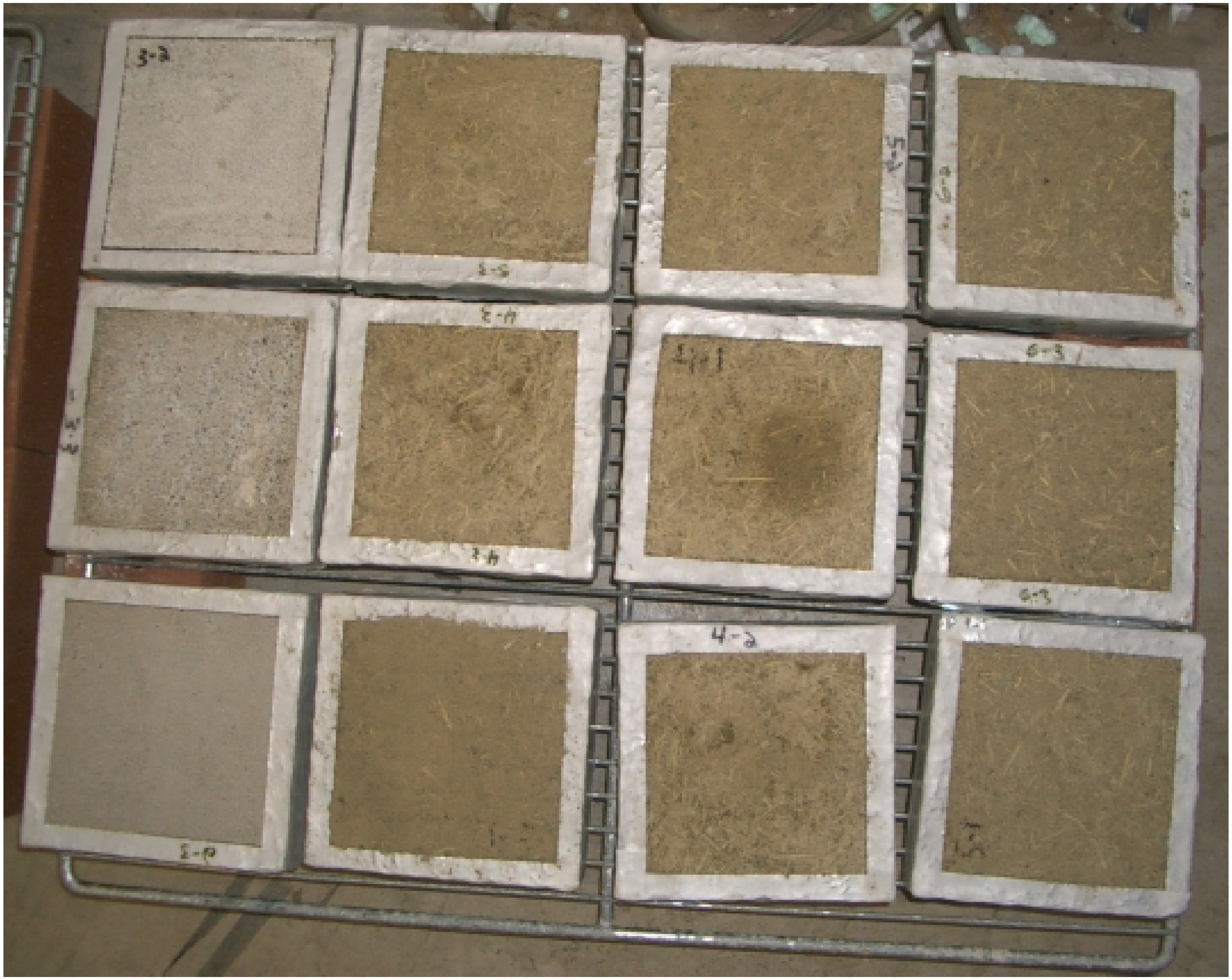
6-1
6-2
6-3
300
250
200
150
100
50
0
-
1
2
3
4
5
Weight Gain (g)
Square Root of Time (hours)^1/2



Absorption Testing - Other samples
1/2 D
3/4 D
D
1-1/4 D
OIL IN
ALIZ
L1
L2
Weight Gain (g)
275
250
225
200
175
150
125
100
75
50
25
0
-
1
2
3
4
5
Square Root of Time (hours)^1/2


3-2
4-2


1-3