STUDY OF THE REPAIR MORTARS
FOR THE
AYYUBID CITY WALL OF CAIRO

Amanda Brooke Thomas

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Advisor Frank G. Matero Associate Professor of Architecture Graduate Program in Historic Preservation University of Pennsylvania	Reader Koenraad Van Balen Associate Professor of Civil Engineering Department of Civil Engineering and Raymond Lemaire International Center for Conservation Katholieke Universiteit Leuven (Belgium)

Graduate Committee Chair
Frank G. Matero
Associate Professor of Architecture
Graduate Program in Historic Preservation
University of Pennsylvania

TO SEBASTIAN

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CHAPTER 1 – INTRODUCTION

1.1 PROJECT BACKGROUND

The conservation and restoration of the Ayyubid city wall of Cairo is one component of a formidable urban planning project supported by collaboration between the Aga Kahn Trust for Culture and the national and local governments of Egypt. Through the Historic Cities Support Program of the Aga Kahn Trust for Culture, a much needed green space – the al-Azhar Park – is being constructed in Cairo which lies adjacent to the city district of al-Darb al-Ahmar. This historic district in the Islamic quarter of Cairo is also part of the project which, through the support program, seeks to revitalize its buildings, including the historic mosques and bazaars; its economy, by way of workshops, retail, and proper infrastructure; and its social fabric, through new community facilities and programming.

Figure 1.1: The eastern section of the Ayyubid wall during restoration (ACL).

The recently excavated Ayyubid city wall, which represents one building campaign of the historic ramparts of Cairo, both defines and separates the park and neighborhood. This portion of the wall was built in the 12th century A.D. during the Ayyubid dynasty and contains gate entrances, towers, and galleries.

It is believed that the wall began to be buried on the external side by debris during the 15th century; this area continued to be a dumping ground until most of the wall was concealed. An additional impediment to the wall occurred on the city side by houses and workshops which were built against, and at times, on top of, the wall since before 1800 A.D.[1]

The conservation of the Ayyubid city wall is imperative as it is an important part of the cultural heritage of Egypt and a listed monument. The project seeks to establish a conservation program that integrates the community to its architectural heritage and the park beyond.

1.2 DETERIORATION OF THE AYYUBID CITY WALL

There are two main phenomena occurring on the Ayyubid wall which contribute to its decay: the presence of soluble salts in the Egyptian limestone and in the surrounding environment and the high clay content inherent in the Egyptian limestone.

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[1] Aga Khan Trust for Culture, "Historic Cities Support Programme: The Azhar Park Project in Cairo and the Conservation and Revitalisation of Darb al-Ahmar." (Switzerland: Imprimeries Reunies Lausanne, 2001): 55.

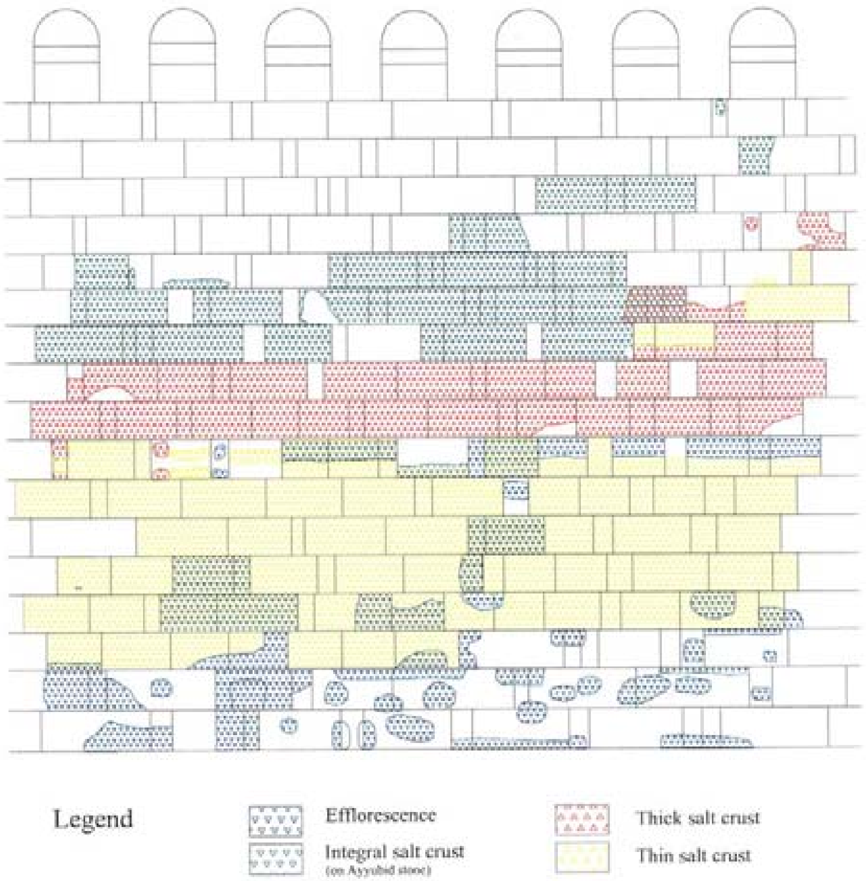

Figure 1.2: Conditions assessment for the eastern section of the Ayyubid wall between towers 4 and 5 (from Bourguignon).

The lower portion of the wall which was buried during the use of the area as a dumping ground initially exhibited efflorescence and thin salt crusts (Fig. 1.2). Since recent excavation, this area has been shedding its salt crusts and revealing stone ashlar in good condition. This is attributed to the sustained dampness of the wall during burial which inhibited salt crystallization. The concern for the future is now that this portion of the wall is exposed to the environment and not sustaining a constant moisture level, deterioration of the stone might accelerate rapidly. Not only will the foundation of the

Figure 1.3: Detail of thin salt crusts on the surface of the Egyptian limestone in the wall (from Bourguignon).

wall be compromised, but the stones that display the original tooling from the 12th century may be lost.

The portion of the wall directly above burial grade exhibits thicker salt crusts up to several centimeters thick on the surface and crystallization at the subsurface. This area experiences frequent wetting and drying cycles through the mechanism of capillary action and evaporation, together which encourage salt crystallization. The upper portion of the wall exhibits minor surface salt crusts and salt growth deep within cracks in the stone probably from diurnal condensation and evaporation cycles. Finally, throughout the facade, there are areas exhibiting loss of the stone.

The deterioration due to salt also affects the deep repair and finish pointing mortar within the masonry system. The primary manifestations, though not indicated in the conditions assessment above, is loss of mortar and the presence of cracks and voids resulting from the stresses applied to the mortar from the cyclical growth of salt crystals.

1.2.1 SALT IN THE MASONRY SYSTEM

The decay mechanisms of salt have been extensively researched, though many uncertainties still exist. It is known that salts accelerate deterioration of masonry but the mechanisms with which it does are still unclear.[2] The mechanisms of crystallization and hydration pressure have been studied and calculations to determine these pressures have been developed, validating this phenomenon as a deterioration mechanism due to salt.[3]

The movement of salts in solution in a masonry system has also been studied and it is known that salts migrate with water. Water as a liquid is introduced into a masonry system via capillarity and infiltration and as condensation and hygroscopicity due to the presence of water vapor. Soluble salts go into solution in the liquid water providing that the water is not already supersaturated with salts. Additionally, salts will move from a higher concentration to a lower concentration of saturated water thus propagating itself throughout the system. When the water is saturated with salts, crystallization will occur, either due to evaporation of the water or because of an excessive concentration of salts in the water. Evaporation occurs at the border between liquid water and water vapor and its rate dictated by heat, relative humidity, and velocity of the wind in conjunction with the capillary potential and hydraulic resistance of the pore system in the masonry. If

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[2] Charola, A. Elena, "Salts in the Deterioration of Porous Materials: An Overview." *Journal of the American Institute for Conservation*, 39. (2000): 332.

[3] Ibid. (hydration pressure calculation translated from Mortenson, H. Die "Salzprengung" und ihre Bedeutung fur die Regionalklimatische Gliederung der Wutsen." *Dr. A. Petermanns Mitteilungen*. Gotha: Justus Perthes. 79 (1965):130-35. Crystallization pressure from Correns, C.W. "Growth and Dissolution of Crystals under Linear Pressure." *Discusssions of the Faraday Society,* 5 (1949):267-271.)

evaporation occurs at the surface of the wall, efflorescence will result. If evaporation occurs internally in the wall, sub-florescence will result which induces spalling and cracking.

The desert climate of Cairo also exacerbates salt deterioration. Cairo experiences high temperatures during the day with a sharp decrease in temperatures at night – typical of a desert climate. Though the environment is arid, the salts go into solution due to the condensation that results from the drop in temperature and the increase in relative humidity. They are then able to migrate within the porous system through capillary action. The sharp increase in temperature during the day subsequently may evaporate the moisture, allowing the salts to crystallize as described above. This repetitive daily cycle aids in the accelerated decay of the stone and mortar.

The salts in the Ayyubid wall originate from several sources. The groundwater which is introduced into the wall via capillary rise is rich in chlorides. In 1915, an analysis of the soil around Cairo found up to 20.25% of salts, with an average of 5.46%.[4] Analysis was also conducted on the Egyptian limestone which revealed the stone as naturally containing halite (sodium chloride). This is due to the formation process of the Egyptian limestone which was formed by the precipitation of calcium carbonate from seawater and the deposition of sand, with gypsum and halite also crystallizing during the precipitation process. In addition, the debris from the dumping ground adjacent to one side of the wall for several centuries is also a source of salts, as is the use of Portland cement as a repair mortar in the 1950s. The following table outlines the salts found in the

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[4] Elsa S. O. Bourguignon, *Study of Deterioration Mechanisms and Protective Treatments for the Egyptian Limestone of the Ayyubid City Wall of Cairo.* (Master's Thesis, University of Pennsylvania, 2000) (study by Lucas, 1915): 20.

original and replacement limestone samples, whether naturally occurring in the stone or from outside sources.

Table 1.1 Micro-Chemical Spot Test Results for 11 Samples[5]

Sample Number	Sulfates	Chlorides	Nitrites	Nitrates	Carbonates	Phosphates
2	ø	+++	+	ø	ø	+
3	ø	+++	+	+	+++	+
5	ø	+++	+++	ø	ø	ø
6	+	+++	+	ø	+	+
9	+	+++	ø	ø	+	+
12	+++	+++	+	ø	ø	+
14	+++	+++	+++	ø	+	ø
15	ø	+++	+	ø	+++	ø
16	ø	+++	+	ø	+	ø
17	+	+++	+++	+++	ø	ø
18	+	+++	+	ø	+++	ø

+++ Presence; + Traces; ø Absence

It should be noted that one study has suggested the evolution of nitrites to nitrates due to nitrate-reducing microorganisms.[6] This would give an indication of why there was a low value of nitrates despite the usually high amounts associated with debris.

1.3 INTRODUCTION TO THE MORTARS

The conservation effort at the Ayyubid wall must address the issues of deterioration exhibited in the Egyptian limestone and the accompanying mortar used to bed the ashlar masonry.

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[5] Ibid. (Dewey, unpublished, 2000): 100.

[6] E. Borelli, "Unexpected reduction of nitrates to nitrites during the analyses of soluble salts," *Proceedings of the Third Symposium on the Conservation of Monuments in the Mediterranean Basin.* (Venice: Soprintendenza ai Beni Artistici e Storici di Venezia, 1994).

Extensive research and testing at the University of Pennsylvania and Cairo University have been conducted on the Egyptian limestone in an attempt to ameliorate and better understand the decay mechanisms at the city wall.[7] In addition to the stone, attention must be paid to the mortar which constitutes a substantial percentage of the wall's material as both deep repair and pointing mortars and occasionally interior plasters.

The Ayyubid portion of the wall contains six known mortar campaigns: two original historic mortars from the 12th century A.D. consisting of the pointing and rubble wall core mortars, an historic repair mortar, two Portland cement repair mortars from the 1950s, and another modern repair gypsum pointing mortar. Analysis of these historic mortars was conducted by the University of Pennsylvania to achieve a better understanding of their components, appearance, and porosity.[8] The Portland cement repair mortars are now being removed as part of the conservation program. The lacunae resulting from the deterioration of the mortars and from the Portland cement mortar removal will be compensated through the conservation program as well.

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[7] Elsa S. O. Bourguignon, *Study of Deterioration Mechanisms and Protective Treatments for the Egyptian Limestone of the Ayyubid City Wall of Cairo.* (Master's Thesis, University of Pennsylvania, 2000). Melissa McCormack, *Conservation Studies for the Ayyubid City Wall, Cairo.* (Master's Thesis, University of Pennsylvania, 2001). Judi Ji won Moon, *A Study to Improve Desalination Methodologies for the Ayyubid City Wall, Cairo.* (Master's Thesis, University of Pennsylvania, 2002). Jennifer Elizabeth Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo.* (Master's Thesis, University of Pennsylvania, 2003). Rock Engineering Laboratory, Unpublished testing results. Cairo: Mining Department, Faculty of Engineering, Cairo University (2000 and 1999).

[8] Rynta Fourie, *Mortar Characterization and Analysis: Ayyubid City Wall, Egypt.* (Unpublished Report, University of Pennsylvania, 2000).

To this end, research has been conducted at the University of Pennsylvania on the repair mortars most suitable for the city wall. Testing was recently completed in 2003 on the fresh, non-cured hardened mortars.[9]

Mortars play a crucial role in the soundness and stability of a masonry system. In this role, mortars must exhibit properties which are both compatible with the surrounding masonry and optimally perform to create a weatherproof surface. Furthermore, there are additional demands placed on mortars to be used in conservation projects, particularly due to the deteriorated state of the historic stone. New formulations are therefore required which are also sympathetic to the properties of the centuries-old stone. In order to develop the most appropriate formulation for a repair mortar, it is necessary to further investigate, beyond the fresh and non-cured hardened state, the behavior and properties of the mortars in a cured state to ensure the greatest compatibility with the historic masonry system.

A compatible mortar can be difficult to define as each situation in which it may be implemented is unique. Universally, however, it is desirable that the repair mortars are sacrificial in relation to the surrounding stone. The low cost of the fabrication and implementation of mortar versus ashlar stone makes mortar replacement much more feasible than stone, particularly on such a large scale as that of the Ayyubid wall.

A compatible mortar for the conservation project at the Ayyubid wall has several other requirements. The mortar in its fresh state should exhibit good workability for the mason, but no bleeding during application. The mortar should set rapidly and sufficiently

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[9] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo.*

to ensure proper strength in a dry environment. The mortar should also exhibit minimal shrinkage upon setting so as not to introduce voids into the masonry system.

A compatible mortar in the cured state must exhibit permeability rates, porosity percentages and drying rates higher than those of the masonry. The mortars must demonstrate good resistance to salt crystallization yet be lower in compressive and flexural strength than the masonry. These properties all lend to the sacrificial nature of the mortar in comparison to the stone. The aforementioned properties of a cured mortar were tested in this research; however, these are not the only requirements for a compatible mortar for the city wall. A mortar's modulus of elasticity, the release of soluble salts, bond strength with the masonry unit, and its thermal expansion coefficient can also be tested for further understanding of a mortar's behavior.

1.4 RESEARCH GOALS

The research for this thesis aims to provide a greater understanding of the properties of lime putty, hydraulic lime, and Portland cement repair mortars in a 90-day cured state.

The tests chosen to be conducted for this research examine various physico-mechanical properties of the cured mortars, many of which have been suggested in the literature on lime and Portland cement formulations. The research included here will continue the analysis of performance for the mortars that have cured for 90 days. The tests for this research were chosen for ease, low cost and reproducibility of test implementation, accessibility to materials and equipment, and capability of being conducted within the time constraints. The tests employed were: water vapor transmission, water absorption by total immersion, drying rate, salt crystallization resistance, compressive strength and flexural strength.

The results of these tests will be looked at in conjunction with the findings of the repair mortars in their fresh state. Both of these results will then be compared to the findings of studies conducted on the Egyptian limestone. The findings for the Egyptian limestone provide an upper limit for the interpretation of the results of the mortar tests. In total, these properties will help evaluate the performance characteristics of the mortars in the context of the conditions at the Ayyubid wall.

The research herein should prove useful to this and other similar projects by adding to the knowledge of these mortar formulations' behavior.

1.5 LITERATURE REVIEW

A literature review presenting some of the works used in this research is presented in Appendix A, though a brief overview will be provided here. The trend seen in recent literature started from the seminal work in Italy that began to investigate the possibility of repair mortars formulated similarly to those of traditional historic mortars being characterized – specifically those without ordinary Portland cement.[10] The search for compatible mortars influenced the direction of much of the research to follow and the research of mortars still continues through the use of standardized tests. The research overall becomes more refined from the early 1980s as more demands are made by the researchers in the field for proper standards which would allow for ease and dissemination of knowledge gained across countries. In the search for properties to

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[10] S. Peroni et al., "Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes" *Mortars, Cements and Grouts used in the Conservation of Historic Buildings.* (Rome: ICCROM, 1982).

enhance lime-based mortars, such as those of mechanical strength and salt crystallization durability, research continues to investigate the properties of hydraulic limes as a binder and the hydraulic reaction. The tests conducted on the lime-based formulations begin to reconsider materials used in historic mortars for modern application, such as pozzolanas and brick dust and the addition of modern additives, such as acrylic emulsions, superplasticizers, and bulking agents. Simultaneously, research is being conducted on cement to investigate its behavior with lime and modern materials in the hopes of decreasing its harm when used in historic buildings, while advantageously employing its benefits of strength and durability against decay.

While research has allowed for repair mortars of much higher compatibility to be implemented in a historic masonry system, more research from the laboratory should be applied in the field and thereafter published. There will always, however, be the reality that no single mortar formulation will be applicable to all historic masonry situations. Each building and structure presents its own challenges in finding a compatible mortar, such as masonry properties and environment as seen in the Ayyubid wall.

CHAPTER 2 – METHODOLOGY

2.1 PAST RESEARCH

2.1.1 ANALYSIS OF HISTORIC MORTARS

Before formulating a repair mortar, the historic mortars of the masonry system must first be analyzed. This research was conducted in an unpublished report in 2000 at the University of Pennsylvania.[11] Through the analytical methods of polarized light microscopy, gravimetric analysis, x-ray diffraction, scanning electron microscopy, and energy dispersive spectroscopy, the historic mortars' components and appearance were revealed.

The original rubble core mortar of the Ayyubid wall was found to contain a lime and gypsum binder in a ratio of 2:1, with large calcareous aggregate. The original ashlar bedding mortar also contained a lime and gypsum binder, but in a ratio of 1:2, with small calcareous aggregate. There were charcoal and crushed brick found in both mortars, however, it was determined that they were present due to accidental inclusion rather than intentionally mixed into the original mortar formulation because of the large size of the particles and the lack of a pozzolanic reaction rim around the brick inclusions. These inclusions, though, contributed to a mortar of high porosity.

The characterization and analysis of the historic mortars suggested that gypsum not be employed in the repair formulations due to potential sulphate salt attack to the

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[11] R. Fourie. *Mortar Characterization and Analysis: Ayyubid City Wall, Egypt.*

surrounding ashlar. The report also recommended a hydraulic component, such as brick dust, be added to the repair formulation.[12]

As a result of the analysis, two mortar formulations were developed thereafter – one for the deep repairs and one for the finish pointing. The deep repair mortar is used for the replacement of mortar loss in the rubble core of the wall and the pointing mortar is used for mortar loss between the limestone ashlar and at the surface joints. The lime putty formulations developed for the deep repairs and finish pointing mortars are presently in use for the repair of the Ayyubid wall; however, further testing was required of the mortars in the non-cured and cured states. The physico-mechanical testing of the lime putty repair mortars in these two states allowed for additional formulations to be tested for comparison of their behavior – the variability in these formulations only being the binder. Below are tables indicating the materials employed in the mortar formulations with more detailed descriptions in Section 2.2.1.

Table 2.1: Deep Repair Mortar Formulations

Label	Formulation	
BP	1.0 part 2.5 parts 0.5 part	high-calcium lime putty - aged 11 months George F. Kempf yellow concrete sand (≤ 4.70 mm grain size) brick dust (≤ 600 μm grain size)
BH	1.0 part 2.5 parts 0.5 part	Riverton natural hydrated hydraulic lime George F. Kempf yellow concrete sand (≤ 4.70 mm grain size) brick dust (≤ 600 μm grain size)
BC	1.0 part 2.5 parts 0.5 part	Cava Portland cement - Type I George F. Kempf yellow concrete sand (≤ 4.70 mm grain size) brick dust (≤ 600 μm grain size)

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[12] Ibid.: 15.

Table 2.2: Finish Pointing Mortars

Label	Formulation	
FP	1.0 part 3.0 parts	high-calcium lime putty – aged 11 months dry mixture (see below)
FH	1.0 part 3.0 parts	Riverton natural hydrated hydraulic lime dry mixture (see below)
FC	1.0 part 3.0 parts	Cava Portland cement - Type I dry mixture (see below)

Table 2.3: Dry Mixture Components

30 parts	George F. Kempf yellow bar sand (≤ 1180 μm grain size)
20 parts	George Schofield yellow mason sand (≤ 1180 μm grain size)
2-3 parts	brick dust (≤ 150 μm grain size)
1.5-2 parts	wood ash (≤ 150 μm grain size)

2.1.2 ANALYSIS OF NON-CURED MORTARS

The following is a summary of the research conducted in 2002-2003 by a different author on the non-cured repair mortars for the Ayyubid wall of Cairo including the three formulations mentioned above.[13] The results of the individual tests are provided; however, they are more conclusive in conjunction with the results of the mechanical testing conducted on the mortars after a 90-day cure time. Those results and their consequences on the fresh mortar results will be presented in the final chapter.

The consistency of fresh mortars was measured according to the standard EN 1015-3: 1995 E Determination of Consistence by Fresh Mortar (by Flow Table). According to the standard, this measurement provides a uniformity of mixing mortar batches for further testing. The optimal amounts indicated in the results were employed in

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[13] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo,* 93-103.

the tests for this current research in mixing the mortar batches to ensure continuity in the formulation proportions. These figures are provided in the following table.

Table 2.4: Optimal Results of Consistency Test for all Mortar Formulations[14]

Mortar Formulation (parts by volume)	Parts by volume of water*	Optimal percentage results of flow measurements
Deep Repair Mortar: 1 Lime Putty : 0.5 Brick Dust : 2.5 Sand	0.250	46.12%
Deep Repair Mortar: 1 Natural Hydraulic Lime : 0.5 Brick Dust : 2.5 Sand	0.700	38.06%
Deep Repair Mortar: 1 Portland Cement : 0.5 Brick Dust : 2.5 Sand	0.75	26.76%
Finish Pointing Mortar: 1 Lime Putty : 3 Dry Mixture	0.425	47.80%
Finish Pointing Mortar: 1 Natural Hydraulic Lime : 3 Dry Mixture	0.775	63.39%
Finish Pointing Mortar: 1 Portland Cement : 3 Dry Mixture	0.875	41.37%

* Note that formulations containing lime putty consisted of lime water and the hydraulic lime and Portland cement formulations consisted of deionized water.

The measurement of water retention was conducted according to the standard EN 1015-8: 1993 E Determination of Water Retentivity of Fresh Mortar. The water retention measurement indicates the workability of the mortar by its retention of moisture during mixing and application. Good workability is critical in a mortar formulation for proper application. Workability is related to three desirable characteristics: resistance to slumping during handling and shortly after application; ease and consistency of spreading and applying; and retention of water to sufficiently stave off suction while the mason is applying the mortar over a large area. Workability is difficult to measure in one test;

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[14] Ibid.: 49-52, 78-80.

however, only one standardized test exists for its measurement. In the formulations for all the finish pointing mortars wood ash is a component of the dry mix, which contributes to the retention of water. Brick dust also contributes to water retention through its increased porosity relative to the aggregate of sand, and, finally, the specific surface of the binder can contribute to water retention – lime putty having a higher specific surface than cement. It was determined that of the various binders, the lime putty and Portland cement deep repair formulations retained the most water and that the natural hydraulic lime and Portland cement finish pointing mortars retained the most water.[15]

The fresh mortar tendency of bleeding was also tested according to the standard RILEM MR-6: The Tendency of Water to Separate from Mortars (Bleeding) – Method A. Bleeding tests of mortars should ideally result in no-to-low rates for masonry systems. The limestone in the Ayyubid city wall, as mentioned, contains an excessive amount of salts, which a high bleeding rate would exacerbate by encouraging the salts to go into solution and cause an increased rate of deterioration. The lime putty and natural hydraulic lime deep repair mortars exhibited moderate rates of bleeding whereas the Portland cement samples exhibited low rates of bleeding. The lime putty finish pointing mortar demonstrated moderate rates of bleeding and the natural hydraulic lime and Portland cement finish pointing mortars both exhibited low rates of bleeding.[16]

The rates of set time were tested according to a modified version of ASTM C191-92: Standard test Method for Time of Setting of Hydraulic Cement by Vicat Needle. The modifications included extending the testing times for lime and storing the mortars in a 50% relative humidity condition as opposed to the recommended 90%. The rate of set for

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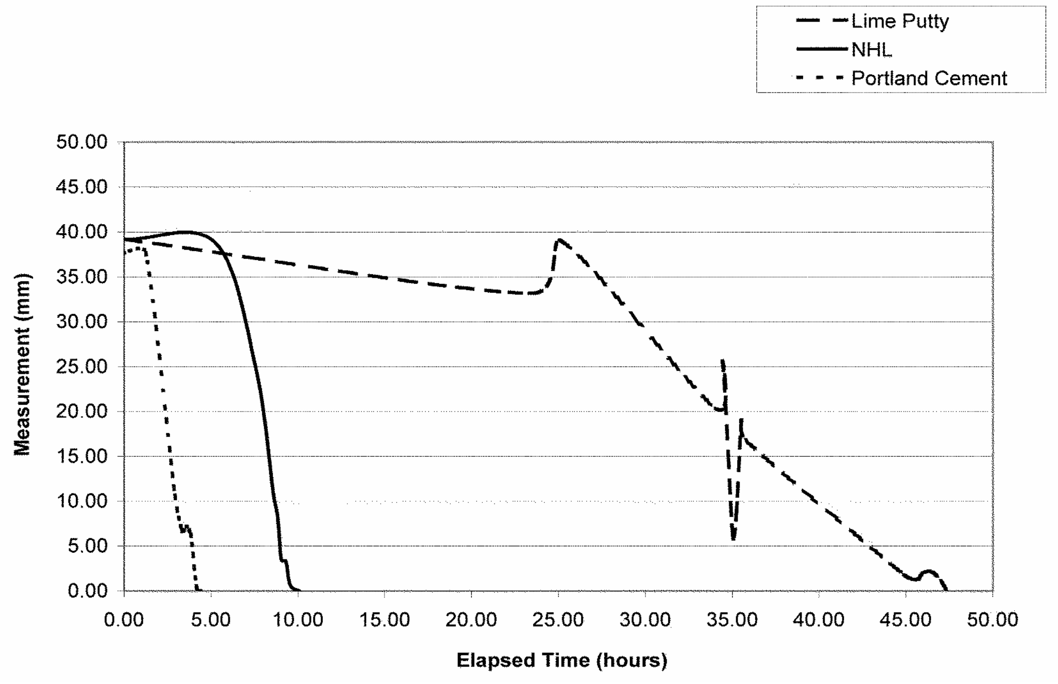
[15] Ibid.: 93 and 99.

[16] Ibid.: 94 and 99.

mortars is measured to ensure the set time is not too rapid to cause shrinkage. Shrinkage introduces voids and water into a system which allows for the ingress of water in what should be a continuous masonry mass. The lime putty deep repair mortars exhibited a slow set time which is desirable; however, in its application in the wall, it must have enough time to carbonate before the finish pointing mortar is applied. The natural hydraulic lime mortar had a more moderate set rate but also requires proper carbonation for its efficacy and the Portland cement mortars exhibited a proper rate of set. In the case of the finish pointing mortars, the lime-based mortars exhibited an acceptable performance while the Portland cement mortar set too rapidly.

Graph 2.1: Average Set Time Results of Deep Repair Mortars[17]



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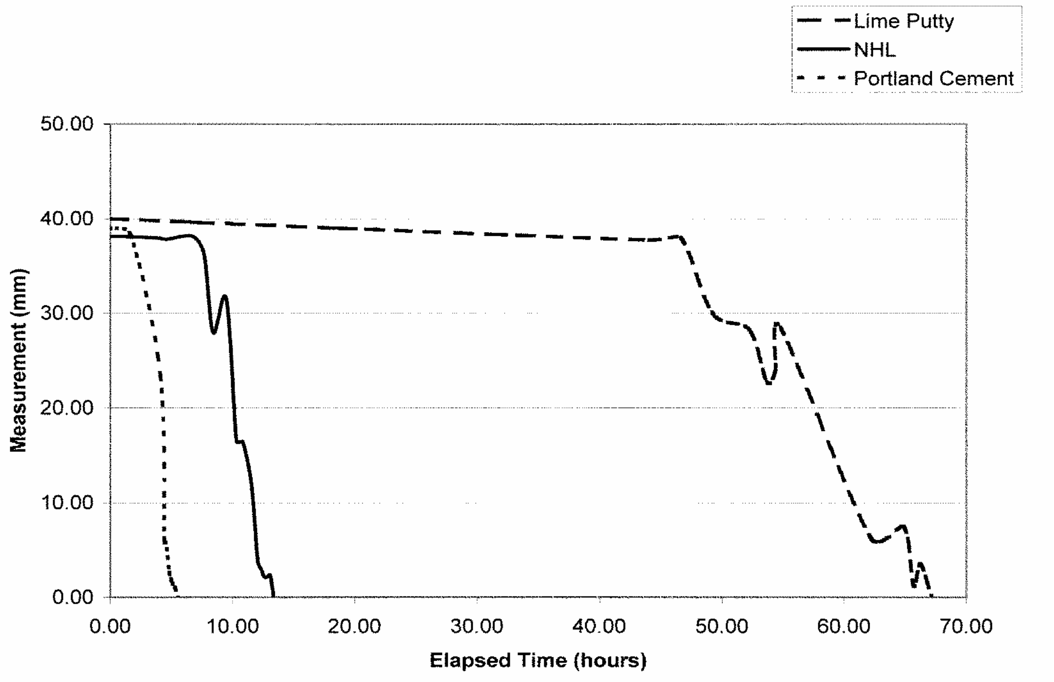
[17] Ibid.: 96.

Graph 2.2: Average Set Time Results for Finish Pointing Mortars[18]



All of the above results for the mortars in a fresh and non-cured hardened state, are discussed further in Chapter 5 as they are inconclusive without their relation to the results of the mortars in a cured state.

2.2 CURRENT RESEARCH

In order to ascertain the most compatible mortar for the Ayyubid wall, testing of mortars in a cured state is also necessary. This research tested the physico-mechanical properties of the mortars after a 90-day curing time. The results in tests of strength and porosity provide further meaning to the results of the tests conducted on the uncured mortar in its plastic state.

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[18] Ibid.: 102.

To this end, the following tests culled from the literature and based on time and equipment available, were conducted on cured mortars: water vapor transmission, water absorption by total immersion, drying rate, resistance to salt crystallization, compressive strength and flexural strength (three-point bending). The significance of these properties on the quality of the mortar and the masonry system as a whole will be elaborated on in the final chapter.

2.2.1 MATERIALS

2.2.1.1 BINDERS

The binder in a mortar formulation is the constituent which holds together all the other components. The binder can aid or inhibit several properties of a mortar such as plasticity and workability of the fresh mortar and porosity and strength of the cured mortar. Thus, the binder significantly affects the overall performance of the mortar in a masonry system. It is the binder in this research that is the variable between formulations: lime putty, hydrated hydraulic lime and Portland cement.

The lime putty used for testing at the University of Pennsylvania was received from Cairo. It is a local high-calcium lime which was sieved to remove impurities from the burning process and subsequently slaked on site in Cairo. The lime putty was aged for a minimum of three months prior to its arrival in the United States, with an additional eight months aging before the mortars for this research were prepared. The lime putty, according to x-ray diffraction analysis, is highly pure with a free lime content of 97% and no insoluble residue.[19] For incorporation into the mortar formulations in this research, the

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[19] Ibid.: 43.

lime putty was again sieved to increase workability and plasticity for mixing as the putty is a stiff block under water at the bottom of the container upon opening.

The natural hydrated hydraulic lime was manufactured by Riverton Corporation and purchased from Cava Building Supply in Philadelphia in October 2002 by the Architectural Conservation Laboratory (ACL), at the University of Pennsylvania. The Riverton hydraulic lime comes from limestone in Front Royal, Virginia and complies with ASTM C141 according to the Riverton Corporation. ASTM C141 requires hydrated hydraulic limes conform to the chemical composition outlined in Table 2.5 in addition to a number of other properties, such as fineness, set time, and compressive strength. ASTM C141 defines hydraulic hydrated lime:

> the hydrated dry cementitious product obtained by calcining a limestone containing silica or alumina, or a synthetic mixture of similar composition, to a temperature short of incipient fusion so as to form sufficient free lime (CaO) to permit hydration and at the same time leaving unhydrated sufficient calcium silicates to give the dry powder, meeting the requirements herein prescribed, its hydraulic properties.[20]

Table 2.5: Required Chemical Composition of Hydrated Hydraulic Lime according to ASTM Standard C141[21]

Chemical Composition	Minimum (%)	Maximum (%)
Calcium and Magnesium oxides (CaO and MgO calculated to the nonvolatile basis)	65	75
Silica (SiO_2 calculated to the nonvolatile basis)	16	26
Iron and aluminum oxides (Fe_2O_3 and Al_2O_3 calculated to the nonvolatile basis)	---	12
Carbon dioxide (CO_2 on an as received basis)	---	8

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[20] American Society for Testing of Materials, "C141-97 Standard Specifications for Hydraulic Hydrated Lime for Structural Purposes," *Annual Book of ASTM Standards*, Vol. 04.02, Cement, Lime, Gypsum. (West Conshohocken, PA: ASTM, 2000), 1.

[21] Ibid.: 1.

The lime is light grey to buff in color with an air-entraining additive in the range of 8% to 10% according to the product literature. The Riverton Corporation provides a chemical analysis as well, seen in Table 2.6.

Table 2.6: Riverton Typical Chemical Analysis[22]

Chemical Compound	Weight by ignited basis %
SiO_2	16.09
Al_2O_3	4.80
Fe_2O_3	1.15
CaO	69.89
MgO	4.31
SO_3	1.60
Na_2O	0.25
K_2O	1.12

The clay constituents of the Riverton lime being approximately 21% in addition to its compressive strength of 7.78 MPa at 28-days cure, suggest the lime is eminently hydraulic.[23]

X-ray diffraction analysis was also conducted which identified the following phases in the Riverton hydraulic lime: calcium carbonate [$CaCO_3$], calcium hydroxide [$Ca(OH)_2$], and calcium silicate [$Ca_2(SiO_4)$], produced by burning clay-rich limestone.[24]

The Type I Portland cement used is a fine gray powder produced by Lehigh Company and was purchased in November 2003 at Cava Building Supply in Philadelphia. Type I specifications correspond to the requirements of ASTM C150:

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[22] Riverton Corporation, "Hydraulic Lime," Riverton Product Literature. (Front Royal, VA: Riverton Corporation, undated).

[23] Peter Ellison. *Hydraulic Lime Mortars.* (Master's Thesis, University of Pennsylvania, 1998): 39. John Ashurst. "The Technology and Use of Lime Mortars." *The Building Conservation Directory.* (Wiltshire, England: Cathedral Communications, 1997): 3.

[24] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo*: 43.

Standard Specification for Portland Cement. Type I Portland cement is "for use when the special properties specified for any other type are not required."[25] The special properties refer to either air-entraining or sulfate resistant needs. The ASTM standard defines Portland cement as:

> a hydraulic cement produced by pulverizing clinker consisting essentially of hydraulic calcium silicates, usually containing one or more of the forms of calcium sulfate as an interground addition.[26]

According to x-ray diffraction analysis, the Portland cement consists of calcium carbonate [$CaCO_3$], sodium calcium silicate[$Na_4Ca_8Si_5O_{20}$)], and calcium silicate [$Ca_2(SiO_4)$].[27]

2.2.1.2 AGGREGATES

Aggregates also greatly influence the properties of a mortar. Aggregates used in mortars act as a bulking medium and assist in determining porosity, but they also impart benefits to control shrinkage of the mortar and provide strength. The aggregate in modern mortar mixes is primarily silica sand, though historically other materials were used such as shells, chalk, and slag.[28]

The local aggregates used in the repair formulations in Cairo were unable to be employed in the testing program at the ACL; however particle size distribution and

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[25] American Society for Testing of Materials, "C150-00 Standard Specifications for Portland Cement," *Annual Book of ASTM Standards*, Vol. 04.02, Cement, Lime, Gypsum. (West Conshohocken, PA: ASTM, 2000), 1.

[26] Ibid.: 1.

[27] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo,* 143-144.

[28] John Ashurst, *Mortars, Plasters and Renders in Conservation: A Basic Guide.* (London: Ecclesiastical Architect's and Surveyor's Association, 1983): 35.

mineral content were examined to obtain aggregates of similar characteristics in the United States and the results are included in Appendix B.[29]

The substitute aggregate for the deep repair mortar formulation was a yellow concrete sand from the George F. Kempf Building Materials Supply Company in Philadelphia. The color of the sand as compared with the Egyptian sand was not important for the appearance of the deep repair mortar which is not visible on the exterior surface of the wall. The yellow concrete sand contains approximately 75% of its mass between 1180 and 300 µm in size and has less than one percent fine particles below 75 µm.[30] For use in this research the yellow concrete sand is sieved through a #4 ASTM standard screen (screen size 4700µm).

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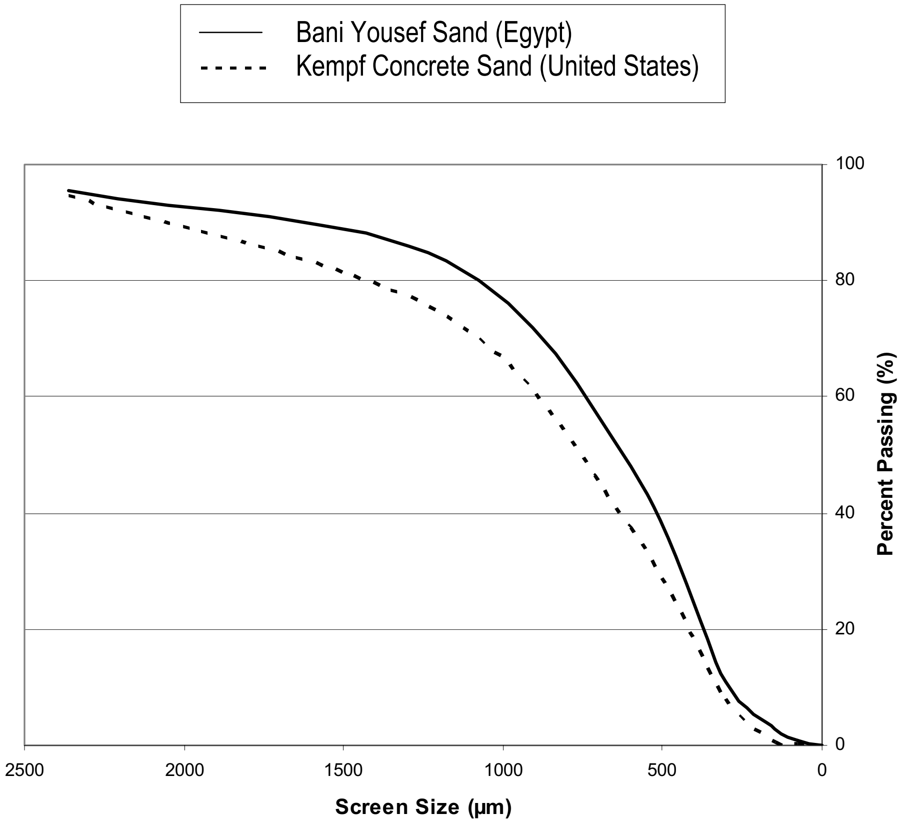
[29] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo,* 132-139.

[30] Ibid.: 41.

Graph 2.3: Particle Size Distribution Comparison of Deep Repair Mortar Sands[31]



The substitute aggregate for one of the sands contained in the dry mixture for the finish pointing mortars was a yellow bar sand also purchased from the George F. Kempf Building Materials Supply Company in Philadelphia. The color of the sand, in this case, was requisite because of the visibility on the exterior of the wall, so it was essential that it be comparable to that of the Bani Yousef sand from Giza, Egypt. The color of the bar sand ranged from a light yellowish brown to a dark yellowish brown corresponding, respectively, to Munsell 10YR 6/4 to 10YR 6/6. This sand contains approximately 83% of its mass between 600 and 300 μm in size and has less than one percent fine particles

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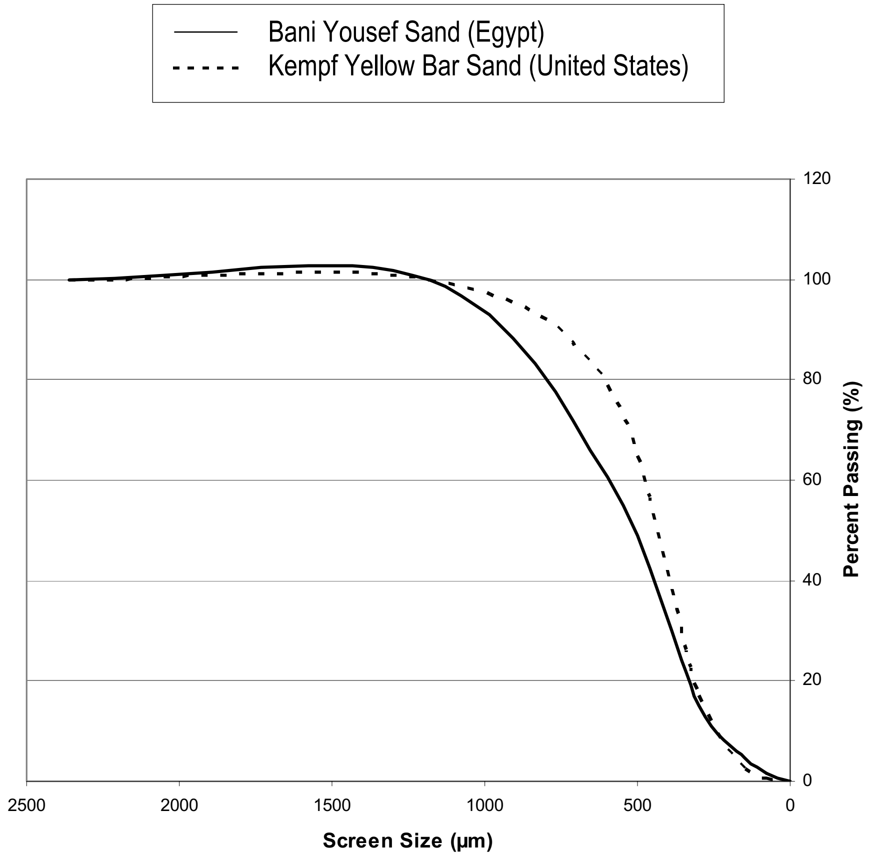
[31] Ibid.: 42.

below 75 µm.[32] For use in this research the yellow bar sand is sieved through a #16 ASTM standard sieve (screen size 1180µm).

Graph 2.4: Particle Size Distribution Comparison of Pointing Mortar Sands[33]



The second sand contained in the dry mixture for the finish pointing mortars was a yellow mason sand purchased from the George Schofield Company in New Jersey. The color of the sand, again, was essential and thus was chosen for its comparability to that of the El Katameia masonry sand from Egypt. The color was pale brown corresponding to Munsell 10YR 8/2. This sand grain size is over 75% between 600 and 300 µm and has

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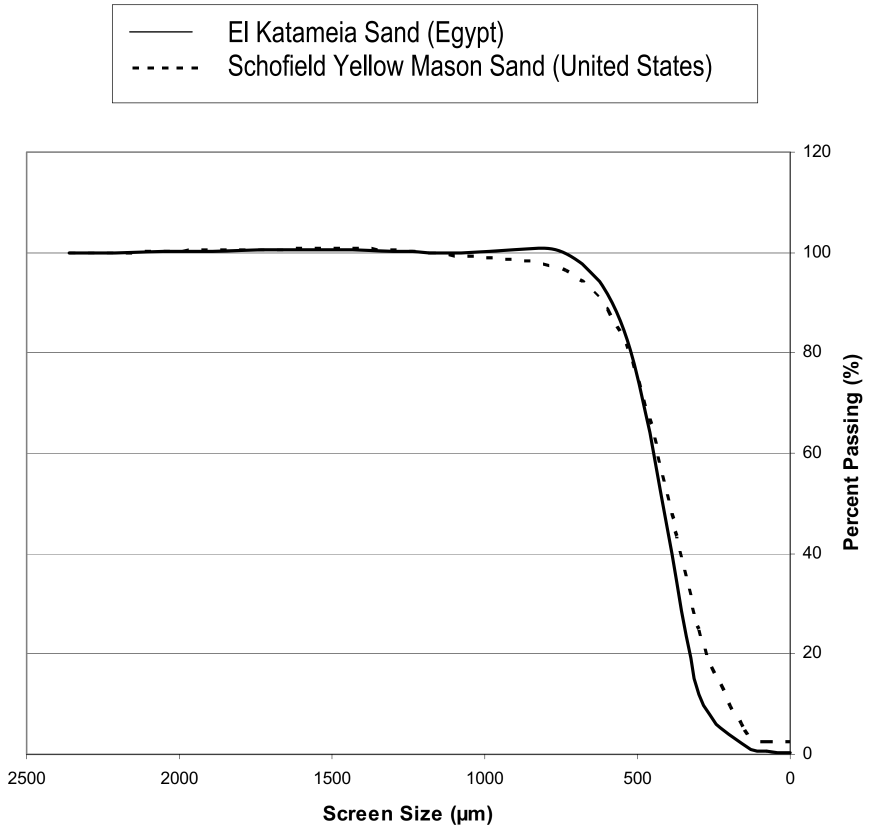
[32] Ibid.: 72.
[33] Ibid.: 72.

less than one percent fine particles below 75 µm.[34] For use in this research the yellow bar sand is sieved through a #16 ASTM standard sieve (screen size 1180µm).

Graph 2.3: Particle Size Distribution Comparison of El Katameia and Schofield Yellow Mason Sands[35]



2.2.1.3 ADDITIVES

The addition of brick dust significantly alters the chemistry and performance of lime mortars. Brick dust has been a component of mortars since Roman times because of the pozzolanic quality it imparts to the mortar. Studies have been conducted to determine the effects of brick dust on mortar performance and it has been found that the quality of

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[34] Ibid.: 73.

[35] Ibid.: 73.

hydraulicity is not the only benefit imparted. The smaller particle sizes of brick dust will also lend increased strength to a lime mortar, while larger particles create an increased porosity in the mortar rather than hydraulicity.[36] Brick dust also takes on a similar role as an aggregate by contributing to bulking and shrinkage control.

The brick dust in use at the Ayyubid wall was sent from Egypt to the ACL for incorporation into the mortar formulations; x-ray diffraction results are provided in Appendix B. The low-fired bricks originate from demolition projects in Cairo and are ground to a fine powder producing particle sizes of 600 µm or less. The red color of the bricks greatly affects the appearance of the mortar, so is not always an ideal pozzolanic additive for visible pointing mortars. However, the red color corresponding to Munsell 10R 4/6 to 10R 4/8 is adequate for matching the colors of the historic mortars.[37]

Wood ash was also added to the dry mixture, which contributes to the water retention of the mortars which is an important aspect to the mortar quality in a hot and arid climate such as Cairo. The wood ash is produced by farmers at Abu El Nomros in Egypt and is incompletely burned to form a fine black powder. It is dark gray in color, ranging from Munsell 5Y 5/1 to 5Y 4/1, and is sieved through a #100 ASTM standard screen (screen size 150 µm).[38] Wood ash also affects the color of the mortar and assists in matching the historic mortar. X-ray diffraction results are provided in Appendix B.

Water is the last important component in the mortar mix for this research. Water hydrates the binder, particularly for the dry lime powder and Portland cement, and it provides the workability necessary for laying and pointing the mortar in the wall. The

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[36] Teutonico et al, "The Smeaton Project: Factors Affecting the Properties of Lime-Based Mortars." *APT Bulletin*. (vol. 25, no. 3-4 1994): 40.
[37] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo,* 42.
[38] Ibid.: 75.

water used in the mortar preparation is in all circumstances deionized water except in the formulations of lime putty as the binder. In the latter formulations, the water covering the lime putty, or “lime water,” from Cairo is used instead.

2.2.2 PREPARATION

2.2.2.1 MIXING

The mortar formulations were mixed according to the standard ASTM C305-99 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. This ensures a uniform procedure for the preparation of the mortar mixes because the amount of time and rate of mixing, if varied, can create different consistencies from formulation to formulation. The room temperature at the time of mixing ranged between 71.9°F to 72.2°F (22.2°C to 22.3°C) with a relative humidity at a constant 33.5%.

A Hobart C-100 mixer was used which provided two variations of speed; Speed 1 at approximately 60 rpm and Speed 2 at approximately 125 rpm. As stated in the standard the bowl and paddle were dry prior to mixing every batch and first filled with water and then the binder added to it. The mixer was started at Speed 1 for 30 seconds and after 30 seconds the sand was slowly poured into the bowl over a period of 30 seconds with the mixer still at Speed 1. Once the sand was introduced, the mixer was stopped and increased to Speed 2 for 30 seconds. The mixer was stopped again and the mortar was left to rest for one and a half minutes during which the first 15 seconds was used to scrape down the sides of the bowl and the paddle with a palette knife and for the remaining time the mortar was covered with plastic wrap. The mixer was then turned on at Speed 2 for a final one minute.

In the case of the deep repair mortars where the brick dust was not mixed into the aggregate, an additional 15 seconds of mixing was added because of the increased time to incorporate the brick dust after the sand. This was not the case for the finish pointing mortars which had all dry components previously mixed together.

2.2.2.2 MOLDING

The molds ranged in size and material according to the requirements of the various standards for each test being conducted. Each mold was covered in a release agent (generic mineral oil) for ease of mortar sample removal and placed on absorbent paper for wicking water. The fresh mortar was placed into the mold at approximately half the height of the mold and tamped with a wooden rod five times. The remaining half of the mold was filled with fresh mortar with an additional amount exceeding the top of the mold to ensure a flush flat surface when scraped off with a putty knife. The mortar was tamped five more times to encourage the filling of any voids. The tops were scraped across to remove excess mortar when the mortar had slightly set on the top surface.

The mortar samples were removed less than 24 hours after molding because of the lack of molds available for the required sample numbers and various formulations. The following table provides the mold shape and size with corresponding quantity and test.

Table 2.5: Mold and Sample Schedule

Test	Standard	Mold Shape	Mold Size	Deep Repair Samples	Finish Pointing Samples
Water Vapor Permeability	ASTM E95 NORMAL 21/85	cylinder	1” x ½”	18	18
Water Absorption / Drying	NORMAL 7/81	cube	2”	9	9
Salt Crystallization	RILEM V. 1a	cube	2”	9	9
Compressive Strength	ASTM C109	cube	2”	9	9
Flexural Strength	ASTM C192	beam	4” x 1” x 1”	9	9

2.2.2.3 CURING

The curing conditions can greatly affect the strength and durability of a lime mortar due to the degree of carbonation it is able to reach over a certain amount of time. The contradiction to this importance is the diversity of standards dictating the curing conditions for lime-based mortars (this can also be said about the preparation of mortar samples). Different countries’ standardization communities recommend various curing conditions. According to British Standard, BS 4551, molds are placed in plastic bags at 20°C for one to three days and subsequently placed in a water-saturated chamber. According to the Centre Scientifique at Technique du Bậtiment (CSTB) standards, the recommended curing conditions are 20°C at 50% relative humidity.[39] The curing conditions chosen for this research followed a variation of the German standard DIN 18 555. The variation was recommended in “Lime Mortar: Some Consideration on Testing

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[39] F.M.A. Henriques and Elena A. Charola, “Comparative Study of Standard Test Procedures for Mortars.” *8th International Congress on Deterioration and Conservation of Stone.* (Berlin: S.N., 1996): 1522.

Standardization,"[40] but further variation was necessary due to environmental constraints. The mortar samples were placed in individual plastic trays on larger trays in a baker's rack in the laboratory at room temperature ranging from 70.5°F to 72.6°F (21.4°C to 22.6°C) with a relative humidity ranging from 30.5% to 33.5% for the first seven days. The baker's rack was then tented with a clear plastic covering, allowing only the bottom of the baker's rack to receive air. The trays were placed on the top ten rails of the rack with one tray full of water each at the top-most rail and the bottom rail directly below the last tray of samples. A hygrometer was placed inside the tent and the atmospheric conditions were 60°F (15.6°C) at 90% relative humidity for 21 days. The curing time for this research was 90 days and the remaining curing time after the first 28 days was at room temperature in 60°F (15.6°C) at 30% humidity with one wall of the plastic tent completely open to allow for the proper availability of carbon dioxide which is quickly consumed by the lime-based mortars.

A balance must be created for the curing of lime-based mortars. This involves a presence of moisture for the facilitation of carbonation which requires water present to solubilize the carbon dioxide and subsequently react with the lime hydrate and allow for the crystallization of calcite. However, too much moisture during the curing process will create a surface film of moisture on the mortar samples. If this surface film is substantial it will prohibit carbon dioxide (CO_2) from reaching the mortar interior which is crucial in the carbonation of lime mortars. Portland cement, however, does not require a dry environment, but rather a damp one due to the cement's increased hydraulicity requiring

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[40] Elena A. Charola and F.M.A. Henriques, "Lime Mortars: Some Considerations on Testing Standardization." *Use of and Need for Preservation Standards in Architectural Conservation, ASTM STP 1355*. (West Conshohocken, PA: American Society for Testing and Materials, 1999): 145.

continual hydration. While carbonation also occurs in the curing of Portland cement, the requirements for the environment to induce carbonation are less stringent. The above curing conditions were applied to all samples – no variations were made according to the binder, because all mortars had a hydraulic component through the addition of the brick dust.

CHAPTER 3 – TESTING PROGRAM

3.1 INTRODUCTION

The current testing program was designed to investigate certain physico-mechanical properties of the cured mortar formulations with the ultimate goal of attaining optimal compatibility as outlined in Chapter One to the historic and repair limestone in the Ayyubid wall. The tests included in this research, by no means exhaustive in the investigations of mortar behavior, were water vapor transmission, water absorption, drying rate, salt crystallization resistance, compressive strength and flexural strength. The tests were conducted on samples of mortar without masonry units attached.

3.2 TESTING STANDARDS

All tests were conducted according to a standardized testing method which varied in provenance in order to best suit the mortar components being tested and the equipment available. Much literature has been written on the disparity between standards for conducting the same test to achieve the same end.[41]

The disparity is usually in the environmental conditions in which the test is carried out and the units of measurements used to communicate results. These differences then make it difficult to compare results across projects and apply the knowledge gained from previous testing programs. In this testing program the disparity in two standards for water vapor transmission was addressed by conducting one test for each standard. The

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[41] F.M.A. Henriques, "Testing Methods for the Evaluation of New Mortars for Old Buildings," *Science and Technology for Cultural Heritage.* 5 (no. 1, 1996). Henriques and Charola, "Comparative Study of Standard Test Procedures for Mortars." Charola and Henriques, "Lime Mortars: Some Considerations on Testing Standardization."

Italian standard, NORMAL 21/85, requires an environmental condition ranging in temperature from 20°C to 25°C with not more than a 0.5°C change in temperature; no relative humidity is dictated. The United States standard, ASTM E96-95, requires an environmental condition of 21°C to 32°C allowing for 0.6°C change in temperature, but the relative humidity is dictated at 50%, plus or minus 2%. The length of time the test is conducted also varies: the NORMAL standard requires a steady state be achieved which is calculated by no more than 5% difference between two successive weighings. The ASTM standard dictates ten data points be acquired with consistent time intervals between each reading and at least six of those ten points be evenly plotted on the straight line in a graph. Additionally, the calculations and units of measurement can differ between standards making comparisons difficult. The units of measurement can be adjusted through relatively simple calculations; however, the variables calculated is more challenging to manipulate. The ASTM standard requires a calculation using the total weight loss of the mortar sample whereas the NORMAL standard requires the average change in weight for the calculations. The calculations have to be adjusted for one of the tests in order to allow for comparison between results, making relationships between different case studies challenging.

Issues of appropriateness in standards when measuring compressive and flexural strengths also need to be addressed within the conservation field. The lack of standards pertaining to lime as the primary component of mortar results in applying standards that have been created for testing cement as the primary component. As is well known, cement has a greater capacity for withstanding compression and flexural stresses and thus is not appropriate for lime's lower capacity to sustain these same stresses. Though developed for cement, the American standards for compressive and flexural strengths, ASTM C109-99 and ASTM C78-94, respectively, were employed in this testing program.

Table 3.1: Standards Consulted for Testing Program

Test	Standard	Origin
Water Absorption by Total Immersion	NORMAL 7/81	Italy
Drying Index	NORMAL 29/88	Italy
Water Vapor Transmission	ASTM E96-95 NORMAL 21/85	United States Italy
Salt Crystallization Resistance	RILEM V. 1a	International non-profit association
Compressive Strength	ASTM C109-99	United States
Flexural Strength	ASTM C78-94	United States

3.3 WATER VAPOR TRANSMISSION

The test for water vapor transmission aids in determining the permeability of a material. Permeability in this case is the movement of moisture as vapor through the pores, voids, and cracks in the material. The inevitable presence of water vapor in a masonry system requires a mortar which can allow for its movement through the system. If the repair mortar introduced to a masonry system is more impermeable to water vapor than the surrounding stone units, the vapor will be concentrated in the stone and depending on environmental conditions, can cause condensation within the pores of the stone, accelerating its decay. In the Ayyubid wall permeability is significant because of the high concentration of salts moving throughout the masonry system via water.

Another detriment to the masonry is that by retaining moisture through condensation and hygroscopicity, the stone displays lower compressive strength which, in turn, may make it fail more readily under stress compared to the mortar.

It is therefore important to quantify the permeability of the repair mortar to enable a comparison to that of the stone ashlar. The standards according to NORMAL and ASTM allow the test to be conducted with minimal equipment and cost.

Water vapor transmission rate is the steady water vapor movement in unit time through an area with parallel surfaces under specific environmental conditions. Water vapor permeability is the amount of water vapor transmitted through a unit area with parallel surfaces and certain thickness at a unit of time, induced by differences in water vapor pressure at either surface.

3.3.1 ASTM E96-95: STANDARD TEST METHODS FOR WATER VAPOR TRANSMISSION OF MATERIALS

This standard requires either a desiccant or wet method be used for determining permeability – the wet method was employed for this research. The same sample size, 12.57 cm^2 by 1.3 cm thick, was used for both the NORMAL and ASTM standard which sufficiently fulfilled the specifications of both standards. The ASTM standard dictates a sample be at least five times the sum of the maximum pit depths in both faces. Each mortar formulation was represented by three samples molded from a 1½-inch diameter rigid polyvinyl chloride pipe cut to ½ inch in height. The samples were cured for 90 days under conditions mentioned in section 2.2.2.3. One modification was made to this standard to coincide with the NORMAL standard which requires an initial drying procedure for the samples. This was not required of the ASTM standard, but implemented for consistency. To attain this consistency between the state of the samples at the onset of both tests, the samples were dried in a 60°C oven until the difference between two successive weighings at 24 hours was less than or equal to 0.01% of the initial weight of the sample.

The samples were then wrapped in electrical tape to seal the edges and prevent any vapor from transporting through the sides of the sample. The sample was then set on an inside ledge of a tri-cornered polypropylene 50 ml. beaker which was filled with 30 ml. of deionized water according to the specified height of ¾ inch ± ¼ inch from the bottom of the sample. The assembly was then sealed with melted paraffin wax between the edges of the sealed sample and the beaker to ensure an airtight chamber.

All assemblies were placed in a controlled climatic chamber with a hygrometer to ascertain a constant temperature and relative humidity. There was little to no anhydrous calcium sulphate used in the chamber because the required 50% relative humidity could be achieved within the sealed chamber through the vapor that was transported through the samples. The relative humidity fluctuated between 48% and 57% throughout the test. The temperature within the chamber remained a constant 21°C as required by the parameters of the standard.

Figure 3.1: Climatic control chamber for ASTM E96-95.

The assemblies were weighed prior to being placed in the chamber and every 24 hours thereafter for ten days to achieve ten data points taken at the same time interval. The electronic scale used had a sensitivity of 0.01 grams and was calibrated every day before measuring with a 100 gram weight.

3.3.2 NORMAL 21/85: WATER VAPOR PERMEABILITY

According to the requirements of the NORMAL standard, the sample thickness has to be at least twice that of the larger grains and the diameter must be at least three times the thickness. It was thus sufficient to use the same sample size as the ASTM standard, 12.57 cm^2 by 1.3 cm thick. Each mortar formulation was represented by three samples and molded from a 1½ inch diameter rigid polyvinyl chloride pipe cut to ½ inch in height. The samples were cured for 90 days under conditions mentioned in section 2.2.2.3.

After curing, the samples were dried in a 60°C oven until the difference between two successive weighings at 24 hours was less than or equal to 0.01% of the initial weight of the sample. The samples were then wrapped in electrical tape to seal the edges and prevent any vapor from transporting through the sides of the sample. The sample was then set on an inside ledge of a tri-cornered polypropylene 50 ml beaker which was filled with 25 ml of deionized water according to the specified height of at least 2 cm from the bottom of the sample. The beaker was also filled with shredded Japanese mulberry paper according to the standard to prevent any liquid drops from making contact with the sample. The assembly was then sealed with melted paraffin wax between the edges of the sealed sample and the beaker to ensure an airtight chamber.

All assemblies were placed in a controlled climatic chamber, in this case a glass fish tank with foam strips along the top edges and closed off with a glass pane. Anhydrous calcium sulphate of a mesh size of eight, manufactured by W. A. Hammond Drierite Company in Ohio, was layered at the bottom of the chamber to attain a relative humidity of approximately 12%. As no relative humidity is recommended in the NORMAL standard, a 12% Rh was determined according to testing programs described in the literature.[42] The temperature within the chamber remained a constant 21°C as required by the parameters of the standard.

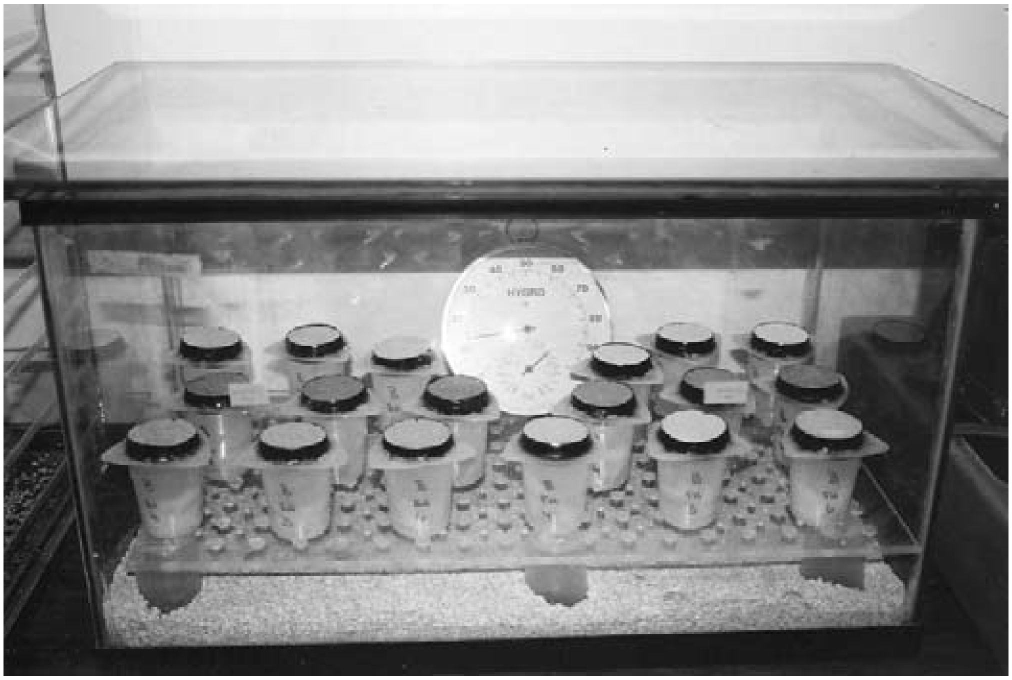

Figure 3.2: Climatic control chamber for NORMAL 21/85.

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[42] Judith Jacob and Norman R. Weiss, "Laboratory Measurements of Water Vapor Transmission Rates of Masonry Mortars and Paints." *APT Bulletin.*21 (no. 3/4, 1989): 65. John Glengary Carr, *An Investigation on the Effect of Brick Dust on Lime-Based Mortars.* (Master's Thesis, University of Pennsylvania, 1995): 86.

The assemblies were weighed prior to being placed in the chamber and every 24 hours thereafter until a stationary state is achieved – defined by the standard as the weight difference between two successive weighings is less than 5%. The electronic scale used had a sensitivity of 0.01 grams and was calibrated every day before measuring with a 100 gram weight.

3.4 WATER ABSORPTION BY TOTAL IMMERSION

The capacity with which a mortar can absorb water addresses similar desirable qualities sought to be quantified in the water vapor transmission test. If water moves through stone units and is impeded at the mortar joint due to an incompatible imbibition capacity relative to the stone, the water can accelerate the decay at the mortar/stone interface. This water saturation incurs a weakness at the bond interface and encourages the deposition of soluble salts. It is thus pertinent to investigate the mortars' ability to absorb water and to allow for some comparison with the associated stone units. More importantly, this test enables a calculation of apparent porosity which can suggest several behavior characteristics of the mortar by itself and in relation to the stone.

Water absorption by total immersion is the amount of water absorbed by the material when fully immersed in deionized water at room temperature. It is expressed as a percentage of the dry weight of the sample. Imbibition capacity is the maximum amount of water absorbed which is determined by proceeding with drying according to NORMAL 29/88 described in Section 3.4.2. Apparent porosity is a measure of the fraction of the total volume of a solid that is occupied by pores.

3.4.1 NORMAL 7/81: Water Absorption by Total Immersion – Imbibition Capacity

According to the requirements of the NORMAL standard, the sample size, if a cube, should not be smaller than 3 cm or larger than 5 cm for a surface-to-volume ratio between 2 cm and 1.2 cm^{-1}. Each mortar formulation was represented by three samples and the cube-shaped samples were molded from a 5 cm^3 steel mold. The samples were cured for 90 days under conditions mentioned in section 2.2.2.3.

After curing, the samples were dried in a 60°C oven until the difference between two successive weighings at 24 hours was less than or equal to 0.1% of the initial weight of the sample. Each sample was then placed in a tri-cornered polypropylene 500 ml beaker with glass rods at the bottom to minimize the impediment of water making contact with the sample surface. Each beaker was filled with deionized water until the sample was covered with 2 cm of water. The containers were stored at room temperature (21°C). According to the standard, the samples were first dried of excess water with a damp paper towel prior to every weighing. The weight measurements began five minutes after being immersed in water and continued every five minutes until one hour had passed. For the next two hours measurements were taken every 15 minutes and then every hour until the samples had been immersed for eight hours. The weighings then proceeded every 24 hours for several days. The measurements concluded when the asymptotical state had been reached – the amount of water absorbed in two successive weighings was less than or equal to 1% of the weight. The electronic scale used had a sensitivity of 0.01 grams and was calibrated every day before measuring with a 100 gram weight.

At the completion of the test, the samples were weighed hydrostatically; i.e., in water by being suspended from a wire in a beaker filled with deionized water. Though not required by the NORMAL standard, this measurement allows for an apparent porosity calculation to be made according to ASTM C948-00: Standard Test Method for Dry and Wet Bulk Density, Water Absorption, and Apparent Porosity of Thin Section of Glass-Fiber Reinforced Concrete.

3.4.2 NORMAL 28/88: MEASUREMENT OF THE DRYING INDEX

The drying index test is conducted in conjunction with NORMAL 7/81 after the samples have been saturated with water at the completion of the test. The excess water is removed from the sample with a damp paper towel one last time prior to the weighing and then placed on a non-corrodible tray in a controlled climatic chamber. The desiccant was filled with anhydrous calcium chloride to control the relative humidity at 50% and the temperature remained a constant 21°C. The weight measurements were taken on a schedule similar to the immersion measurements: every five minutes for the first hour, every 15 minutes for the next two hours and then every 24 hours for two days. The samples were removed from the desiccant after the following equation was true:

$$1.0 \geq \frac{M_0 - M_{i-1}}{M_0 - M_i} \geq 0.90$$

The samples were then placed in a 60°C oven and weighed every 24 hours until the difference between two weighings was less than or equal to 0.01% of the weight of the dry sample.

3.5 SALT CRYSTALLIZATION RESISTANCE

Salt is an aggressive deteriorating substance that moves with moisture through the pores of a masonry system. The investigation of the porosity of the mortars as mentioned in the tests above in conjunction with the mortar’s resistance to salt will suggest some behavior patterns of the mortar and its durability in a masonry system. It is necessary to have a mortar that resists the attack of salt but in manner that is more beneficial to the surrounding stone units. If a mortar withstands the threat of salt so successively as to severely damage the stone, that resistance behavior is not desirable. If a mortar does not withstand the salt attack well, but does allow for the movement of salt in solution to the exterior, the salt will effloresce at the exterior, which is preferable than within the masonry system. This test is of particular importance due to the prevalence of salts in the Ayyubid wall.

The test subjects the mortar samples to decaying agents in an accelerated manner. Through this simulation of weathering, the test seeks to quantify salt resistance through the measurement of weight loss, if any, in addition to presenting photographic documentation for a visual record of the behavior.

3.5.1 RILEM V. 1A: CRYSTALLIZATION TEST BY TOTAL IMMERSION

The sample size used for the test is not critical according to the RILEM standard, though a 5 cm cube is recommended, which was employed in this program. Each mortar formulation was represented by three samples and the cube-shaped samples were molded from a steel mold. The samples were cured for 90 days under conditions mentioned in section 2.2.2.3.

After curing, the samples were dried in a 110°C oven for eight days and then brought to room temperature. Each sample was photographed to document their initial appearance and then placed in a tri-cornered polypropylene 500 ml beaker with glass beads at the bottom to maximize the contact of the salt solution with the sample. A 14% solution of sodium sulphate decahydrate ($Na_2SO_4 \cdot 10H_2O$) was prepared. The solution was made with deionized water which was tested for sulphates by adding two drops of 2N hydrochloric acid (HCl) and 2 drops of a 10% solution of barium chloride ($BaCl_2$). No white precipitate of barium sulfate ($BaSO_4$) was formed in the test tube which indicated no sulphates were in the deionized water, allowing for a more accurate 14% solution of sodium sulphate decahydrate. Each beaker was filled with the solution until the sample was covered with 2 cm of water. The samples were immersed in the solution for two hours at room temperature (21°C) and then placed in an oven at 110°C. The standard requires a high humidity oven at the onset of each drying cycle which was achieved by adding 150 ml of water in a dish at the bottom of the oven immediately after the samples were placed in the oven. The samples were dried in the oven for 24 hours and then removed to reach room temperature before soaking in the salt solution for two hours. This cycle was repeated 15 times unless a sample was broken. The samples were weighed after the final drying on an electronic scale with a sensitivity of 0.01 grams which was calibrated before measuring with a 100 gram weight. The samples were also photographed after the final drying cycle to record the visual appearance after the completion of the test.

3.6 COMPRESSIVE STRENGTH

The strength of a repair mortar is imperative in research for conservation of a masonry system, particularly when "stronger" is not necessarily "better." The ability of mortar to withstand compressive loads and stresses in a masonry system is critical when considering the microcracking resulting from failure. The microcracking which in turn encourages large crack propagation, introduces voids for moisture and salts to accumulate and accelerate decay. The interpretation of an appropriate mortar strength, however, is relative to the surrounding stone. If the mortar withstands more load than the stone, any failure may occur in the stone rather than the mortar.

The compressive strength of the mortar is its capacity to withstand axially directed pushing forces and was tested in this program independent of the stone.

3.6.1 ASTM C109-99: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars

The sample size according to the standard was a 5 cm cube and each mortar formulation was represented by three samples shaped from steel gauge molds. The samples were cured for 90 days under conditions mentioned in section 2.2.2.3. While the standard recommends methods of preparing and storing the samples for the compression test, the samples were made as all the other samples, according to ASTM C305-99 Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. Curing was also done as all the other samples according to a variation of the German standard DIN 18 555.

After curing, the samples were dusted and the faces checked with a level. In cases where the face was not level, sandpaper was used to grind down the higher portions until a level surface was attained. The testing was conducted at the

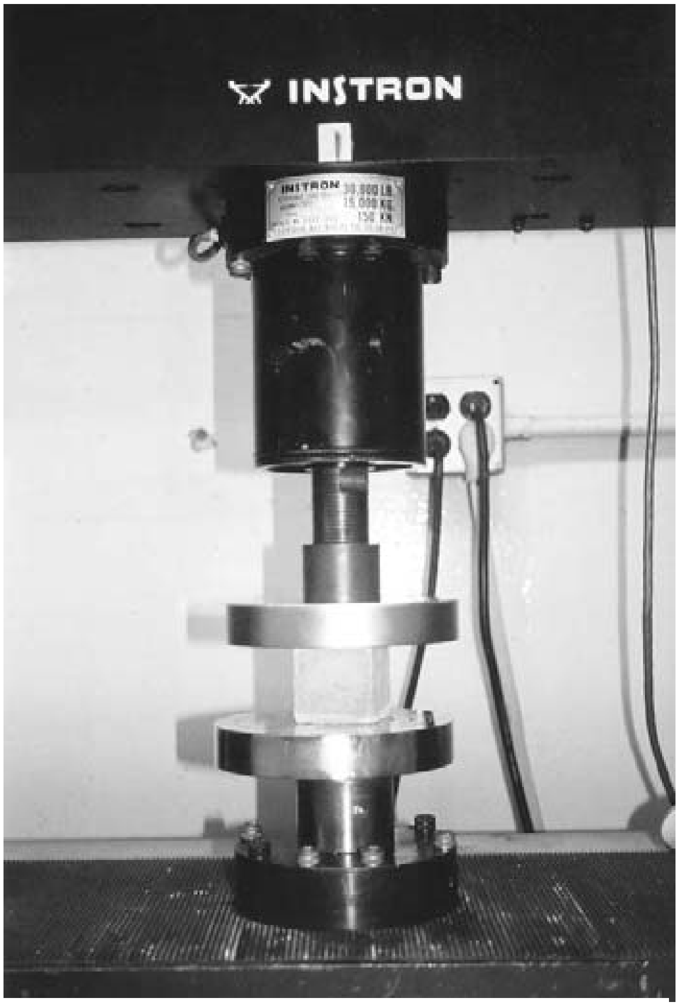


Figure 3.3: Instron Model 4206 for compression.

Laboratory for Research on the Structure of Matter at the University of Pennsylvania. The sample was placed below the center of the upper bearing block on the static testing machine, Instron model 4206. The block was lowered until uniform contact was made with the sample surface. The machine was connected to a computer in which the parameters of the test were established. The first test was conducted on a Portland cement finish pointing sample to help determine the necessary parameters. It was programmed for a 15,000 lb. load limit at a speed of 0.01 inches per minute with a tolerance of 0.2 inch displacement. These parameters were used on all the remaining Portland cement samples with the exception of a change in displacement to 0.1 inch due to the low value of the first test. The remainder of the samples – all of the hydrated hydraulic lime and lime putty samples – were set to similar parameters with the exception of the load limit at 7,500 lbs. The readings were at five scans per second with a maximum of 2000 scans, which were automatically recorded during each test in Microsoft Excel.

3.7 FLEXURAL STRENGTH

The flexural strength of a repair mortar is a measure of the mortar's resistance to cracking under bending stress which results from movement by thermal expansion in the stone. The microcracking resulting from failure to withstand the bending stress encourages large crack propagation, and introduces voids for moisture and salts to accumulate and accelerate decay. Similarly, the interpretation of an appropriate mortar strength is relative to the surrounding stone. If the mortar withstands more bending load than the stone, any failure may occur in the stone rather than the mortar. The flexural strength of the mortar was tested independent of the stone.

3.7.1 ASTM C78-94: STANDARD TEST METHOD FOR FLEXURAL STRENGTH OF CONCRETE USING SIMPLE BEAM WITH THIRD-POINT LOADING

The sample size was stipulated in another standard, ASTM C192: Practice for Making and Curing Concrete Test Specimens in the Laboratory, which suggested a rectangular beam 125 mm long by 25 mm high and 25 mm wide. Each mortar formulation was represented by three samples and the beam was shaped from a steel mold which had to be dammed midway with a wood wedge and putty to anchor it, to attain the proper length. The samples were cured for 90 days under conditions mentioned in section 2.2.2.3.

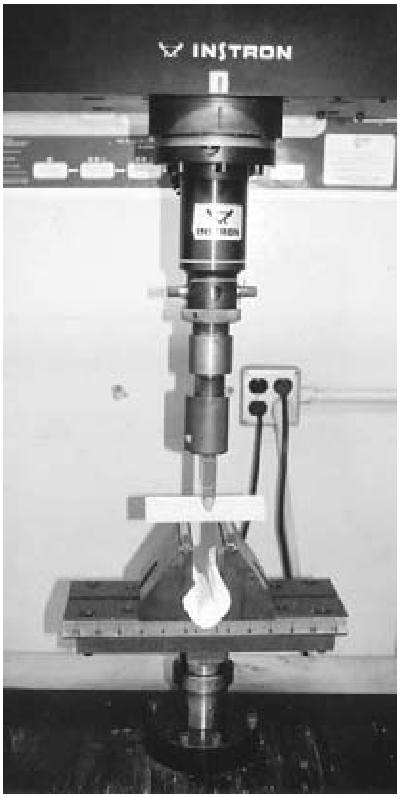


Figure 3.4: Instron Model 4206 for flexural test.

CHAPTER 4 – RESULTS

The results of the testing program are presented for each test conducted with the deep repair mortar samples represented first, followed by finish pointing mortar samples. All mortar samples were cured for 90 days.

4.1 WATER VAPOR TRANSMISSION ACCORDING TO ASTM E96-95

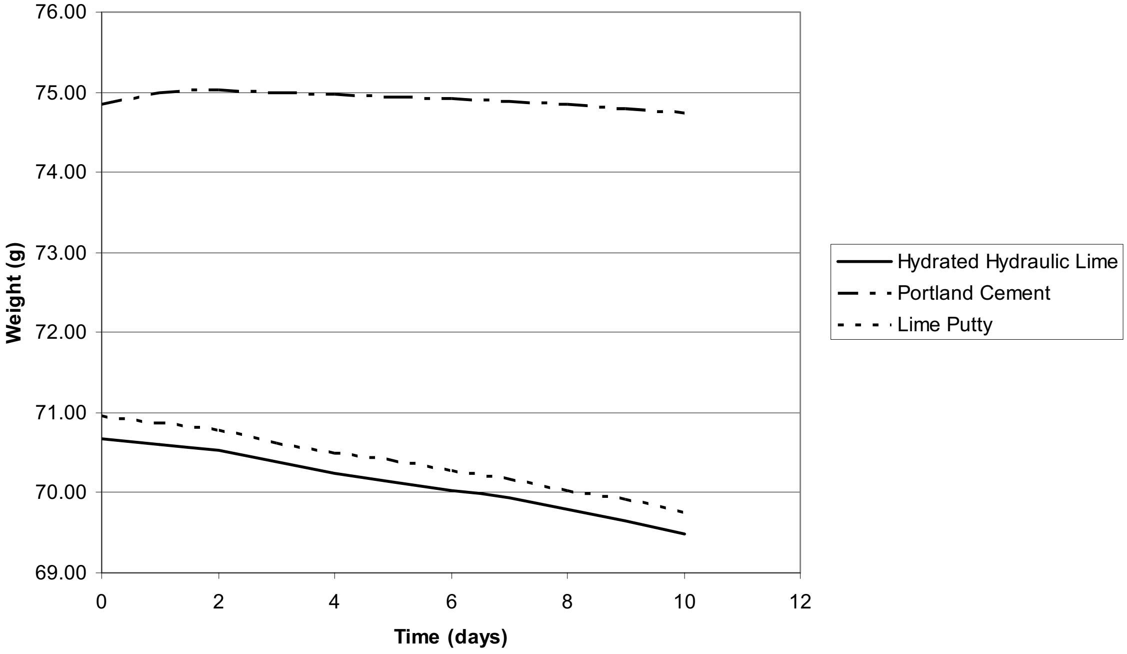
4.1.1 DEEP REPAIR MORTARS

All deep repair mortars achieved a nominally steady state, dictated by the standard, as the water vapor transmission curve tends toward a straight line with at least six evenly spaced points, presented in Graph 4.1, as averages of sample sets. By the completion of the test at day 10 a sufficient number of points were achieved by all samples.

The averages are presented below; however, all of the Portland cement samples exhibited an initial weight gain until they decreased for the first time on the third day. The hydrated hydraulic lime and lime putty samples exhibited a weight loss throughout the entire test. The data collected and all sample curves are available in Appendix C.

Graph 4.1: Average Water Vapor Transmission Curve by Binder in Deep Repair Mortars - ASTM E96-95

All samples cured for 90 days



The following table presents the values in metric units for the samples' water vapor transmission, permeance, and permeability and their averages within the sample sets, as required by the standard.

Table 4.1: Water Vapor Transmission, Permeance and Permeability of Deep Repair Mortars - ASTM E96-95

All samples cured for 90 days

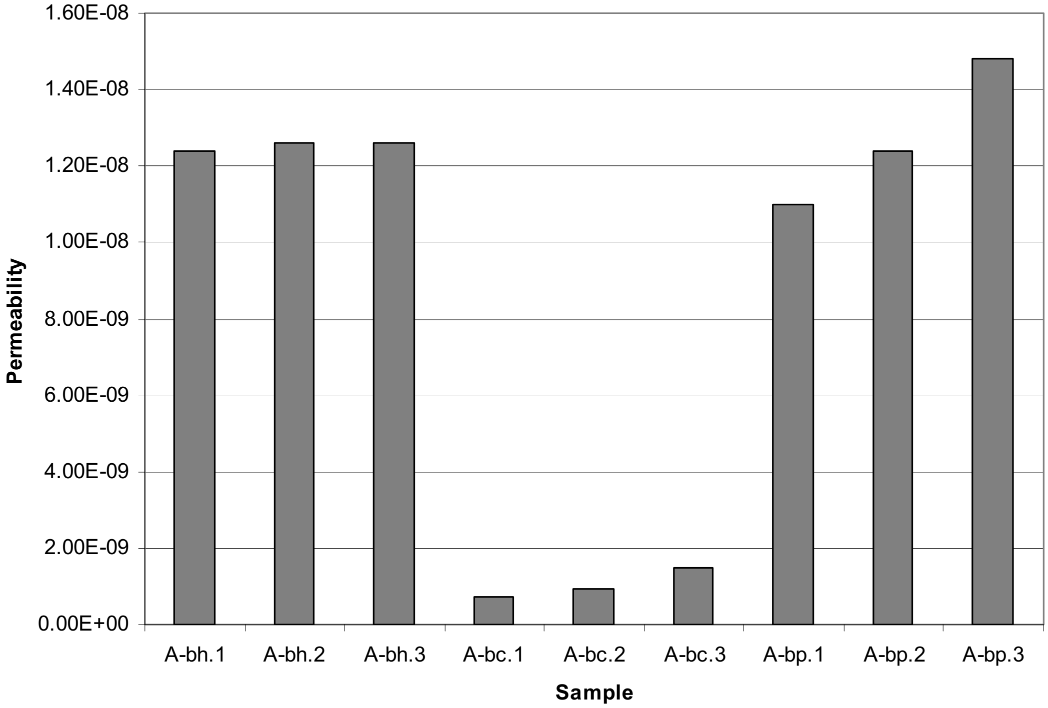
Sample	WVT (g/h·m²)	Average WVT	Permeance (g/Pa·s·m²)	Average Permeance	Permeability (perm·cm)	Average Permeability
A-bh.1	0.04		9.53E-09		1.24E-08	
A-bh.2	0.04	0.038	9.69E-09	9.63E-09	1.26E-08	1.25E-08
A-bh.3	0.04		9.69E-09		1.26E-08	
A-bc.1	0.00		5.70E-10		7.41E-10	
A-bc.2	0.00	0.003	7.33E-10	8.14E-10	9.53E-10	1.06E-09
A-bc.3	0.00		1.14E-09		1.48E-09	
A-bp.1	0.03		8.47E-09		1.10E-08	
A-bp.2	0.04	0.039	9.53E-09	9.80E-09	1.24E-08	1.27E-08
A-bp.3	0.04		1.14E-08		1.48E-08	

Key to Samples
Group A-bh: hydrated hydraulic lime deep repair mortars
Group A-bc: Portland cement deep repair mortars
Group A-bp: lime putty deep repair mortars

As indicated in Table 4.1, the Portland cement samples had a lower water vapor transmission, permeance and permeability than the hydrated hydraulic lime and lime putty. The hydrated hydraulic lime had the highest water vapor transmission, permeance and permeability, though only by a negligible amount in relation to the lime putty. The hydrated hydraulic lime and Portland cement present a more consistent permeability throughout all three samples whereas the lime putty had greater fluctuation throughout the three samples. These trends are illustrated in the permeability of the deep repair mortar samples in Graph 4.2, below.

Graph 4.2: Permeability of Deep Repair Mortars - ASTM E96-95

All samples cured for 90 days



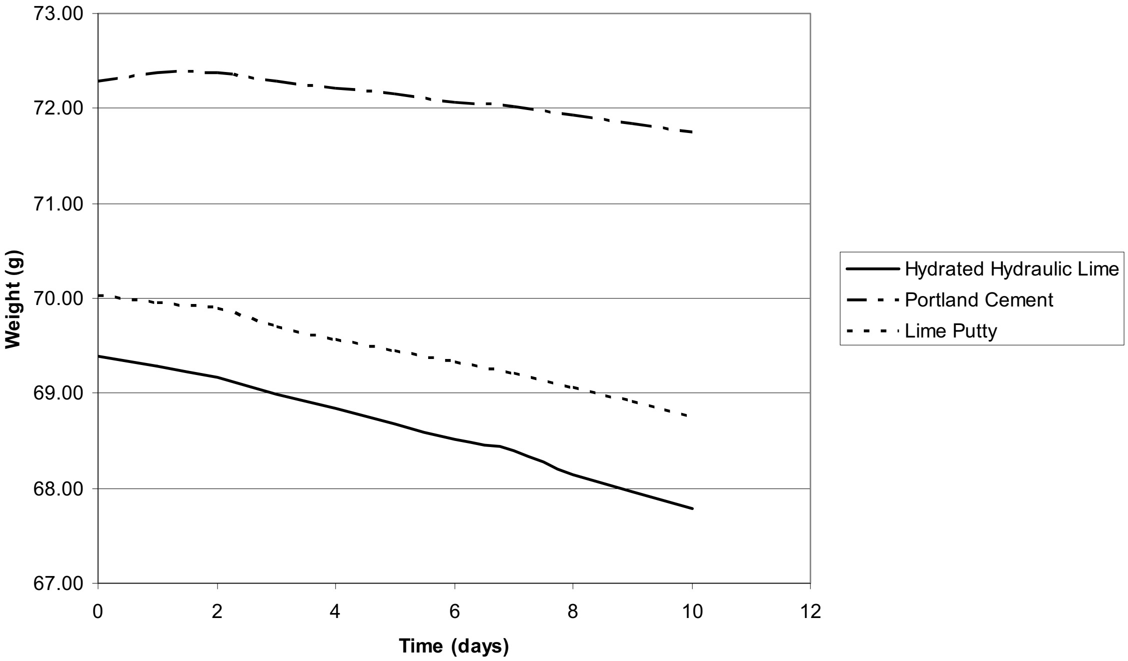
4.1.2 FINISH POINTING MORTARS

All finish pointing mortars achieved a nominally steady state, dictated by the standard, as the water vapor transmission curve tends toward a straight line with at least six evenly spaced points, presented in Graph 4.3, as averages of sample sets. By the completion of the test at day 10 a sufficient number of points were achieved by all samples.

The averages are presented below and it should be noted that all of the Portland cement samples exhibited an initial weight gain until they decreased for the first time on the third day. The hydrated hydraulic lime and lime putty samples exhibited a weight loss throughout the entire test. The data collected and all sample curves are available in Appendix C.

Graph 4.3: Average Water Vapor Transmission Curve by Binder in Finish Pointing Mortars - ASTM E96-95

All samples cured for 90 days



The following table presents the values in metric units for water vapor transmission, permeance, and permeability and their averages within the sample sets, as required by the standard.

Table 4.2: Water Vapor Transmission, Permeance and Permeability of Finish Pointing Mortars - ASTM E96-95

All samples cured for 90 days

Sample	WVT ($g/h \cdot m^2$)	Average WVT	Permeance ($g/Pa \cdot s \cdot m^2$)	Average Permeance	Permeability (perm·cm)	Average Permeability
A-fh.1	0.06		1.49E-08		1.94E-08	
A-fh.2	0.06	0.052	1.43E-08	1.31E-08	1.86E-08	1.71E-08
A-fh.3	0.04		1.02E-08		1.32E-08	
A-fc.1	0.03		7.65E-09		9.95E-09	
A-fc.2	0.01	0.017	2.20E-09	4.40E-09	2.86E-09	5.72E-09
A-fc.3	0.01		3.34E-09		4.34E-09	
A-fp.1	0.04		9.77E-09		1.27E-08	
A-fp.2	0.04	0.041	1.07E-08	1.04E-08	1.40E-08	1.35E-08
A-fp.3	0.04		1.07E-08		1.39E-08	

Key to Samples

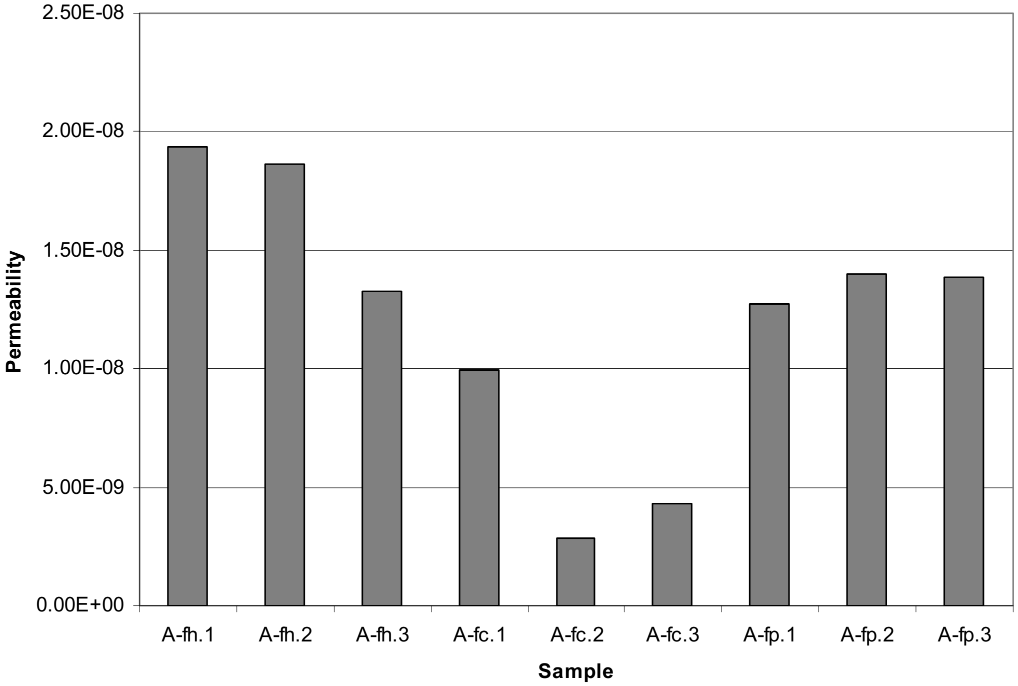
Group A-fh:	hydrated hydraulic lime finish pointing mortars
Group A-fc:	Portland cement finish pointing mortars
Group A-fp:	lime putty finish pointing mortars

As indicated in Table 4.2, the Portland cement samples had a lower water vapor transmission, permeance and permeability than the hydrated hydraulic lime and lime putty. The hydrated hydraulic lime had the highest average water vapor transmission, permeance and permeability, though only slightly above those values for lime putty. Those trends are illustrated in the permeability of the individual finish pointing samples in Graph 4.4, below.

Overall the average values for water vapor transmission, permeance and permeability of the finish pointing mortars are higher than those of the deep repair mortar samples suggesting a more porous mortar formulation.

Graph 4.4: Permeability of Finish Pointing Mortars - ASTM E96-95

All samples cured for 90 days



4.2 WATER VAPOR TRANSMISSION ACCORDING TO NORMAL 21/85

4.2.1 DEEP REPAIR MORTARS

The test was completed, according to the standard, when the following equation was satisfied:

$$[(\Delta M_i - \Delta M_{i-1})/\Delta M_i] \times 100 \leq 5\%$$

where:

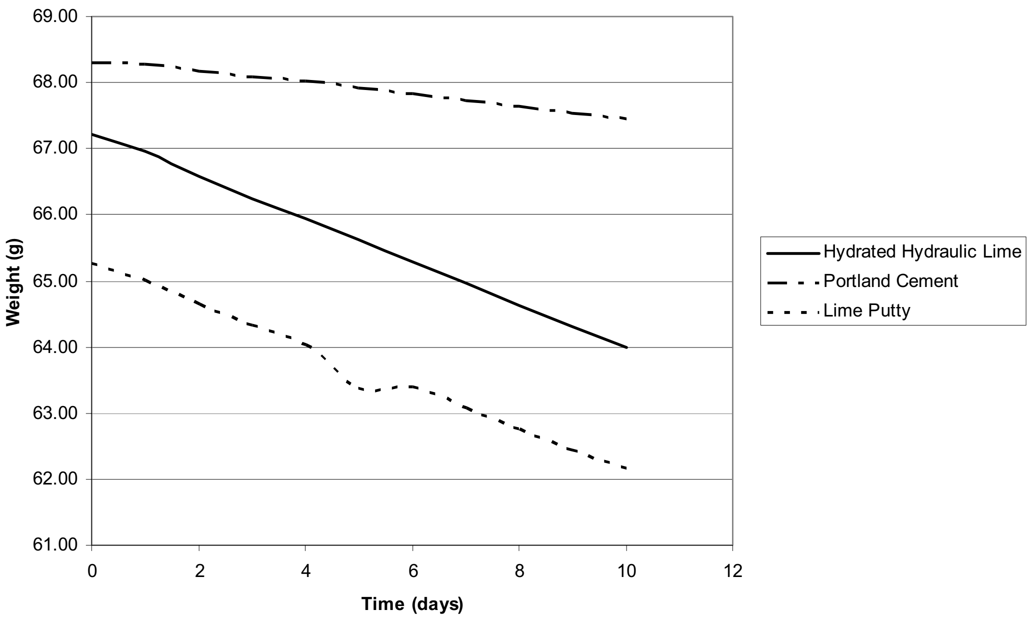
$$\Delta M_i = \Delta M_{t=1} - \Delta M_{t=i-1}$$

$$\Delta M_{i-1} = \Delta M_{t=i-1} - \Delta M_{t=i-2}$$

The time of completion varied according to the mortar sample: all deep repair samples reached an asymptotical state on the sixth day except for one sample from each mortar formulation (B-bh.6, B-bc.6 and B-bp.6) which all reached an asymptotical state on the eighth day. The test, however, was continued until all samples, including the finish pointing mortars, satisfied the equation, which was on the tenth day, to enable an equivalent graphic comparison for the rate of water vapor transmission for the different formulations. Graph 4.5 illustrates the asymptotical state achieved by the samples. All samples decreased in weight from the onset of the test unlike the Portland cement samples in the ASTM water vapor transmission test which expressed an initial weight gain. The increased rate of water vapor transmission in the NORMAL test from the ASTM test is illustrated in Graph 4.5 by the increased slope of the line in the NORMAL test results (see also Graph 4.1).

Graph 4.5: Average Water Vapor Transmission Curve by Binder in Deep Repair Mortars - NORMAL 21/85

All samples cured for 90 days



The following tables present the values in metric units for water vapor transmission, permeance, permeability, and the averages and standard deviations of the sample sets.

Table 4.3: Water Vapor Transmission for Deep Repair Mortars - NORMAL 21/85

All samples cured for 90 days

Sample	WVT (g/m² · h)	Average WVT	Standard Deviation
B-bh.4	0.10		
B-bh.5	0.10	0.10	0.01
B-bh.6	0.11		
B-bc.4	0.03		
B-bc.5	0.03	0.03	0.00
B-bc.6	0.02		
B-bp.4	0.10		
B-bp.5	0.11	0.10	0.01
B-bp.6	0.10		

Table 4.4: Permeance and Permeability for Deep Repair Mortars - NORMAL 21/85

All samples cured for 90 days

Sample	Permeance (g/Pa·s·m²)	Average Permeance	Standard Deviation	Permeability (perm·cm)	Average Permeability	Standard Deviation
B-bh.4	1.48E-08			1.92E-08		
B-bh.5	1.42E-08	1.49E-08	7.91E-10	1.84E-08	1.94E-08	1.03E-09
B-bh.6	1.57E-08			2.04E-08		
B-bc.4	3.75E-09			4.87E-09		
B-bc.5	4.35E-09	3.87E-09	4.30E-10	5.65E-09	5.03E-09	5.59E-10
B-bc.6	3.52E-09			4.57E-09		
B-bp.4	1.37E-08			1.79E-08		
B-bp.5	1.54E-08	1.44E-08	8.74E-10	2.00E-08	1.87E-08	1.14E-09
B-bp.6	1.41E-08			1.83E-08		

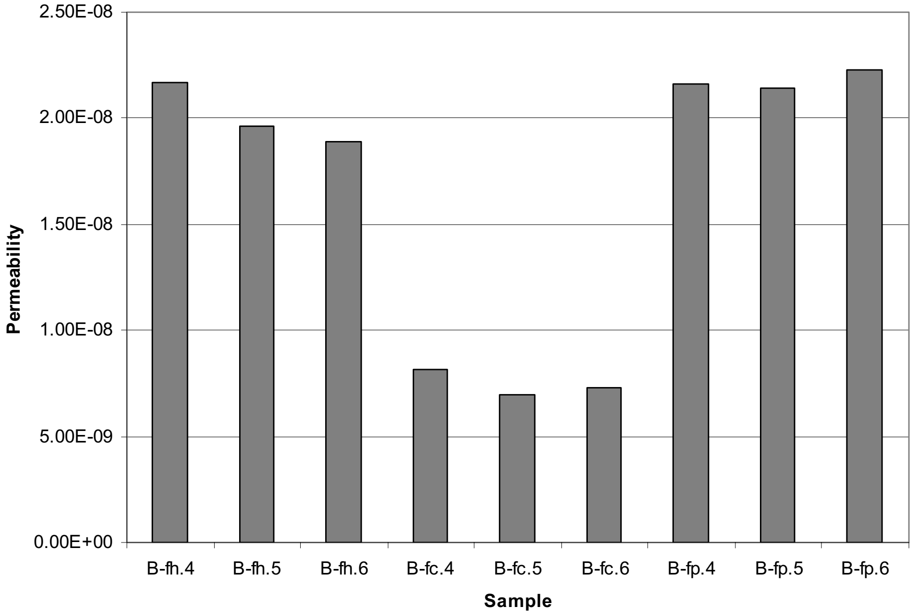
Key to Samples

Group B-bh:	hydrated hydraulic lime deep repair mortars
Group B-bc:	Portland cement deep repair mortars
Group B-bp:	lime putty deep repair mortars

As indicated in Tables 4.3 and 4.4, the Portland cement samples had a lower water vapor transmission, permeance and permeability than the hydrated hydraulic lime and lime putty. The hydrated hydraulic lime and lime putty were almost equal – hydrated hydraulic lime was slightly higher – in value for water vapor transmission, permeance and permeability. Those trends are illustrated in the permeability of the deep repair samples in Graph 4.6, below.

Graph 4.6: Permeability of Deep Repair Mortars for NORMAL 21/85

All samples cured for 90 days



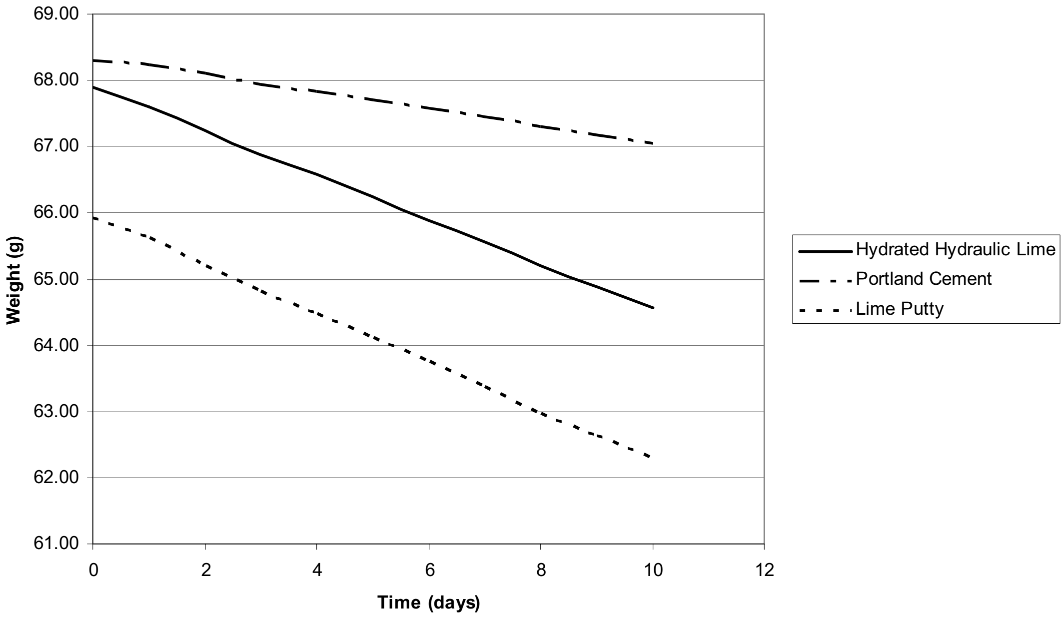
4.2.2 FINISH POINTING MORTARS

All finish pointing mortars achieved an asymptotical state, dictated by the standard, according to the equation in Section 4.3.1. The time of completion varied according to the mortar sample: all finish pointing samples reached an asymptotical state on the sixth day except for one hydrated hydraulic lime and two Portland cement samples

(B-fh.6 on the eighth day, B-fc.4 on the seventh day and B-fc.5 on the tenth day). The test, however, was continued until all samples satisfied the equation, which was on the tenth day, to enable an equivalent graphic comparison for the rate of water vapor transmission for the different formulations. Graph 4.7 illustrates the asymptotical state achieved by the samples. All samples decreased in weight from the onset of the test unlike the Portland cement samples in the ASTM water vapor transmission test which expressed an initial weight gain. The increased rate of water vapor transmission in the NORMAL test from the ASTM test is illustrated in Graph 4.7 by the increase in the slope of the line in the NORMAL test results (see also Graph 4.3).

Graph 4.7: Average Water Vapor Transmission Curve by Binder in Finish Pointing Mortars - NORMAL 21/85

All samples cured for 90 days



The following tables present the values in metric units for water vapor transmission, permeance, permeability, and the averages and standard deviations of the sample sets.

Table 4.5: Water Vapor Transmission for Finish Pointing Mortars - NORMAL 21/85

All samples cured for 90 days

Sample	WVT (g/m² · h)	Average WVT
B-fh.4	0.12	
B-fh.5	0.10	0.11
B-fh.6	0.10	
B-fc.4	0.04	
B-fc.5	0.04	0.04
B-fc.6	0.04	
B-fp.4	0.12	
B-fp.5	0.11	0.12
B-fp.6	0.12	

Table 4.6: Permeance and Permeability for Finish Pointing Mortars - NORMAL 21/85

All samples cured for 90 days

Sample	Permeance (g/Pa·s·m²)	Average Permeance	Standard Deviation	Permeability (perm·cm)	Average Permeability	Standard Deviation
B-fh.4	1.67E-08			2.17E-08		
B-fh.5	1.51E-08	1.54E-08	1.13E-09	1.96E-08	2.01E-08	1.47E-09
B-fh.6	1.45E-08			1.89E-08		
B-fc.4	6.29E-09			8.18E-09		
B-fc.5	5.37E-09	5.75E-09	4.81E-10	6.98E-09	7.48E-09	6.26E-10
B-fc.6	5.60E-09			7.28E-09		
B-fp.4	1.66E-08			2.16E-08		
B-fp.5	1.65E-08	1.67E-08	3.41E-10	2.14E-08	2.18E-08	4.43E-10
B-fp.6	1.71E-08			2.23E-08		

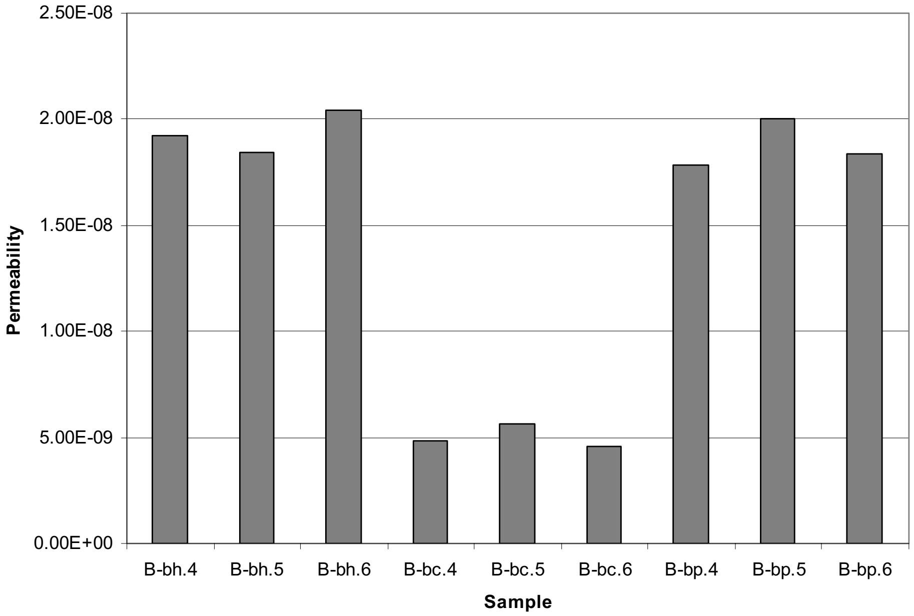
Key to Samples

Group	Description
Group B-fh:	hydrated hydraulic lime finish pointing mortars
Group B-fc:	Portland cement finish pointing mortars
Group B-fp:	lime putty finish pointing mortars

As indicated in Tables 4.5 and 4.6, the Portland cement samples had a lower water vapor transmission, permeance and permeability than the hydrated hydraulic lime and lime putty. The hydrated hydraulic lime and lime putty were almost equal in value – lime putty was just slightly higher – for water vapor transmission, permeance and permeability. Those trends are illustrated in the permeability of the finish pointing samples in Graph 4.8, below.

Graph 4.8: Permeability of Finish Pointing Mortars - NORMAL 21/85

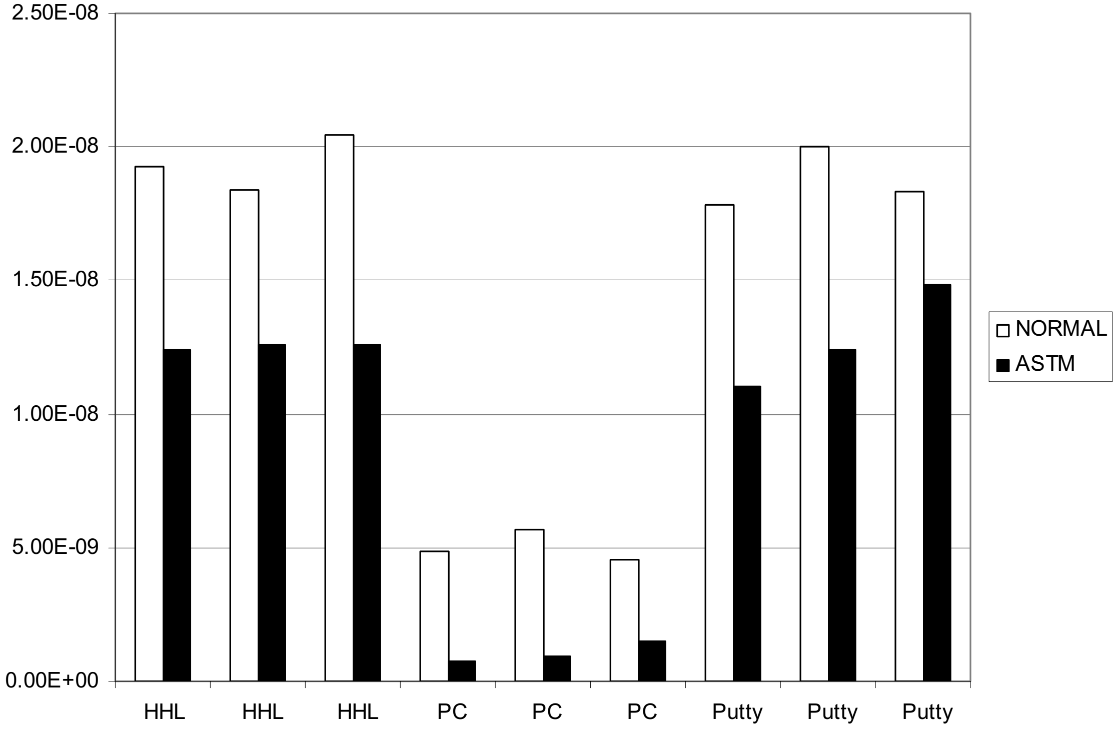
All samples cured for 90 days



As discussed in Section 3.2, the discrepancy in the various standards that attempt to achieve the same goal makes comparison between results challenging. A comparison can be made between the ASTM and NORMAL tests with some manipulation of the calculations leaving the difference in recommended percentages of relative humidity in the climatic chamber the only variable. To achieve the ASTM calculations for water vapor transmission, the total change in weight is the figure used. However, in the NORMAL calculations the average change in weight is used. To attempt to make a comparison between the permeabilities of both tests' samples as represented in the graphs below, the total change in weight was used for the NORMAL calculations of water vapor transmission (though these figures were not used in the results discussed above).

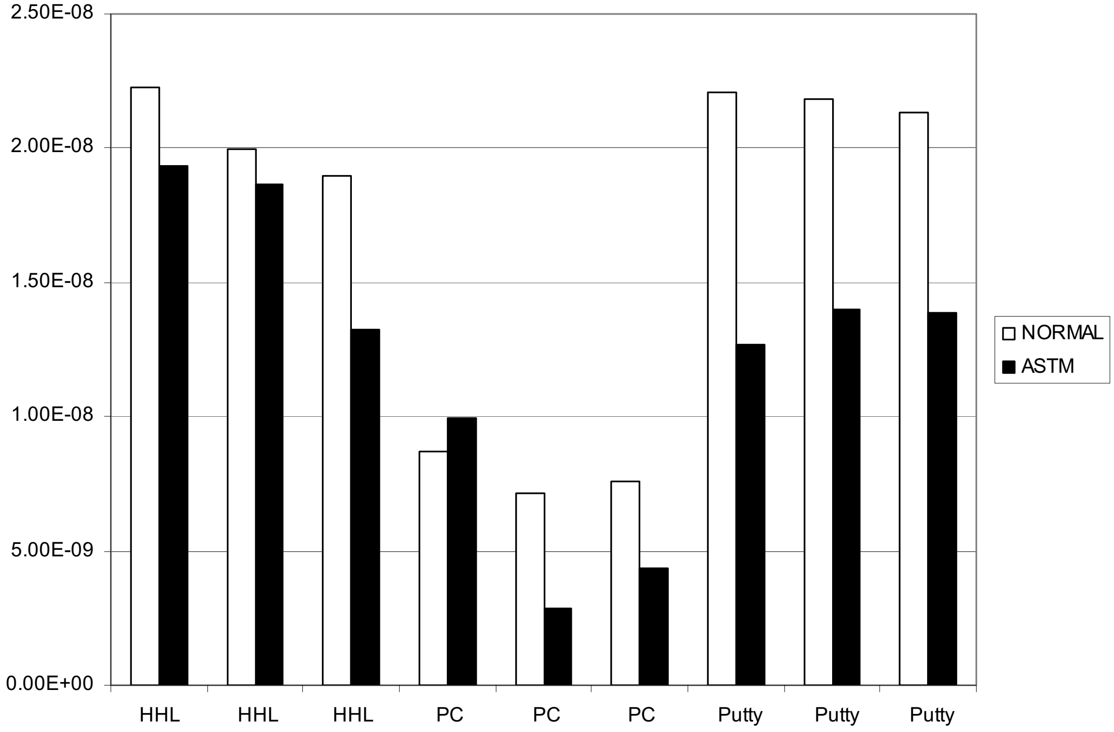
Graph 4.9: Permeability of ASTM versus NORMAL Deep Repair Mortars

All samples cured for 90 days



Graph 4.10: Permeability of ASTM versus NORMAL Finish Pointing Mortars

All samples cured for 90 days



The NORMAL test samples had a higher permeability than those of the ASTM test, due to the lower relative humidity of the NORMAL test's climatic chamber. The lower relative humidity increases the difference in vapor pressure between the chamber and the assembly, thus decreasing the total vapor pressure difference in relation to the ASTM test. Water vapor moves more readily from areas of high vapor pressure to areas low vapor pressure which explains the higher permeability rates for the NORMAL test. The difference between the two chambers was 38% relative humidity. This was the case for both the deep repair and finish pointing mortar samples. The climatic chamber for the NORMAL test with a relative humidity of 12% is more indicative of the environment of Cairo than the 50% relative humidity of the ASTM test.

4.3 WATER ABSORPTION BY TOTAL IMMERSION ACCORDING TO NORMAL 7/81

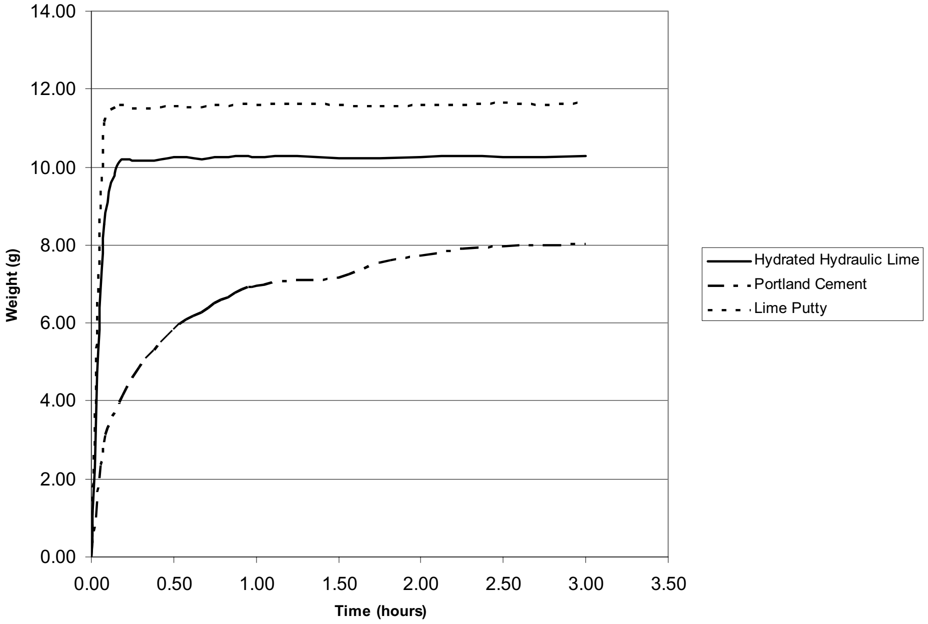
4.3.1 DEEP REPAIR MORTARS

All deep repair mortars achieved a nominally steady state, dictated by the standard, as the amount of water in two successive weighings being less than or equal to 1% of the dry weight of the sample. This occurred at the third day of weighing for all of the samples.

As illustrated in Graph 4.11, the lime putty deep repair mortars absorbed the highest amount of water, followed by the hydrated hydraulic lime and lastly the Portland cement samples. This indicates a higher porosity for the lime putty samples.

Graph 4.11: Water Absorption Curve for Deep Repair Mortars – First Three Hours

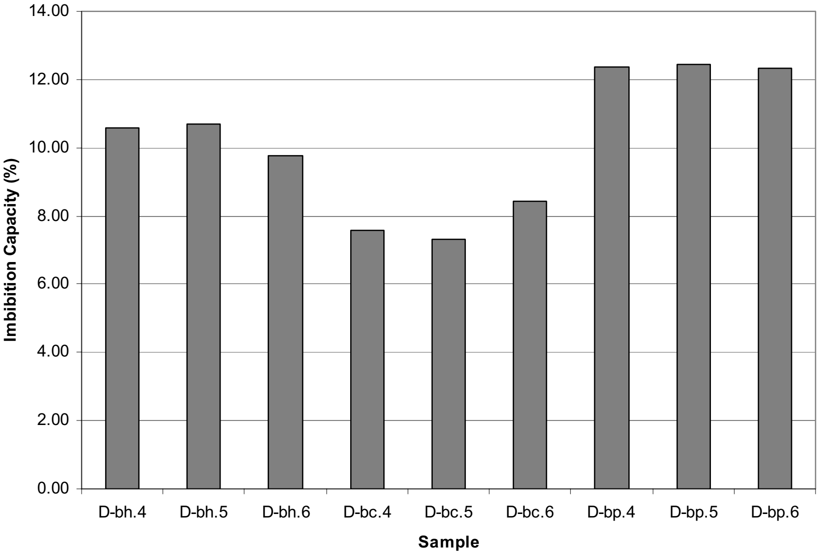
All samples cured for 90 days



The following graph represents the imbibition capacity of the deep repair mortars showing the higher water absorption capacity and, thus, apparent porosity, of the lime putty mortars.

Graph 4.12 Imbibition Capacities for Deep Repair Mortars

All samples cured for 90 days



Key to Samples

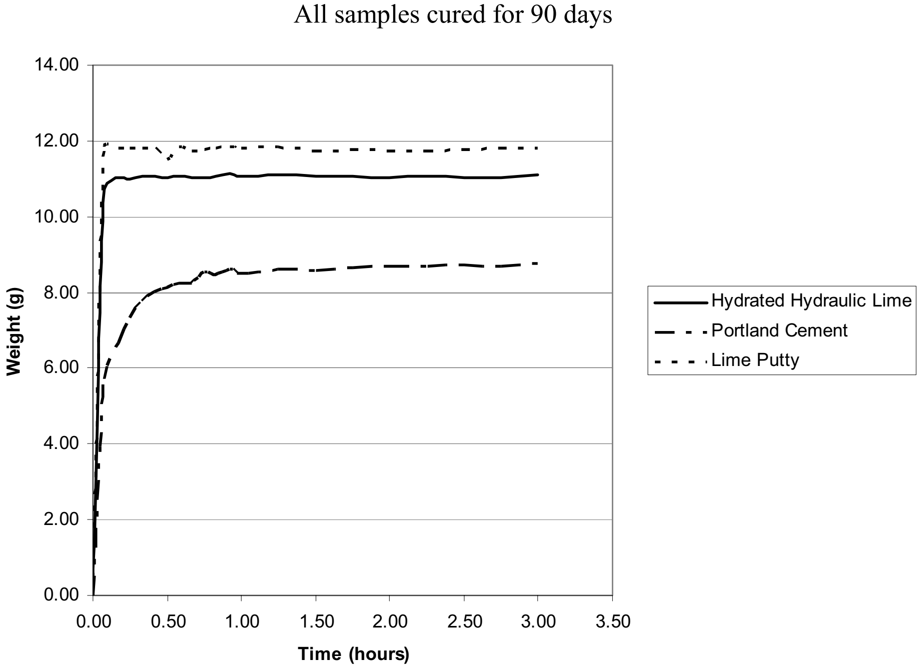
Group D-bh:	hydrated hydraulic lime deep repair mortars
Group D-bc:	Portland cement deep repair mortars
Group D-bp:	lime putty deep repair mortars

4.3.2 FINISH POINTING MORTARS

All finish pointing mortars achieved a nominally steady state, dictated by the standard, as the amount of water in two successive weighings as less than or equal to 1% of the weight of the dry sample. This occurred at the third day of weighing for all of the samples.

As illustrated in Graph 4.13, the lime putty finish pointing mortars absorbed the highest amount of water, followed by the hydrated hydraulic lime and lastly the Portland cement samples.

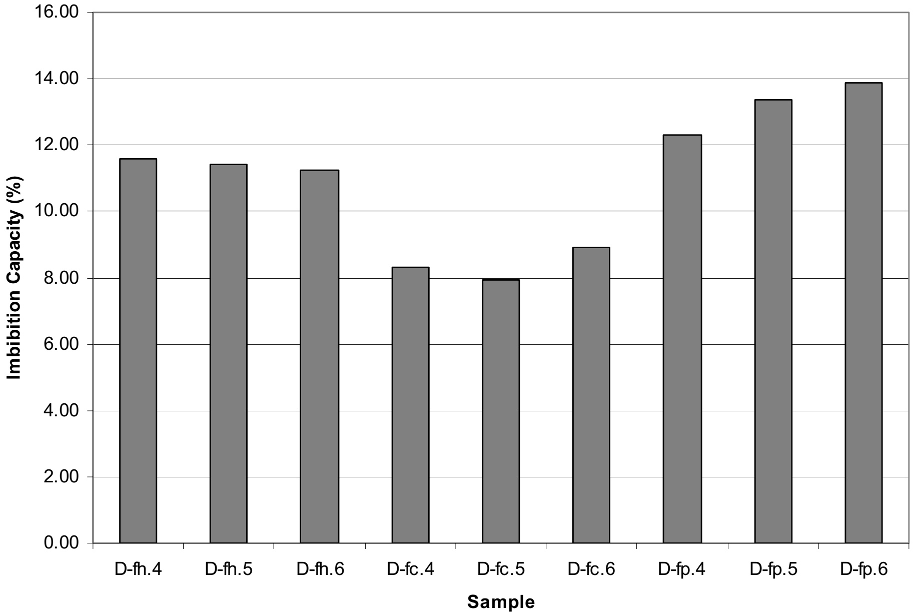
Graph 4.13: Water Absorption Curve for Finish Pointing Mortars – First Three Hours



The following graph represents the imbibition capacity of the finish pointing mortars showing the higher water absorption capacity and, thus, the apparent porosity, of the lime putty mortars.

Graph 4.14 Imbibition Capacities for Finish Pointing Mortars

All samples cured for 90 days



Key to Samples

Group D-fh:	hydrated hydraulic lime finish pointing mortars
Group D-fc:	Portland cement finish pointing mortars
Group D-fp:	lime putty finish pointing mortars

Table 4.7: Imbibition Capacity and Apparent Porosity for All Mortars

All samples cured for 90 days

Sample	Final Weight of Water Absorption	Final Dry Weight	Imbibition Capacity	Average Imbibition Capacity	Apparent Porosity %	Average Apparent Porosity
D-bh.4	259.43	234.58	10.59		15.96	
D-bh.5	254.06	229.49	10.71	10.36	16.12	15.64
D-bh.6	250.27	227.97	9.78		14.85	
D-bc.4	285.87	265.75	7.57		10.83	
D-bc.5	281.14	261.99	7.31	7.77	10.48	11.09
D-bc.6	298.78	275.52	8.44		11.98	
D-bp.4	263.96	234.94	12.35		18.63	
D-bp.5	253.40	225.35	12.45	12.38	18.76	18.67
D-bp.6	260.24	231.68	12.33		18.60	
D-fh.4	251.18	225.10	11.59		17.30	
D-fh.5	255.41	229.27	11.40	11.42	17.06	17.08
D-fh.6	248.49	223.34	11.26		16.87	
D-fc.4	291.75	269.33	8.32		11.82	
D-fc.5	279.25	258.67	7.96	8.40	11.34	11.92
D-fc.6	278.17	255.39	8.92		12.60	
D-fp.4	248.98	221.67	12.32		18.59	
D-fp.5	241.67	213.14	13.39	13.20	20.01	19.76
D-fp.6	255.38	224.23	13.89		20.67	

There is a slight increase in water absorption and apparent porosity in the finish pointing mortars compared to that of the deep repair mortars, as seen in Table 4.7.

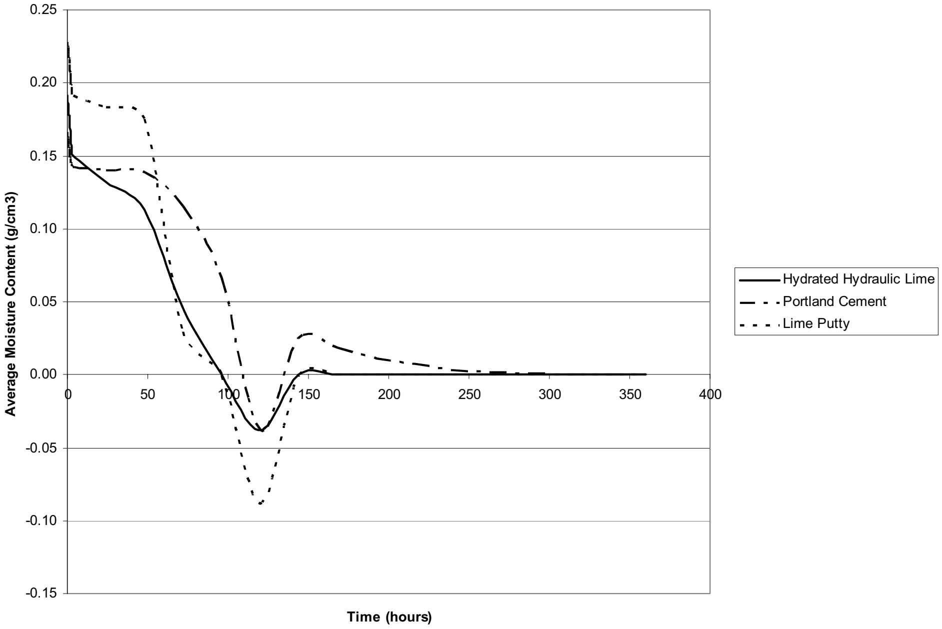
4.4 DRYING CURVES ACCORDING TO NORMAL 29/88

4.4.1 DEEP REPAIR MORTARS

The rate of drying for the sample sets varied according to the binder. The rate was higher for the hydrated hydraulic lime and lime putty samples and was lower for the Portland cement samples. All of the hydraulic lime and lime putty samples achieved an asymptotical state (0.01% of the weight of the dry sample in two successive weighings) after the eighth day of drying. The Portland cement samples took substantially longer to achieve an asymptotical state: two of the samples after the 14th day and one of the samples after the 15th day of drying. The mortar samples declined steadily in weight while in the desiccant, however, there was a sharp decrease after the first day in the oven followed by a sharp increase in weight after the second day in the oven. The average moisture content as a function of time was graphed for the deep repair mortars.

Graph 4.15: Average Moisture Content during Drying of Deep Repair Mortars

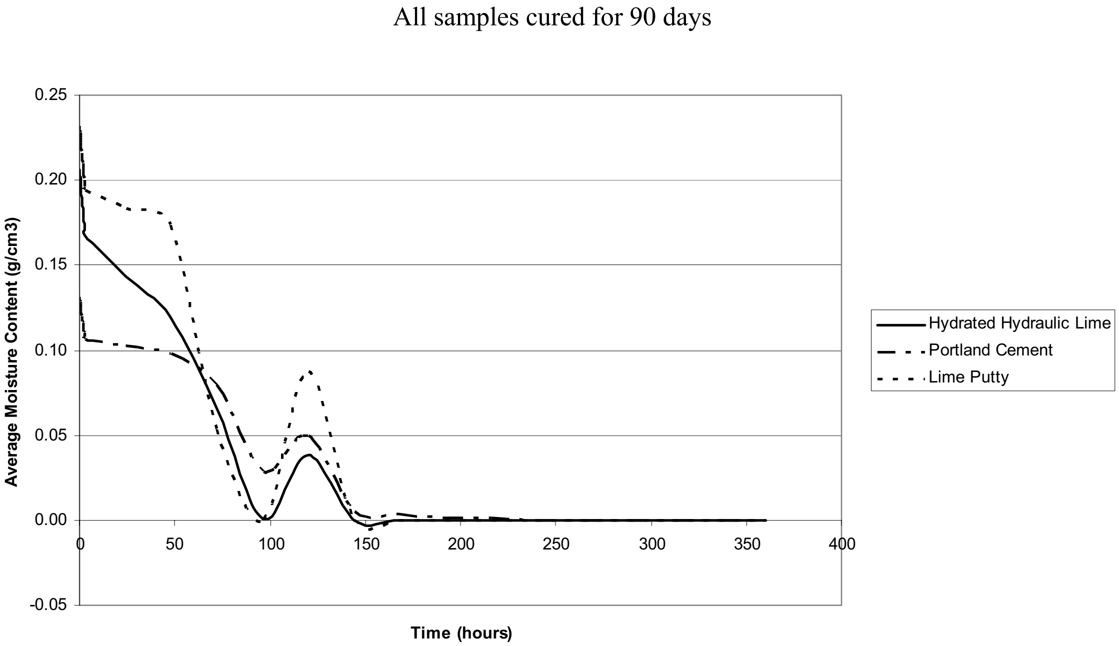
All samples cured for 90 days



4.4.2 Finish Pointing Mortars

The rate of drying for the sample sets varied according to the binder. The rate was higher for the hydrated hydraulic lime and lime putty samples and was lower for the Portland cement samples. All of the hydraulic lime and lime putty samples achieved an asymptotical state (0.01% of the weight of the dry sample in two successive weighings) after the eighth day of drying. The Portland cement samples took longer to achieve an asymptotical state: two of the samples after the ninth day and one of the samples after the 13th day of drying – a shorter amount of time than for the Portland cement deep repair mortars. The mortar samples declined steadily in weight while in the desiccant, however, there was a sharp increase after the first day in the oven followed by a sharp decrease in weight after the second day in the oven. This behavior was opposite than what occurred for the deep repair mortars in the same span of time. The average moisture content as a function of time was graphed for the finish pointing mortars.

Graph 4.16: Average Moisture Content during Drying of Finish Pointing Mortars



4.5 SALT CRYSTALLIZATION RESISTANCE ACCORDING TO RILEM V. 1A

4.5.1 DEEP REPAIR MORTARS

All of the deep repair mortar samples survived all 15 cycles of immersion in 14% sodium sulphate decahydrate solution. Contrary to the standard, however, the samples exhibited weight gain as opposed to loss. This was probably caused by the migration of the salts in solution into the pores of the mortar, which crystallized during drying in the oven. The repeated cycles may have encouraged the continual growth of the crystals which accounts for the significant increase in weight. As seen in Table 4.8, the weight increase is even more significant in consideration of the fact that the lime putty and hydrate hydraulic lime mortars lost material in the beakers while being immersed in the salt solution.

Table 4.8: Salt Crystallization Weight Change of Deep Repair Mortars

All samples cured for 90 days

Sample	Initial Weight	Final Weight	Weight Gained (%)
C-bh.1	225.76	237.30	5.11
C-bh.2	230.05	242.34	5.34
C-bh.3	226.68	238.87	5.38
C-bc.1	270.59	286.84	6.01
C-bc.2	258.55	271.56	5.03
C-bc.3	264.62	279.66	5.68
C-bp.1	227.54	238.60	4.86
C-bp.2	239.26	251.81	5.25
C-bp.3	231.55	241.66	4.37

Key to Samples

Group C-bh:	hydrated hydraulic lime deep repair mortars
Group C-bc:	Portland cement deep repair mortars
Group C-bp:	lime putty deep repair mortars

The visual appearance of the mortars was recorded and photographed for documentation of material loss or surface erosion (see Appendix G). The hydrated hydraulic lime mortars had two samples which had become disaggregated at the edges and corners of the sample and one which retained its shape with almost no disaggregation. The Portland cement mortars exhibited little to no cracking or erosion through all 15 cycles. The lime putty samples exhibited disaggregation at the edges and corners and minor cracking on some of the faces. After the samples were subjected to the 15 wet/dry cycles they were able to be handled and weighed at the completion of the test.

4.5.2 FINISH POINTING MORTARS

Most of the finish pointing mortar samples, with the exception of four samples, survived all 15 cycles of immersion in 14% sodium sulphate decahydrate solution. All of the samples exhibited weight gain as opposed to weight loss, the latter of which is assumed by the standard. As mentioned above, this was probably caused by the migration of the salts in solution into the pores of the mortar, which crystallized during drying in the oven. As seen in Table 4.9, the weight increase is significant, particularly in consideration of the fact that the lime putty and hydrated hydraulic lime mortars lost material in the beakers while being immersed in the salt solution.

Table 4.9: Salt Crystallization Weight Change of Finish Pointing Mortars

All samples cured for 90 days

Sample	Initial Weight	Final Weight	Weight Gained (%)
C-fh.1	226.09	235.10	3.99
C-fh.2	221.87	234.52	5.70
C-fh.3	226.81	232.24	2.39
C-fc.1	244.71	259.64	6.10
C-fc.2	248.24	265.52	6.96
C-fc.3	246.58	261.39	6.01
C-fp.1	218.29	226.39	3.71
C-fp.2	214.55	225.51	5.11
C-fp.3	219.10	227.31	3.75

Key to Samples

Group C-fh:	hydrated hydraulic lime finish pointing mortars
Group C-fc:	Portland cement finish pointing mortars
Group C-fp:	lime putty finish pointing mortars

The visual appearance of the mortars was recorded and photographed for documentation of material loss or surface erosion (see Appendix G). One of the hydrated hydraulic lime samples experienced deterioration from internal stress and expanded out towards the faces severely splitting four of the cube's faces after the eighth salt solution immersion cycle and was not immersed thereafter. The remaining two samples exhibited cracking and surface erosion. The Portland cement samples exhibited no change or definition in shape, while all three lime putty samples experienced deterioration from internal stress and expanded out towards the faces severely splitting three faces on each cube. All three lime putty samples completed 12 cycles of salt solution immersion before being destroyed, and though they could be handled, they were not immersed thereafter. All cubes were able to be handled and weighed at the completion of the test.

4.6 COMPRESSIVE STRENGTH ACCORDING TO ASTM C109-99

4.6.1 DEEP REPAIR MORTARS

The pound force limit for the deep repair mortars had to vary according to binder. The Portland cement samples began with a 15,000 pound force limit until one of the samples exceeded that strength and was increased to a 30,000 pound force limit. The hydrated hydraulic lime samples began at a 750 pound-force limit, which was able to be decreased to 300 pounds for the duration of the test for both hydraulic lime and lime putty deep repair mortars. The figures for compressive strength and the average per sample set are measured in megaPascals (MPa). In the International System this is a pressure/strength measurement of force per unit area equal to 1,000,000 Pascals (equivalent to one kilogram force per meter square).

Table 4.10: Compressive Strength for Deep Repair Mortars

All samples cured for 90 days

Sample	MPa	Average MPa
F-bh.7	2.04	
F-bh.8	3.52	2.40
F-bh.9	1.65	
F-bc.7	41.37	
F-bc.8	56.99	43.47
F-bc.9	32.06	
F-bp.7	2.69	
F-bp.8	3.00	3.03
F-bp.9	3.41	

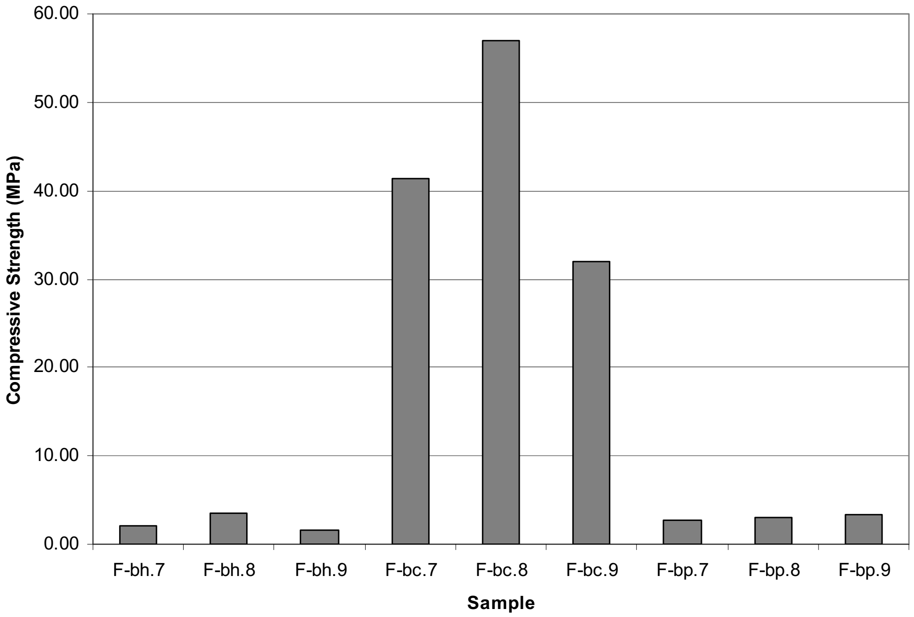
Key to Samples

Group F-bh:	hydrated hydraulic lime deep repair mortars
Group F-bc:	Portland cement deep repair mortars
Group F-bp:	lime putty deep repair mortars

As can be seen, the Portland cement samples exhibited a higher strength as is expected for the binder. This is particularly apparent in comparison to the compressive strength for the hydrated hydraulic lime and lime putty binders, which exhibit strengths approximately 94% less than the Portland cement samples after 90 days cure. The lime putty demonstrated a surprising higher strength than the hydrated hydraulic lime. The comparison of strengths is illustrated in Graph 4.17.

Graph 4.17: Compressive Strength of Deep Repair Mortars

All samples cured for 90 days



4.6.2 FINISH POINTING MORTARS

The pound force limit for the finish pointing mortars also varied according to binder. The Portland cement samples were tested at a 15,000 pound limit and the hydraulic lime and lime putty samples were tested at a 300 pound limit. The figures for compressive strength and the average per sample set in MPa units are presented in Table 4.11.

Table 4.11: Compressive Strength for Finish Pointing Mortars

All samples cured for 90 days

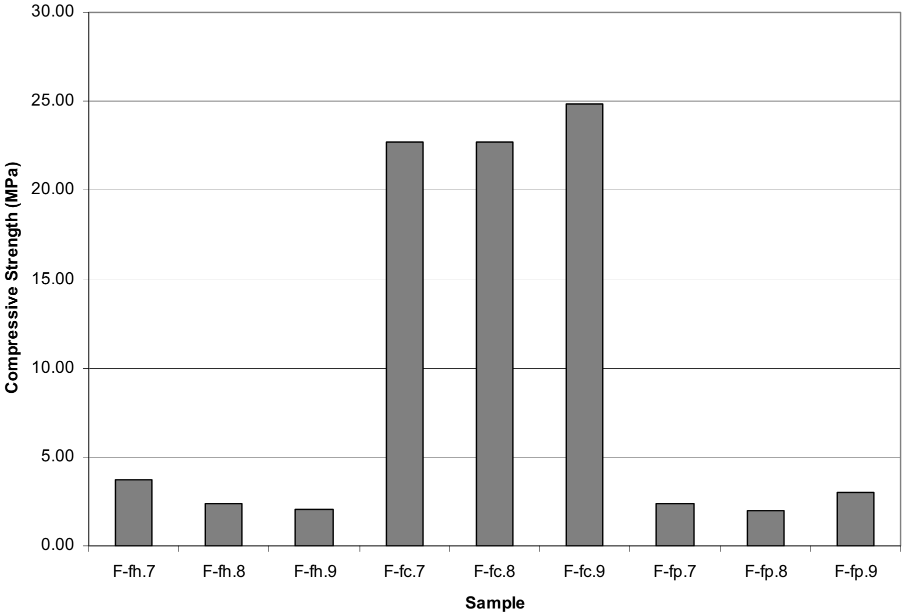
Sample	MPa	Average MPa
F-fh.7	3.72	
F-fh.8	2.38	2.72
F-fh.9	2.07	
F-fc.7	22.75	
F-fc.8	22.75	23.44
F-fc.9	24.82	
F-fp.7	2.38	
F-fp.8	1.97	2.45
F-fp.9	3.00	

Key to Samples
Group F-fh: hydrated hydraulic lime finish pointing mortars
Group F-fc: Portland cement finish pointing mortars
Group F-fp: lime putty finish pointing mortars

The Portland cement samples exhibited a high strength as is expected for the binder. This is particularly apparent in comparison to the compressive strength for the hydrated hydraulic lime and lime putty binders, which exhibit strengths approximately 86% less than the Portland cement samples. The finish pointing Portland cement mortar samples are significantly lower (approximately 50%) in compressive strength than the deep repair mortar samples and the lime-based samples are similar in compressive strength between the finish pointing and deep repair mortar samples. The comparison of strengths of the finish pointing mortar is illustrated in Graph 4.18.

Graph 4.18: Compressive Strength of Finish Pointing Mortars

All samples cured for 90 days



4.7 FLEXURAL STRENGTH ACCORDING TO ASTM C78-94

4.7.1 DEEP REPAIR MORTARS

The pound force limit for the deep repair mortars did not have to vary according to binder, unlike the compression tests. All samples were subjected to a 500 pound-force limit with the exception of the first Portland cement sample (G-fc.1) tested at 2,000 pounds to acquire an accurate pound-force limit for the remaining samples. There was a two-inch gauge length between the lower bearing blocks for every sample with the upper bearing block in the center which was lowered until fracture. The figures for flexural strength and the average per sample set in MPa units are presented in Table 4.12.

Table 4.12: Flexural Strength for Deep Repair Mortars

All samples cured for 90 days

Sample	MPa	Average MPa
G-bh.1	0.38	
G-bh.2	0.41	0.40
G-bh.3	0.41	
G-bc.1	0.83	
G-bc.2	0.66	0.68
G-bc.3	0.55	
G-bp.1	0.34	
G-bp.2	0.34	0.34
G-bp.3	0.34	

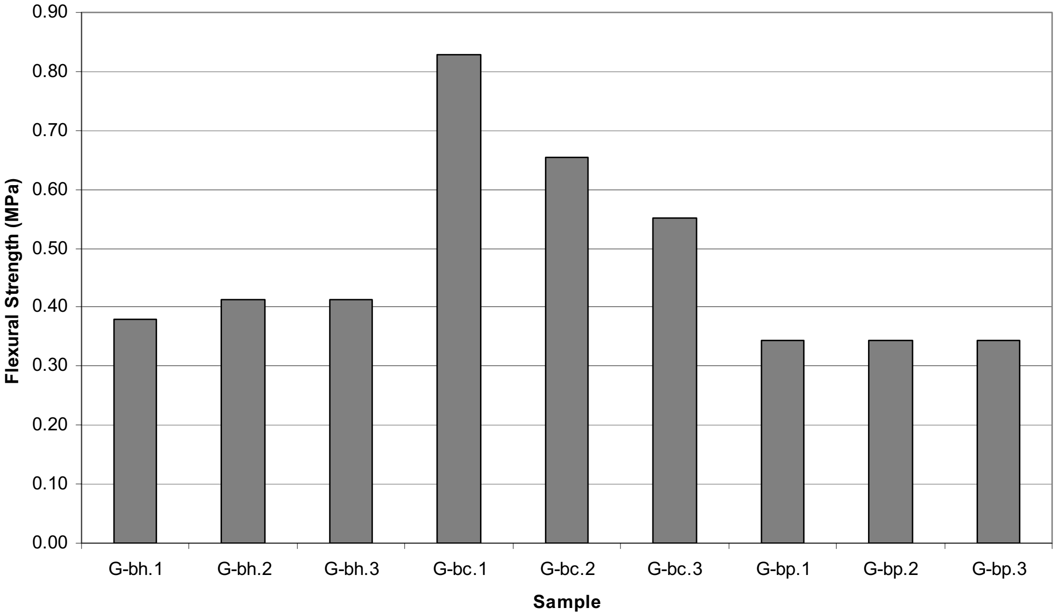
Key to Samples

Group G-bh:	hydrated hydraulic lime deep repair mortars
Group G-bc:	Portland cement deep repair mortars
Group G-bp:	lime putty deep repair mortars

The Portland cement samples exhibited a higher flexural strength than the hydrated hydraulic lime and lime putty binders, with the lime putty deep repair samples exhibiting the lowest flexural strength. The figures, however, are not as disparate as those between the compression strength figures according to binder. The comparison of flexural strengths is illustrated in Graph 4.19.

Graph 4.19: Flexural Strength of Deep Repair Mortars

All samples cured for 90 days



4.7.2 FINISH POINTING MORTARS

The pound force limit for the finish pointing mortars did not have to vary according to binder. All samples were subjected to a 500 pound-force limit with a two-inch gauge length between the lower bearing blocks for every sample with the upper bearing block in the center. The figures for flexural strength and the average per sample set in MPa units are presented in Table 4.13.

Table 4.13: Flexural Strength for Finish Pointing Mortars

All samples cured for 90 days

Sample	MPa	Average MPa
G-fh.1	0.31	
G-fh.2	0.24	0.29
G-fh.3	0.31	
G-fc.1	1.24	
G-fc.2	1.31	1.30
G-fc.3	1.34	
G-fp.1	0.28	
G-fp.2	0.34	0.31
G-fp.3	0.31	

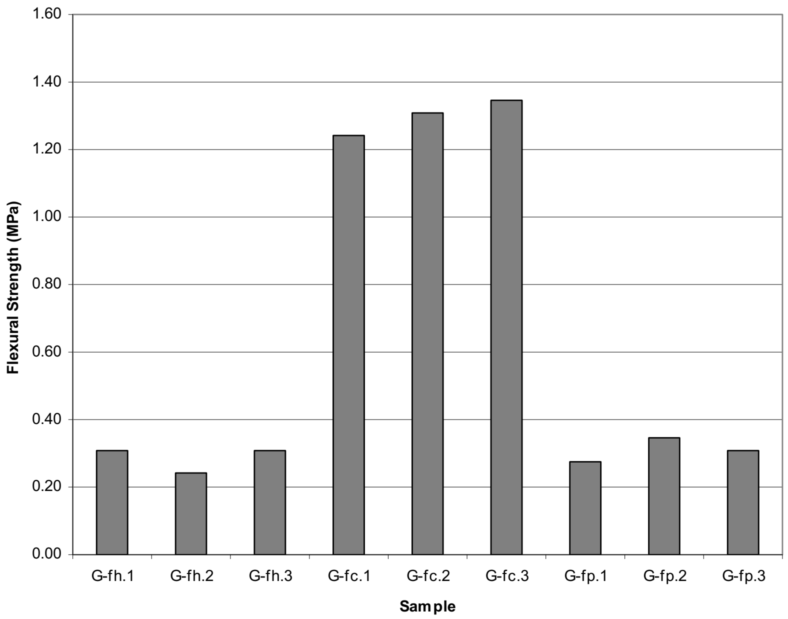
Key to Samples

Group G-fh:	hydrated hydraulic lime finish pointing mortars
Group G-fc:	Portland cement finish pointing mortars
Group G-fp:	lime putty finish pointing mortars

The Portland cement samples exhibited a higher flexural strength than the hydrated hydraulic lime and lime putty binders as expected. The hydrated hydraulic lime finish pointing samples exhibited the lowest flexural strength by only a marginal amount compared to that of the lime putty samples. There was a significant increase in the average flexural strength for the Portland cement finish pointing mortar compared to that of the deep repair mortar, yet a small decrease for both the lime-based finish pointing mortars compared to the deep repair mortars. The comparison of flexural strengths of the finish pointing mortars is illustrated in Graph 4.20.

Graph 4.20: Flexural Strength of Finish Pointing Mortars

All samples cured for 90 days



CHAPTER 5 – DISCUSSION OF RESULTS AND CONCLUSIONS

The individual properties tested for the mortars say much about their independent behavior. When attempting to understand how a masonry system will work as a whole, the results of the tests on the mortars are more revealing relative to the same properties tested for the unit masonry and the original mortars. A discussion will follow on the properties of the mortars – both in a fresh and cured state – independent of the stone properties as ideal from a laboratory perspective. Additionally, the discussion will attempt to compare the results of the mortar tests with the results of the tests conducted on the Egyptian limestone. Table 5.1 quantitatively compares the available data for the Egyptian limestone properties to that of the 90-day cured mortar properties.[43]

Table 5.1: Comparison of Properties of Egyptian Limestone and Mortars

Sample Sets	Average Apparent Porosity (%)	Average Water Absorption (%)	Average Compressive Strength (MPa)	Average Flexural Strength (MPa)
Egyptian Limestone	18.83 / 6.1	8.49	20.28	2.06
Hydraulic Lime Deep Repair Mortars (90 days)	15.64	10.36	2.4	0.40
Portland Cement Deep Repair Mortars (90 days)	11.09	7.77	43.47	0.68
Lime Putty Deep Repair Mortars (90 days)	18.67	12.38	3.03	0.34
Hydraulic Lime Finish Pointing Mortars (90 days)	17.08	11.42	2.72	0.29
Portland Cement Finish Pointing Mortars (90 days)	11.92	8.4	23.44	1.30
Lime Putty Finish Pointing Mortars (90 days)	19.76	13.2	2.45	0.31

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[43] Bourguignon, *Study of Deterioration Mechanisms and Protective Treatments for the Egyptian Limestone of the Ayyubid City Wall of Cairo* (from the Rock Engineering Laboratory of Cairo University): 83.

5.1 WATER VAPOR TRANSMISSION

Water is present in a masonry system in the liquid and vapor state. Water vapor which can become liquid water through condensation or hygroscopicity can enable the transport of water in a masonry system. It is therefore important to consider especially in Cairo's desert climate. In conditions of optimal ground water pressure, wind pressure, temperature and relative humidity, proper water vapor permeability in the mortar will draw away moisture from the masonry units and transport it to the exterior surface of the wall decreasing the accelerated decay by salt crystallization within the masonry units.

The results of the water vapor transmission test show that the permeability for Portland cement, according to both ASTM and NORMAL standards, coincided with published research.[44] Portland cement, upon hardening, forms a crystalline network of calcium silicate hydrate which replaces the voids left by the free water in the mix and thus results in very small pores, decreasing its permeability. The average permeability of the Portland cement deep repair mortar samples in this research was 75% and 70% (ASTM and NORMAL respectively) less than the permeability of the hydrated hydraulic lime and lime putty mortars (ASTM average permeabilities were: $1.06 \cdot 10^{-9}$ perm/cm, $1.25 \cdot 10^{-8}$ perm/cm, and $1.27 \cdot 10^{-8}$ perm/cm respectively and according to NORMAL average permeabilities were : $5.03 \cdot 10^{-9}$ perm/cm, $1.94 \cdot 10^{-8}$ perm/cm, and $1.87 \cdot 10^{-8}$ perm/cm respectively). Similarly, the Portland cement finish pointing mortar samples in this research was 50% and 66% (ASTM and NORMAL respectively) less than the permeability of the hydrated hydraulic lime and lime putty mortars (ASTM average permeabilities were: $5.72 \cdot 10^{-9}$ perm/cm, $1.71 \cdot 10^{-8}$ perm/cm, and $1.35 \cdot 10^{-8}$ perm/cm

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[44] Judith Jacob and Norman R. Weiss, "Laboratory Measurements of Water Vapor Transmission Rates of Masonry Mortars and Paints." *APT Bulletin* 21 (no. 3/4, 1989): 66.

respectively and according to NORMAL average permeabilities were: $7.48 \cdot 10^{-9}$ perm/cm, $2.01 \cdot 10^{-8}$ perm/cm, and $2.18 \cdot 10^{-8}$ perm/cm respectively).

The vapor permeabilities for the hydrated hydraulic lime and lime putty mortars were within 2% to 8% of each other according to the results of both standards. This is somewhat unexpected in comparison with published research. In a study conducted by English Heritage and the Building Research Establishment, the hydraulic lime mortars were 25% to 66% (depending on hydraulic lime manufacturer and type) lower in permeability than that of the lime putty mortar.[45] The study inconclusively found that lower permeabilities coincided with higher hydraulicity. If this is the case, the increased hydraulicity of the lime putty due to the addition of brick dust in this research may have decreased the permeability of the lime putty deep repair mortars. This is also supported by the Smeaton project which found lower water vapor permeability rates in the lime formulations with brick dust.[46] It is unclear why the Riverton hydrated hydraulic lime which is eminently hydraulic was not less permeable due to the addition of brick dust as well. Eminently hydraulic limes cure through a carbonation process and harden in a manner similar to cement due to its clay components. It may be that the brick dust has a minimal effect on the hydraulicity of the Riverton lime being already hydraulic and instead makes its contribution more as an air-entraining component.

There were also higher permeability values in the finish pointing mortars than the deep repair mortars. This may be due to a couple of reasons. The increased surface area of the aggregate which is finer in the finish pointing mortar may cause the increase of

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[45] Teutonico et al., “A Comparative Study of Hydraulic Lime-Based Mortars,” *International RILEM Workshop on Historic Mortars. Paisley, Scotland, May 1999.* (France: RILEM Publications, 2000): 344.

[46] Teutonico et al, “The Smeaton Project: Factors Affecting the Properties of Lime-Based Mortars.” *APT Bulletin*. (vol. 25, no. 3-4 1994): 42.

permeability. Additionally, a study conducted reported that wood ash as an additive in a mortar formulation slightly increases the permeability of a mortar.[47]

The role of brick dust is more unclear. One research project presented findings of larger particle size brick dust acting as an air-entraining additive and smaller particle size brick dust contributing to pozzolanic qualities of quicker setting and increased strength.[48] In this research the deep repair mortar with larger brick dust particles was less permeable than the finish pointing mortars with smaller particle size brick dust, though the particle size in the finish pointing mortar (≤ 150 μm) was not as small as suggested in the literature (≤ 75 to 38 μm). The same argument of increased surface area may be applied in this case.

A low value for permeability would not be desirable for the Ayyubid wall particularly due to the high concentration of soluble salts extant in the masonry units. If different permeabilities exist at the mortar/masonry plane, internal stresses will result due to salt crystallization growth fed by the water vapor. This is a common cause of structural failure in porous building materials.[49] Therefore, the permeability values would suggest the use of either the hydrated hydraulic lime or lime putty mortar formulations for use in the Ayyubid wall.

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[47] Mark Goodman, *The Effects of Wood Ash Additive on the Structural Properties of Lime Plaster.* (Master's Thesis, University of Pennsylvania, 1998): 89.

[48] Teutonico et al, "The Smeaton Project,": 40.

[49] Giorgio Torraca, *Porous Building Materials: Materials Science for Architectural Conservation*, (Rome: ICCROM, 1982):109.

5.2 WATER ABSORPTION AND EVAPORATION

The other state in which moisture is present in a masonry system is as a liquid. The liquid moves through the system via two mechanisms: capillarity and infiltration. The water absorption test is useful for providing information on the capacity of water absorption and, more critically, the apparent porosity of a mortar. According to one study, a mortar "should absorb its generous share of the water circulating in the masonry pores."[50] In this case, this is to impede the water which provides mobility to soluble salts from entreating on the masonry unit instead of the mortar.

The average water absorption of the Portland cement samples was 25% less than that of the hydrated hydraulic lime and 40% less than the lime putty in both deep repair and finish pointing mortars. The Portland cement reached its saturation level approximately 2.75 hours after immersion commenced while the hydrated hydraulic lime and lime putty reached their saturation levels in approximately the first ten minutes. The average apparent porosity of the Portland cement samples was approximately 30% less than that of the hydrated hydraulic lime and 40% less than that of the lime putty for both deep repair and finish pointing mortars. These results are to be expected as, mentioned above, the voids in Portland cement mortars are predominantly filled with calcium silicate hydrate crystals upon hardening which results in a low proportion of pores remaining. Additionally, the pores are known to be small in diameter – radii of less than $10^5\eta m$[51] – compared to the lime-based binders. Pores of small diameters, in turn, increase

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[50] S. Peroni et al., "Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes" *Mortars, Cements and Grouts used in the Conservation of Historic Buildings.* (Rome: ICCROM, 1982): 71.

[51] J. Schafer and H.K. Hilsdorf, "Ancient and New Lime Mortars--The Correlation Between Their Composition, Structure and Properties" *Conservation of Stone and Other Materials: Proceedings of the*

the capability of capillary rise in a masonry system due to suction and surface tension. The water can carry soluble salts with it which crystallize in the pores and contribute an additional attraction for water. These patterns can continue, resulting in capillary rise of several meters in a wall – particularly throughout centuries of time. Capillary action can carry water to heights, in some cases, of eight to ten meters, but also can carry water far distances horizontally.[52] Lime-based mortars also exhibit capillary rise capabilities, though their pore size distribution is known to greatly vary compared to Portland cement. The presence of larger pore sizes decreases the extent of capillary rise which function primarily by small pores.

The ability for a material to evaporate the moisture contained within it also plays a critical role in the effect of water mobility and salt crystallization. If equilibrium of the rates of water intake and evaporation exist in a masonry system, the capillary rise is impeded and should, theoretically, stop.[53] The evaporation rate of the mortar should then be higher than the masonry unit's rate of evaporation to allow for the transport of the moisture out of the system more efficiently. The critical moisture content determined from the drying test defines the transition from the capillarity of water to the diffusion of water vapor in a material, eventually resulting in evaporation depending on porosity, pore size, and environmental conditions. The rate of diffusion, a less efficient mechanism for drying, varied between the binders (diffusion being represented by the figures below the determined critical moisture content). The lime-based mortars reached an asymptotical state after the eighth day of drying and the Portland cement after the 14th and 15th day of

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International RILEM/UNESCO Congress held at the UNESCO Headquarters, Paris, June 29-July 1, 1993. (London: E. & F.N. Spon Ltd., 1993): 608.

[52] Bernard Feilden, *Conservation of Historic Buildings.* (London: Butterworths and Co. Ltd., 1982): 99.

[53] Torraca, *Porous Building Materials:* 17.

drying. The longer rate of evaporation by vapor diffusion for the Portland cement would suggest a tendency for the mortar to retain moisture in the masonry system longer enriching these areas with soluble salts and encouraging decay.

The lower absorption capacity, lower apparent porosity, and slower drying rate of the Portland cement would be less desirable for use in the Ayyubid wall. However, the fast rate at which the lime-based mortars reached saturation compared to that of the Portland cement could also be detrimental to the masonry system. In this case, the permeability and drying behavior exhibited by the lime-based mortars could be sufficient to counteract some of the negative effects of the high saturation tendency.

The comparison of the mortar binders may be more illuminating when seen in conjunction with porosity percentages available for the Egyptian limestone. The apparent porosity of the limestone was 18.83% according to the one sample tested by the Rock Engineering Laboratory of Cairo University.[54] However, a study was conducted at the University of Pennsylvania to determine apparent porosity because the test method by the laboratory in Cairo was unknown and there was no sample set. The average apparent porosity of four samples was 6.1%.[55] The latter study may present such a discrepancy in percentages because the samples used were small flakes which could have had a lower porosity and their small size would make for large experimental errors. It is difficult to compare these figures to those attained for the mortars; however, an overall higher value for porosity is generally desirable. It would therefore be recommended to implement either of the lime-based mortars for use in the Ayyubid wall.

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[54] Ibid.

[55] Ibid. (Dewey, unpublished, 2000): 83.

5.3 SALT CRYSTALLIZATION RESISTANCE

The most deleterious effects of water in a masonry system can be connected to its transport of soluble salts. There are several sources for soluble salts at the Ayyubid wall and they are the leading cause of the Egyptian limestone deterioration, as discussed in Chapter One.

The salt resistance test implemented in this research subjected the samples to a 14% solution of calcium sulfate decahydrate solution to simulate accelerated weathering. This test has been criticized for inapplicability due to the rapid deterioration exhibited by mortars containing calcium carbonate, though no other standardized test has replaced it.[56]

The Portland cement mortars in this research, as expected, exhibited little to no deterioration after the salt crystallization test. The lime-based deep repair mortars fared better, visually, than the finish pointing mortars which experienced internal stress and fracture. This is partially because the crystallization and dissolution of salts takes place primarily in medium to large pores which is accommodated for in the lime-based binders and not in the Portland cement samples. It is also attributed to the lower strength of the lime-based mortars to sustain the crystal growth.

It has been found in studies that the addition of low-fired brick dust aids in the resistance to salt attack, particularly of particles over 300 microns in size. This may be that the contribution of the brick dust to the lime-based mortar formulations is as an air-

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[56] S. Peroni et al., "Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes," *Mortars, Cements and Grouts used in the Conservation of Historic Buildings.* (Rome: ICCROM, 1982): 71. A. Paloma et al., "Mortars for Restoration: Decay Due to Salt Crystallization," *Proceedings of the 8th Congress on Deterioration and Conservation of Stone, Berlin, 30 September – 4 October, 1996.* (Berlin: S.N., 1996): 1549.

entraining additive which allows for an increased rate of carbonation, thus increasing the durability of the mortar against salt attack.[57]

Another research project conducted the salt resistance test on samples containing wood ash which suggested that the addition of wood ash is detrimental to a mortar's resistance to salt attack as large percentages of weight loss differences compared to control samples were recorded.[58]

Similarly, the larger sand particles in the deep repair mortars contribute to a greater resistance and durability than those of smaller particles as in the finish pointing mortars.

These materials' contributions may provide some indication of the performance of the mortars resistance to salt attack and suggest the reason the deep repair mortars fared better in the salt solution cycling. These mechanisms, though, are complicated and the raw materials' contributions to the mortars are not definite.

The high resistance of the Portland cement mortars would suggest that they are better for use in the Ayyubid wall. The high resistance also needs to be considered in the context of mechanical strength, discussed below. It has also been published that Portland cement forms soluble salts of sodium and potassium upon setting which are leached long thereafter into the masonry system.[59] The recommendation of Portland cement as a binder for the deep repair and finish pointing mortars due to salt resistance would be reconsidered, due to the harm of releasing additional soluble salts into an already salt-laden masonry system.

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[57] Teutonico et al. "The Smeaton Project," *APT Bulletin*: 40.

[58] Mark Goodman, *The Effects of Wood Ash Additive on the Structural Properties of Lime Plaster.*: 118.

[59] Peroni et al.: 71.

5.4 COMPRESSIVE STRENGTH

A masonry system as a whole must be able to withstand loads so a mortar should contribute to that end and not introduce new stresses into the system because of too low or high strengths compared to that of the stone.

According to general recommendations suggested in research conducted in 1993, the compressive strength of a pointing mortar should be lower than 10 MPa and higher than 2 MPa in the mortar joint.[60] These recommendations exclude any relationship to the masonry unit; however, taken at face value, they would suggest the lime putty mortars are more compatible as repair mortars for an historic masonry system (two out of three of the hydrated hydraulic lime mortars demonstrated values under or just above 2 MPa for the deep repair mortars).

The lime putty mortars exhibited values higher than expected, being almost equal in strength to the hydrated hydraulic lime mortars. This may be due to the presence of the brick dust. It is known that the mechanical strength of mortars increases due to the presence of brick dust, which is attributed to the hydraulic reaction occurring at the edge of the brick dust particles.[61] Again, it would seem that the brick dust affects the properties of the lime putty more than the hydrated hydraulic lime.

When considering the mortars' performances relative to the Egyptian limestone, the Portland cement deep repair mortar far exceeded, by 100%, the limestone in compressive strength. The finish pointing mortars also exceeded, by 14%, the limestone

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[60] Jose Delgado Rodrigues, "In the Search for Tentative Recommendations Regarding Compatible Restoration Mortars," *Compatible Materials for the Protection of European Cultural Heritage, PACT 56.* (study by Knöfel and Huesmann, 1993); (Athens: Technical Chamber of Greece, 1998): 145.

[61] A. Elena Charola and Fernando M.A. Henriques, "Hydraulicity in Lime Mortars Revisited," *International RILEM Workshop on Historic Mortars. Paisley, Scotland, May 1999.* (France: RILEM Publications, 2000): 99.

in compressive strength. The hydrated hydraulic lime and lime putty deep repair mortars demonstrated strengths below that of the Egyptian limestone – 88% to 85% respectively – and 88% to 90% for the finish pointing mortars. The excessive high strength of the Portland cement will not allow for give under load which instead would be carried solely by the stone accelerating its decay due to stress. For the long term soundness of the wall a mortar of excessively low strength can also be detrimental. If the mortar cracks easily in response to an applied compressive load, it will similarly fail the system by introducing new voids for water and salt infiltration. While the lime-based mortars exhibit quite low strengths, a benefit of them is their continued increase in compressive strength over time (up to one year and longer) do to a more complete process of carbonation.[62]

The recommendation for use in the Ayyubid wall would be the lime-based mortars – erring on the side of low compressive strength is more sustainable for the masonry system than erring on the side of a higher compressive strength.

5.5 FLEXURAL STRENGTH

The flexural strength is an indication of a mortar's resistance to bending stress, or tensile stress, resulting from structural settlement, thermal cycles, or fluctuations of humidity.

The flexural strength of the Egyptian limestone is more comparable with that of the Portland cement. However, in the cement industry a rule of thumb recommends that the flexural strength of cement be 10% of the cement's compressive strength.[63] From this perspective, the Portland cement is not as good an option for use in the wall as the

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[62] Teutonico et al., "A Comparative Study of Hydraulic Lime-Based Mortars,": 345.

[63] Anon. "Compressive versus Flexural Strength." *The Concrete Producer.* December 2003.

dynamic loads in the system will preferentially compromise the bending capacity of the mortar. The lime-based mortars demonstrate a better compatibility with the Egyptian limestone in consideration of their own compressive strengths. For the deep repair mortars, the Portland cement's flexural strength is only 1.6% of its compressive strength, while the hydrated hydraulic lime mortar's strength is 16.7% of its compressive strength and the lime putty mortar's flexural strength is 11% of its compressive strength. For the finish pointing mortars, the Portland cement's flexural strength is only 5.5% of its compressive strength, while the hydrated hydraulic lime mortar's strength is 10.7% of its compressive strength and the lime putty mortar's flexural strength is 12.7% of its compressive strength.

An increase of almost 100% was exhibited by the Portland cement finish pointing mortar over that of the deep repair mortar. It is uncertain why the increase would be so drastic unless the finer sand grains, brick dust and wood ash all contributed to such a large increase in flexural strength. Wood ash did increase flexural strength in a study conducted.[64] However, both of the lime-based mortars decreased in flexural strength from the deep repair mortar to the finish pointing mortar (the hydrated hydraulic lime by a somewhat high, 25% and the lime putty by 8%).

Overall, the flexural strengths were quite low for the mortars. One reason may be that the bending test is more accurate for materials that are homogenous and isotropic. In this research, the lime-based mortars are anisotropic due to incomplete carbonation and may therefore reduce the flexural strength recorded during the test. Additionally, when molding the mortars in their fresh state, more homogenous samples may have been

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[64] Mark Goodman, *The Effects of Wood Ash Additive on the Structural Properties of Lime Plaster.*: 91.

achieved by vibrating the mold as the method for tamping. In this research, though the mortars were tamped according to the standard which required a nonabsorbent rod with a flat surface and right angles, the process is considered more insufficient. The result is a more heterogeneous sample which may also contribute to the low flexural strengths.

The recommendations, however, based on flexural strength of the mortar formulations would be those of the lime-based mortars due to their more appropriate proportion of flexural strength and compressive strength. Additionally, the proportion of flexural strength of the Egyptian limestone is 10% compared to that of its compressive strength which would also suggest a better compatibility with the lime-based mortars.

5.6 FRESH MORTARS

The fresh mortars of the same formulations as this research were tested in a previous study as discussed in Chapter Two. The following results are presented of the fresh mortar formulations by binder samples and relative to the above findings, including those of the Egyptian limestone.[65]

Portland cement has good working properties in the fresh and non-cured state. This is a benefit of Portland cement, as it is known that lime putty-based mortar mixes require more highly skilled masons for application than that of Portland cement.

The bleeding rate of the Portland cement was comparable to that of the lime-based mortars for the deep repair mortar formulation; however, the bleeding ceased after four hours when the cement had set. This is a desirable quality for the Ayyubid wall. The porosity of the Egyptian limestone would encourage the water that is leached from the

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[65] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo.*

lime putty and hydrated hydraulic lime, which exhibited bleeding rates that did not cease after four hours, to rise through the ashlar by capillary action and accelerate its decay. The hydrated hydraulic lime and Portland cement finish pointing mortars had a significantly lower bleed rate than their deep repair mortars which makes them appropriate for use in the wall. However, when applied to the context of the surrounding stone which exhibits lower rates of water absorption and evaporation, the higher water retention and increased rate of evaporation of the lime putty mortars would be of greater benefit to the stone.

The set time of Portland cement is appropriate for the deep repair mortar due to its reliance of hydration for cure as opposed to carbonation when in the deeper recesses of the masonry wall. This would allow the masons to finish point the wall soon after the deep repair mortar compensation was completed. However, in the context of the cured state, and in particular, the notoriously high compressive strength and low porosity of Portland cement, the Portland cement is not a viable option for use in the rubble core interior, bedding of the ashlar or finish pointing. The set time for the deep repair and finish pointing hydrated hydraulic lime mortars was more rapid than that of the lime putty due to its combination in the curing process between hydraulic action and carbonation. The lime putty mortars set one and a half to two days for the deep repair and finish pointing mortars respectively, which was suggested by Cappeto as too slow for use in the wall. Conversely, however, one study suggested a maximum set time of three days, in which case the lime putty mortars could be considered sufficient, though no indication was made as to whether the criteria was based on deep repair or finish pointing mortars.[66]

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[66] Peroni et al.: 91.

The application of the lime putty mortars in the Ayyubid wall may necessitate a delay before the application of the pointing mortars, but in the pursuit of the proper conservation of the wall, this delay is acceptable. Additionally, an advantage in the application of the lime putty mortars in the wall is that their rate of set may increase due to the favorable environmental conditions. In one study it was suggested that the optimal conditions for the carbonation of lime-based mortars is low relative humidity, strong wind velocity, and high temperature, all of which are present at the Ayyubid wall.[67]

Table 5.2: Acceptable Binders for Fresh Mortars According to Cappeto Research[68]

Test	Deep Repair Mortar	Finish Pointing Mortar
Water Retention	Lime Putty or Portland Cement	Hydrated Hydraulic Lime or Portland Cement
Bleeding*	Portland Cement	Hydrated Hydraulic Lime or Portland Cement
Set Time	Lime Putty, Hydrated Hydraulic Lime or Portland Cement	Lime Putty or Hydrated Hydraulic Lime

* It was determined that lower bleeding rates are more appropriate than higher bleeding rates for mortar, which is contradictory to the conclusions in Cappeto's research from 2003.

Table 5.3: Acceptable Binders for 90-Day Cured Mortars According to this Research

Test	Deep Repair Mortar	Finish Pointing Mortar
Water Vapor Permeability	Lime Putty or Hydrated Hydraulic Lime	Lime Putty or Hydrated Hydraulic Lime
Water Absorption / Drying	Lime Putty or Hydrated Hydraulic Lime	Lime Putty or Hydrated Hydraulic Lime
Salt Crystallization Resistance	Portland Cement	Portland Cement
Compressive Strength	Lime Putty or Hydrated Hydraulic Lime	Lime Putty or Hydrated Hydraulic Lime
Flexural Strength	Lime Putty or Hydrated Hydraulic Lime	Lime Putty or Hydrated Hydraulic Lime

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[67] K. Van Balen and G. Van Gemert, "Modeling Lime Mortar Carbonation," *Materials and Structures*. 27 (1994): 394.

[68] Cappeto, *A Performance Analysis of Repair Mortars for the Ayyubid Wall of Cairo*: 98 and 103.

The research conducted on the fresh, non-cured mortars and the 90-day cured mortars suggests that the optimal formulations for use in the Ayyubid wall would be the hydrated hydraulic lime and lime putty with brick dust mortars. The behavior of a mortar cannot be determined by one property alone, but rather approached more holistically in relation to several of its properties and the properties of the masonry units extant in the wall.

5.7 FUTURE RESEARCH

The next phase of research relating to the mortars employed at the Ayyubid wall should investigate the mortar formulations in this research after one year of curing in the same conditions. The same tests should be conducted, but additional tests would be more beneficial. Tests for bond strength to the Egyptian limestone according to ASTM C952-97: Standard Test Method for Bond Strength of Mortar to Masonry Units and a test for the modulus of elasticity according to ASTM C469-94: Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression. Other tests could be recommended such as abrasion resistance and the release of soluble salts. Lastly, an analysis of the carbonation of the lime-based mortars with x-ray diffraction would further the discussion on porosity, permeability, and strength.

APPENDIX A: LITERATURE REVIEW

Brief Literature Review Related to Mortars, Particularly with Brick Dust Additives

Date	Author(s)	Title and Source	Summary
1982	S. Peroni, C. Tersigni, G. Torraca, S. Cerea, M. Forti, F. Guidobaldi, P. Rossi-Doria, A De Rege, D. Picchi. F.J. Pietrafitta, G. Benedetti	"Lime Based Mortars for the Repair of Ancient Masonry and Possible Substitutes" *Mortars, Cements and Grouts used in the Conservation of Historic Buildings*	This seminal research outlines the positive and negative qualities of various mortar formulations, primarily differentiated by binder, and the several requirements necessary for a compatible mortar in an historic building. The following tests were conducted with the corresponding recommendations after the results: maximum set time of three days; compressive strengths between 0.5 and 3.0 MPa; flexural strengths between 0.4 MPa and 2.5 MPa; modulus of elasticity: no indicative results were able to be provided; minimum 20% porosity with 65% above 0.1 micron (though the porosity would have to be taken in to consideration with permeability which was not tested in this research); water absorption minimums should be set, none provided; and a maximum release of alkaline elements at 8 meg/kg. This research was conducted in an attempt to provide standardized values to apply to mortar formulation criteria in historic buildings. The results did not relate to specific properties of a masonry unit nor were they applied in the field, but it was the first work to suggest successful repair mortars could be formulated without the sole use of cement.
1989	Judith Jacob and Norman R. Weiss	"Laboratory Measurements of Water Vapor Transmission Rates of Masonry Mortars and Paints." *APT Bulletin* 21	This article aimed to shed approaches of restoration as "weak" or "strong" by researching the subtleties of water vapor permeability according to ASTM E96-80 on mortars and paints. The method closely followed the standard except the climatic control chamber was at a relative humidity of 10%. The conclusions for the mortars found that

Date	Author(s)	Title and Source	Summary
			the cement mortar had the lowest permeability, followed by the cement mortar with one part hydrated lime, then the mortar of equal amounts cement and hydrated lime, followed by the highest permeability of the one part cement two parts hydrated lime mortars. This article was the first to publish rates of permeability comparing cement with lime based mortars with use of a standard.
1993	I. Papayianni and K. Theocharidou	"Efflorescence Tendency of Mortars Used in Interventions on Old Maosnry" *Conservation of stone and other materials: proceedings of the international RILEM/UNESCO congress held at the UNESCO headquarters, Paris, June 29-July 1, 1993.*	This research attempted to draw a correlation between the efflorescence of mortars and strength rather than the usual correlation of porosity and chemical composition. Mortar formulations were all with lime, some with cement and a variation between pozzolana and brick dust (the latter in high proportion). Samples were cured for two years and tested for tensile and compressive strength, and absorption. The study concluded that the fine solid constituent content including brick dust allowed a higher absorption of water yet took longer in time for a tested height of capillary action. However, samples with smaller brick dust particles were higher in absorption which led the authors to believe that the brick dust does not contribute to porosity but to water retentivity. Similarly, the mortars with brick dust exhibited the highest strength, even those without cement added to the formulation. The release of soluble salts was determined to be highest in mortar containing cement or lower portions of pozzolana with lime.

APPENDIX A: LITERATURE REVIEW

Date	Author(s)	Title and Source	Summary
1994	Jeanne Marie Teutonico, Iain McCaig, Colin Burns, John Ashurst	"The Smeaton Project: Factors Affecting the Properties of Lime-Based Mortars." *APT Bulletin*	This research provides preliminary findings of mortars' behaviors according to binders and some additives, including brick dust, for use in Hadrian's wall in England. The following tests were conducted: moisture content, stiffening rate, compressive strength, water vapor permeability, depth of carbonation, and sodium sulphate resistance. The conclusions were as such: the addition of brick dust significantly alters the lime mortars' behavior (particularly in mixtures of lime:sand:brick dust of 1:3:1). Low-fired brick dust positively effects strength and durability in lime mortars of a higher brick dust proportion. Lastly, a small portion of white cement to lime mortars negatively affects the lime mortars' behavior. This phase did not include implementation of the mortar formulation in the wall, though it was planned for a future phase.
1995	John Carr	*An Investigation on the Effect of Brick Dust on Lime-Based Mortars*	This research was conducted at the University of Pennsylvania for a thesis requirement. Tests performed were: workability, set time, set under water, shrinkage, bulk density, compressive strength, water vapor transmission, water absorption, and salt resistance. The study concluded that brick dust exhibited a positive influence on the salt resistance of the lime putty mortars and seemed to impart pozzolanic qualities to the mortars.
1996	F.M.A. Henriques	"Testing Methods for the Evaluation of New Mortars for Old Buildings," *Science and Technology for*	This article outlines the various standards used through different countries for testing the properties of mortars. It presents the difference standards for mortar preparation,

APPENDIX A: LITERATURE REVIEW

Date	Author(s)	Title and Source	Summary
		Cultural Heritage.	molding, curing and a few exemplary tests, such as water absorption by capillary action and water vapor permeability. The differences discussed are related to the units used, ambient conditions of the test, and length of time. Overall, it is a plea for the international community to agree on common procedures and specifications.
1996	Elena A. Charola and F.M.A. Henriques	"Lime Mortars: Some Considerations on Testing Standardization." *Use of and Need for Preservation Standards in Architectural Conservation, ASTM STP 1355*.	This article further criticizes the lack of a common international standard for various tests associated with the conservation industry. This research went further to conduct sample preparations and curing followed by tests of compressive and flexural strengths, dynamic modulus of elasticity, capillary water absorption, and water vapor permeability; all according to RILEM, NORMAL, CSTB, NF, or BS standards. The tests were shown to vary in results according to curing conditions which augments the argument that standard procedures are necessary. Similarly, though the tests were primarily created for cement, it is critical that the study of lime mortars be subjected to testing procedures.
1998	Mark Goodman	*The Effects of Wood Ash Additive on the Structural Properties of Lime Plaster*	This research was conducted at the University of Pennsylvania for a thesis requirement. Tests performed were: water retention, stiffening rate, shrinkage, capillary absorption, flexural strength, water vapor transmission, adhesion, and salt resistance. The study concluded that in a mortar of lime:sand::1:1.5 with a 10%-20% wood ash additive a positive influence was exhibited on workability, adhesion, stiffening rate, permeability, and flexural strength.

APPENDIX A: LITERATURE REVIEW

Date	Author(s)	Title and Source	Summary
2000	Jeanne Marie Teutonico, Geoff Ashall, Elizabeth Garrod, Tim Yates	"A Comparative Study of Hydraulic Lime-Based Mortars," *International RILEM Workshop on Historic Mortars. Paisley, Scotland, May 1999.*	This is the first of a new phase investigating hydraulic lime in mortar. The mixes were cured for 60 days with a 90% relative humidity for ten days and a 75% relative humidity for 50 days. The fresh mortars were tested for moisture content, flow, and stiffening rate and the cured mortars were tested for porosity, water vapor permeability, compressive and flexural strengths, and resistance to salt crystallization and free-thaw. The conclusions drawn were that the water vapor permeability of hydraulic lime mortars is less than that of lime putty mortars, but higher than those with no addition of lime putty. The addition of significant proportions of lime putty to the hydraulic lime:sand mortars reduced the compressive strength and negatively affected the resistance to salt crystallization. It was also observed that the addition of lime putty slightly increased porosity and slowed stiffening.
2000	D. C. Hughes and D. B. Sugden	"A Comparative Study of Hydraulic Lime-Based Mortars," *International RILEM Workshop on Historic Mortars. Paisley, Scotland, May 1999.*	The mortars studied in this research employed natural hydraulic lime with brick dust at different temperatures and grading. The mortars were subjected to various methods and times of curing and thereafter their compressive strengths were tested. The study found that strength is enhanced by brick dust and brick dust at a low calcination temperature increases strength where there is a poor opportunity for pozzolanic reactions to occur. If there is the opportunity to attain finer brick dust particles and add more water, a wide range of strengths can be engineered.

APPENDIX A: LITERATURE REVIEW

Date	**Author(s)**	**Title and Source**	**Summary**
2000	A. Elena Charola and Fernando M.A. Henriques	"Hydraulicity in Lime Mortars Revisited," *International RILEM Workshop on Historic Mortars. Paisley, Scotland, May 1999.*	This article provides a brief background into the use of brick dust in lime mortars and hydraulicity research. The general hydraulic reactions are understood, however, identification of hydraulic compounds is still unknown due to the variation of composition of the pozzolanic materials, conditions of the pozzolana/lime/water reaction and the rapid loss of water during setting only allowing for small sized reactions to take place. The phases that have been identified were calcium aluminate hydrate, calcium silicate hydrate, and calcium alumino silicate hydrate. The reaction between brick dust and lime was observed that the lime side was enriched by calcium silicates and calcite deposits occur on the brick dust side.
2000	P.F.G. Banfill A.M. Forster	"A Relationship Between Hydraulicity and Permeability of Hydraulic Lime," *International RILEM Workshop on Historic Mortars. Paisley, Scotland, May 1999.*	This article gives a good description of how moisture moves through porous materials and discusses the chemical composition of hydraulic limes in comparison to indices available. They sought to establish a relationship between permeability and hydraulic activity in mortars. The research was in its early stages, but they investigated the permeability by the dry cup method according to BS 3177:1959, a conduction calorimeter to identify the stages of hydration and SEM. Unfortunately, no conclusions are provided but suggest that the correlation can be made between hydraulicity and permeability.

APPENDIX B: MATERIAL CHARACTERIZATION

High-Calcium Lime Putty

X-Ray Diffraction Analysis
G&W Science and Engineering Company
Cairo, Egypt
December 18, 2002
Cc = Calcite, CH = Hydrated Lime

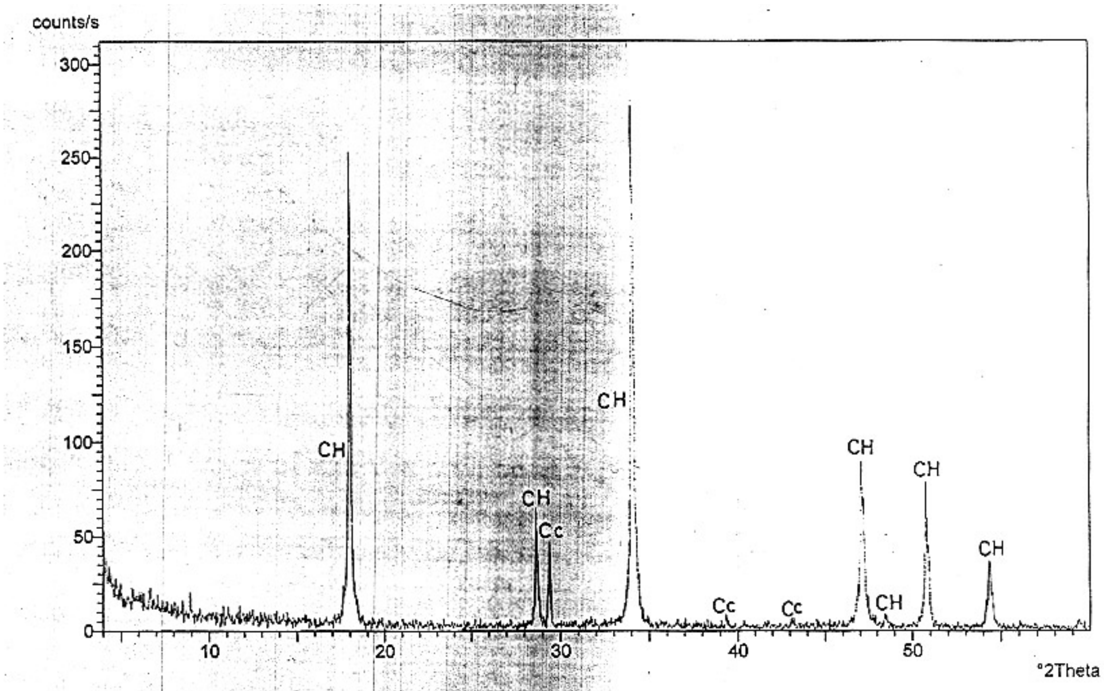
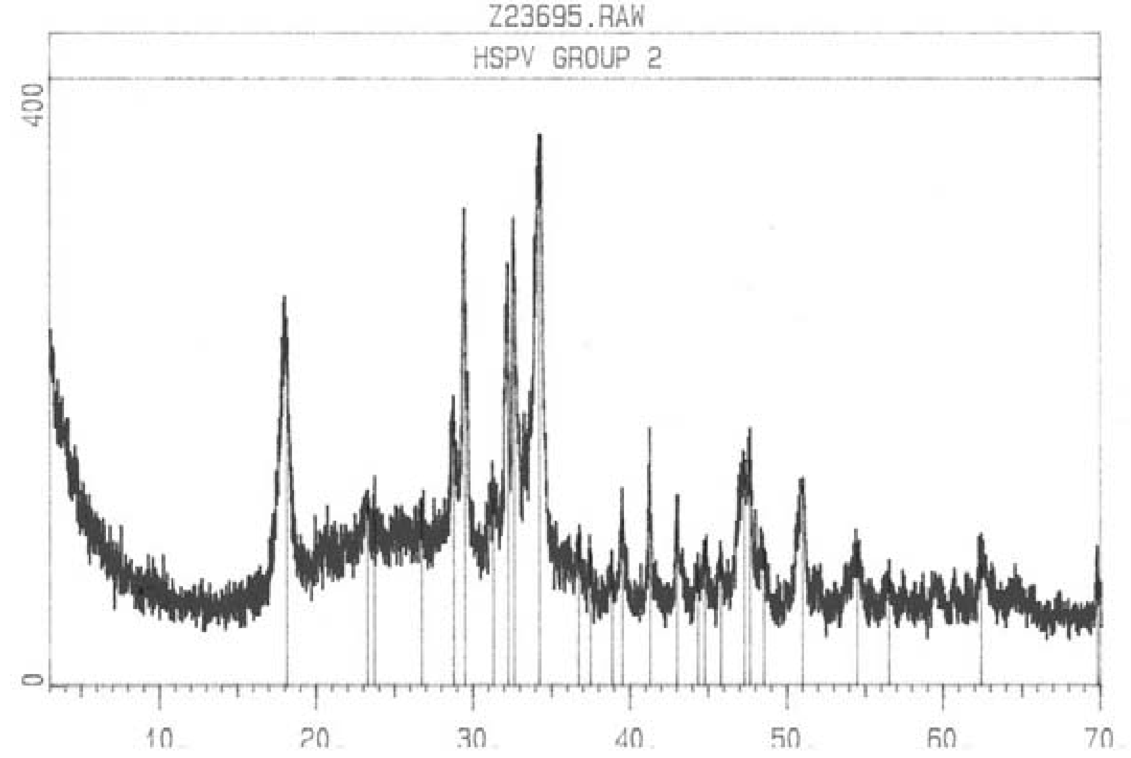


Figure 1: The X-ray diffraction patterns of the lime putty, 3-4months in water
AKCS-E (lab code 361/02)

APPENDIX B: MATERIAL CHARACTERIZATION

Riverton Natural Hydraulic Lime

X-Ray Diffraction Analysis
Laboratory for Research on the Structure of Matter
University of Pennsylvania
March 2003



APPENDIX B: MATERIAL CHARACTERIZATION

Riverton Natural Hydraulic Lime

X-Ray Diffraction Analysis

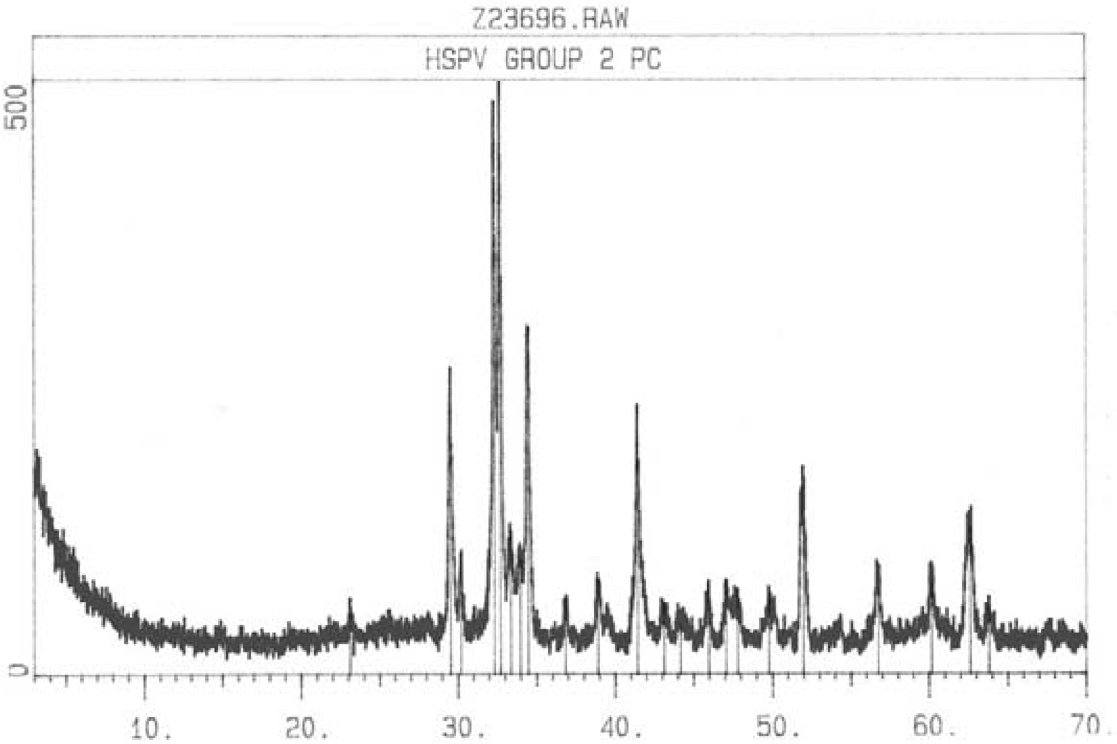
```
Peak search on 17-MAR-0314:20:06

    d      I     d        I     d         I     d         I     d         I     d         I
4.914     67 3.036     87 2.4527    27 2.1063    28 1.9112    41 1.4895    22
3.837     33 2.8632    34 2.4046    24 2.0447    21 1.8785    25 1.3481    25
3.764     32 2.7816    77 2.3221    24 2.0265    26 1.7927    36
3.344     33 2.7483    79 2.2848    31 1.9828    23 1.6860    26
3.108     52 2.6248   100 2.1901    35 1.9249    42 1.6304    20

  27 lines in pattern.

Identified Phases:

 JCPDS#    SI   ML/X  At%  Identity . . .

83-0460C  129*  18/1   96  Calcium Silicate / Larnite = Ca2(SiO4)
         Ierr:50,150    derr:2.0  Bground:20    dmax/min:29.41/1.343

 4-0733I  115     7/0  114  *Calcium Hydroxide / Portlandite, syn = Ca(OH)2
         Ierr:50,150    derr:2.0  Bground:20    dmax/min:29.41/1.343

 5-0586*   58     4/1  117  *Calcium Carbonate / Calcite, syn = CaCO3
         Ierr:50,150    derr:2.0  Bground:20    dmax/min:29.41/1.343
```

```
Summary Report:

       Full  Resid  83-0460: 96%    4-0733:114%    5-0586:117%
  d      I     I      d       I      d       I      d       I
4.914     67  None                   4.90    84
3.837     33    13  3.8325   5.8*                   3.86    14
3.764     32    32
3.344     33    33
3.108     52    26                  3.112    26
3.036     87  None                                 3.035   117
2.8632    34    17  2.8789    17
2.7816    77  None  2.7883    75
 "  "    "          2.7803    96
2.7483    79  None  2.7448    77
 "  "    "          2.7350    58
                   <2.7210    32>
2.6248   100  None  2.6197    55    2.628   114
2.4527    27     8  2.4430    16    2.447     3
2.4046    24  None  2.4072    15
2.3221    24    24
2.2848    31  None  2.2921   5.8                  [2.285    21]
 "  "    "          2.2854    19
2.1901    35  None  2.1994    13
 "  "    "          2.1907    37
2.1063    28    28
                                                  <2.095    21>
2.0447    21  None  2.0521    11
 "  "    "          2.0468   8.6
2.0265    26  None  2.0285   9.6
 "  "    "          2.0228    13
1.9828    23  None  1.9802    18
1.9249    42  None                  1.927    48   [1.927     6]
1.9112    41  None  1.9162    11*                  1.913    20
 "  "    "          1.9046   5.8*
1.8785    25  None                                 1.875    20
1.7927    36  None  1.7940   8.6*   1.796    41
1.6860    26  None                  1.687    24
1.6304    20  None  1.6287    12   [1.634     1]  [1.626     5]
1.4895    22    22
1.3481    25    25
          * = Obscured    <..> = Missing    [..] = Previously Removed
```

APPENDIX B: MATERIAL CHARACTERIZATION

Type I Gray Portland Cement

X-Ray Diffraction Analysis
Laboratory for Research on the Structure of Matter
University of Pennsylvania
March 2003



APPENDIX B: MATERIAL CHARACTERIZATION

Type I Gray Portland Cement

X-Ray Diffraction Analysis

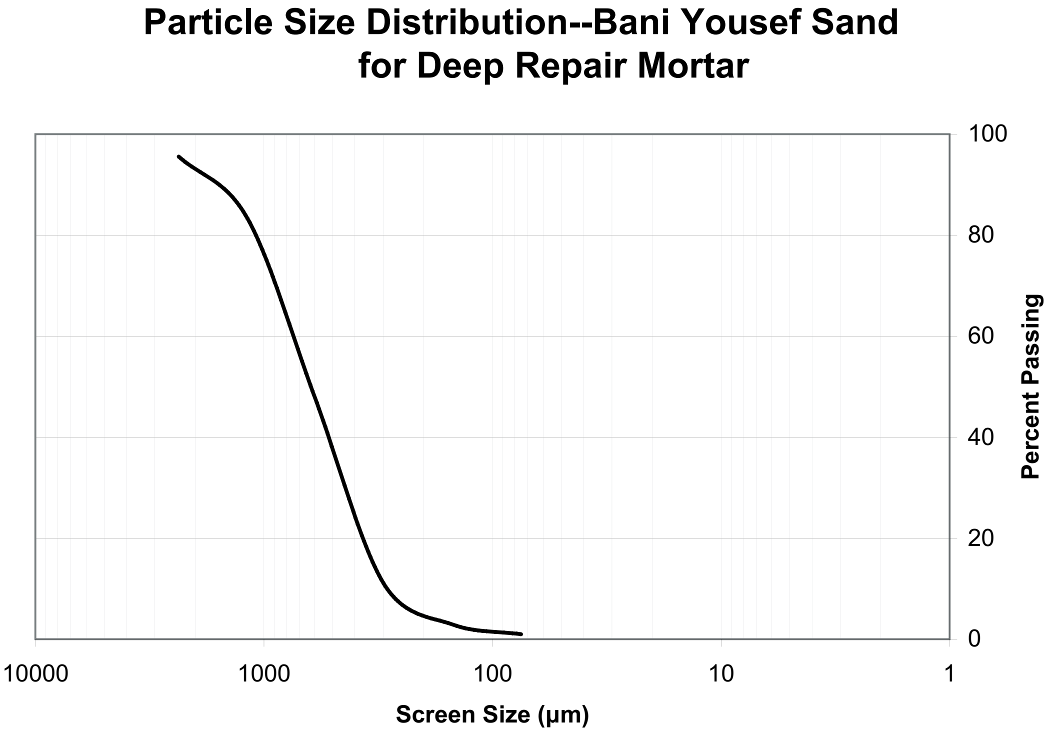
```
Input Pattern

HSPV GROUP 2 PC
Peak search on 17-MAR-0314:58:03

    d      I     d      I     d      I     d      I     d      I     d      I
3.857     13 2.7403   100 2.4437    13 2.0518   8.4 1.8331    15 1.4848    25
3.029     52 2.6875    24 2.3187    16 1.9755    16 1.7605    35 1.4597    13
2.9651    20 2.6414    19 2.1810    45 1.9318    16 1.6235    14
2.7721    97 2.6040    59 2.0998    12 1.9044    14 1.5391    15

  22 lines in pattern.

Identified Phases:

 JCPDS#    SI   ML/X  At%  Identity . . .

42-0551*  265*  29/2   79  Calcium Silicate = Ca3SiO5
         Ierr:50,150    derr:2.0  Bground:8.4   dmax/min:29.41/1.343

72-1651C   29    3/2   51  Calcium Carbonate / CALCITE = CaCO3
         Ierr:50,150    derr:2.0  Bground:8.4   dmax/min:29.41/1.343

30-1174O   35    3/1   24  Sodium Calcium Silicate = Na4Ca8Si5O20
         Ierr:50,150    derr:2.0  Bground:8.4   dmax/min:29.41/1.343


Summary Report:

       Full  Resid  42-0551: 79%   72-1651: 51%    30-1174: 24%
  d      I     I      d       I      d       I      d       I
                     <5.93   9.5>
3.857     13  None    3.87   2.4   3.8515   5.1
 "  "     "          3.861   3.2
3.029     52  None   3.036    32  [3.0279    51]
 "  "     "          3.025    59
2.9651    20  None   2.968   9.5
 "  "     "          2.962    20
                                                   <2.86     11>
2.7721    97    30   2.773    67
2.7403   100  None   2.748    36                   [2.75     16]
 "  "     "          2.738    59
2.6875    24  None   2.690   4.7*                   2.69     24
2.6414    19  None                                  2.65     16
2.6040    59  None   2.604    79                   [2.61    7.2]
2.4437    13  None   2.444   7.1
2.3187    16  None   2.323   7.1                   [2.32    3.8]
 "  "     "          2.316    16
                                  <2.2832   9.7>
2.1810    45  None   2.181    47
                    <2.165    12>
2.0998    12  None                 2.0943   7.6
2.0518   8.4   8.4
1.9755    16  None   1.980   4.0                   [1.98    6.0]
 "  "     "          1.974   7.9
1.9318    16  None   1.935   5.5  [1.9258   3.1]
 "  "     "          1.930    10
1.9044    14  None                 1.9045   9.2
                                  <1.8714   9.7>
1.8331    15  None   1.832   5.5                    1.83    6.0
1.7605    35  None   1.764    44
 "  "     "          1.758    24
1.6235    14  None   1.626   4.0  [1.6262   1.5]
 "  "     "          1.623    12
1.5391    15  None   1.539    16
1.4848    25  None   1.489   7.9
 "  "     "          1.487   7.9
 "  "     "          1.485   7.9
1.4597    13  None   1.462   3.2
 "  "     "          1.457   7.9
          * = Obscured    <..> = Missing    [..] = Previously Removed
```

APPENDIX B: MATERIAL CHARACTERIZATION

Bani Yousef Sand for Deep Repair Mortar

Particle Size Distribution

ASTM Sieve Number	Screen Size (μm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent passing
8	2360	6.55	12.73	6.18	4.46	4.46	95.54
16	1180	6.85	23.85	17.00	12.25	16.71	83.29
30	600	6.67	55.64	48.97	35.30	52.01	47.99
50	300	6.57	57.78	51.21	36.92	88.93	11.07
100	150	6.65	17.94	11.29	8.14	97.07	2.93
200	75	6.70	9.42	2.72	1.96	99.03	0.97
Pan	0	6.80	7.96	1.16	0.84	99.86	0.14



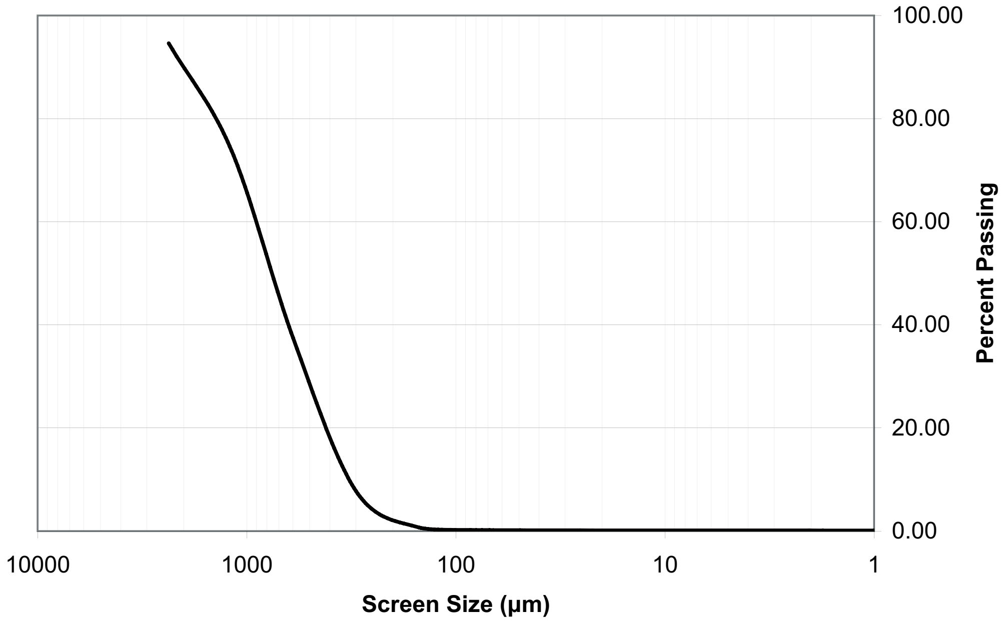
APPENDIX B: MATERIAL CHARACTERIZATION

Kempf Concrete Sand

Particle Size Distribution

ASTM Sieve Number	Screen Size (μm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent passing
8	2360	7.16	13.28	6.12	5.38	5.38	94.62
16	1180	6.84	30.60	23.76	20.88	26.26	73.74
30	600	7.14	48.41	41.27	36.27	62.52	37.48
50	300	7.31	41.13	33.82	29.72	92.24	7.76
100	150	7.16	15.19	8.03	7.06	99.30	0.70
200	75	7.09	7.67	0.58	0.51	99.81	0.19
Pan	0	7.19	7.28	0.09	0.08	99.89	0.11

Particle Size Distribution--Kempf Concrete Sand

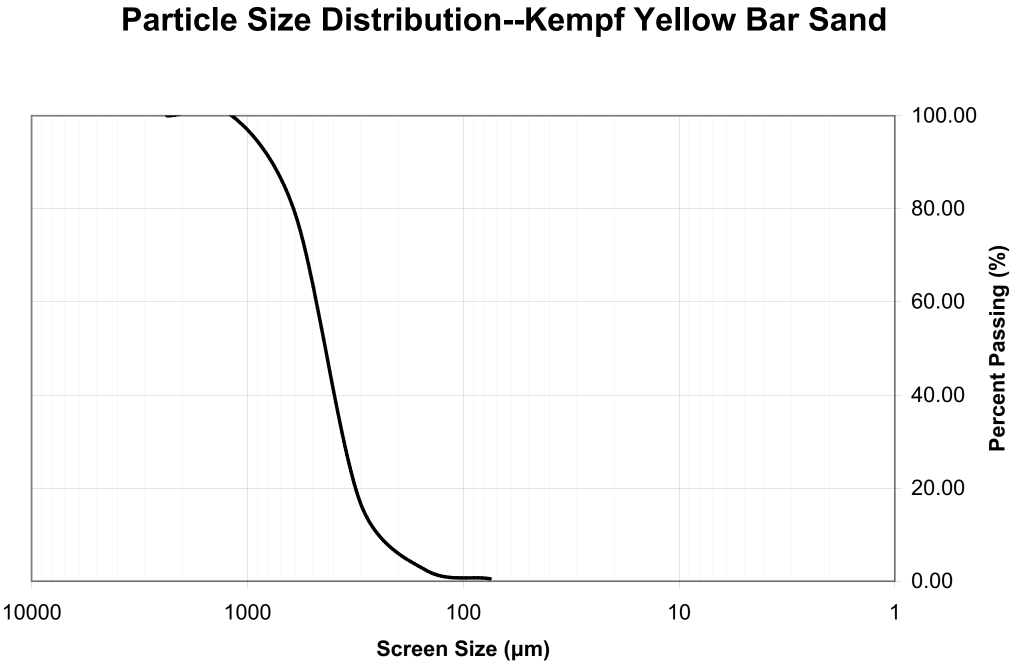


APPENDIX B: MATERIAL CHARACTERIZATION

Kempf Yellow Bar Sand

Particle Size Distribution

ASTM Sieve Number	Screen Size (μm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent passing
8	2360	7.16	7.16	0.00	0.00	0.00	100.00
16	1180	6.83	6.83	0.00	0.00	0.00	100.00
30	600	7.14	32.05	24.91	21.12	21.12	78.88
50	300	7.29	80.41	73.12	61.98	83.10	16.90
100	150	7.15	24.20	17.05	14.45	97.55	2.45
200	75	7.08	9.35	2.27	1.92	99.47	0.53
Pan	0	7.18	7.80	0.62	0.53	100.00	0.00



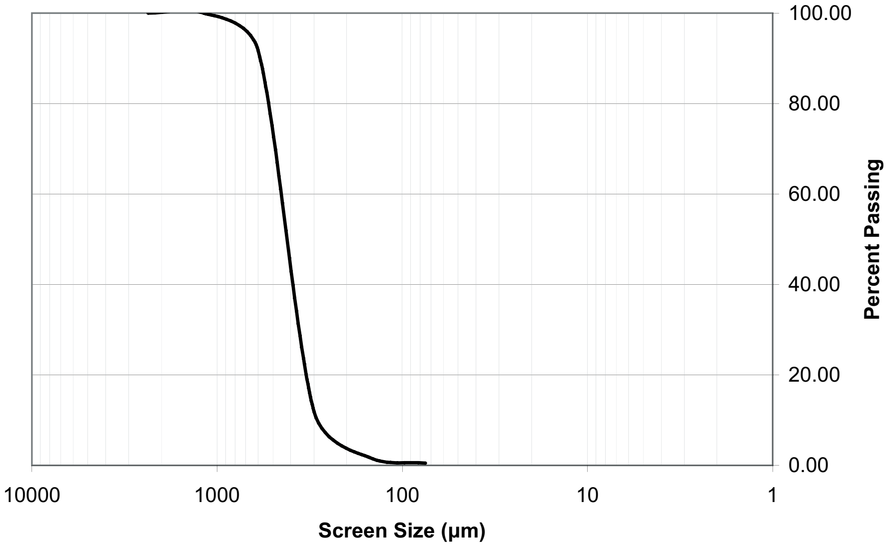
APPENDIX B: MATERIAL CHARACTERIZATION

El Katameia Sand for Finish Pointing Mortar

Particle Size Distribution

ASTM Sieve Number	Screen Size (μm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent passing
8	2360	1.97	1.97	0.00	0.00	0.00	100.00
16	1180	1.97	1.97	0.00	0.00	0.00	100.00
30	600	2.00	11.03	9.03	8.24	8.24	91.76
50	300	1.99	89.45	87.46	79.85	88.09	11.91
100	150	6.56	17.68	11.12	10.15	98.25	1.75
200	75	6.64	8.03	1.39	1.27	99.52	0.48
Pan	0	6.67	7.03	0.36	0.33	99.84	0.16

Particle Size Distribution--El Katameia Sand

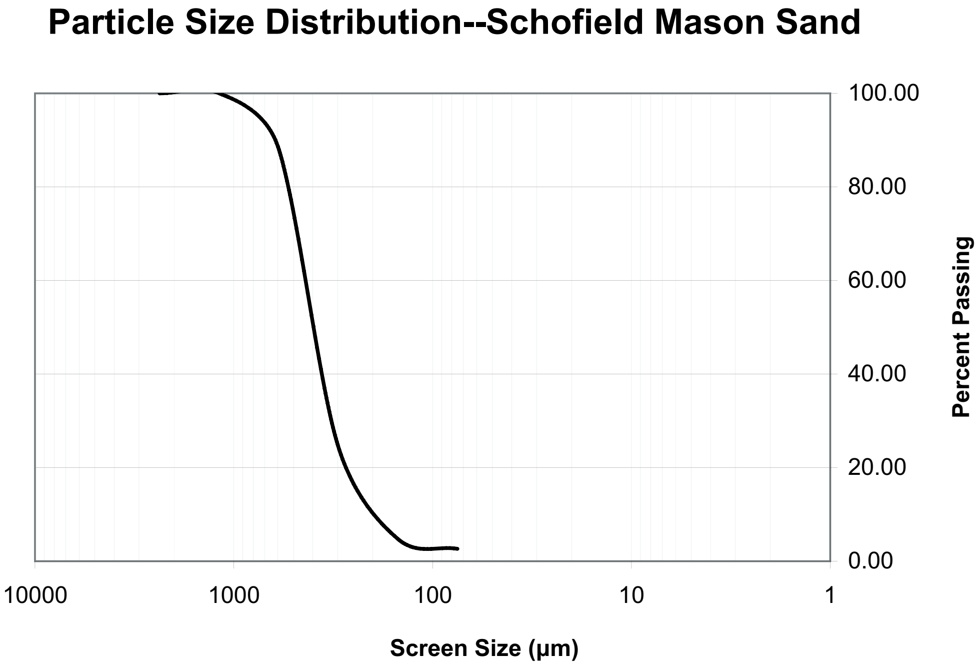


APPENDIX B: MATERIAL CHARACTERIZATION

Schofield Yellow Mason Sand

Particle Size Distribution

ASTM Sieve Number	Screen Size (μm)	Mass of container (g)	Mass of sample & container (g)	Mass retained (g)	Percent mass retained	Percent on or above	Percent passing
8	2360	7.16	7.16	0.00	0.00	0.00	100.00
16	1180	7.12	7.12	0.00	0.00	0.00	100.00
30	600	7.03	27.13	20.10	11.36	11.36	88.64
50	300	7.07	119.91	112.84	63.77	75.12	24.88
100	150	7.22	42.71	35.49	20.06	95.18	4.82
200	75	7.03	10.85	3.82	2.16	97.34	2.66
Pan	0	7.05	7.59	0.54	0.31	97.64	2.36



APPENDIX B: MATERIAL CHARACTERIZATION

Brick Dust

X-Ray Diffraction Analysis
G&W Science and Engineering Company
Cairo, Egypt
December 18, 2002
Q = Quartz, F = Feldspar, He = Hematite

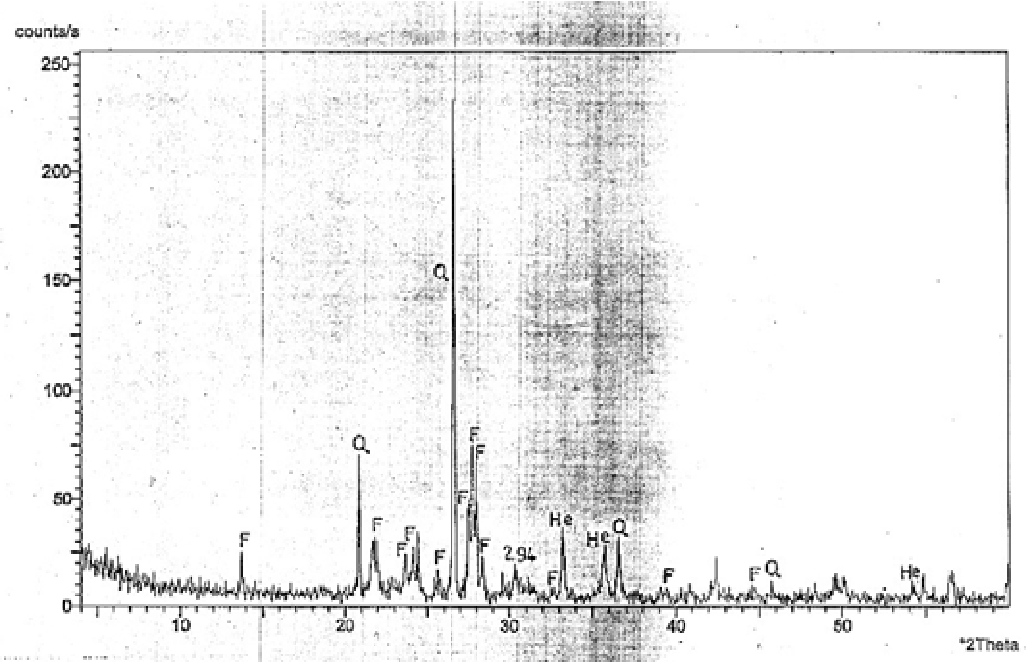


Figure 2: The X-ray diffraction patterns of the brick powder (sieved) . Bricks from demolition AKCS-E (lab code 360/02)

APPENDIX B: MATERIAL CHARACTERIZATION

Wood Ash

X-Ray Diffraction Analysis
G&W Science and Engineering Company
Cairo, Egypt
December 18, 2002
Q = Quartz, F = Feldspar, Ha = Halite

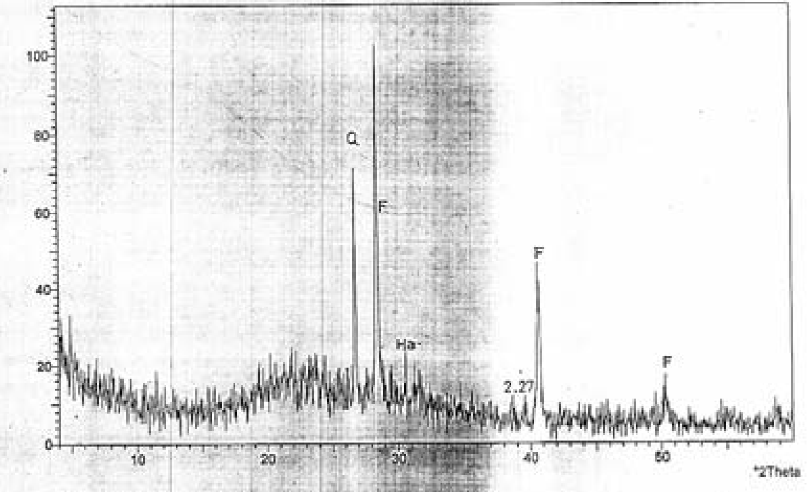


Figure 3: The X-ray diffraction patterns of the wood ash. Provenance: Oven from farmers at Abu Nomros AKCS-E (lab code 359/02)

APPENDIX C: WATER VAPOR TRANSMISSION – ASTM E96-95

KEY TO SAMPLES IN ALL TESTS

Samples were labeled according to the test represented by a letter in the alphabet, followed by either a “b” for bedding mortar or “f” for finish pointing mortar, followed by either an “h” for hydrated hydraulic lime, a “c” for Portland cement, or a “p” for lime putty, and lastly with the sample number. Tests with the same shape of sample were numbered consecutively.

Example: C-fp.3 = Salt test, finish pointing lime putty mortar, sample #3

Appendix C: Water Vapor Transmission – ASTM E96-95

Experiment Conditions
Temperature: 21°C
Relative Humidity: 50% in chamber, 100% in dish
Water Vapor Partial Pressure: 18.65 mm Hg

Samples
0.13 m²
1.3 cm in height
3 samples in each set

Daily Weight Measurements (grams)

	Days										
Sample	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
A-bh.1	71.21	71.13	71.07	70.92	70.79	70.68	70.59	70.48	70.34	70.20	70.04
A-bh.2	69.29	69.21	69.14	68.99	68.86	68.74	68.63	68.53	68.39	68.25	68.10
A-bh.3	71.52	71.44	71.37	71.22	71.09	70.98	70.88	70.78	70.62	70.49	70.33
A-bc.1	74.78	74.92	74.97	74.94	74.91	74.89	74.87	74.85	74.80	74.75	74.71
A-bc.2	76.58	76.73	76.78	76.74	76.71	76.68	76.65	76.63	76.58	76.54	76.49
A-bc.3	73.18	73.31	73.35	73.31	73.28	73.25	73.22	73.19	73.14	73.09	73.04
A-bp.1	72.85	72.76	72.72	72.58	72.47	72.37	72.28	72.20	72.07	71.95	71.81
A-bp.2	71.97	71.90	71.84	71.70	71.59	71.49	71.34	71.20	71.05	70.93	70.80
A-bp.3	68.04	67.95	67.76	67.58	67.44	67.33	67.22	67.12	66.98	66.85	66.64
A-fh.1	67.20	67.05	66.90	66.72	66.56	66.37	66.19	66.05	65.75	65.55	65.37
A-fh.2	69.45	69.32	69.18	69.02	68.87	68.69	68.50	68.37	68.08	67.89	67.69
A-fh.3	71.54	71.49	71.43	71.25	71.10	70.97	70.86	70.76	70.60	70.46	70.29
A-fc.1	72.31	72.35	72.29	72.20	72.10	72.02	71.86	71.76	71.67	71.49	71.37
A-fc.2	73.67	73.80	73.83	73.75	73.70	73.65	73.62	73.59	73.52	73.47	73.40
A-fc.3	70.89	70.99	71.00	70.91	70.84	70.78	70.73	70.70	70.62	70.56	70.48
A-fp.1	74.40	74.34	74.27	74.10	73.97	73.86	73.75	73.65	73.50	73.36	73.20
A-fp.2	68.21	68.13	68.08	67.88	67.73	67.60	67.48	67.37	67.20	67.06	66.89
A-fp.3	67.47	67.40	67.33	67.15	66.99	66.87	66.75	66.64	66.48	66.33	66.16

APPENDIX C: WATER VAPOR TRANSMISSION – ASTM E96-95

WATER VAPOR TRANSMISSION CALCULATIONS

Sample	% Weight Loss	Average Weight Loss	Weight Change (g)	WVT (g/h·m²)	Average WVT
A-bh.1	1.64		1.17	0.04	
A-bh.2	1.72	1.67	1.19	0.04	0.038
A-bh.3	1.66		1.19	0.04	
A-bc.1	0.09		0.07	0.00	
A-bc.2	0.12	0.13	0.09	0.00	0.003
A-bc.3	0.19		0.14	0.00	
A-bp.1	1.43		1.04	0.03	
A-bp.2	1.63	1.70	1.17	0.04	0.039
A-bp.3	2.06		1.40	0.04	
A-fh.1	2.72		1.83	0.06	
A-fh.2	2.53	2.33	1.76	0.06	0.052
A-fh.3	1.75		1.25	0.04	
A-fc.1	1.30		0.94	0.03	
A-fc.2	0.37	0.75	0.27	0.01	0.017
A-fc.3	0.58		0.41	0.01	
A-fp.1	1.61		1.20	0.04	
A-fp.2	1.94	1.83	1.32	0.04	0.041
A-fp.3	1.94		1.31	0.04	

Appendix C: Water Vapor Transmission – ASTM E96-95

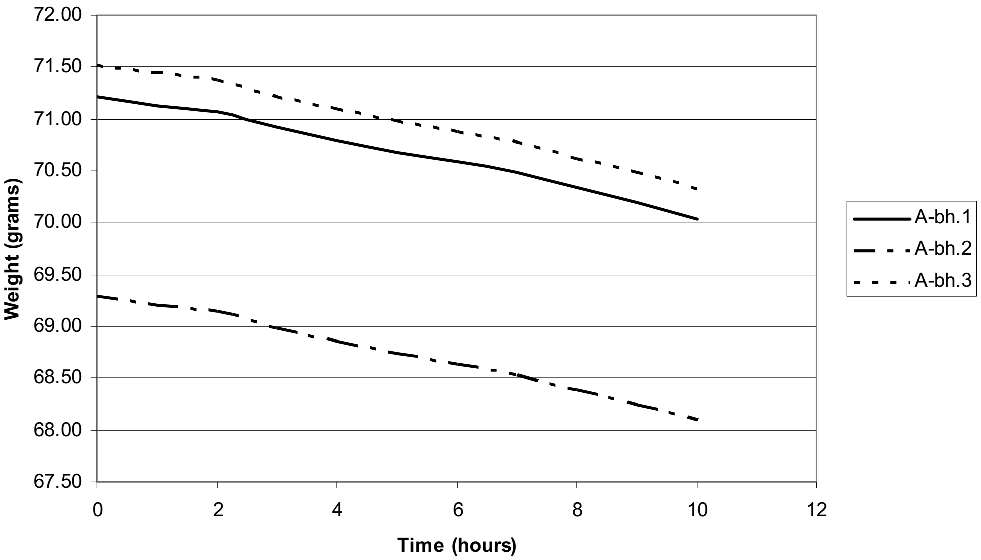
Permeance and Permeability Calculations

Sample	Time (hours)	S (mm Hg)	S(R1-R2)	Permeance (g/Pa·s·m²)	Average Permeance	Permeability (perm·cm)	Average Permeability
A-bh.1	240	2.19E+03	1.09E+03	9.53E-09		1.24E-08	
A-bh.2	240	2.19E+03	1.09E+03	9.69E-09	9.63E-09	1.26E-08	1.25E-08
A-bh.3	240	2.19E+03	1.09E+03	9.69E-09		1.26E-08	
A-bc.1	240	2.19E+03	1.09E+03	5.70E-10		7.41E-10	
A-bc.2	240	2.19E+03	1.09E+03	7.33E-10	8.14E-10	9.53E-10	1.06E-09
A-bc.3	240	2.19E+03	1.09E+03	1.14E-09		1.48E-09	
A-bp.1	240	2.19E+03	1.09E+03	8.47E-09		1.10E-08	
A-bp.2	240	2.19E+03	1.09E+03	9.53E-09	9.80E-09	1.24E-08	1.27E-08
A-bp.3	240	2.19E+03	1.09E+03	1.14E-08		1.48E-08	
A-fh.1	240	2.19E+03	1.09E+03	1.49E-08		1.94E-08	
A-fh.2	240	2.19E+03	1.09E+03	1.43E-08	1.31E-08	1.86E-08	1.71E-08
A-fh.3	240	2.19E+03	1.09E+03	1.02E-08		1.32E-08	
A-fc.1	240	2.19E+03	1.09E+03	7.65E-09		9.95E-09	
A-fc.2	240	2.19E+03	1.09E+03	2.20E-09	4.40E-09	2.86E-09	5.72E-09
A-fc.3	240	2.19E+03	1.09E+03	3.34E-09		4.34E-09	
A-fp.1	240	2.19E+03	1.09E+03	9.77E-09		1.27E-08	
A-fp.2	240	2.19E+03	1.09E+03	1.07E-08	1.04E-08	1.40E-08	1.35E-08
A-fp.3	240	2.19E+03	1.09E+03	1.07E-08		1.39E-08	

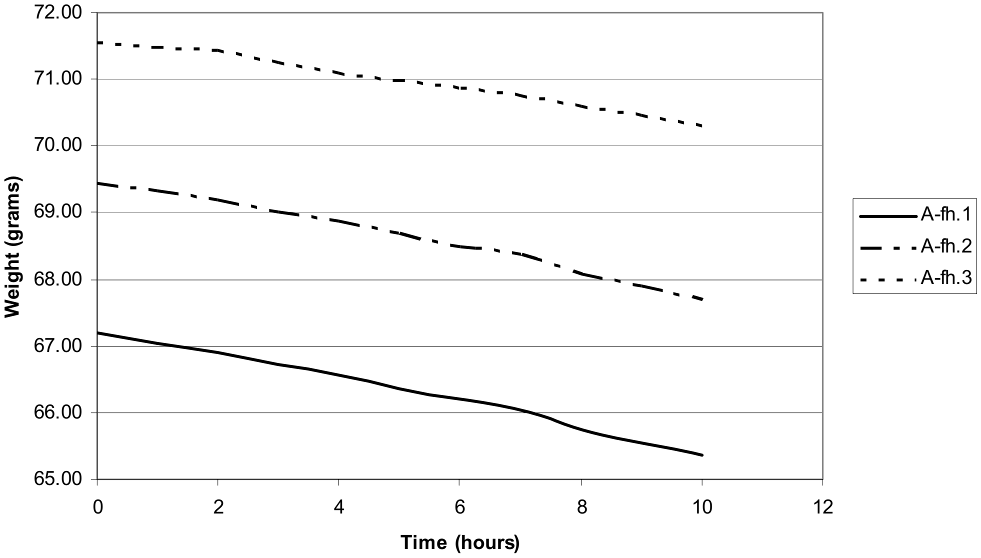
APPENDIX C: WATER VAPOR TRANSMISSION – ASTM E96-95

WATER VAPOR TRANSMISSION GRAPHS

Water Vapor Transmission - Weight Change
Hydrated Hydraulic Lime Bedding Samples

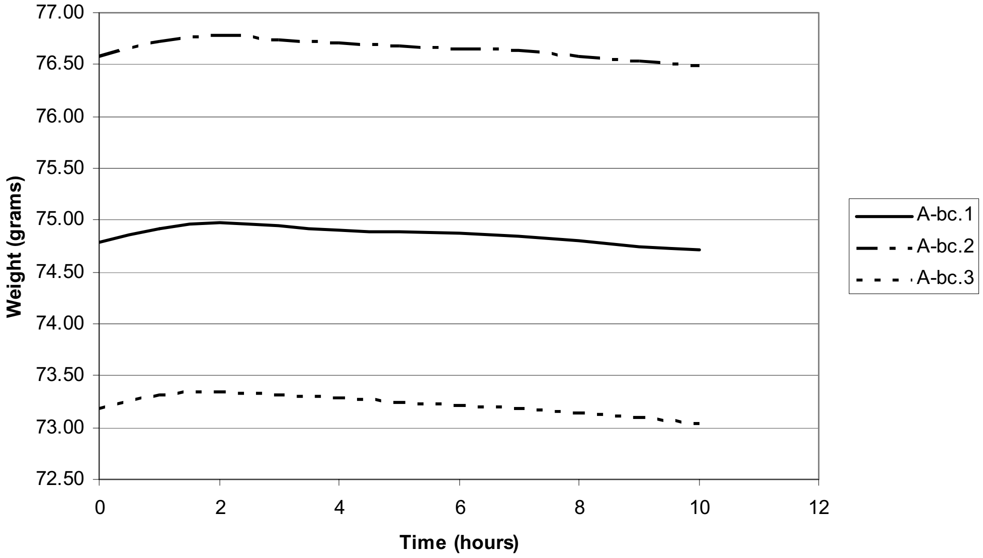


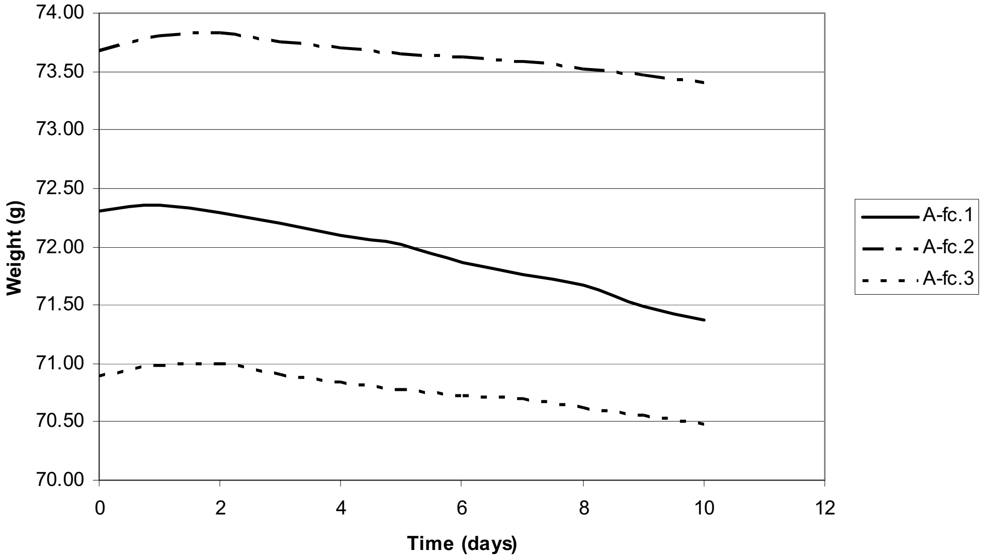
Water Vapor Transmission - Weight Change
Hydrated Hydraulic Lime Finish Pointing Samples



Appendix C: Water Vapor Transmission – ASTM E96-95

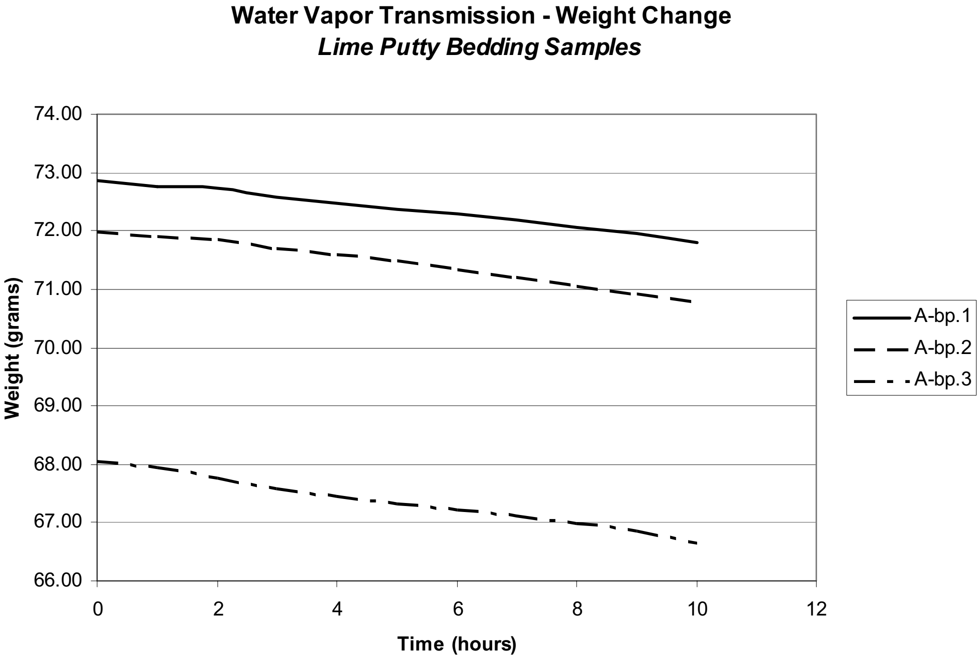
Water Vapor Transmission Graphs

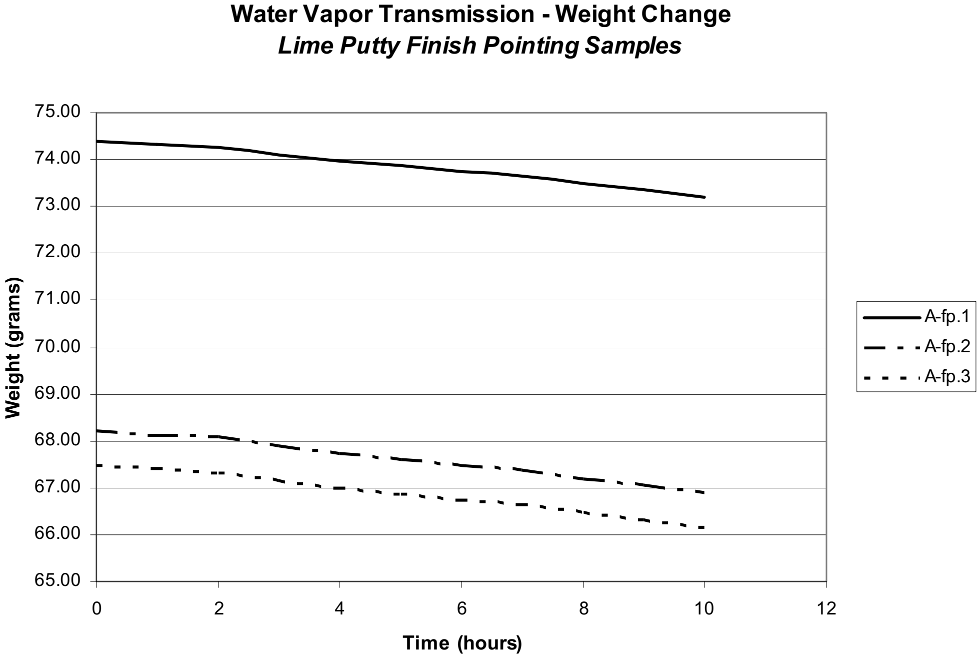

Water Vapor Transmission - Weight Change
Portland Cement Bedding Samples


Water Vapor Transmission- Weight Change
Portland Cement Finish Pointing Samples

APPENDIX C: WATER VAPOR TRANSMISSION – ASTM E96-95

WATER VAPOR TRANSMISSION GRAPHS





Appendix D: Water Vapor Transmission – NORMAL 21/85

Daily Weight Measurements (grams)

Experiment Conditions
Temperature: 21°C
Relative Humidity: 12% in chamber, 100% in dish
Water Vapor Partial Pressure: 18.65 mm Hg

Samples
0.13 m²
1.3 cm in height
3 samples in each set

	Days														
Sample	**0.00**	**0.01**	**0.01**	**0.02**	**0.04**	**1.00**	**2.00**	**3.00**	**4.00**	**5.00**	**6.00**	**7.00**	**8.00**	**9.00**	**10.00**
B-bh.4	70.49	70.49	70.49	70.49	70.48	70.23	69.86	69.52	69.23	68.90	68.57	68.24	67.91	67.59	67.29
B-bh.5	67.03	67.03	67.03	67.03	67.03	66.79	66.42	66.10	65.82	65.51	65.19	64.92	64.57	64.26	63.97
B-bh.6	64.14	64.14	64.14	64.14	64.13	63.87	63.46	63.11	62.79	62.45	62.09	61.75	61.40	61.06	60.74
B-bc.4	69.27	69.27	69.27	69.27	69.27	69.25	69.16	69.08	69.00	68.91	68.82	68.73	68.64	68.55	68.46
B-bc.5	65.94	65.94	65.94	65.94	65.94	65.91	65.80	65.70	65.62	65.51	65.40	65.30	65.20	65.10	65.00
B-bc.6	69.66	69.66	69.66	69.66	69.66	69.65	69.57	69.50	69.43	69.33	69.25	69.16	69.07	68.98	68.90
B-bp.4	68.67	68.67	68.67	68.67	68.66	68.41	68.07	67.77	67.48	67.18	66.87	66.57	66.27	65.97	65.70
B-bp.5	61.24	61.24	61.24	61.24	61.23	60.98	60.58	60.23	59.92	59.58	59.24	58.90	58.56	58.22	57.92
B-bp.6	65.90	65.90	65.90	65.90	65.90	65.67	65.30	64.98	64.70	64.39	64.08	63.76	63.45	63.15	62.86
B-fh.4	69.32	69.32	69.32	69.32	69.32	68.98	68.64	68.26	67.91	67.53	67.16	66.86	66.43	66.09	65.73
B-fh.5	66.48	66.48	66.48	66.48	66.48	66.22	65.83	65.48	65.19	64.86	64.52	64.18	63.85	63.53	63.23
B-fh.6	67.87	67.87	67.87	67.87	67.87	67.63	67.24	66.90	66.62	66.31	65.98	65.67	65.35	65.04	64.74
B-fc.4	66.25	66.25	66.25	66.25	66.25	66.19	66.03	65.85	65.76	65.62	65.47	65.32	65.18	65.04	64.90
B-fc.5	69.39	69.39	69.39	69.39	69.40	69.34	69.21	69.08	68.97	68.85	68.72	68.60	68.47	68.35	68.23
B-fc.6	69.25	69.25	69.25	69.25	69.25	69.19	69.06	68.91	68.80	68.67	68.54	68.41	68.28	68.15	68.04
B-fp.4	65.76	65.76	65.76	65.76	65.76	65.47	65.03	64.66	64.33	63.96	63.59	63.23	62.86	62.50	62.17
B-fp.5	66.92	66.92	66.92	66.92	66.92	66.64	66.21	65.83	65.49	65.13	64.76	64.40	64.04	63.69	63.36
B-fp.6	65.06	65.06	65.06	65.06	65.06	64.78	64.35	63.98	63.65	63.29	62.94	62.48	62.03	61.69	61.36

Grey boxes indicate day asymptotical state was reached

APPENDIX D: WATER VAPOR TRANSMISSION – NORMAL 21/85

WATER VAPOR TRANSMISSION CALCULATIONS

Sample	% Weight Loss	Average weight loss (%)	Weight Change (g)	g/h	WVT (g/m² · h)	Average WVT	Standard Deviation
B-bh.4	**4.54**		3.20	0.01	0.10		
B-bh.5	**4.57**	**4.80**	3.06	0.01	0.10	0.10	0.01
B-bh.6	**5.30**		3.40	0.01	0.11		
B-bc.4	**1.17**		0.81	0.00	0.03		
B-bc.5	**1.43**	**1.23**	0.94	0.00	0.03	0.03	0.00
B-bc.6	**1.09**		0.76	0.00	0.02		
B-bp.4	**4.33**		2.97	0.01	0.10		
B-bp.5	**5.44**	**4.80**	3.33	0.01	0.11	0.10	0.01
B-bp.6	**4.63**		3.05	0.01	0.10		
B-fh.4	**5.21**		3.61	0.02	0.12		
B-fh.5	**4.90**	**4.91**	3.26	0.01	0.10	0.11	0.01
B-fh.6	**4.63**		3.14	0.01	0.10		
B-fc.4	**2.05**		1.36	0.01	0.04		
B-fc.5	**1.67**	**1.82**	1.16	0.00	0.04	0.04	0.00
B-fc.6	**1.75**		1.21	0.01	0.04		
B-fp.4	**5.46**		3.59	0.01	0.12		
B-fp.5	**5.32**	**5.49**	3.56	0.01	0.11	0.12	0.00
B-fp.6	**5.69**		3.70	0.02	0.12		

APPENDIX D: WATER VAPOR TRANSMISSION – NORMAL 21/85

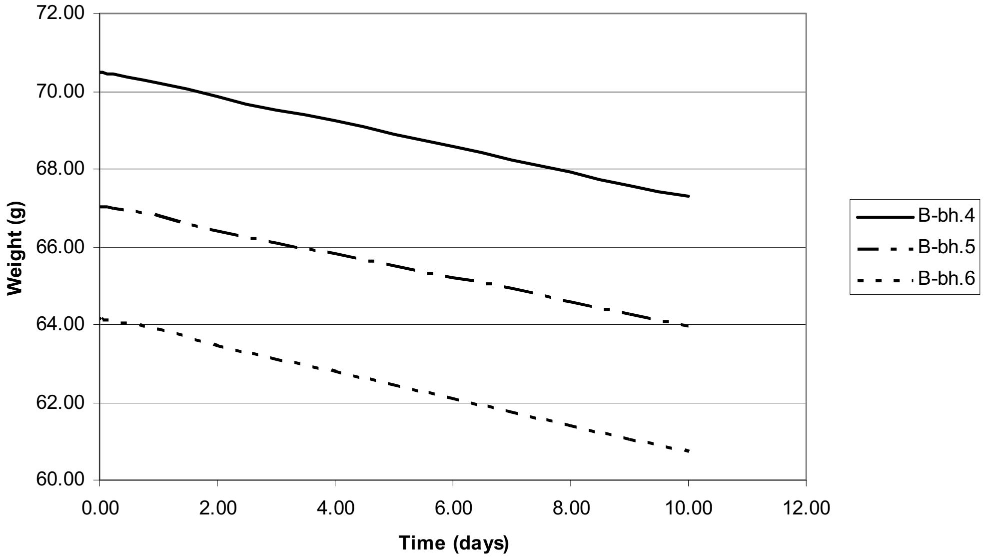
PERMEANCE AND PERMEABILITY CALCULATIONS

Sample	Permeance (g/Pa·s·m²)	Average Permeance	Standard Deviation	Permeability (perm·cm)	Average Permeability	Standard Deviation
B-bh.4	1.48E-08			1.92E-08		
B-bh.5	1.42E-08	1.49E-08	7.91E-10	1.84E-08	1.94E-08	1.03E-09
B-bh.6	1.57E-08			2.04E-08		
B-bc.4	3.75E-09			4.87E-09		
B-bc.5	4.35E-09	3.87E-09	4.30E-10	5.65E-09	5.03E-09	5.59E-10
B-bc.6	3.52E-09			4.57E-09		
B-bp.4	1.37E-08			1.79E-08		
B-bp.5	1.54E-08	1.44E-08	8.74E-10	2.00E-08	1.87E-08	1.14E-09
B-bp.6	1.41E-08			1.83E-08		
B-fh.4	1.67E-08			2.17E-08		
B-fh.5	1.51E-08	1.54E-08	1.13E-09	1.96E-08	2.01E-08	1.47E-09
B-fh.6	1.45E-08			1.89E-08		
B-fc.4	6.29E-09			8.18E-09		
B-fc.5	5.37E-09	5.75E-09	4.81E-10	6.98E-09	7.48E-09	6.26E-10
B-fc.6	5.60E-09			7.28E-09		
B-fp.4	1.66E-08			2.16E-08		
B-fp.5	1.65E-08	1.67E-08	3.41E-10	2.14E-08	2.18E-08	4.43E-10
B-fp.6	1.71E-08			2.23E-08		

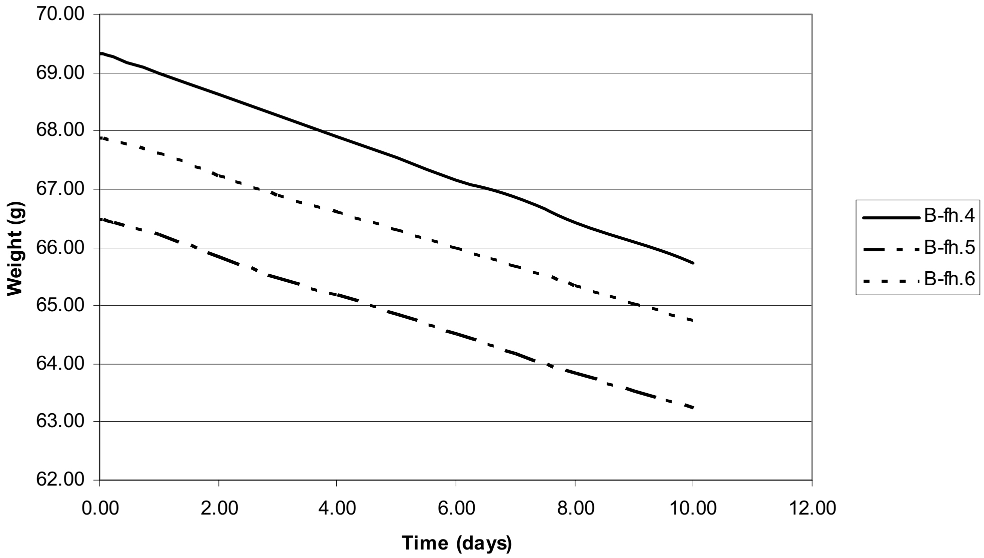
APPENDIX D: WATER VAPOR TRANSMISSION – NORMAL 21/85

WATER VAPOR TRANSMISSION GRAPHS

Water Vapor Transmission - NORMAL 21/85
Hydrated Hydraulic Lime Bedding Samples

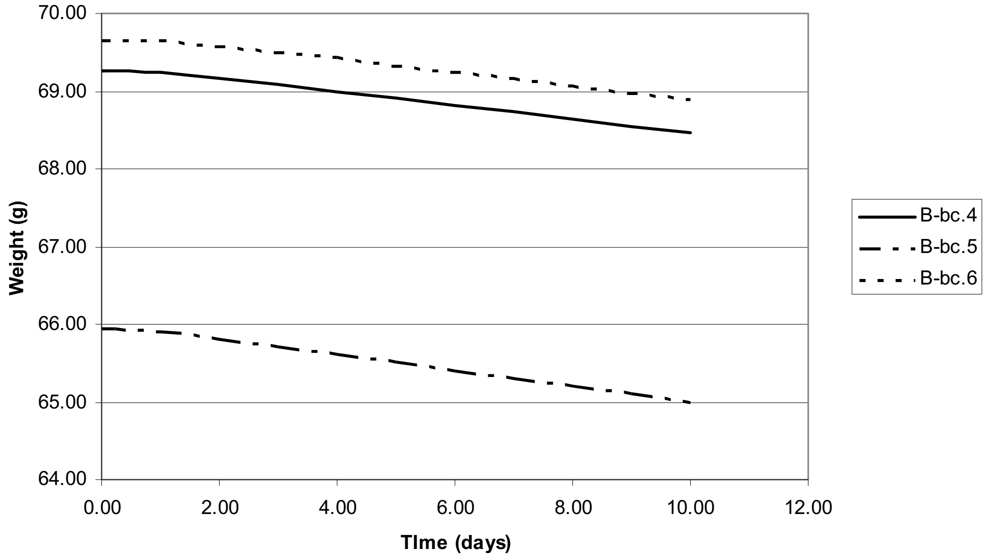


Water Vapor Transmission - NORMAL 21/85
Hydrated Hydraulic Lime Finish Pointing Samples

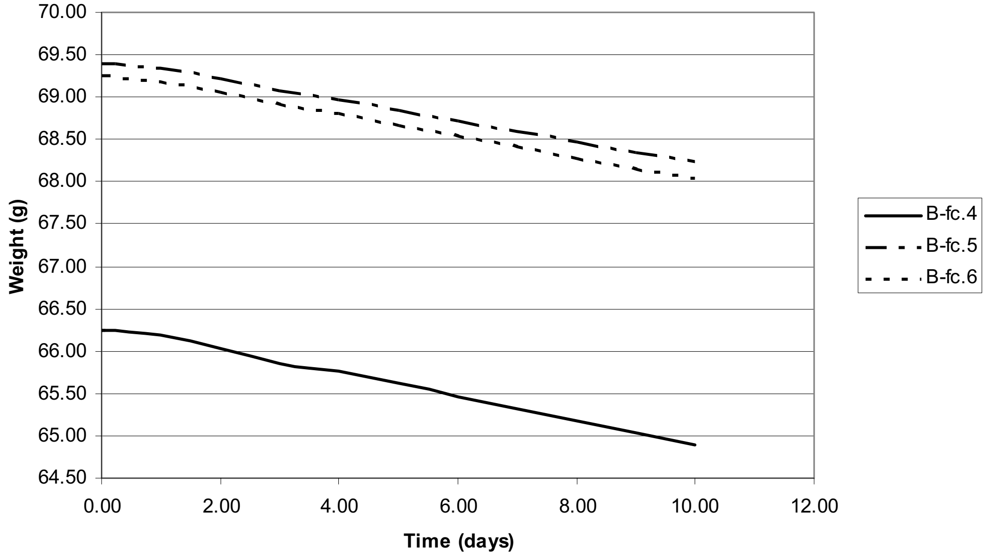


Appendix D: Water Vapor Transmission – NORMAL 21/85

Water Vapor Transmission Graphs



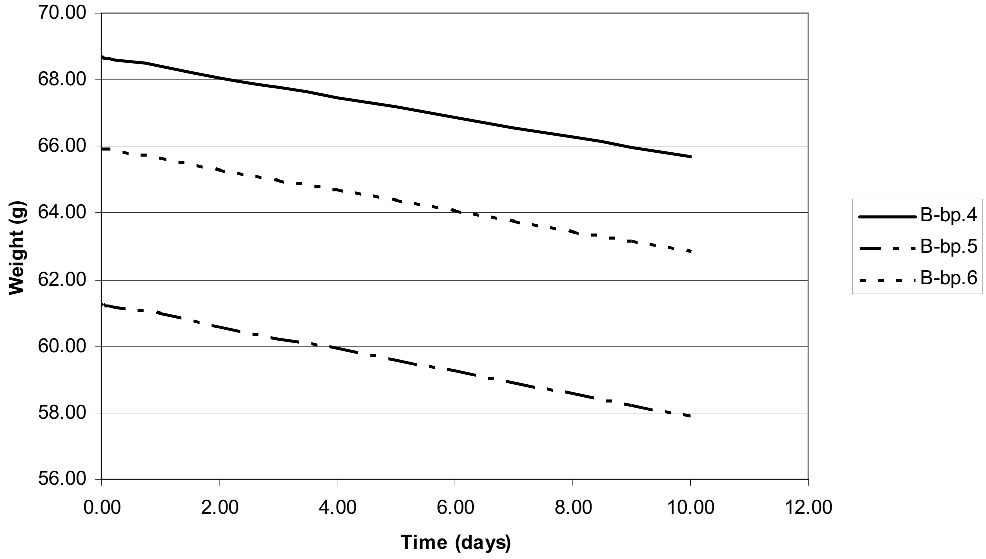
Water Vapor Transmission - NORMAL 21/85
Portland Cement Bedding Samples

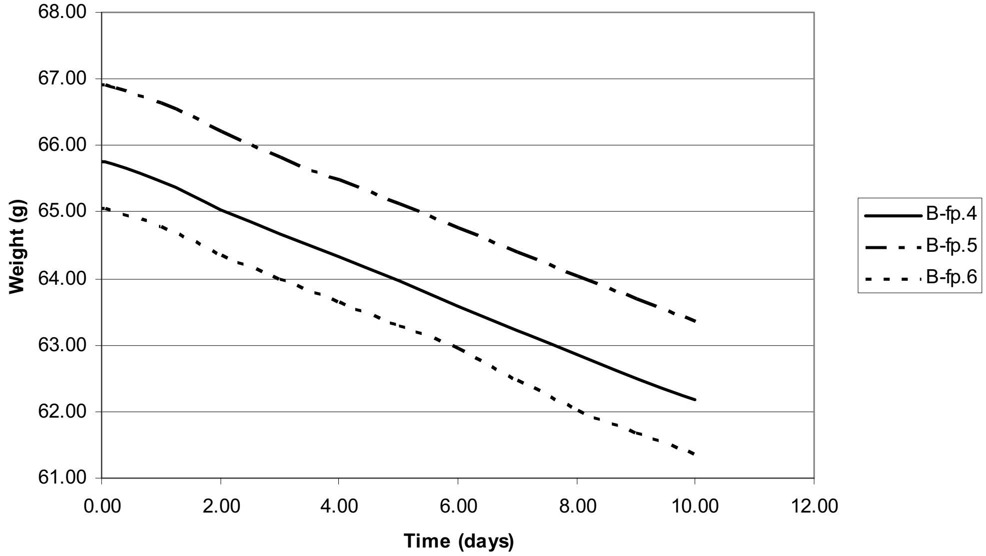


Water Vapor Transmission - NORMAL 21/85
Portland Cement Finish Pointing Samples

APPENDIX D: WATER VAPOR TRANSMISSION – NORMAL 21/85

WATER VAPOR TRANSMISSION GRAPHS


Water Vapor Transmission - NORMAL 21/85
Lime Putty Bedding Samples


Water Vapor Transmission - NORMAL 21/85
Lime Putty Finish Pointing Samples

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BH.4

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	234.32	0.00	0.00	0.00	0.00
0.08	254.43	20.11	20.11	8.58	4.29
0.17	258.62	4.19	24.30	10.37	9.48
0.25	258.65	0.03	24.33	10.38	10.38
0.33	258.60	-0.05	24.28	10.36	10.37
0.42	258.79	0.19	24.47	10.44	10.40
0.50	258.81	0.02	24.49	10.45	10.45
0.58	258.99	0.18	24.67	10.53	10.49
0.67	258.89	-0.10	24.57	10.49	10.51
0.75	258.94	0.05	24.62	10.51	10.50
0.83	258.91	-0.03	24.59	10.49	10.50
0.92	259.04	0.13	24.72	10.55	10.52
1.00	258.97	-0.07	24.65	10.52	10.53
1.25	258.99	0.02	24.67	10.53	10.52
1.50	258.84	-0.15	24.52	10.46	10.50
1.75	258.88	0.04	24.56	10.48	10.47
2.00	258.86	-0.02	24.54	10.47	10.48
2.25	258.92	0.06	24.60	10.50	10.49
2.50	258.87	-0.05	24.55	10.48	10.49
2.75	258.96	0.09	24.64	10.52	10.50
3.00	258.98	0.02	24.66	10.52	10.52
4.00	258.95	-0.03	24.63	10.51	10.52
5.00	259.07	0.12	24.75	10.56	10.54
6.00	259.04	-0.03	24.72	10.55	10.56
7.00	259.12	0.08	24.80	10.58	10.57
8.00	259.02	-0.10	24.70	10.54	10.56
1440	259.21	0.19	24.89	10.62	10.58
2880	259.33	0.12	25.01	10.67	10.65
4320	259.43	0.10	25.11	10.72	10.69

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BH.5

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	229.30	0.00	0.00	0.00	0.00
0.08	249.92	20.62	20.62	8.99	4.50
0.17	253.32	3.40	24.02	10.48	9.73
0.25	253.43	0.11	24.13	10.52	10.50
0.33	253.37	-0.06	24.07	10.50	10.51
0.42	253.34	-0.03	24.04	10.48	10.49
0.50	253.59	0.25	24.29	10.59	10.54
0.58	253.61	0.02	24.31	10.60	10.60
0.67	253.37	-0.24	24.07	10.50	10.55
0.75	253.56	0.19	24.26	10.58	10.54
0.83	253.70	0.14	24.40	10.64	10.61
0.92	253.65	-0.05	24.35	10.62	10.63
1.00	253.55	-0.10	24.25	10.58	10.60
1.25	253.64	0.09	24.34	10.61	10.60
1.50	253.54	-0.10	24.24	10.57	10.59
1.75	253.47	-0.07	24.17	10.54	10.56
2.00	253.53	0.06	24.23	10.57	10.55
2.25	253.73	0.20	24.43	10.65	10.61
2.50	253.59	-0.14	24.29	10.59	10.62
2.75	253.50	-0.09	24.20	10.55	10.57
3.00	253.58	0.08	24.28	10.59	10.57
4.00	253.53	-0.05	24.23	10.57	10.58
5.00	253.66	0.13	24.36	10.62	10.60
6.00	253.78	0.12	24.48	10.68	10.65
7.00	253.72	-0.06	24.42	10.65	10.66
8.00	253.67	-0.05	24.37	10.63	10.64
1440	253.84	0.17	24.54	10.70	10.67
2880	254.00	0.16	24.70	10.77	10.74
4320	254.06	0.06	24.76	10.80	10.78

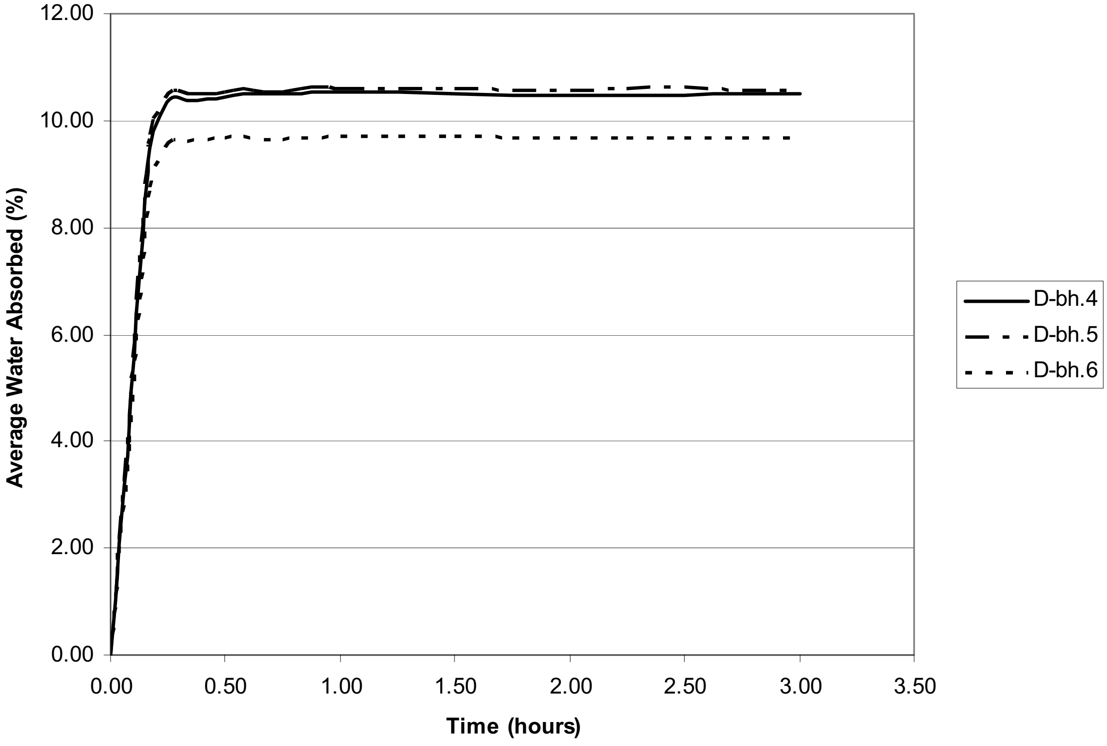
APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BH.6

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	227.65	0.00	0.00	0.00	0.00
0.08	245.82	18.17	18.17	7.98	3.99
0.17	249.36	3.54	21.71	9.54	8.76
0.25	249.57	0.21	21.92	9.63	9.58
0.33	249.53	-0.04	21.88	9.61	9.62
0.42	249.63	0.10	21.98	9.66	9.63
0.50	249.77	0.14	22.12	9.72	9.69
0.58	249.67	-0.10	22.02	9.67	9.69
0.67	249.60	-0.07	21.95	9.64	9.66
0.75	249.67	0.07	22.02	9.67	9.66
0.83	249.62	-0.05	21.97	9.65	9.66
0.92	249.78	0.16	22.13	9.72	9.69
1.00	249.65	-0.13	22.00	9.66	9.69
1.25	249.83	0.18	22.18	9.74	9.70
1.50	249.69	-0.14	22.04	9.68	9.71
1.75	249.65	-0.04	22.00	9.66	9.67
2.00	249.70	0.05	22.05	9.69	9.67
2.25	249.72	0.02	22.07	9.69	9.69
2.50	249.70	-0.02	22.05	9.69	9.69
2.75	249.67	-0.03	22.02	9.67	9.68
3.00	249.74	0.07	22.09	9.70	9.69
4.00	249.77	0.03	22.12	9.72	9.71
5.00	249.91	0.14	22.26	9.78	9.75
6.00	249.94	0.03	22.29	9.79	9.78
7.00	249.93	-0.01	22.28	9.79	9.79
8.00	250.06	0.13	22.41	9.84	9.82
1440	250.13	0.07	22.48	9.87	9.86
2880	250.38	0.25	22.73	9.98	9.93
4320	250.27	-0.11	22.62	9.94	9.96

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR HYDRATED HYDRAULIC LIME BEDDING SAMPLES



APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BC.4

Time (hours)	**Weight (g)**	**Difference in successive weighings (grams)**	**Change in weight from initial weight (grams)**	**Amount of water absorbed (%)**	**Average water absorbed (%)**
0.00	263.69	0.00	0.00	0.00	0.00
0.08	270.64	6.95	6.95	2.64	1.32
0.17	273.26	2.62	9.57	3.63	3.13
0.25	275.04	1.78	11.35	4.30	3.97
0.33	276.35	1.31	12.66	4.80	4.55
0.42	277.48	1.13	13.79	5.23	5.02
0.50	278.32	0.84	14.63	5.55	5.39
0.58	279.05	0.73	15.36	5.83	5.69
0.67	279.58	0.53	15.89	6.03	5.93
0.75	280.29	0.71	16.60	6.30	6.16
0.83	280.68	0.39	16.99	6.44	6.37
0.92	281.31	0.63	17.62	6.68	6.56
1.00	281.56	0.25	17.87	6.78	6.73
1.25	281.97	0.41	18.28	6.93	6.85
1.50	282.10	0.13	18.41	6.98	6.96
1.75	283.07	0.97	19.38	7.35	7.17
2.00	283.63	0.56	19.94	7.56	7.46
2.25	284.19	0.56	20.50	7.77	7.67
2.50	284.26	0.07	20.57	7.80	7.79
2.75	284.36	0.10	20.67	7.84	7.82
3.00	284.45	0.09	20.76	7.87	7.86
4.00	284.66	0.21	20.97	7.95	7.91
5.00	284.75	0.09	21.06	7.99	7.97
6.00	284.91	0.16	21.22	8.05	8.02
7.00	284.93	0.02	21.24	8.05	8.05
8.00	284.96	0.03	21.27	8.07	8.06
1440	285.33	0.37	21.64	8.21	8.14
2880	285.76	0.43	22.07	8.37	8.29
4320	285.87	0.11	22.18	8.41	8.39

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BC.5

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	260.19	0.00	0.00	0.00	0.00
0.08	267.49	7.30	7.30	2.81	1.40
0.17	270.09	2.60	9.90	3.80	3.31
0.25	271.38	1.29	11.19	4.30	4.05
0.33	272.64	1.26	12.45	4.78	4.54
0.42	273.55	0.91	13.36	5.13	4.96
0.50	274.27	0.72	14.08	5.41	5.27
0.58	274.95	0.68	14.76	5.67	5.54
0.67	275.41	0.46	15.22	5.85	5.76
0.75	275.92	0.51	15.73	6.05	5.95
0.83	276.35	0.43	16.16	6.21	6.13
0.92	276.78	0.43	16.59	6.38	6.29
1.00	277.15	0.37	16.96	6.52	6.45
1.25	277.42	0.27	17.23	6.62	6.57
1.50	277.63	0.21	17.44	6.70	6.66
1.75	278.43	0.80	18.24	7.01	6.86
2.00	279.04	0.61	18.85	7.24	7.13
2.25	279.44	0.40	19.25	7.40	7.32
2.50	279.77	0.33	19.58	7.53	7.46
2.75	279.81	0.04	19.62	7.54	7.53
3.00	279.97	0.16	19.78	7.60	7.57
4.00	280.10	0.13	19.91	7.65	7.63
5.00	280.32	0.22	20.13	7.74	7.69
6.00	280.42	0.10	20.23	7.78	7.76
7.00	280.36	-0.06	20.17	7.75	7.76
8.00	280.46	0.10	20.27	7.79	7.77
1440	280.81	0.35	20.62	7.92	7.86
2880	281.24	0.43	21.05	8.09	8.01
4320	281.14	-0.10	20.95	8.05	8.07

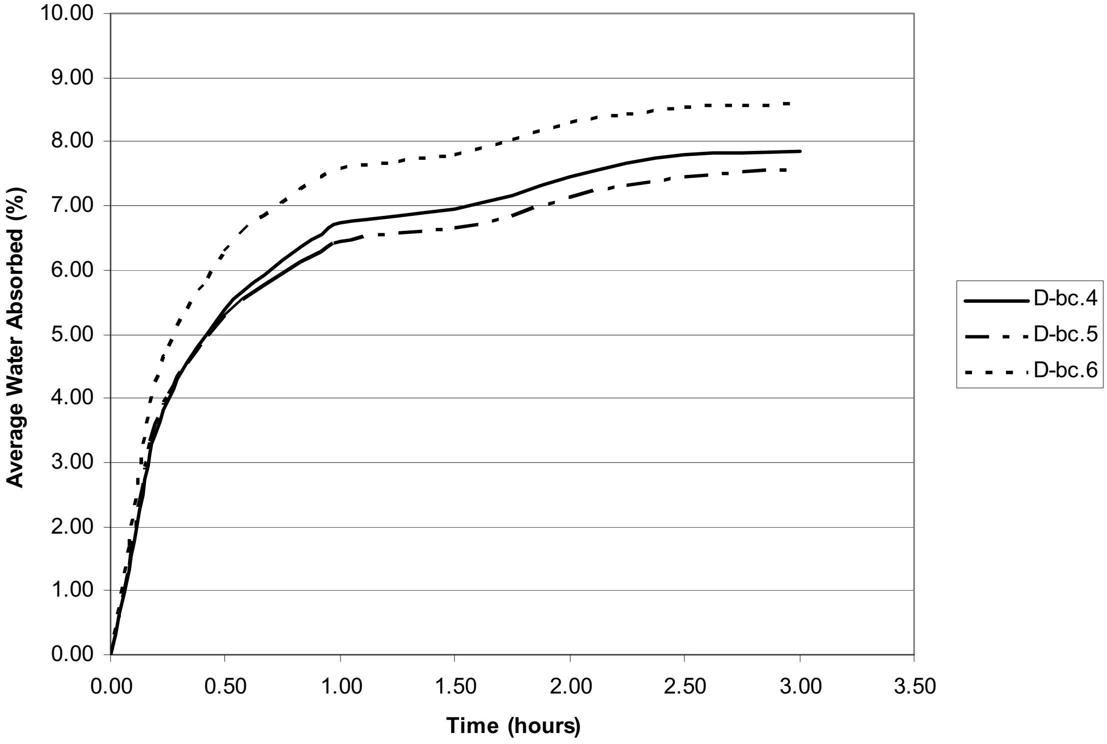
APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BC.6

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	273.79	0.00	0.00	0.00	0.00
0.08	283.06	9.27	9.27	3.39	1.69
0.17	285.99	2.93	12.20	4.46	3.92
0.25	287.90	1.91	14.11	5.15	4.80
0.33	289.20	1.30	15.41	5.63	5.39
0.42	290.50	1.30	16.71	6.10	5.87
0.50	291.52	1.02	17.73	6.48	6.29
0.58	292.24	0.72	18.45	6.74	6.61
0.67	292.76	0.52	18.97	6.93	6.83
0.75	293.50	0.74	19.71	7.20	7.06
0.83	293.86	0.36	20.07	7.33	7.26
0.92	294.50	0.64	20.71	7.56	7.45
1.00	294.64	0.14	20.85	7.62	7.59
1.25	295.03	0.39	21.24	7.76	7.69
1.50	295.28	0.25	21.49	7.85	7.80
1.75	296.37	1.09	22.58	8.25	8.05
2.00	296.65	0.28	22.86	8.35	8.30
2.25	297.13	0.48	23.34	8.52	8.44
2.50	297.19	0.06	23.40	8.55	8.54
2.75	297.29	0.10	23.50	8.58	8.56
3.00	297.35	0.06	23.56	8.61	8.59
4.00	297.49	0.14	23.70	8.66	8.63
5.00	297.65	0.16	23.86	8.71	8.69
6.00	297.82	0.17	24.03	8.78	8.75
7.00	297.65	-0.17	23.86	8.71	8.75
8.00	298.00	0.35	24.21	8.84	8.78
1440	298.28	0.28	24.49	8.94	8.89
2880	298.60	0.32	24.81	9.06	9.00
4320	298.78	0.18	24.99	9.13	9.09

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR PORTLAND CEMENT BEDDING SAMPLES



Appendix E: Water Absorption – NORMAL 7/81

Water Absorption Measurements for Sample D-bp.4

Time (hours)	**Weight (g)**	**Difference in successive weighings (grams)**	**Change in weight from initial weight (grams)**	**Amount of water absorbed (%)**	**Average water absorbed (%)**
0.00	235.49	0.00	0.00	0.00	0.00
0.08	261.69	26.20	26.20	11.13	5.56
0.17	262.90	1.21	27.41	11.64	11.38
0.25	262.50	-0.40	27.01	11.47	11.55
0.33	262.64	0.14	27.15	11.53	11.50
0.42	262.63	-0.01	27.14	11.52	11.53
0.50	262.62	-0.01	27.13	11.52	11.52
0.58	262.56	-0.06	27.07	11.50	11.51
0.67	262.57	0.01	27.08	11.50	11.50
0.75	262.72	0.15	27.23	11.56	11.53
0.83	262.67	-0.05	27.18	11.54	11.55
0.92	262.83	0.16	27.34	11.61	11.58
1.00	262.71	-0.12	27.22	11.56	11.58
1.25	262.73	0.02	27.24	11.57	11.56
1.50	262.72	-0.01	27.23	11.56	11.57
1.75	262.72	0.00	27.23	11.56	11.56
2.00	262.71	-0.01	27.22	11.56	11.56
2.25	262.80	0.09	27.31	11.60	11.58
2.50	262.77	-0.03	27.28	11.58	11.59
2.75	262.79	0.02	27.30	11.59	11.59
3.00	262.73	-0.06	27.24	11.57	11.58
4.00	262.81	0.08	27.32	11.60	11.58
5.00	262.88	0.07	27.39	11.63	11.62
6.00	263.00	0.12	27.51	11.68	11.66
7.00	262.89	-0.11	27.40	11.64	11.66
8.00	262.98	0.09	27.49	11.67	11.65
1440	263.18	0.20	27.69	11.76	11.72
2880	263.45	0.27	27.96	11.87	11.82
4320	263.96	0.51	28.47	12.09	11.98

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BP.5

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	225.71	0.00	0.00	0.00	0.00
0.08	251.32	25.61	25.61	11.35	5.67
0.17	251.98	0.66	26.27	11.64	11.49
0.25	251.84	-0.14	26.13	11.58	11.61
0.33	251.76	-0.08	26.05	11.54	11.56
0.42	251.85	0.09	26.14	11.58	11.56
0.50	251.90	0.05	26.19	11.60	11.59
0.58	251.86	-0.04	26.15	11.59	11.59
0.67	251.82	-0.04	26.11	11.57	11.58
0.75	252.03	0.21	26.32	11.66	11.61
0.83	251.91	-0.12	26.20	11.61	11.63
0.92	251.97	0.06	26.26	11.63	11.62
1.00	251.95	-0.02	26.24	11.63	11.63
1.25	252.06	0.11	26.35	11.67	11.65
1.50	251.98	-0.08	26.27	11.64	11.66
1.75	251.90	-0.08	26.19	11.60	11.62
2.00	251.99	0.09	26.28	11.64	11.62
2.25	252.00	0.01	26.29	11.65	11.65
2.50	252.13	0.13	26.42	11.71	11.68
2.75	252.01	-0.12	26.30	11.65	11.68
3.00	252.12	0.11	26.41	11.70	11.68
4.00	252.26	0.14	26.55	11.76	11.73
5.00	252.34	0.08	26.63	11.80	11.78
6.00	252.46	0.12	26.75	11.85	11.82
7.00	252.42	-0.04	26.71	11.83	11.84
8.00	252.59	0.17	26.88	11.91	11.87
1440	252.67	0.08	26.96	11.94	11.93
2880	253.03	0.36	27.32	12.10	12.02
4320	253.40	0.37	27.69	12.27	12.19

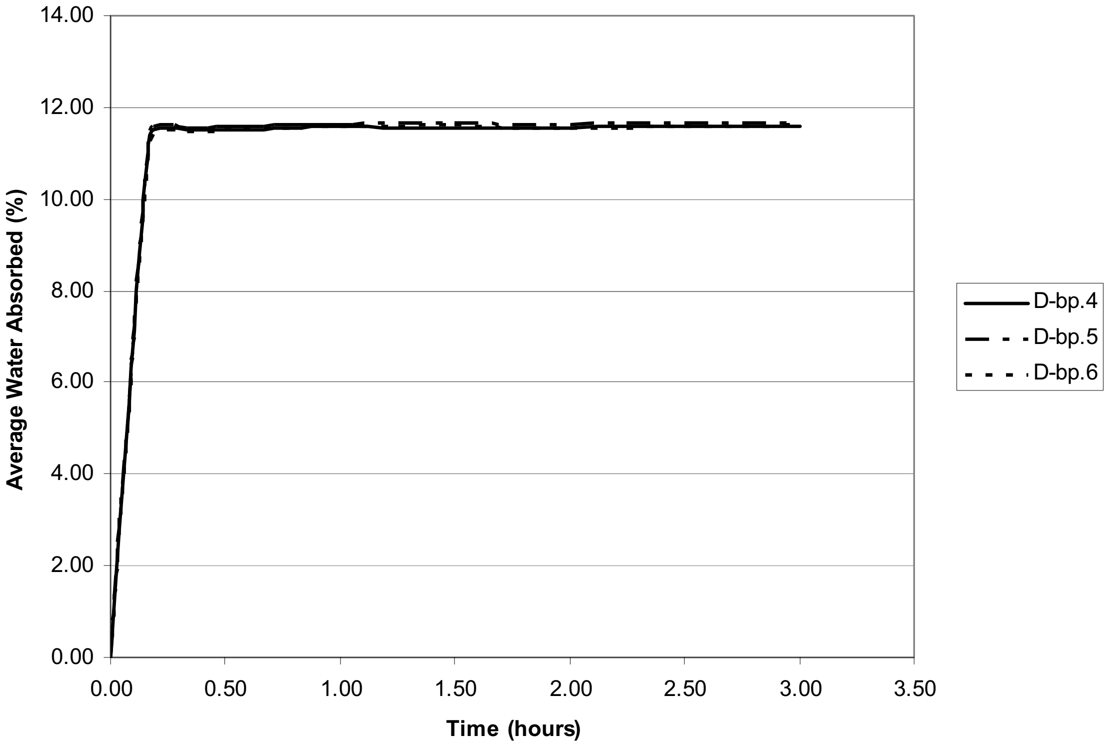
APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-BP.6

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	232.10	0.00	0.00	0.00	0.00
0.08	257.60	25.50	25.50	10.99	5.49
0.17	258.87	1.27	26.77	11.53	11.26
0.25	258.69	-0.18	26.59	11.46	11.50
0.33	258.72	0.03	26.62	11.47	11.46
0.42	258.79	0.07	26.69	11.50	11.48
0.50	258.90	0.11	26.80	11.55	11.52
0.58	258.93	0.03	26.83	11.56	11.55
0.67	258.82	-0.11	26.72	11.51	11.54
0.75	258.92	0.10	26.82	11.56	11.53
0.83	258.90	-0.02	26.80	11.55	11.55
0.92	259.06	0.16	26.96	11.62	11.58
1.00	258.94	-0.12	26.84	11.56	11.59
1.25	259.04	0.10	26.94	11.61	11.59
1.50	259.04	0.00	26.94	11.61	11.61
1.75	258.83	-0.21	26.73	11.52	11.56
2.00	258.93	0.10	26.83	11.56	11.54
2.25	258.95	0.02	26.85	11.57	11.56
2.50	259.08	0.13	26.98	11.62	11.60
2.75	258.93	-0.15	26.83	11.56	11.59
3.00	259.15	0.22	27.05	11.65	11.61
4.00	259.12	-0.03	27.02	11.64	11.65
5.00	259.28	0.16	27.18	11.71	11.68
6.00	259.40	0.12	27.30	11.76	11.74
7.00	259.33	-0.07	27.23	11.73	11.75
8.00	259.52	0.19	27.42	11.81	11.77
1440	259.63	0.11	27.53	11.86	11.84
2880	259.98	0.35	27.88	12.01	11.94
4320	260.24	0.26	28.14	12.12	12.07

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR LIME PUTTY BEDDING SAMPLES



Appendix E: Water Absorption – NORMAL 7/81

Water Absorption Measurements for Sample D-fh.4

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	224.99	0.00	0.00	0.00	0.00
0.08	248.29	23.30	23.30	10.36	5.18
0.17	249.86	1.57	24.87	11.05	10.70
0.25	249.73	-0.13	24.74	11.00	11.02
0.33	249.98	0.25	24.99	11.11	11.05
0.42	249.75	-0.23	24.76	11.00	11.06
0.50	249.93	0.18	24.94	11.08	11.04
0.58	249.94	0.01	24.95	11.09	11.09
0.67	249.95	0.01	24.96	11.09	11.09
0.75	249.91	-0.04	24.92	11.08	11.08
0.83	250.07	0.16	25.08	11.15	11.11
0.92	250.08	0.01	25.09	11.15	11.15
1.00	250.01	-0.07	25.02	11.12	11.14
1.25	250.11	0.10	25.12	11.16	11.14
1.50	250.06	-0.05	25.07	11.14	11.15
1.75	249.94	-0.12	24.95	11.09	11.12
2.00	250.10	0.16	25.11	11.16	11.12
2.25	250.06	-0.04	25.07	11.14	11.15
2.50	250.01	-0.05	25.02	11.12	11.13
2.75	249.93	-0.08	24.94	11.08	11.10
3.00	250.19	0.26	25.20	11.20	11.14
4.00	250.18	-0.01	25.19	11.20	11.20
5.00	250.26	0.08	25.27	11.23	11.21
6.00	250.29	0.03	25.30	11.24	11.24
7.00	250.39	0.10	25.40	11.29	11.27
8.00	250.27	-0.12	25.28	11.24	11.26
1440	250.45	0.18	25.46	11.32	11.28
2880	250.82	0.37	25.83	11.48	11.40
4320	251.18	0.36	26.19	11.64	11.56

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FH.5

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	229.38	0.00	0.00	0.00	0.00
0.08	254.30	24.92	24.92	10.86	5.43
0.17	254.65	0.35	25.27	11.02	10.94
0.25	254.70	0.05	25.32	11.04	11.03
0.33	254.77	0.07	25.39	11.07	11.05
0.42	254.82	0.05	25.44	11.09	11.08
0.50	254.69	-0.13	25.31	11.03	11.06
0.58	254.86	0.17	25.48	11.11	11.07
0.67	254.63	-0.23	25.25	11.01	11.06
0.75	254.64	0.01	25.26	11.01	11.01
0.83	254.72	0.08	25.34	11.05	11.03
0.92	254.86	0.14	25.48	11.11	11.08
1.00	254.77	-0.09	25.39	11.07	11.09
1.25	254.90	0.13	25.52	11.13	11.10
1.50	254.74	-0.16	25.36	11.06	11.09
1.75	254.79	0.05	25.41	11.08	11.07
2.00	254.58	-0.21	25.20	10.99	11.03
2.25	254.64	0.06	25.26	11.01	11.00
2.50	254.62	-0.02	25.24	11.00	11.01
2.75	254.63	0.01	25.25	11.01	11.01
3.00	254.84	0.21	25.46	11.10	11.05
4.00	254.78	-0.06	25.40	11.07	11.09
5.00	254.72	-0.06	25.34	11.05	11.06
6.00	254.88	0.16	25.50	11.12	11.08
7.00	254.95	0.07	25.57	11.15	11.13
8.00	254.99	0.04	25.61	11.16	11.16
1440	255.10	0.11	25.72	11.21	11.19
2880	255.37	0.27	25.99	11.33	11.27
4320	255.41	0.04	26.03	11.35	11.34

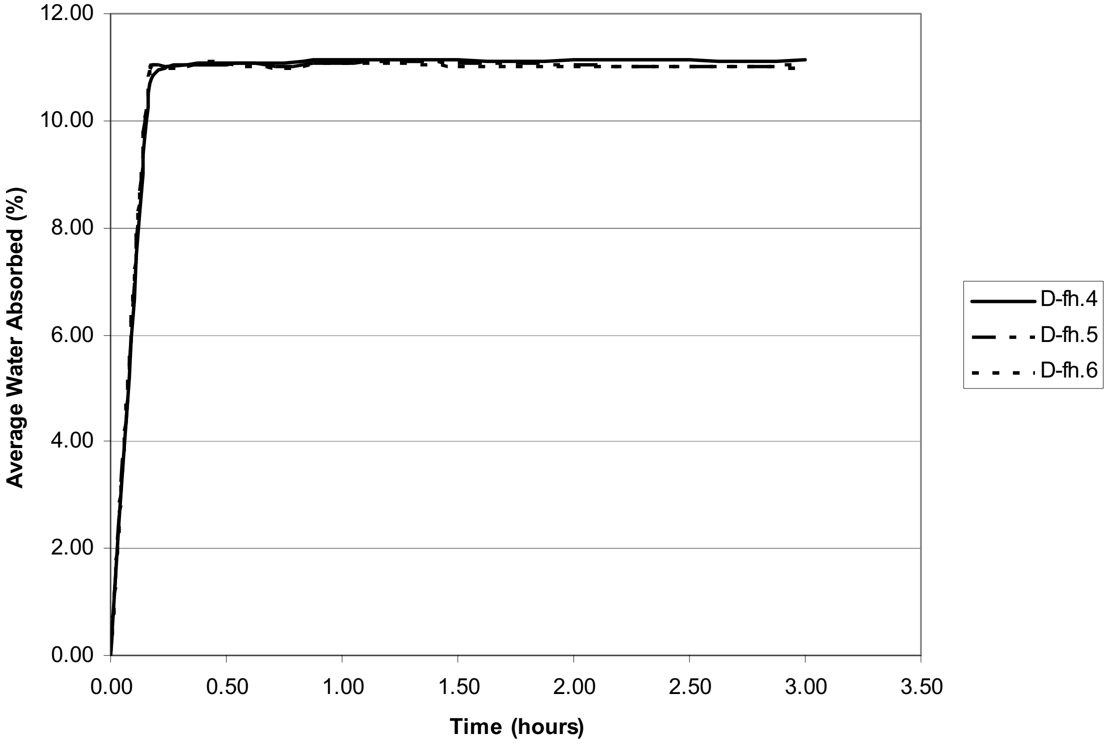
APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FH.6

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	223.39	0.00	0.00	0.00	0.00
0.08	247.85	24.46	24.46	10.95	5.47
0.17	247.96	0.11	24.57	11.00	10.97
0.25	247.91	-0.05	24.52	10.98	10.99
0.33	248.12	0.21	24.73	11.07	11.02
0.42	248.29	0.17	24.90	11.15	11.11
0.50	247.97	-0.32	24.58	11.00	11.07
0.58	248.08	0.11	24.69	11.05	11.03
0.67	247.91	-0.17	24.52	10.98	11.01
0.75	247.90	-0.01	24.51	10.97	10.97
0.83	248.04	0.14	24.65	11.03	11.00
0.92	248.21	0.17	24.82	11.11	11.07
1.00	248.10	-0.11	24.71	11.06	11.09
1.25	248.12	0.02	24.73	11.07	11.07
1.50	247.91	-0.21	24.52	10.98	11.02
1.75	248.06	0.15	24.67	11.04	11.01
2.00	247.94	-0.12	24.55	10.99	11.02
2.25	248.05	0.11	24.66	11.04	11.01
2.50	248.00	-0.05	24.61	11.02	11.03
2.75	247.93	-0.07	24.54	10.99	11.00
3.00	247.92	-0.01	24.53	10.98	10.98
4.00	247.98	0.06	24.59	11.01	10.99
5.00	248.01	0.03	24.62	11.02	11.01
6.00	248.10	0.09	24.71	11.06	11.04
7.00	248.00	-0.10	24.61	11.02	11.04
8.00	248.26	0.26	24.87	11.13	11.07
1440	248.33	0.07	24.94	11.16	11.15
2880	248.30	-0.03	24.91	11.15	11.16
4320	248.49	0.19	25.10	11.24	11.19

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR HYDRATED HYDRAULIC LIME FINISH POINTING SAMPLES



APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FC.4

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	267.71	0.00	0.00	0.00	0.00
0.08	280.03	12.32	12.32	4.60	2.30
0.17	282.34	2.31	14.63	5.46	5.03
0.25	283.79	1.45	16.08	6.01	5.74
0.33	285.19	1.40	17.48	6.53	6.27
0.42	286.10	0.91	18.39	6.87	6.70
0.50	286.66	0.56	18.95	7.08	6.97
0.58	287.35	0.69	19.64	7.34	7.21
0.67	287.56	0.21	19.85	7.41	7.38
0.75	289.90	2.34	22.19	8.29	7.85
0.83	288.54	-1.36	20.83	7.78	8.03
0.92	289.01	0.47	21.30	7.96	7.87
1.00	288.97	-0.04	21.26	7.94	7.95
1.25	289.27	0.30	21.56	8.05	8.00
1.50	289.32	0.05	21.61	8.07	8.06
1.75	290.04	0.72	22.33	8.34	8.21
2.00	290.23	0.19	22.52	8.41	8.38
2.25	290.19	-0.04	22.48	8.40	8.40
2.50	290.33	0.14	22.62	8.45	8.42
2.75	290.33	0.00	22.62	8.45	8.45
3.00	290.45	0.12	22.74	8.49	8.47
4.00	290.62	0.17	22.91	8.56	8.53
5.00	290.70	0.08	22.99	8.59	8.57
6.00	290.84	0.14	23.13	8.64	8.61
7.00	290.70	-0.14	22.99	8.59	8.61
8.00	290.98	0.28	23.27	8.69	8.64
1440	291.50	0.52	23.79	8.89	8.79
2880	291.83	0.33	24.12	9.01	8.95
4320	291.75	-0.08	24.04	8.98	8.99

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FC.5

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	257.33	0.00	0.00	0.00	0.00
0.08	271.40	14.07	14.07	5.47	2.73
0.17	273.91	2.51	16.58	6.44	5.96
0.25	275.61	1.70	18.28	7.10	6.77
0.33	276.69	1.08	19.36	7.52	7.31
0.42	277.43	0.74	20.10	7.81	7.67
0.50	277.43	0.00	20.10	7.81	7.81
0.58	277.69	0.26	20.36	7.91	7.86
0.67	277.37	-0.32	20.04	7.79	7.85
0.75	277.55	0.18	20.22	7.86	7.82
0.83	277.80	0.25	20.47	7.95	7.91
0.92	277.70	-0.10	20.37	7.92	7.94
1.00	277.77	0.07	20.44	7.94	7.93
1.25	277.90	0.13	20.57	7.99	7.97
1.50	277.77	-0.13	20.44	7.94	7.97
1.75	277.88	0.11	20.55	7.99	7.96
2.00	277.68	-0.20	20.35	7.91	7.95
2.25	277.80	0.12	20.47	7.95	7.93
2.50	277.86	0.06	20.53	7.98	7.97
2.75	277.84	-0.02	20.51	7.97	7.97
3.00	277.99	0.15	20.66	8.03	8.00
4.00	278.01	0.02	20.68	8.04	8.03
5.00	278.13	0.12	20.80	8.08	8.06
6.00	278.19	0.06	20.86	8.11	8.09
7.00	278.24	0.05	20.91	8.13	8.12
8.00	278.29	0.05	20.96	8.15	8.14
1440	278.78	0.49	21.45	8.34	8.24
2880	279.13	0.35	21.80	8.47	8.40
4320	279.25	0.12	21.92	8.52	8.49

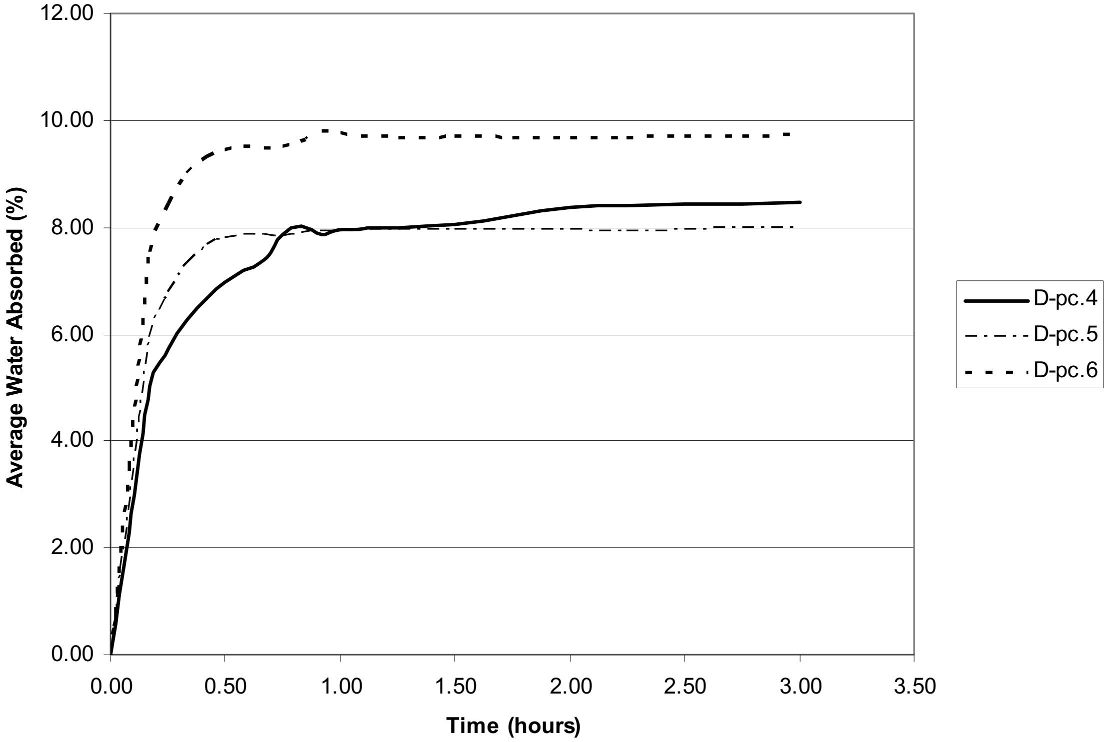
APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FC.6

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	254.19	0.00	0.00	0.00	0.00
0.08	270.20	16.01	16.01	7.03	3.52
0.17	272.55	2.35	18.36	8.07	7.55
0.25	274.19	1.64	20.00	8.79	8.43
0.33	275.18	0.99	20.99	9.22	9.00
0.42	275.60	0.42	21.41	9.40	9.31
0.50	275.86	0.26	21.67	9.52	9.46
0.58	275.84	-0.02	21.65	9.51	9.51
0.67	275.79	-0.05	21.60	9.49	9.50
0.75	275.88	0.09	21.69	9.53	9.51
0.83	276.22	0.34	22.03	9.68	9.60
0.92	276.80	0.58	22.61	9.93	9.80
1.00	276.08	-0.72	21.89	9.62	9.77
1.25	276.39	0.31	22.20	9.75	9.68
1.50	276.21	-0.18	22.02	9.67	9.71
1.75	276.23	0.02	22.04	9.68	9.68
2.00	276.27	0.04	22.08	9.70	9.69
2.25	276.22	-0.05	22.03	9.68	9.69
2.50	276.29	0.07	22.10	9.71	9.69
2.75	276.24	-0.05	22.05	9.69	9.70
3.00	276.50	0.26	22.31	9.80	9.74
4.00	276.55	0.05	22.36	9.82	9.81
5.00	276.72	0.17	22.53	9.90	9.86
6.00	276.80	0.08	22.61	9.93	9.91
7.00	276.94	0.14	22.75	9.99	9.96
8.00	276.96	0.02	22.77	10.00	10.00
1440	277.34	0.38	23.15	10.17	10.09
2880	277.94	0.60	23.75	10.43	10.30
4320	278.17	0.23	23.98	10.53	10.48

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR PORTLAND CEMENT FINISH POINTING SAMPLES



APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FP.4

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	222.42	0.00	0.00	0.00	0.00
0.08	247.58	25.16	25.16	11.31	5.66
0.17	247.51	-0.07	25.09	11.28	11.30
0.25	247.54	0.03	25.12	11.29	11.29
0.33	247.45	-0.09	25.03	11.25	11.27
0.42	247.58	0.13	25.16	11.31	11.28
0.50	247.59	0.01	25.17	11.32	11.31
0.58	247.52	-0.07	25.10	11.28	11.30
0.67	247.32	-0.20	24.90	11.20	11.24
0.75	247.50	0.18	25.08	11.28	11.24
0.83	247.59	0.09	25.17	11.32	11.30
0.92	247.55	-0.04	25.13	11.30	11.31
1.00	247.52	-0.03	25.10	11.28	11.29
1.25	247.66	0.14	25.24	11.35	11.32
1.50	247.44	-0.22	25.02	11.25	11.30
1.75	247.46	0.02	25.04	11.26	11.25
2.00	247.36	-0.10	24.94	11.21	11.24
2.25	247.39	0.03	24.97	11.23	11.22
2.50	247.50	0.11	25.08	11.28	11.25
2.75	247.50	0.00	25.08	11.28	11.28
3.00	247.51	0.01	25.09	11.28	11.28
4.00	247.45	-0.06	25.03	11.25	11.27
5.00	247.49	0.04	25.07	11.27	11.26
6.00	247.60	0.11	25.18	11.32	11.30
7.00	247.63	0.03	25.21	11.33	11.33
8.00	247.84	0.21	25.42	11.43	11.38
1440	248.01	0.17	25.59	11.51	11.47
2880	248.27	0.26	25.85	11.62	11.56
4320	248.98	0.71	26.56	11.94	11.78

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FP.5

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	213.59	0.00	0.00	0.00	0.00
0.08	239.02	25.43	25.43	11.91	5.95
0.17	238.92	-0.10	25.33	11.86	11.88
0.25	238.97	0.05	25.38	11.88	11.87
0.33	239.04	0.07	25.45	11.92	11.90
0.42	238.86	-0.18	25.27	11.83	11.87
0.50	237.03	-1.83	23.44	10.97	11.40
0.58	239.02	1.99	25.43	11.91	11.44
0.67	238.76	-0.26	25.17	11.78	11.85
0.75	238.85	0.09	25.26	11.83	11.81
0.83	238.98	0.13	25.39	11.89	11.86
0.92	239.06	0.08	25.47	11.92	11.91
1.00	238.89	-0.17	25.30	11.85	11.88
1.25	239.15	0.26	25.56	11.97	11.91
1.50	238.86	-0.29	25.27	11.83	11.90
1.75	238.92	0.06	25.33	11.86	11.85
2.00	238.85	-0.07	25.26	11.83	11.84
2.25	238.93	0.08	25.34	11.86	11.85
2.50	238.89	-0.04	25.30	11.85	11.85
2.75	238.93	0.04	25.34	11.86	11.85
3.00	239.03	0.10	25.44	11.91	11.89
4.00	239.08	0.05	25.49	11.93	11.92
5.00	239.07	-0.01	25.48	11.93	11.93
6.00	239.31	0.24	25.72	12.04	11.99
7.00	239.50	0.19	25.91	12.13	12.09
8.00	239.75	0.25	26.16	12.25	12.19
1440	240.27	0.52	26.68	12.49	12.37
2880	240.80	0.53	27.21	12.74	12.62
4320	241.67	0.87	28.08	13.15	12.94

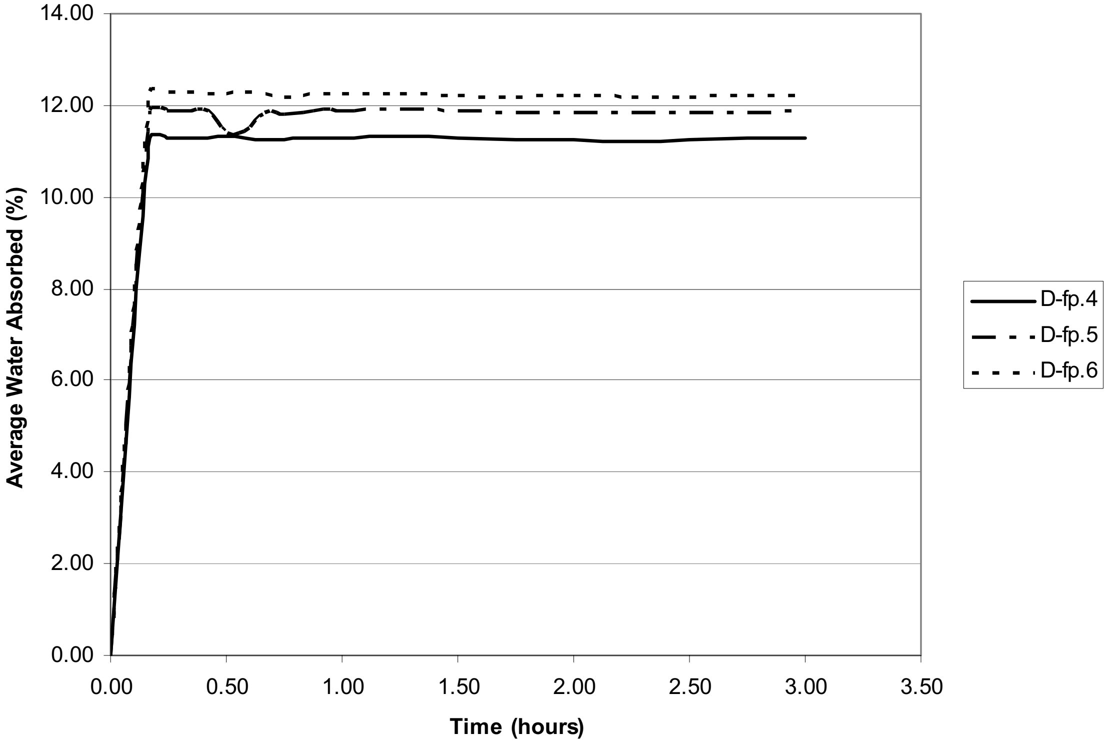
APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION MEASUREMENTS FOR SAMPLE D-FP.6

Time (hours)	Weight (g)	Difference in successive weighings (grams)	Change in weight from initial weight (grams)	Amount of water absorbed (%)	Average water absorbed (%)
0.00	224.93	0.00	0.00	0.00	0.00
0.08	252.70	27.77	27.77	12.35	6.17
0.17	252.52	-0.18	27.59	12.27	12.31
0.25	252.57	0.05	27.64	12.29	12.28
0.33	252.51	-0.06	27.58	12.26	12.27
0.42	252.44	-0.07	27.51	12.23	12.25
0.50	252.50	0.06	27.57	12.26	12.24
0.58	252.59	0.09	27.66	12.30	12.28
0.67	252.37	-0.22	27.44	12.20	12.25
0.75	252.35	-0.02	27.42	12.19	12.19
0.83	252.49	0.14	27.56	12.25	12.22
0.92	252.52	0.03	27.59	12.27	12.26
1.00	252.52	0.00	27.59	12.27	12.27
1.25	252.47	-0.05	27.54	12.24	12.25
1.50	252.32	-0.15	27.39	12.18	12.21
1.75	252.37	0.05	27.44	12.20	12.19
2.00	252.38	0.01	27.45	12.20	12.20
2.25	252.25	-0.13	27.32	12.15	12.17
2.50	252.33	0.08	27.40	12.18	12.16
2.75	252.45	0.12	27.52	12.23	12.21
3.00	252.36	-0.09	27.43	12.19	12.21
4.00	252.45	0.09	27.52	12.23	12.21
5.00	252.56	0.11	27.63	12.28	12.26
6.00	252.65	0.09	27.72	12.32	12.30
7.00	252.71	0.06	27.78	12.35	12.34
8.00	252.80	0.09	27.87	12.39	12.37
1440	253.63	0.83	28.70	12.76	12.58
2880	254.21	0.58	29.28	13.02	12.89
4320	255.38	1.17	30.45	13.54	13.28

APPENDIX E: WATER ABSORPTION – NORMAL 7/81

WATER ABSORPTION CURVES
FOR LIME PUTTY FINISH POINTING SAMPLES



APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**;** ∆T = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **∆Y/∆T** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**0**	**0.25**	**0.33**	**0.42**	**0.5**	**0.58**	**0.67**	**0.75**	**0.83**	**0.92**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**
∆T	**0**	**0.25**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
SAMPLE																
D-bh.4																
Wt	259.43	259.17	258.97	258.72	258.58	258.38	258.17	258.06	257.89	257.74	257.56	257.12	256.70	256.25	255.81	255.37
Qi	10.59	10.48	10.40	10.29	10.23	10.15	10.06	10.01	9.94	9.87	9.80	9.61	9.43	9.24	9.05	8.86
Ut	24.85	24.59	24.39	24.14	24.00	23.80	23.59	23.48	23.31	23.16	22.98	22.54	22.12	21.67	21.23	20.79
Uo	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85
Y%	100.00	98.95	98.15	97.14	96.58	95.77	94.93	94.49	93.80	93.20	92.47	90.70	89.01	87.20	85.43	83.66
∆Y/∆T	0.00	1.04	5.75	7.89	10.63	13.13	14.00	17.13	19.25	18.78	23.38	9.24	10.92	12.72	14.48	16.24
Ψ	0.20	0.20	0.20	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.17	0.17	0.17
D-bh.5																
Wt	254.06	253.81	253.64	253.40	253.24	253.07	252.87	252.77	252.62	252.48	252.35	251.94	251.56	251.15	250.76	250.37
Qi	10.71	10.60	10.52	10.42	10.35	10.27	10.19	10.14	10.08	10.02	9.96	9.78	9.62	9.44	9.27	9.10
Ut	24.57	24.32	24.15	23.91	23.75	23.58	23.38	23.28	23.13	22.99	22.86	22.45	22.07	21.66	21.27	20.88
Uo	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57
Y	100.00	98.98	98.29	97.31	96.66	95.97	95.16	94.75	94.14	93.57	93.04	91.37	89.82	88.16	86.57	84.98
∆Y/∆T	0.00	1.00	5.25	7.33	10.25	12.38	13.22	16.13	18.00	17.56	21.38	8.48	10.00	11.64	13.20	14.76
Ψ	0.20	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.17	0.17	0.17
D-bh.6																
Wt	250.27	249.01	249.85	249.59	249.46	249.28	249.07	248.98	248.83	248.70	248.56	248.16	247.77	247.36	246.98	246.60
Qi	9.78	9.23	9.60	9.48	9.43	9.35	9.26	9.22	9.15	9.09	9.03	8.86	8.69	8.51	8.34	8.17
Ut	22.30	21.04	21.88	21.62	21.49	21.31	21.10	21.01	20.86	20.73	20.59	20.19	19.80	19.39	19.01	18.63
Uo	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30
Y	100.00	94.35	98.12	96.95	96.37	95.56	94.62	94.22	93.54	92.96	92.33	90.54	88.79	86.95	85.25	83.54
∆Y/∆T	0.00	5.04	5.25	7.56	10.12	12.38	13.33	16.13	18.00	17.44	21.38	8.44	10.00	11.64	13.16	14.68
Ψ	0.18	0.17	0.18	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.16	0.16	0.16	0.15	0.15

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**;** **ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	2.5	2.75	3	24	48	72	96	120	144	168	192	216	240	264	288	312	336	360
ΔT	0.25	0.25	0.25	21	24	24	24	24	24	24	24	24	24	24	24	24	24	24
SAMPLE																		
D-bh.4																		
Wt	254.90	254.48	254.00	250.31	246.62	239.40	234.66	225.13	234.56	234.58	234.58	234.58	234.58	234.58	234.58	234.58	234.58	234.58
Qi	8.66	8.48	8.28	6.71	5.13	2.05	0.03	-4.03	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	20.32	19.90	19.42	15.73	12.04	4.82	0.08	-9.45	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85	24.85
Y%	81.77	80.08	78.15	63.30	48.45	19.40	0.32	-38.03	-0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	18.12	19.80	21.72	0.43	0.53	0.83	1.03	1.43	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04	1.04
Ψ	0.16	0.16	0.16	0.13	0.10	0.04	0.00	-0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-bh.5																		
Wt	249.94	249.57	249.11	247.05	244.99	235.44	229.55	229.28	229.47	229.49	229.49	229.49	229.49	229.49	229.49	229.49	229.49	229.49
Qi	8.91	8.75	8.55	7.65	6.75	2.59	0.03	-0.09	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	20.45	20.08	19.62	17.56	15.50	5.95	0.06	-0.21	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57	24.57
Y	83.23	81.73	79.85	71.47	63.09	24.22	0.24	-0.85	-0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	16.48	17.96	19.80	0.33	0.38	0.78	1.02	1.03	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Ψ	0.16	0.16	0.16	0.14	0.12	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-bh.6																		
Wt	246.16	245.78	245.27	244.07	242.87	234.22	228.03	223.35	227.98	227.97	227.97	227.97	227.97	227.97	227.97	227.97	227.97	227.97
Qi	7.98	7.81	7.59	7.06	6.54	2.74	0.03	-2.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	18.19	17.81	17.30	16.10	14.90	6.25	0.06	-4.62	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30	22.30
Y	81.57	79.87	77.58	72.20	66.82	28.03	0.27	-20.72	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	16.44	17.96	20.00	0.30	0.31	0.67	0.93	1.12	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93	0.93
Ψ	0.15	0.14	0.14	0.13	0.12	0.05	0.00	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**;** ΔT = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**0**	**0.25**	**0.33**	**0.42**	**0.5**	**0.58**	**0.67**	**0.75**	**0.83**	**0.92**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**
ΔT	**0**	**0.25**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
SAMPLE																
D-bc.4																
Wt	285.87	285.62	285.43	285.21	285.08	284.89	284.70	284.61	284.47	284.35	284.22	283.94	283.70	283.50	283.36	283.22
Qi	7.57	7.48	7.41	7.32	7.27	7.20	7.13	7.10	7.04	7.00	6.95	6.84	6.75	6.68	6.63	6.57
Ut	20.12	19.87	19.68	19.46	19.33	19.14	18.95	18.86	18.72	18.60	18.47	18.19	17.95	17.75	17.61	17.47
Uo	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12
Y	100.00	98.76	97.81	96.72	96.07	95.13	94.18	93.74	93.04	92.45	91.80	90.41	89.21	88.22	87.52	86.83
ΔY/ΔT	0.00	1.00	5.50	7.33	9.88	12.25	13.00	15.75	17.50	16.89	20.62	7.72	8.68	9.48	10.04	10.60
Ψ	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14
D-bc.5																
Wt	281.14	280.93	280.79	280.62	280.49	280.34	280.19	280.10	279.99	279.88	279.79	279.53	279.29	279.09	278.94	278.80
Qi	7.31	7.23	7.18	7.11	7.06	7.00	6.95	6.91	6.87	6.83	6.79	6.69	6.60	6.53	6.47	6.42
Ut	19.15	18.94	18.80	18.63	18.50	18.35	18.20	18.11	18.00	17.89	17.80	17.54	17.30	17.10	16.95	16.81
Uo	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15
Y	100.00	98.90	98.17	97.28	96.61	95.82	95.04	94.57	93.99	93.42	92.95	91.59	90.34	89.30	88.51	87.78
ΔY/ΔT	0.00	0.84	4.37	5.78	8.12	10.00	10.56	13.00	14.38	14.00	16.87	6.44	7.40	8.20	8.80	9.36
Ψ	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.13
D-bc.6																
Wt	298.78	298.56	298.42	298.18	298.06	297.89	297.70	297.61	297.47	297.36	297.23	296.91	296.62	296.36	296.14	295.95
Qi	8.44	8.36	8.31	8.22	8.18	8.12	8.05	8.02	7.97	7.93	7.88	7.76	7.66	7.56	7.48	7.42
Ut	23.26	23.04	22.90	22.66	22.54	22.37	22.18	22.09	21.95	21.84	21.71	21.39	21.10	20.84	20.62	20.43
Uo	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26
Y	100.00	99.05	98.45	97.42	96.90	96.17	95.36	94.97	94.37	93.90	93.34	91.96	90.71	89.60	88.65	87.83
ΔY/ΔT	0.00	0.88	4.50	6.67	9.00	11.13	12.00	14.62	16.37	15.78	19.37	7.48	8.64	9.68	10.56	11.32
Ψ	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.17	0.17	0.17	0.16	0.16

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**;** **ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**2.5**	**2.75**	**3**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**	**264**	**288**	**312**	**336**	**360**
ΔT	**0.25**	**0.25**	**0.25**	**21**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
SAMPLE																		
D-bc.4																		
Wt	283.10	283.00	282.85	282.48	282.11	279.55	274.12	272.84	269.15	268.30	267.35	266.91	266.26	266.07	265.88	265.79	265.77	265.75
Qi	6.53	6.49	6.43	6.30	6.16	5.19	3.15	2.67	1.28	0.96	0.60	0.44	0.19	0.12	0.05	0.02	0.01	0.00
Ut	17.35	17.25	17.10	16.73	16.36	13.80	8.37	7.09	3.40	2.55	1.60	1.16	0.51	0.32	0.13	0.04	0.02	0.00
Uo	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12	20.12
Y	86.23	85.74	84.99	83.15	81.31	68.59	41.60	35.24	16.90	12.67	7.95	5.77	2.53	1.59	0.65	0.20	0.10	0.00
ΔY/ΔT	11.08	11.48	12.08	0.16	0.16	0.26	0.49	0.54	0.70	0.73	0.77	0.79	0.82	0.83	0.83	0.84	0.84	0.84
Ψ	0.14	0.14	0.14	0.13	0.13	0.11	0.07	0.06	0.03	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
D-bc.5																		
Wt	278.67	278.57	278.41	278.16	277.91	275.27	269.59	260.05	264.88	264.14	263.31	262.95	262.37	262.19	262.07	261.98	261.99	261.99
Qi	6.37	6.33	6.27	6.17	6.08	5.07	2.90	-0.74	1.10	0.82	0.50	0.37	0.15	0.08	0.03	0.00	0.00	0.00
Ut	16.68	16.58	16.42	16.17	15.92	13.28	7.60	-1.94	2.89	2.15	1.32	0.96	0.38	0.20	0.08	-0.01	0.00	0.00
Uo	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15	19.15
Y	87.10	86.58	85.74	84.44	83.13	69.35	39.69	-10.13	15.09	11.23	6.89	5.01	1.98	1.04	0.42	-0.05	0.00	0.00
ΔY/ΔT	9.88	10.28	10.92	0.14	0.13	0.24	0.48	0.88	0.68	0.71	0.74	0.76	0.78	0.79	0.79	0.80	0.80	0.80
Ψ	0.13	0.13	0.13	0.13	0.13	0.11	0.06	-0.02	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
D-bc.6																		
Wt	295.77	295.64	295.42	295.29	295.16	291.57	284.29	256.18	278.53	277.66	276.73	276.35	275.78	275.62	275.52	275.45	275.50	275.52
Qi	7.35	7.30	7.22	7.18	7.13	5.83	3.18	-7.02	1.09	0.78	0.44	0.30	0.09	0.04	0.00	-0.03	-0.01	0.00
Ut	20.25	20.12	19.90	19.77	19.64	16.05	8.77	-19.34	3.01	2.14	1.21	0.83	0.26	0.10	0.00	-0.07	-0.02	0.00
Uo	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26	23.26
Y	87.06	86.50	85.55	85.00	84.44	69.00	37.70	-83.15	12.94	9.20	5.20	3.57	1.12	0.43	0.00	-0.30	-0.09	0.00
ΔY/ΔT	12.04	12.56	13.44	0.17	0.15	0.30	0.60	1.78	0.84	0.88	0.92	0.93	0.96	0.96	0.97	0.97	0.97	0.97
Ψ	0.16	0.16	0.16	0.16	0.16	0.13	0.07	-0.15	0.02	0.02	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**;** ΔT = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **$\Delta Y/\Delta T$** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**0**	**0.25**	**0.33**	**0.42**	**0.5**	**0.58**	**0.67**	**0.75**	**0.83**	**0.92**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**
ΔT	**0**	**0.25**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
SAMPLE																
D-bp.4																
Wt	263.96	263.78	263.60	263.38	263.22	263.05	262.86	262.75	262.58	262.43	262.28	261.84	261.45	261.02	260.60	260.20
Qi	12.35	12.28	12.20	12.11	12.04	11.96	11.88	11.84	11.76	11.70	11.64	11.45	11.28	11.10	10.92	10.75
Ut	29.02	28.84	28.66	28.44	28.28	28.11	27.92	27.81	27.64	27.49	27.34	26.90	26.51	26.08	25.66	25.26
Uo	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02
Y	100.00	99.38	98.76	98.00	97.45	96.86	96.21	95.83	95.24	94.73	94.21	92.69	91.35	89.87	88.42	87.04
$\Delta Y/\Delta T$	0.00	0.72	4.50	6.44	9.25	11.37	12.22	15.13	17.25	17.00	21.00	8.48	10.04	11.76	13.44	15.04
Ψ	0.23	0.23	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.20
D-bp.5																
Wt	253.40	253.22	253.07	252.88	252.75	252.60	252.42	252.34	252.20	252.09	251.96	251.59	251.25	250.88	250.52	250.19
Qi	12.45	12.37	12.30	12.22	12.16	12.09	12.01	11.98	11.91	11.87	11.81	11.64	11.49	11.33	11.17	11.02
Ut	28.05	27.87	27.72	27.53	27.40	27.25	27.07	26.99	26.85	26.74	26.61	26.24	25.90	25.53	25.17	24.84
Uo	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05
Y	100.00	99.36	98.82	98.15	97.68	97.15	96.51	96.22	95.72	95.33	94.87	93.55	92.34	91.02	89.73	88.56
$\Delta Y/\Delta T$	0.00	0.72	4.13	5.78	8.12	10.00	10.89	13.25	15.00	14.56	18.00	7.24	8.60	10.08	11.52	12.84
Ψ	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20
D-bp.6																
Wt	260.24	260.08	259.95	259.75	259.61	259.44	259.26	259.16	259.03	258.90	258.78	258.41	258.04	257.66	257.28	256.92
Qi	12.33	12.26	12.20	12.12	12.06	11.98	11.90	11.86	11.81	11.75	11.70	11.54	11.38	11.21	11.05	10.89
Ut	28.56	28.40	28.27	28.07	27.93	27.76	27.58	27.48	27.35	27.22	27.10	26.73	26.36	25.98	25.60	25.24
Uo	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56
Y	100.00	99.44	98.98	98.28	97.79	97.20	96.57	96.22	95.76	95.31	94.89	93.59	92.30	90.97	89.64	88.38
$\Delta Y/\Delta T$	0.00	0.64	3.63	5.44	7.87	10.00	10.89	13.50	15.13	14.89	18.25	7.32	8.80	10.32	11.84	13.28
Ψ	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.20	0.20

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**;** **ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **$\Delta Y/\Delta T$** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**2.5**	**2.75**	**3**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**	**264**	**288**	**312**	**336**	**360**
ΔT	**0.25**	**0.25**	**0.25**	**21**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
SAMPLE																		
D-bp.4																		
Wt	259.74	259.37	258.93	257.27	255.60	238.19	234.87	221.62	234.91	234.95	234.94	234.94	234.94	234.94	234.94	234.94	234.94	234.94
Qi	10.56	10.40	10.21	9.50	8.79	1.38	-0.03	-5.67	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	24.80	24.43	23.99	22.33	20.66	3.25	-0.07	-13.32	-0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02	29.02
Y	85.46	84.18	82.67	76.93	71.19	11.20	-0.24	-45.90	-0.10	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\Delta Y/\Delta T$	16.88	18.36	20.12	0.32	0.35	1.07	1.21	1.76	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21	1.21
Ψ	0.20	0.20	0.19	0.18	0.17	0.03	0.00	-0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-bp.5																		
Wt	249.79	249.47	249.13	248.33	247.53	229.25	225.30	213.09	225.33	225.36	225.35	225.35	225.35	225.35	225.35	225.35	225.35	225.35
Qi	10.85	10.70	10.55	10.20	9.84	1.73	-0.02	-5.44	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	24.44	24.12	23.78	22.98	22.18	3.90	-0.05	-12.26	-0.02	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05	28.05
Y	87.13	85.99	84.78	81.93	79.07	13.90	-0.18	-43.71	-0.07	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\Delta Y/\Delta T$	14.44	15.72	17.08	0.24	0.24	1.01	1.17	1.68	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17	1.17
Ψ	0.20	0.19	0.19	0.18	0.18	0.03	0.00	-0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-bp.6																		
Wt	256.50	256.16	255.74	255.20	254.66	235.68	231.60	224.19	231.64	231.69	231.68	231.68	231.68	231.68	231.68	231.68	231.68	231.68
Qi	10.71	10.57	10.39	10.15	9.92	1.73	-0.03	-3.23	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	24.82	24.48	24.06	23.52	22.98	4.00	-0.08	-7.49	-0.04	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56	28.56
Y	86.90	85.71	84.24	82.35	80.46	14.01	-0.28	-26.23	-0.14	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
$\Delta Y/\Delta T$	14.96	16.32	18.00	0.24	0.23	1.02	1.19	1.50	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
Ψ	0.20	0.20	0.19	0.19	0.18	0.03	0.00	-0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours; **ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**0**	**0.25**	**0.33**	**0.42**	**0.5**	**0.58**	**0.67**	**0.75**	**0.83**	**0.92**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**
ΔT	**0**	**0.25**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
SAMPLE																
D-fh.4																
Wt	251.18	250.93	250.73	250.49	250.33	250.16	249.95	249.86	249.70	249.57	249.43	249.02	248.63	248.24	247.84	247.47
Qi	11.59	11.47	11.39	11.28	11.21	11.13	11.04	11.00	10.93	10.87	10.81	10.63	10.45	10.28	10.10	9.94
Ut	26.08	25.83	25.63	25.39	25.23	25.06	24.85	24.76	24.60	24.47	24.33	23.92	23.53	23.14	22.74	22.37
Uo	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08
Y	100.00	99.04	98.27	97.35	96.74	96.09	95.28	94.94	94.33	93.83	93.29	91.72	90.22	88.73	87.19	85.77
ΔY/ΔT	0.00	1.00	5.63	7.67	10.62	12.75	13.67	16.50	18.50	17.89	21.87	8.64	10.20	11.76	13.36	14.84
Ψ	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19	0.18	0.18
D-fh.5																
Wt	255.41	255.20	255.04	254.84	254.69	254.51	254.33	254.24	254.10	253.97	253.84	253.45	253.07	252.70	252.31	251.96
Qi	11.40	11.31	11.24	11.15	11.09	11.01	10.93	10.89	10.83	10.77	10.72	10.55	10.38	10.22	10.05	9.90
Ut	26.14	25.93	25.77	25.57	25.42	25.24	25.06	24.97	24.83	24.70	24.57	24.18	23.80	23.43	23.04	22.69
Uo	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14
Y	100.00	99.20	98.58	97.82	97.25	96.56	95.87	95.52	94.99	94.49	93.99	92.50	91.05	89.63	88.14	86.80
ΔY/ΔT	0.00	0.84	4.63	6.33	9.00	11.25	12.00	14.63	16.38	16.00	19.63	7.84	9.36	10.84	12.40	13.80
Ψ	0.21	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.18	0.18
D-fh.6																
Wt	248.49	248.25	248.09	247.90	247.74	247.56	247.37	247.27	247.12	246.98	246.84	246.44	246.03	245.63	245.22	244.84
Qi	11.26	11.15	11.08	11.00	10.93	10.84	10.76	10.71	10.65	10.58	10.52	10.34	10.16	9.98	9.80	9.63
Ut	25.15	24.91	24.75	24.56	24.40	24.22	24.03	23.93	23.78	23.64	23.50	23.10	22.69	22.29	21.88	21.50
Uo	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15
Y	100.00	99.05	98.41	97.65	97.02	96.30	95.55	95.15	94.55	94.00	93.44	91.85	90.22	88.63	87.00	85.49
ΔY/ΔT	0.00	0.96	5.00	6.56	9.37	11.63	12.44	15.25	17.13	16.78	20.63	8.20	9.84	11.44	13.08	14.60
Ψ	0.20	0.20	0.20	0.20	0.20	0.19	0.19	0.19	0.19	0.19	0.19	0.18	0.18	0.18	0.18	0.17

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**; ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**2.5**	**2.75**	**3**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**	**264**	**288**	**312**	**336**	**360**
ΔT	**0.25**	**0.25**	**0.25**	**21**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
SAMPLE																		
D-fh.4																		
Wt	247.04	246.67	246.24	241.64	237.04	231.00	225.19	234.60	225.09	225.10	225.10	225.10	225.10	225.10	225.10	225.10	225.10	225.10
Qi	9.75	9.58	9.39	7.35	5.30	2.62	0.04	4.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	21.94	21.57	21.14	16.54	11.94	5.90	0.09	9.50	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08	26.08
Y	84.13	82.71	81.06	63.42	45.78	22.62	0.35	36.43	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	16.56	18.04	19.76	0.45	0.59	0.84	1.08	0.69	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
Ψ	0.18	0.17	0.17	0.13	0.10	0.05	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-fh.5																		
Wt	251.55	251.19	250.79	247.93	245.07	237.60	229.33	229.50	229.25	229.27	229.27	229.27	229.27	229.27	229.27	229.27	229.27	229.27
Qi	9.72	9.56	9.39	8.14	6.89	3.63	0.03	0.10	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	22.28	21.92	21.52	18.66	15.80	8.33	0.06	0.23	-0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14	26.14
Y	85.23	83.86	82.33	71.38	60.44	31.87	0.23	0.88	-0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	15.44	16.88	18.48	0.36	0.43	0.74	1.09	1.08	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09	1.09
Ψ	0.18	0.18	0.17	0.15	0.13	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-fh.6																		
Wt	244.40	244.02	243.59	241.93	240.26	233.80	223.38	228.00	223.35	223.34	223.34	223.34	223.34	223.34	223.34	223.34	223.34	223.34
Qi	9.43	9.26	9.07	8.32	7.58	4.68	0.02	2.09	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	21.06	20.68	20.25	18.59	16.92	10.46	0.04	4.66	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15	25.15
Y	83.74	82.23	80.52	73.90	67.28	41.59	0.16	18.53	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	16.36	17.88	19.60	0.31	0.34	0.61	1.05	0.85	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05	1.05
Ψ	0.17	0.17	0.16	0.15	0.14	0.08	0.00	0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**;** **ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**0**	**0.25**	**0.33**	**0.42**	**0.5**	**0.58**	**0.67**	**0.75**	**0.83**	**0.92**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**
ΔT	**0**	**0.25**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
SAMPLE																
D-fc.4																
Wt	291.75	291.51	291.37	291.16	291.03	290.85	290.67	290.57	290.43	290.28	290.15	289.76	289.40	289.07	288.79	288.55
Qi	8.32	8.24	8.18	8.11	8.06	7.99	7.92	7.89	7.83	7.78	7.73	7.59	7.45	7.33	7.23	7.14
Ut	22.42	22.18	22.04	21.83	21.70	21.52	21.34	21.24	21.10	20.95	20.82	20.43	20.07	19.74	19.46	19.22
Uo	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42
Y	100.00	98.93	98.31	97.37	96.79	95.99	95.18	94.74	94.11	93.44	92.86	91.12	89.52	88.05	86.80	85.73
ΔY/ΔT	0.00	0.96	4.75	6.56	9.00	11.25	12.00	14.75	16.50	16.33	20.00	7.96	9.40	10.72	11.84	12.80
Ψ	0.18	0.18	0.18	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.16	0.16	0.16	0.15
D-fc.5																
Wt	279.25	279.08	278.93	278.76	278.64	278.48	278.32	278.24	278.11	277.97	277.85	277.49	277.14	276.80	276.45	276.14
Qi	7.96	7.89	7.83	7.77	7.72	7.66	7.60	7.57	7.52	7.46	7.41	7.28	7.14	7.01	6.87	6.75
Ut	20.58	20.41	20.26	20.09	19.97	19.81	19.65	19.57	19.44	19.30	19.18	18.82	18.47	18.13	17.78	17.47
Uo	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58
Y	100.00	99.17	98.45	97.62	97.04	96.26	95.48	95.09	94.46	93.78	93.20	91.45	89.75	88.10	86.39	84.89
ΔY/ΔT	0.00	0.68	4.00	5.44	7.63	9.62	10.33	12.63	14.25	14.22	17.50	7.04	8.44	9.80	11.20	12.44
Ψ	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15	0.14	0.14
D-fc.6																
Wt	278.17	277.97	277.83	277.62	277.48	277.31	277.14	277.04	276.91	276.75	276.63	276.23	275.84	275.46	275.07	274.71
Qi	8.92	8.84	8.79	8.70	8.65	8.58	8.52	8.48	8.43	8.36	8.32	8.16	8.01	7.86	7.71	7.56
Ut	22.78	22.58	22.44	22.23	22.09	21.92	21.75	21.65	21.52	21.36	21.24	20.84	20.45	20.07	19.68	19.32
Uo	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78
Y	100.00	99.12	98.51	97.59	96.97	96.22	95.48	95.04	94.47	93.77	93.24	91.48	89.77	88.10	86.39	84.81
ΔY/ΔT	0.00	0.80	4.25	6.11	8.62	10.75	11.44	14.12	15.75	15.78	19.25	7.76	9.32	10.84	12.40	13.84
Ψ	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.17	0.17	0.17	0.17	0.17	0.16	0.16	0.16	0.15

APPENDIX F: DRYING RATE –NORMAL 29/88

DRYING MEASUREMENTS

KEY: Time = hours**; ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**2.5**	**2.75**	**3**	**24**	**48**	**72**	**96**	**120**	**144**	**168**	**192**	**216**	**240**	**264**	**288**	**312**	**336**	**360**
ΔT	**0.25**	**0.25**	**0.25**	**21**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**	**24**
SAMPLE																		
D-fc.4																		
Wt	288.32	288.14	287.91	287.09	286.27	283.41	276.18	271.10	271.16	270.59	269.99	269.85	269.44	269.37	269.34	269.33	269.33	269.33
Qi	7.05	6.98	6.90	6.59	6.29	5.23	2.54	0.66	0.68	0.47	0.25	0.19	0.04	0.01	0.00	0.00	0.00	0.00
Ut	18.99	18.81	18.58	17.76	16.94	14.08	6.85	1.77	1.83	1.26	0.66	0.52	0.11	0.04	0.01	0.00	0.00	0.00
Uo	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42	22.42
Y	84.70	83.90	82.87	79.21	75.56	62.80	30.55	7.89	8.16	5.62	2.94	2.32	0.49	0.18	0.04	0.00	0.00	0.00
ΔY/ΔT	13.72	14.44	15.36	0.22	0.23	0.35	0.65	0.86	0.86	0.88	0.91	0.91	0.93	0.93	0.93	0.93	0.93	0.93
Ψ	0.15	0.15	0.15	0.14	0.14	0.11	0.05	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-fc.5																		
Wt	275.81	275.56	275.28	274.51	273.73	270.81	262.91	266.62	259.10	258.92	258.67	258.67	258.67	258.67	258.67	258.67	258.67	258.67
Qi	6.63	6.53	6.42	6.12	5.82	4.69	1.64	3.07	0.17	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	17.14	16.89	16.61	15.84	15.06	12.14	4.24	7.95	0.43	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58	20.58
Y	83.28	82.07	80.71	76.94	73.18	58.99	20.60	38.63	2.09	1.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	13.76	14.76	15.88	0.23	0.23	0.35	0.68	0.53	0.84	0.85	0.86	0.86	0.86	0.86	0.86	0.86	0.86	0.86
Ψ	0.14	0.14	0.13	0.13	0.12	0.10	0.03	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-fc.6																		
Wt	274.31	273.96	273.58	272.94	272.29	268.87	258.69	270.62	255.63	255.53	255.38	255.39	255.39	255.39	255.39	255.39	255.39	255.39
Qi	7.41	7.27	7.12	6.87	6.62	5.28	1.29	5.96	0.09	0.05	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	18.92	18.57	18.19	17.55	16.90	13.48	3.30	15.23	0.24	0.14	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78	22.78
Y	83.06	81.52	79.85	77.02	74.19	59.17	14.49	66.86	1.05	0.61	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	15.44	16.84	18.36	0.25	0.24	0.39	0.81	0.31	0.94	0.94	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Ψ	0.15	0.15	0.15	0.14	0.14	0.11	0.03	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Appendix F: Drying Rate –NORMAL 29/88

Drying Measurements

Key: Time = hours; **ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	**0**	**0.25**	**0.33**	**0.42**	**0.5**	**0.58**	**0.67**	**0.75**	**0.83**	**0.92**	**1**	**1.25**	**1.5**	**1.75**	**2**	**2.25**
ΔT	**0**	**0.25**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.08**	**0.09**	**0.08**	**0.25**	**0.25**	**0.25**	**0.25**	**0.25**
SAMPLE																
D-fp.4																
Wt	248.98	248.79	248.65	248.43	248.28	248.09	247.91	247.81	247.66	247.50	247.37	246.94	246.54	246.13	245.73	245.36
Qi	12.32	12.23	12.17	12.07	12.00	11.92	11.84	11.79	11.72	11.65	11.59	11.40	11.22	11.03	10.85	10.69
Ut	27.31	27.12	26.98	26.76	26.61	26.42	26.24	26.14	25.99	25.83	25.70	25.27	24.87	24.46	24.06	23.69
Uo	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31
Y	100.00	99.30	98.79	97.99	97.44	96.74	96.08	95.72	95.17	94.58	94.10	92.53	91.07	89.56	88.10	86.74
ΔY/ΔT	0.00	0.76	4.12	6.11	8.75	11.12	11.89	14.62	16.50	16.44	20.12	8.16	9.76	11.40	13.00	14.48
Ψ	0.22	0.22	0.22	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.21	0.20	0.20	0.20	0.19	0.19
D-fp.5																
Wt	241.67	241.54	241.41	241.20	241.05	240.88	240.71	240.61	240.47	240.33	240.20	239.79	239.41	239.04	238.66	238.31
Qi	13.39	13.32	13.26	13.17	13.09	13.01	12.94	12.89	12.82	12.76	12.70	12.50	12.33	12.15	11.97	11.81
Ut	28.53	28.40	28.27	28.06	27.91	27.74	27.57	27.47	27.33	27.19	27.06	26.65	26.27	25.90	25.52	25.17
Uo	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53
Y	100.00	99.54	99.09	98.35	97.83	97.23	96.64	96.28	95.79	95.30	94.85	93.41	92.08	90.78	89.45	88.22
ΔY/ΔT	0.00	0.52	3.25	5.22	7.75	9.87	10.67	13.25	15.00	14.89	18.38	7.52	9.04	10.52	12.04	13.44
Ψ	0.23	0.23	0.23	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.21	0.21	0.21	0.20	0.20
D-fp.6																
Wt	255.38	255.23	255.10	254.89	254.75	254.56	254.37	254.26	254.12	253.97	253.82	253.38	252.97	252.55	252.15	251.77
Qi	13.89	13.83	13.77	13.67	13.61	13.53	13.44	13.39	13.33	13.26	13.20	13.00	12.82	12.63	12.45	12.28
Ut	31.15	31.00	30.87	30.66	30.52	30.33	30.14	30.03	29.89	29.74	29.59	29.15	28.74	28.32	27.92	27.54
Uo	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15
Y	100.00	99.52	99.10	98.43	97.98	97.37	96.76	96.40	95.96	95.47	94.99	93.58	92.26	90.91	89.63	88.41
ΔY/ΔT	0.00	0.60	3.50	5.44	7.87	10.25	11.22	14.00	15.75	15.67	19.50	8.00	9.64	11.32	12.92	14.44
Ψ	0.25	0.25	0.25	0.25	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.23	0.23	0.23	0.22	0.22

APPENDIX F: DRYING RATE –NORMAL 29/88

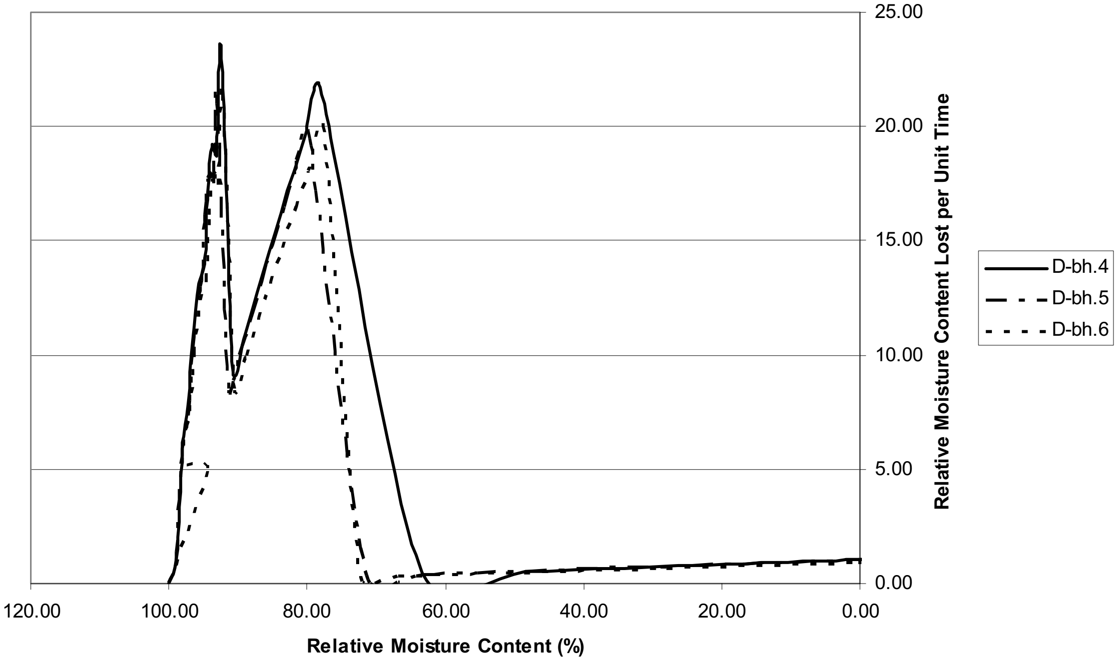
DRYING MEASUREMENTS

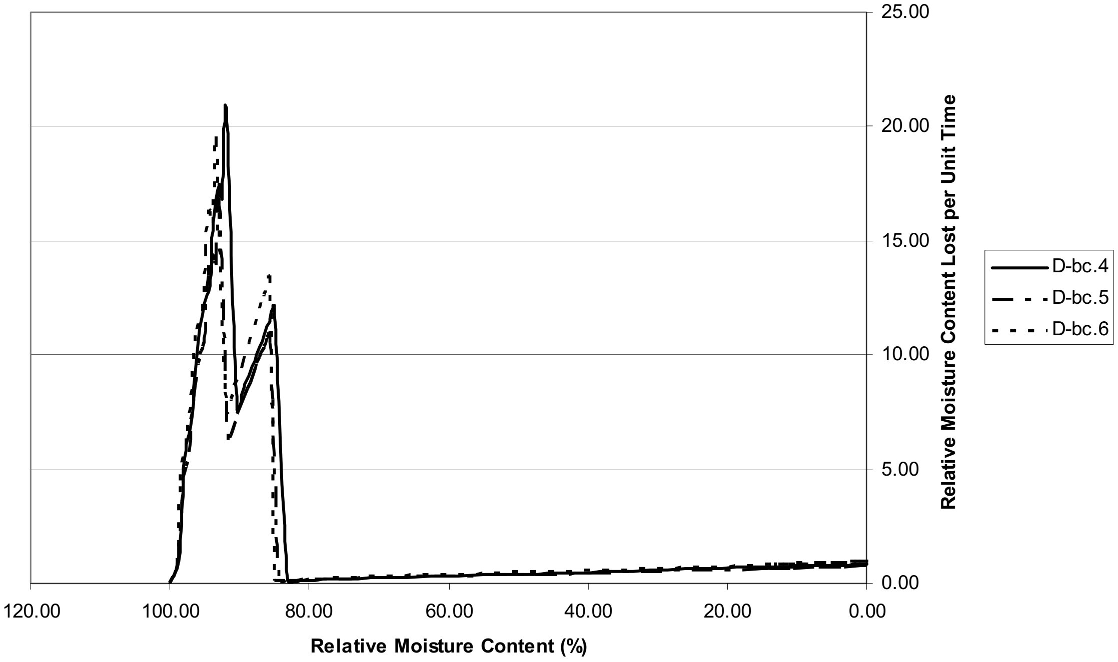
KEY: Time = hours**;** **ΔT** = difference in time between measurements; **Wt** = recorded weighings; **Qi** = residual water content; **Ut** = amount of water absorbed; **Uo** = total water content; **Y%** = percent of relative moisture content; **ΔY/ΔT** = amount of relative moisture content lost per unit time; **Ψ** = moisture content

TIME	2.5	2.75	3	24	48	72	96	120	144	168	192	216	240	264	288	312	336	360
ΔT	0.25	0.25	0.25	21	24	24	24	24	24	24	24	24	24	24	24	24	24	24
SAMPLE																		
D-fp.4																		
Wt	244.92	244.53	244.12	242.00	239.88	225.66	221.62	234.91	221.66	221.69	221.67	221.67	221.67	221.67	221.67	221.67	221.67	221.67
Qi	10.49	10.31	10.13	9.17	8.21	1.80	-0.02	5.97	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	23.25	22.86	22.45	20.33	18.21	3.99	-0.05	13.24	-0.01	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31	27.31
Y	85.13	83.71	82.20	74.44	66.68	14.61	-0.18	48.48	-0.04	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	16.24	17.80	19.44	0.33	0.38	0.97	1.14	0.59	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14	1.14
Ψ	0.19	0.18	0.18	0.16	0.15	0.03	0.00	0.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-fp.5																		
Wt	237.88	237.53	237.13	235.96	234.78	218.92	213.08	225.33	213.13	213.14	213.14	213.14	213.14	213.14	213.14	213.14	213.14	213.14
Qi	11.61	11.44	11.26	10.70	10.15	2.71	-0.03	5.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	24.74	24.39	23.99	22.82	21.64	5.78	-0.06	12.19	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53	28.53
Y	86.72	85.49	84.09	79.97	75.85	20.26	-0.21	42.73	-0.04	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	15.16	16.56	18.16	0.27	0.29	0.95	1.19	0.68	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19	1.19
Ψ	0.20	0.20	0.19	0.18	0.17	0.05	0.00	0.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
D-fp.6																		
Wt	251.32	250.92	250.51	250.00	249.49	234.50	224.17	231.63	224.22	224.23	224.23	224.23	224.23	224.23	224.23	224.23	224.23	224.23
Qi	12.08	11.90	11.72	11.49	11.27	4.58	-0.03	3.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ut	27.09	26.69	26.28	25.77	25.26	10.27	-0.06	7.40	-0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Uo	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15	31.15
Y	86.97	85.68	84.37	82.73	81.09	32.97	-0.19	23.76	-0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ΔY/ΔT	16.24	17.84	19.48	0.26	0.25	0.87	1.30	0.99	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30	1.30
Ψ	0.22	0.21	0.21	0.21	0.20	0.08	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

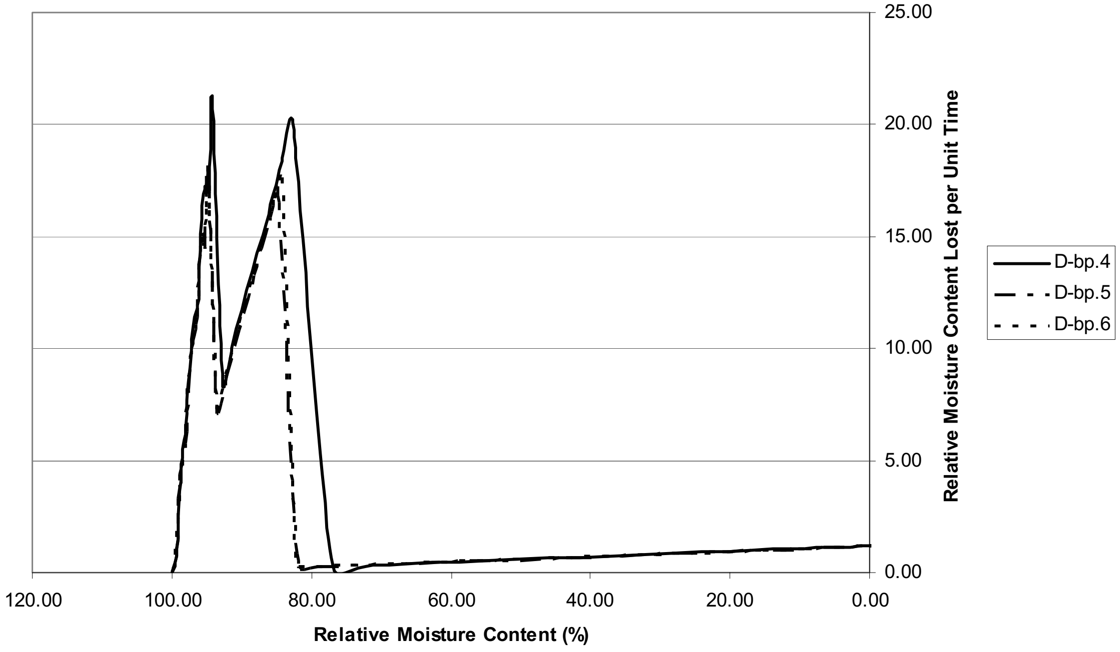
APPENDIX F: DRYING RATE – NORMAL 29/88

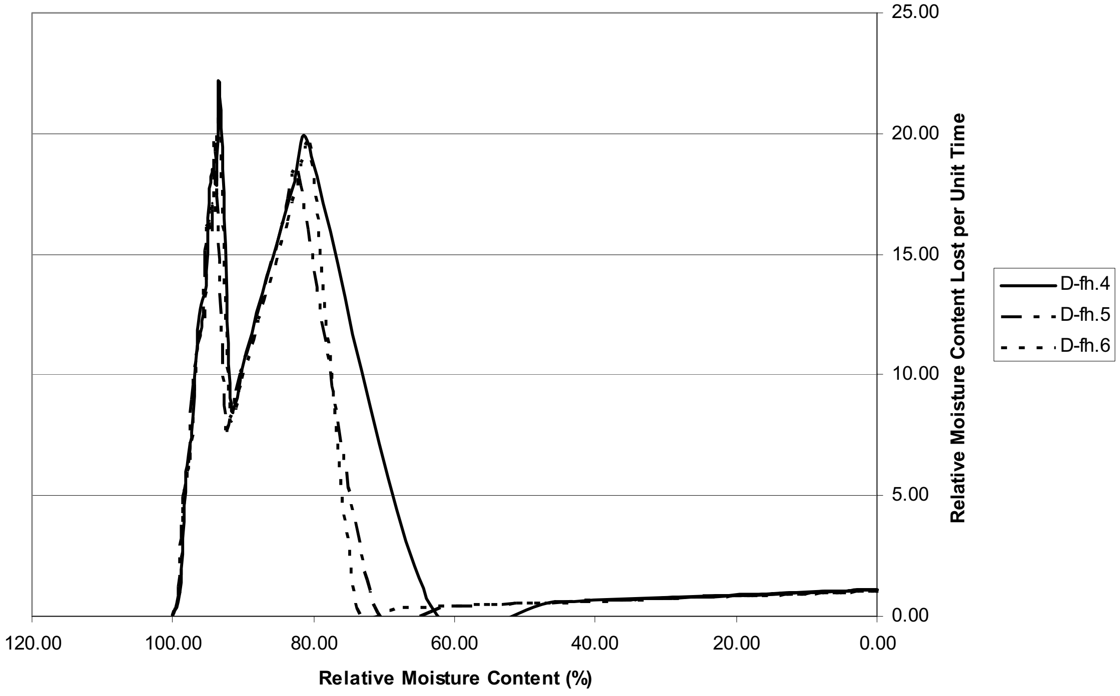
Critical moisture content for all samples was at one hour and 15 minutes. Critical moisture content is the point at which the transition from the capillarity of water to the diffusion of water vapor in a material occurs.



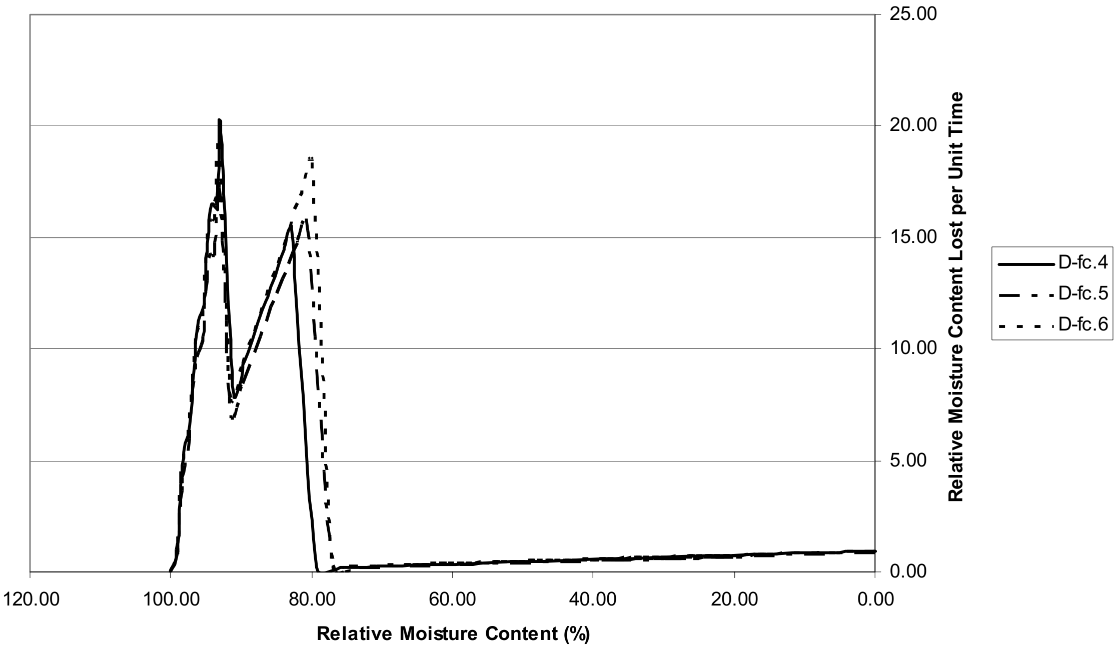


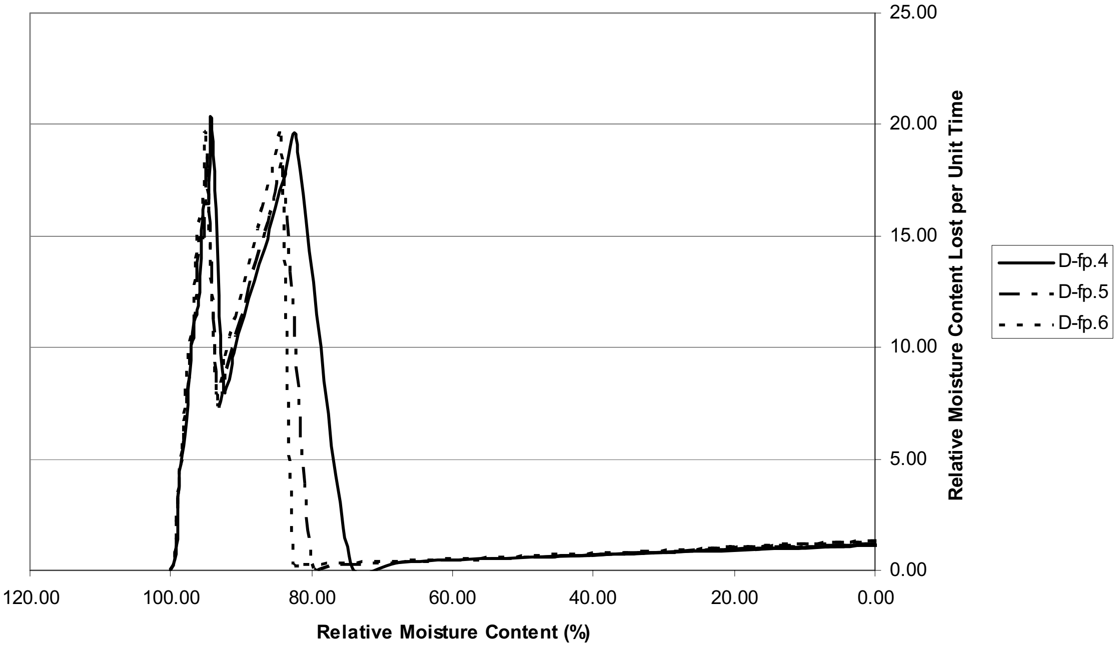
APPENDIX F: DRYING RATE – NORMAL 29/88





APPENDIX F: DRYING RATE – NORMAL 29/88





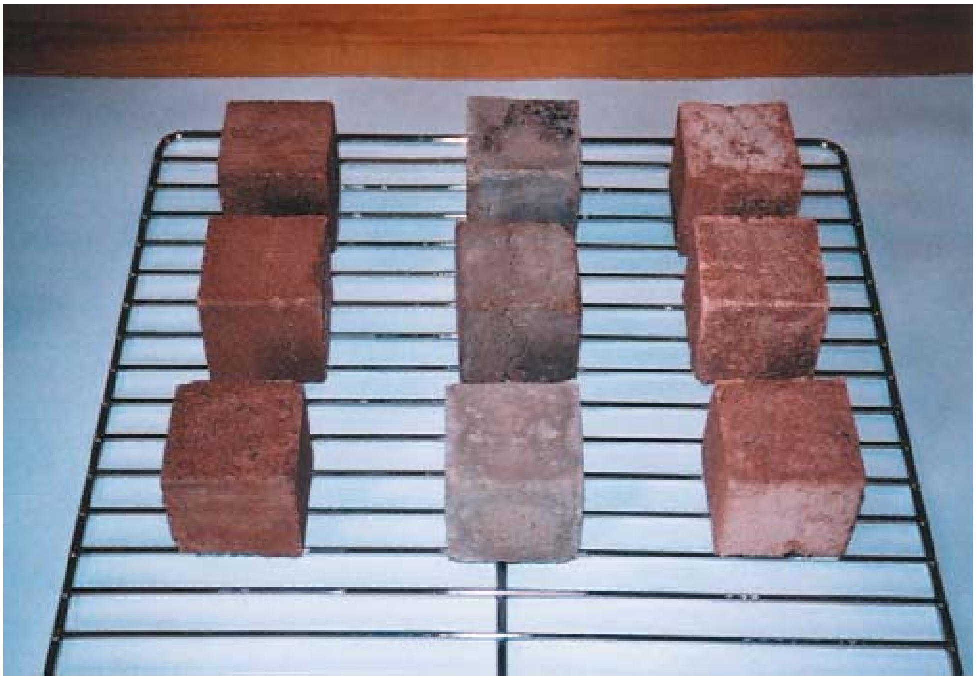


Figure G-1: The bedding mortar samples before first cycle of 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: Hydrated hydraulic lime. Center: Portland cement. Right: Lime putty.

Figure G-2: The finish pointing mortar samples before first cycle of 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: Hydrated hydraulic lime. Center: Portland cement. Right: Lime putty.

Figure G-3: The hydrated hydraulic lime bedding mortar samples after 15 cycles of immersion in 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: bh.1 Center: bh.2 Right: bh.3. Notice disaggregation at corners and edges of bh.1 and bh.2.

Figure G-4: The Portland cement bedding mortar samples after 15 cycles of immersion in 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: bc.1 Center: bc.2 Right: bc.3. No change occurred in shape or edges of bh.1 and bh.3., but bh.2 exhibits disaggregation at the corners. Please note, line on the side of sample bh.2 is original to sample.

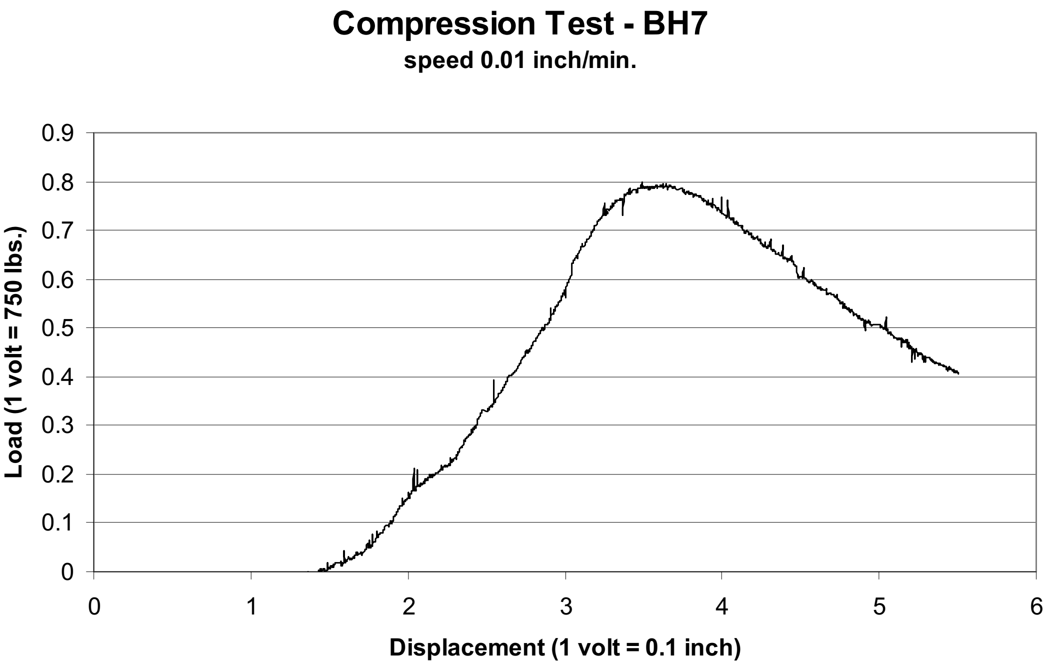
Figure G-5: The lime putty bedding mortar samples after 15 cycles of immersion in 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: bp.1 Center: bp.2 Right: bp.3. Notice disaggregation at edges and corners.

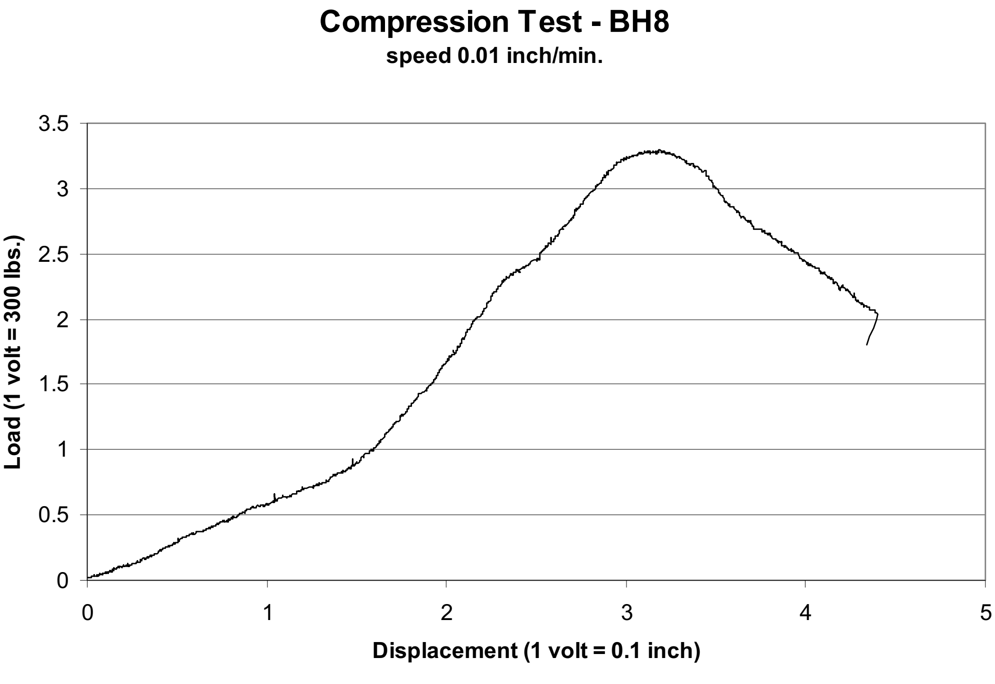
Figure G-6: The hydrated hydraulic lime finish pointing mortar samples after 15 cycles of immersion in 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: fh.1 Center: fh.2 Right: fh.3. Notice disaggregation at edges and cracking of fh.1 and fh.2 and fracture from internal stress of fh.3.

Figure G-7: The Portland cement finish pointing mortar samples after 15 cycles of immersion in 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: fc.1 Center: fc.2 Right: fc.3. No change in shape or edges and corners occurred (fc.1 inconsistencies original to sample).

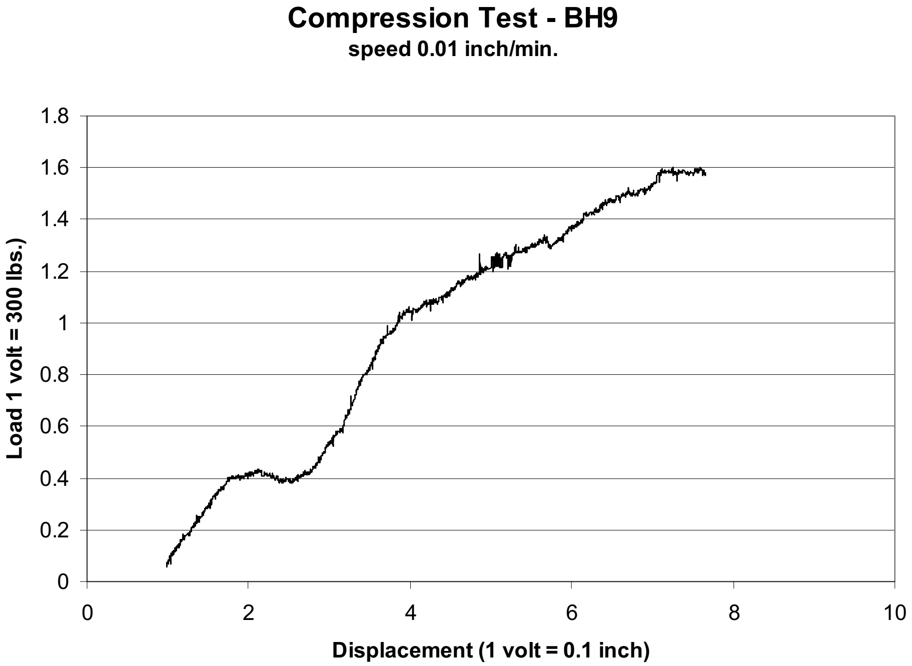
Figure G-8: The lime putty finish pointing mortar samples after 15 cycles of immersion in 14% solution of sodium sulphate decahydrate immersion and drying in oven. Left: fp.1 Center: fp.2 Right: fp.3. Notice fracture occurred in all samples.

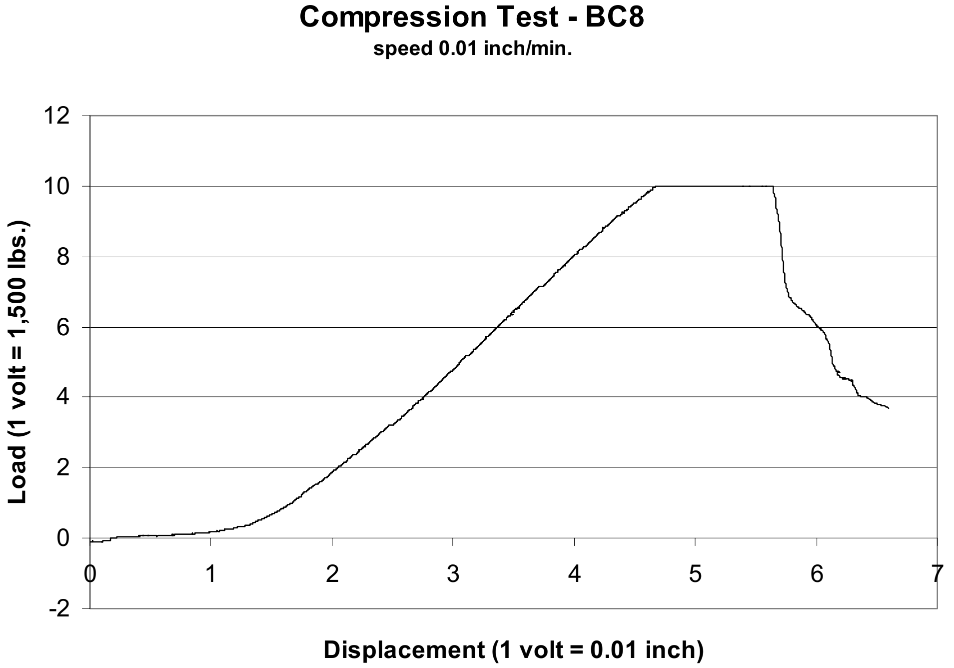
APPENDIX H: COMPRESSION TEST – ASTM C109-99



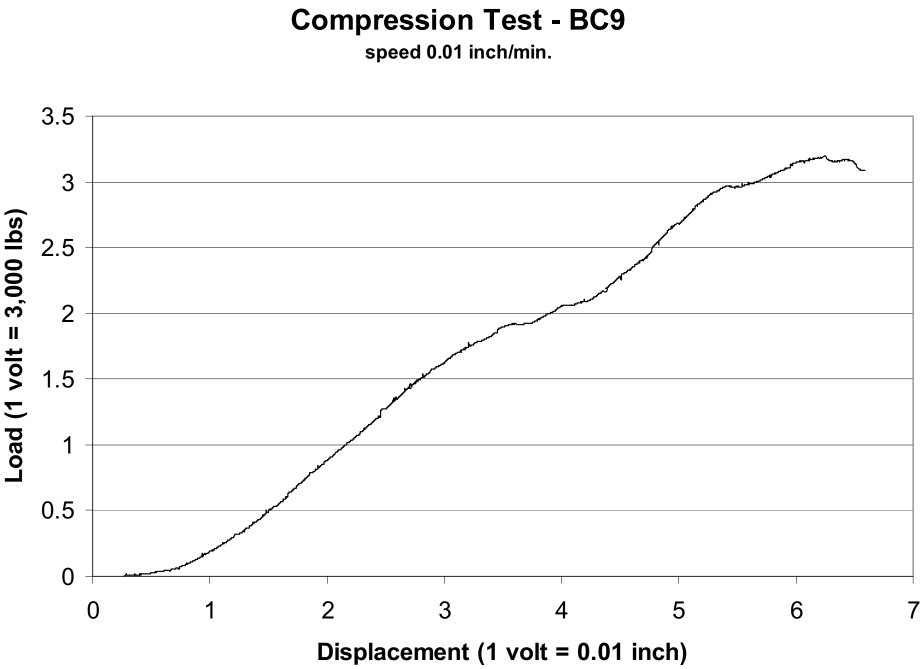


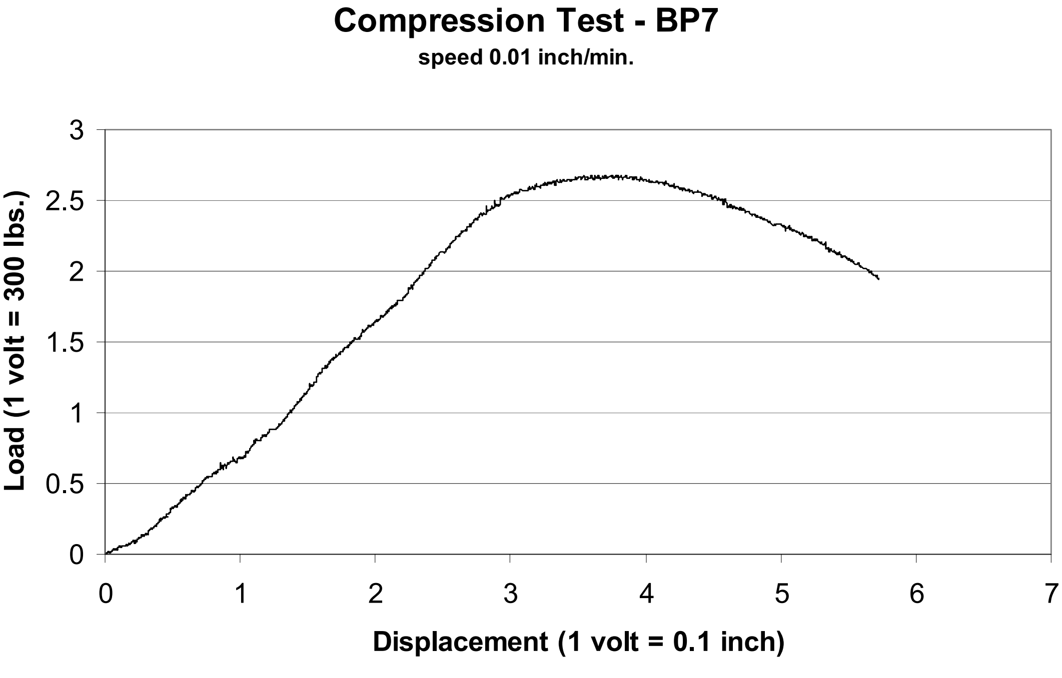
APPENDIX H: COMPRESSION TEST – ASTM C109-99



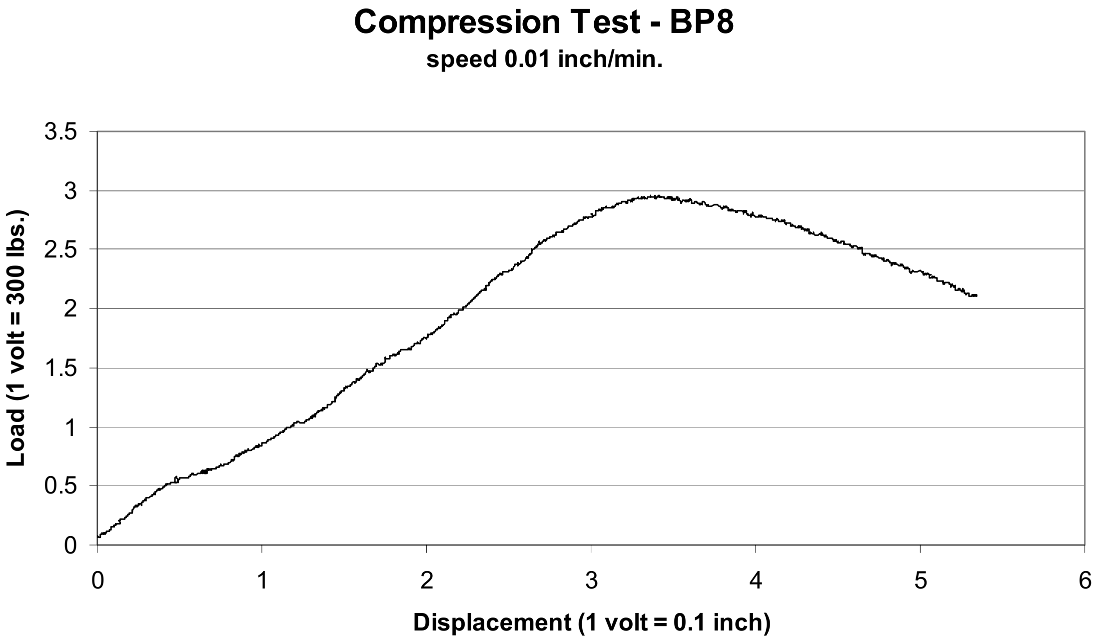


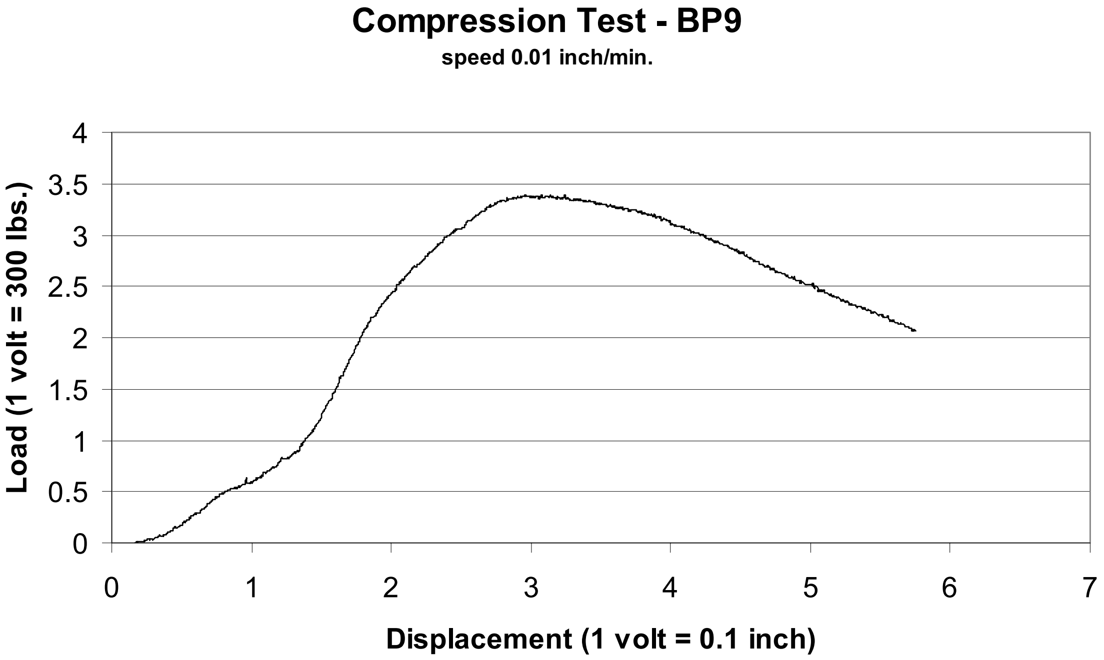
APPENDIX H: COMPRESSION TEST – ASTM C109-99





APPENDIX H: COMPRESSION TEST – ASTM C109-99





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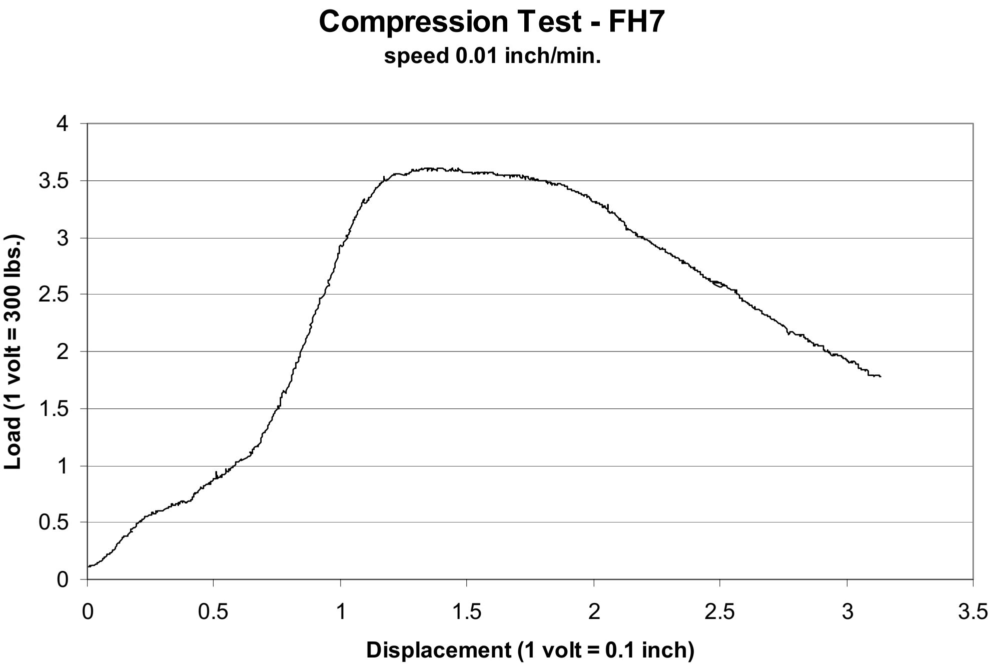

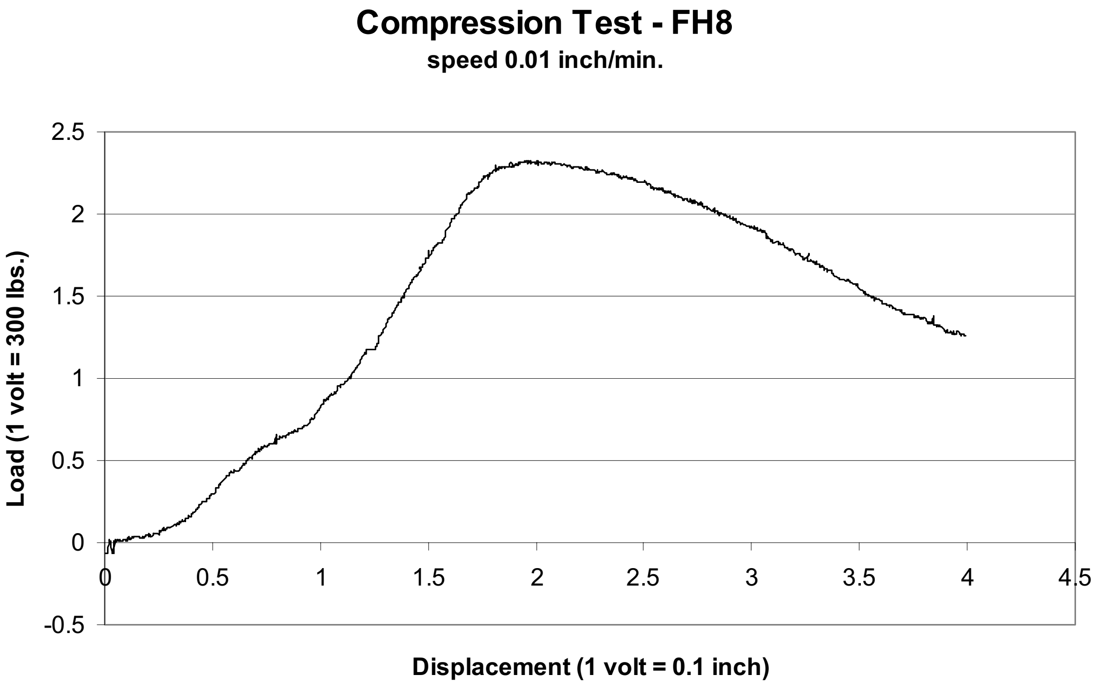

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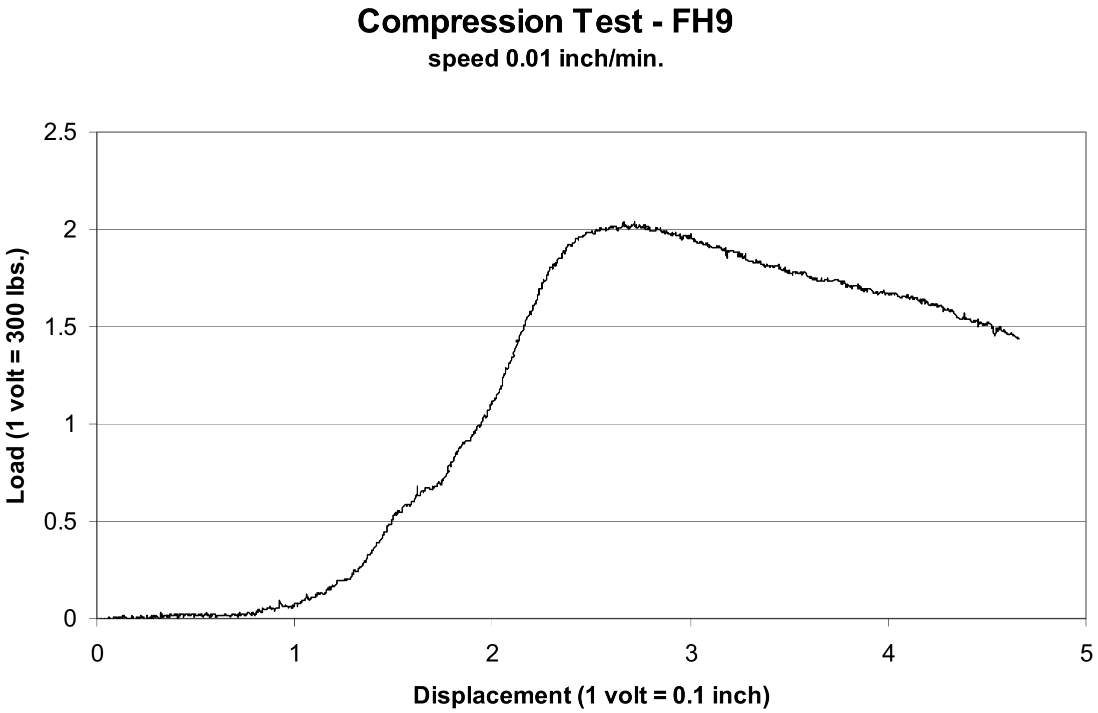

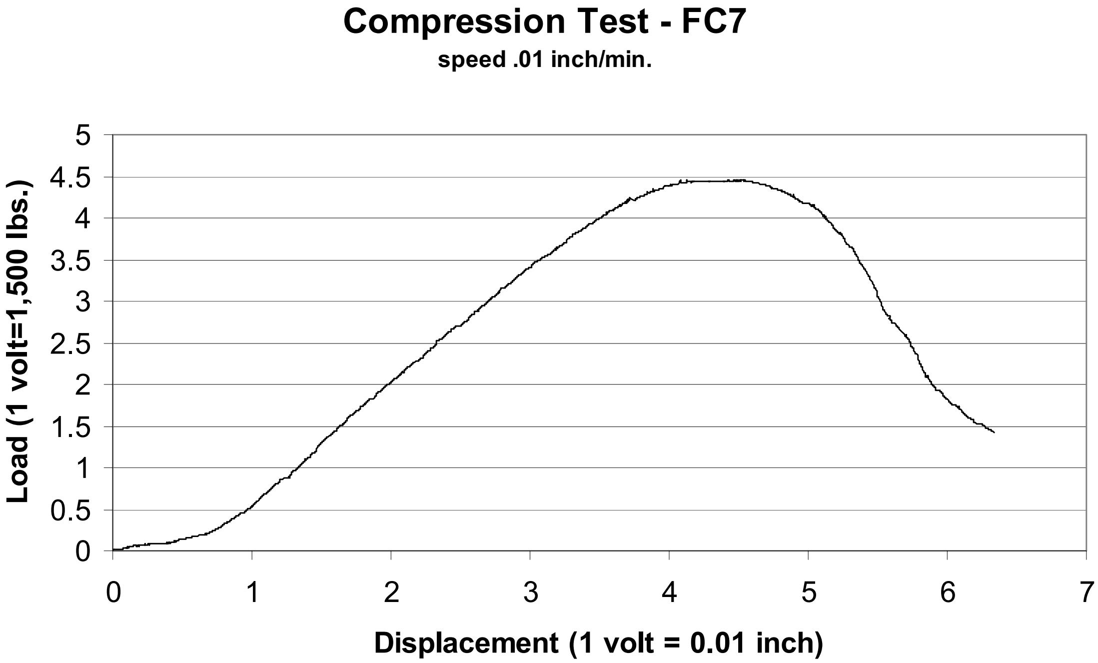

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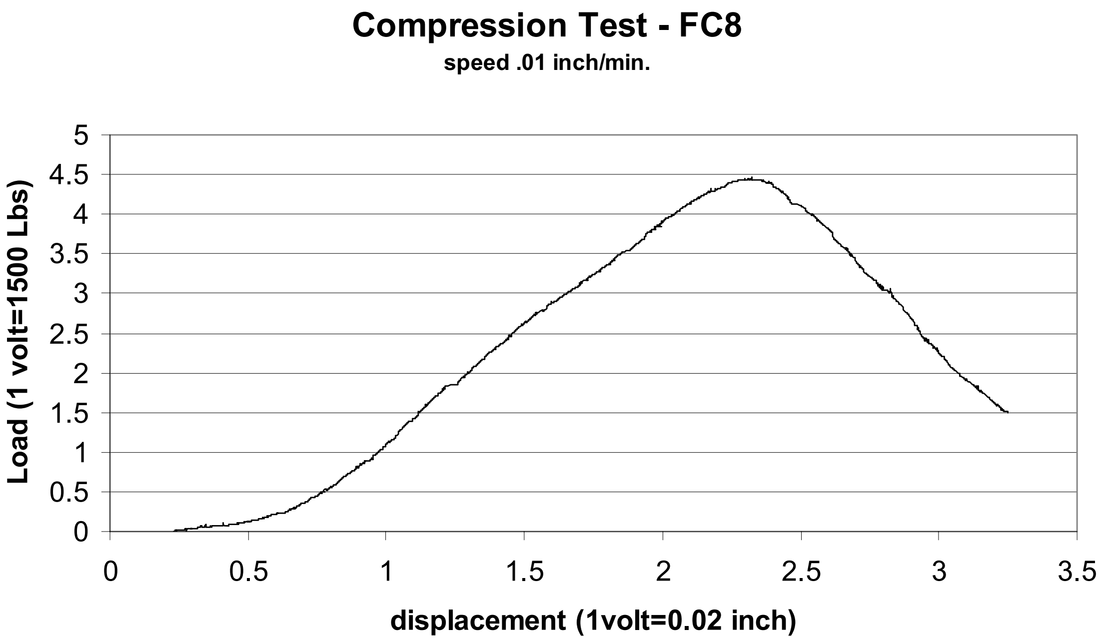

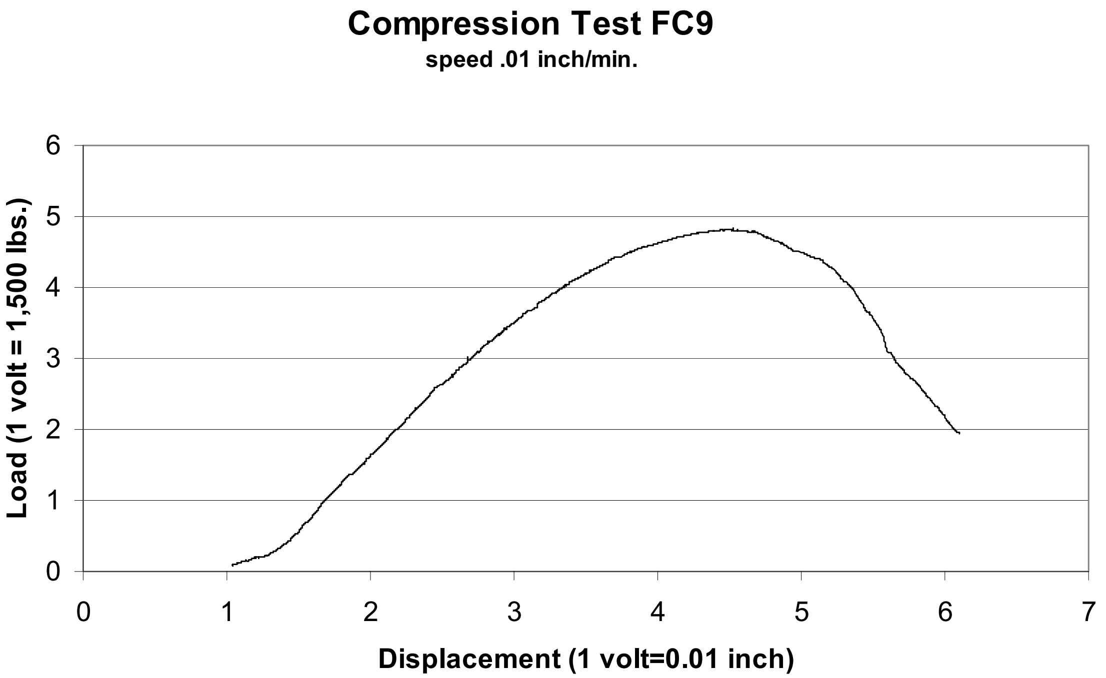

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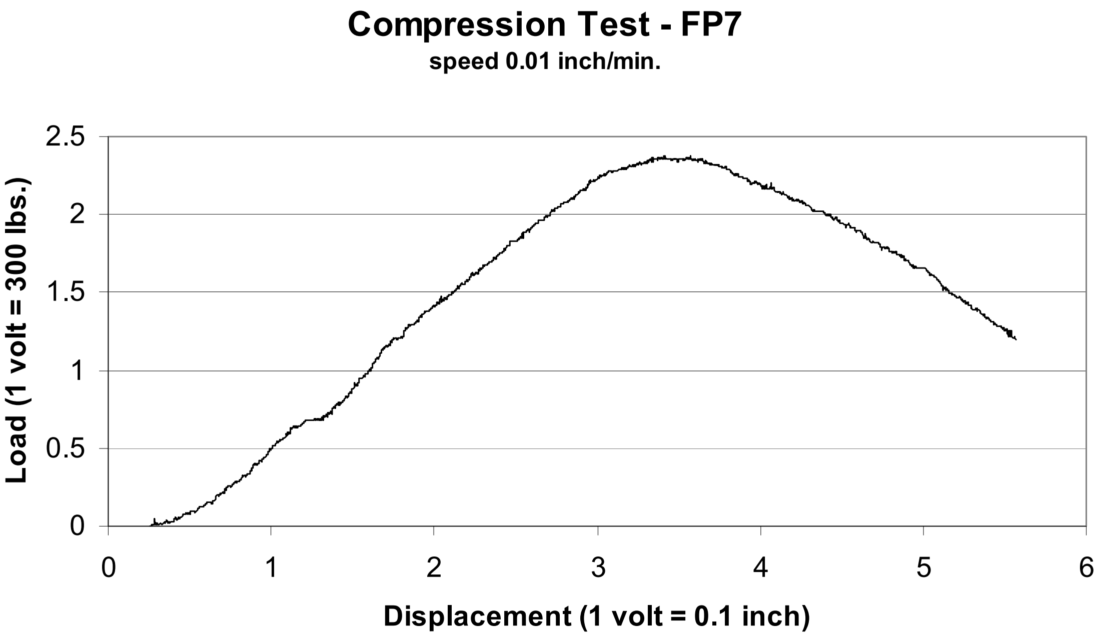

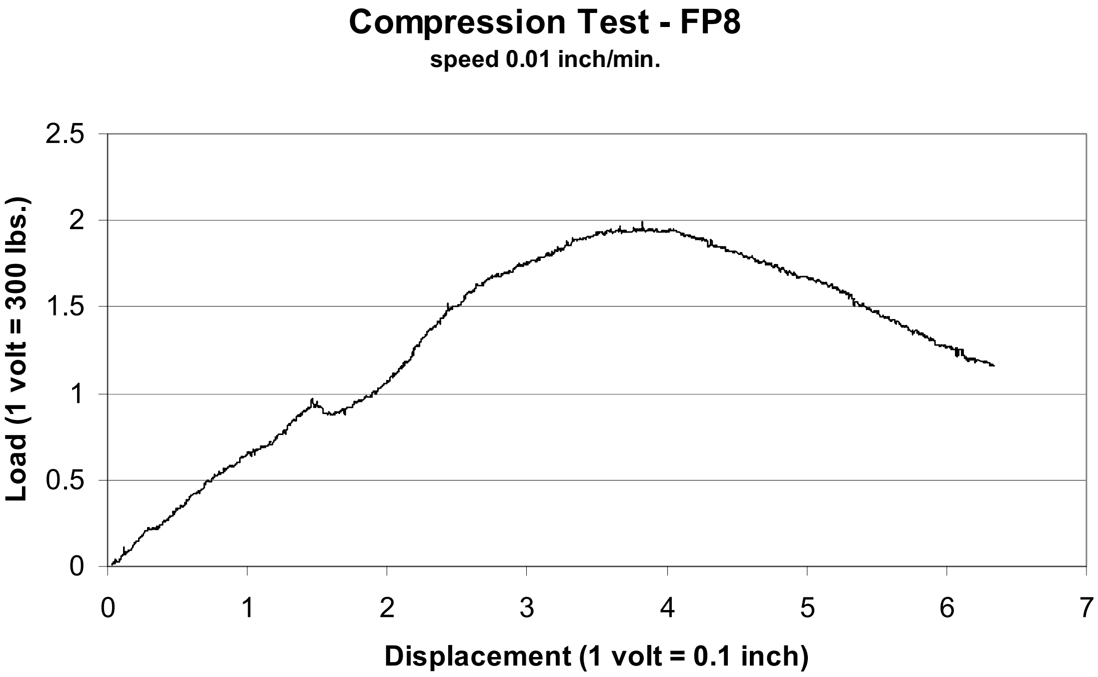

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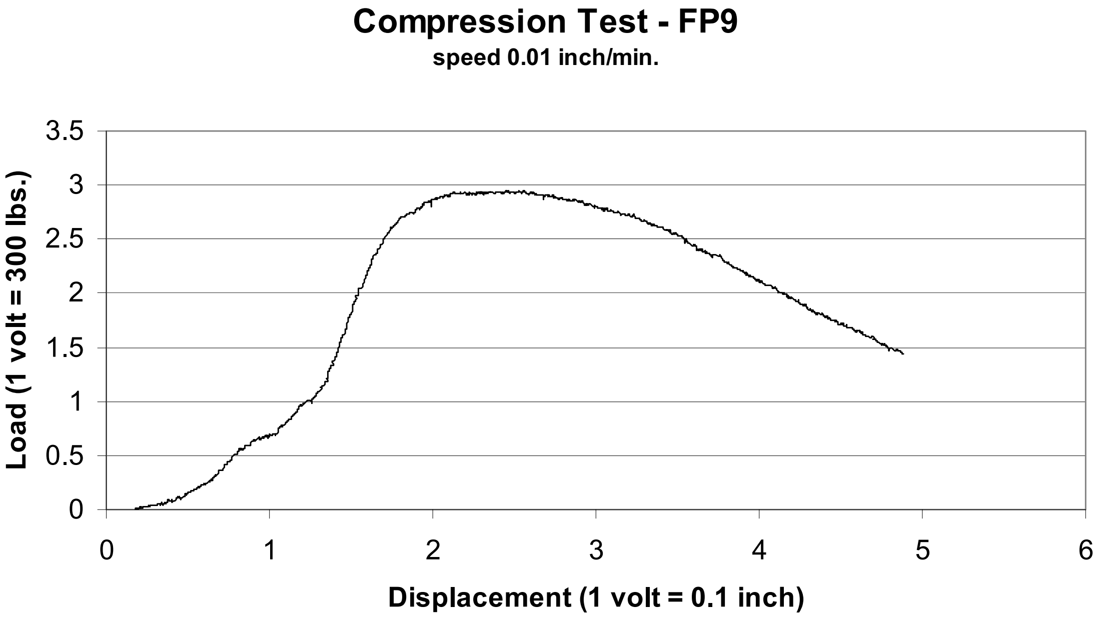
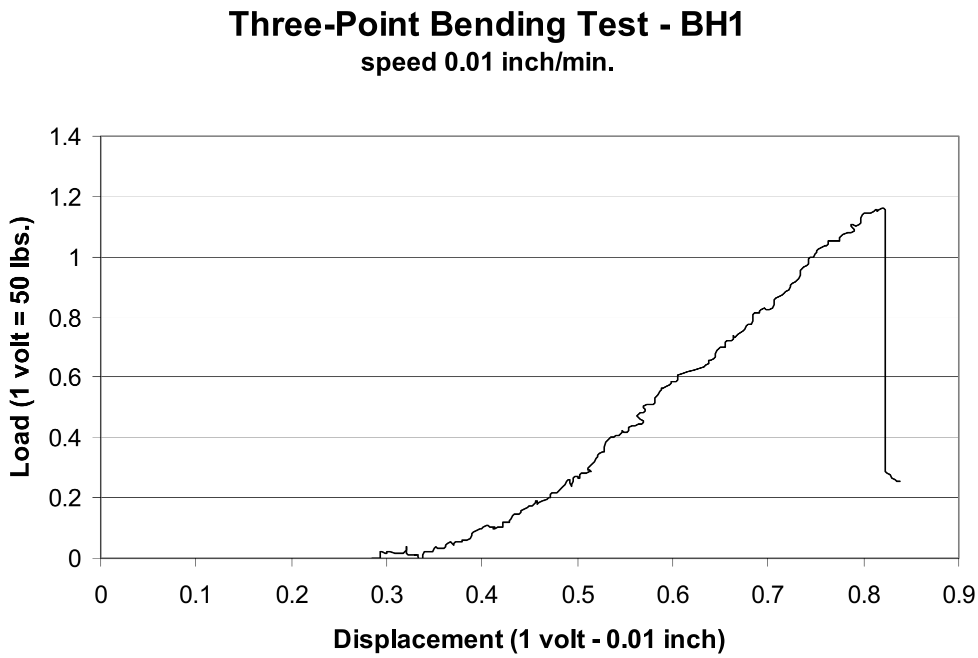
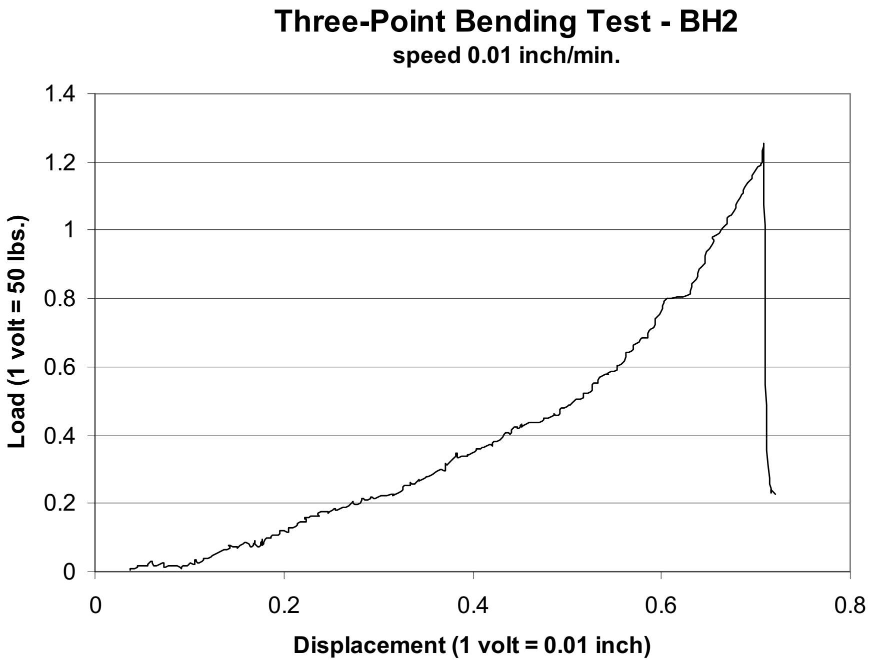
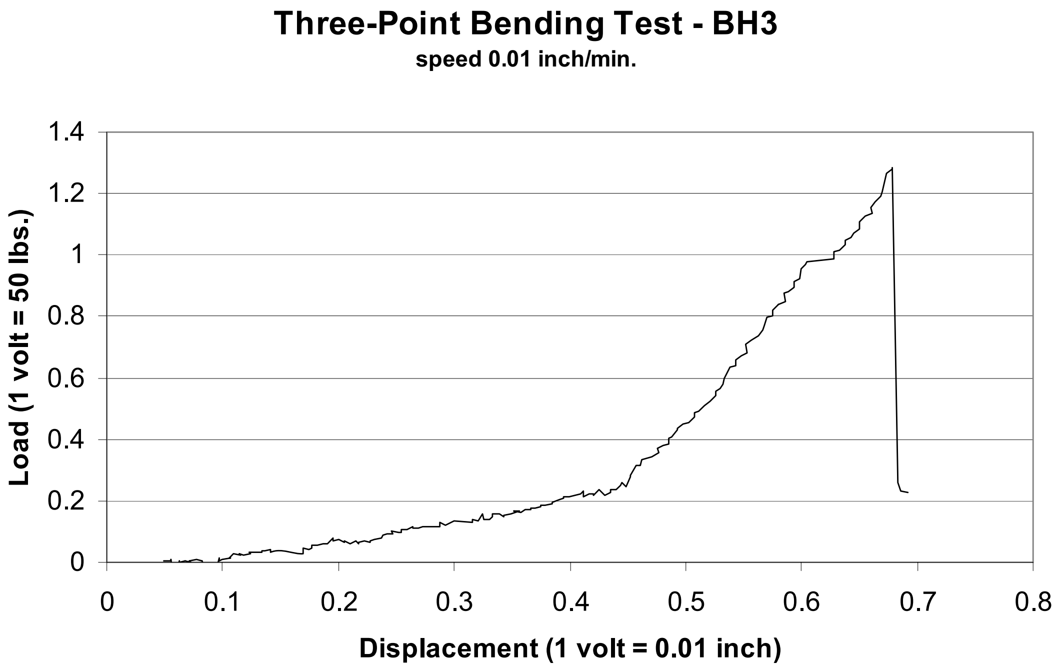


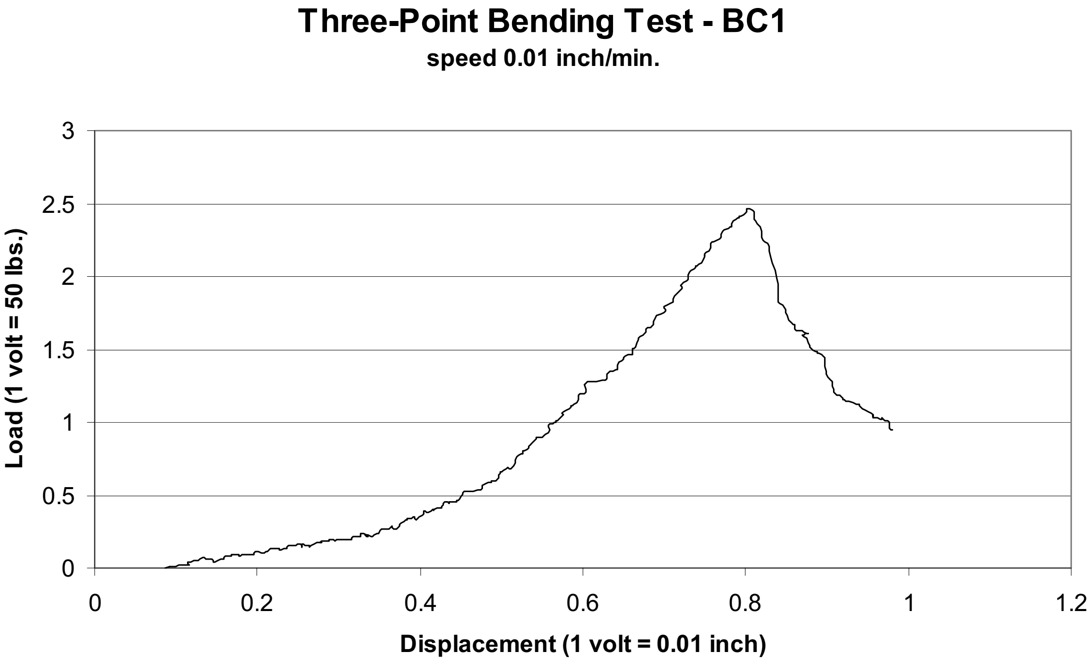
Appendix I: Flexural Test – ASTM C78-94



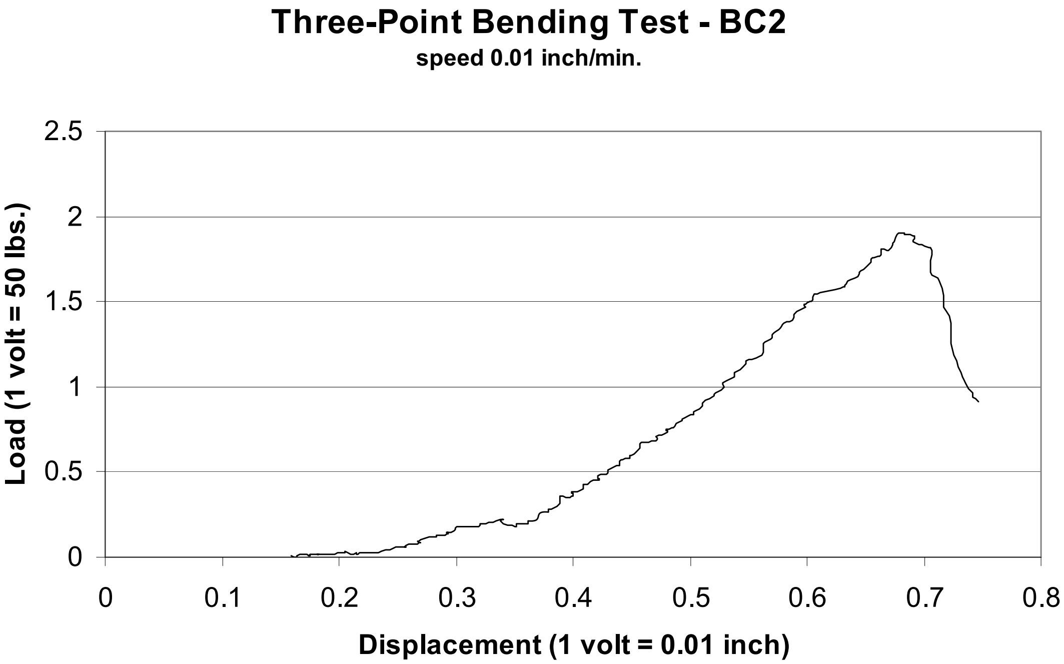


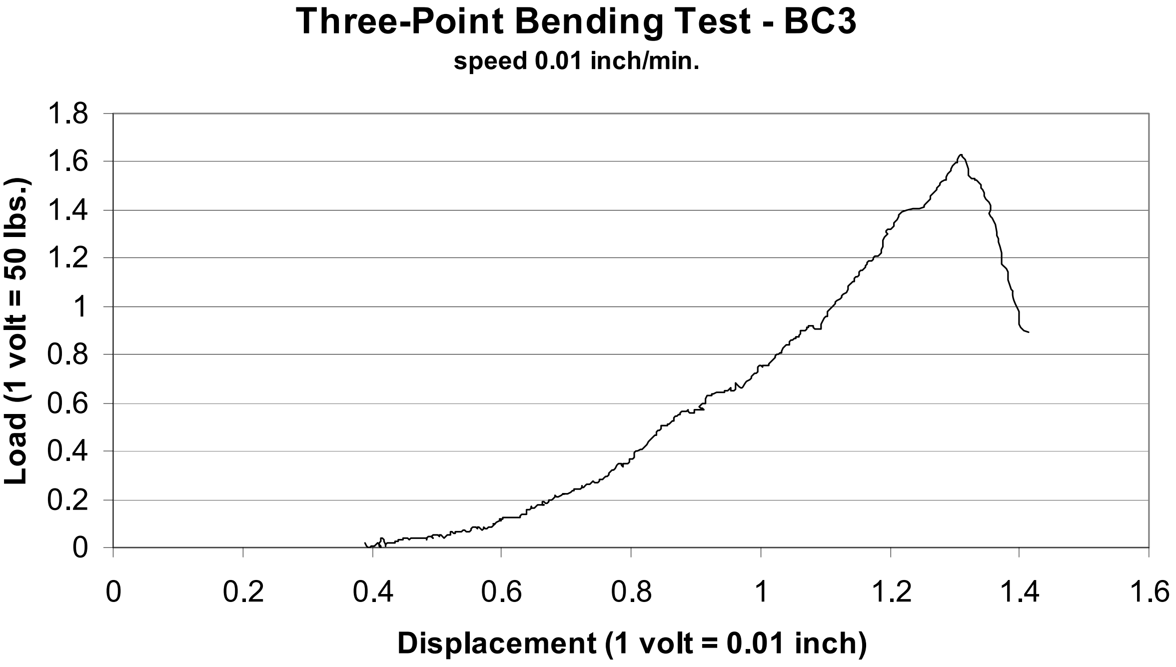
APPENDIX I: FLEXURAL TEST – ASTM C78-94



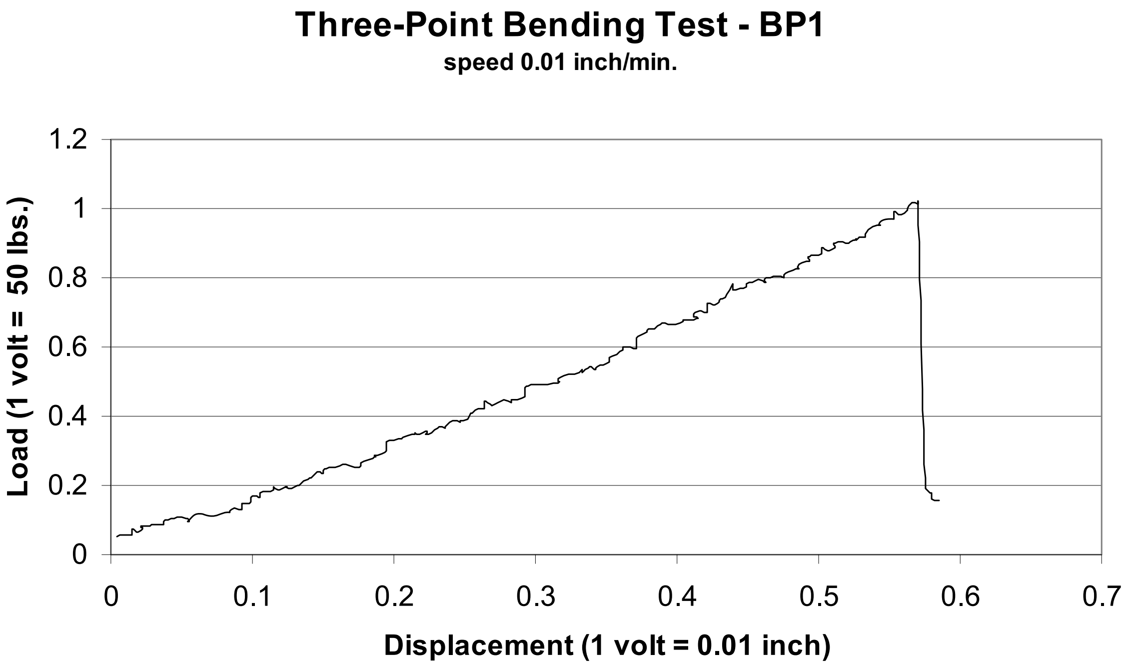


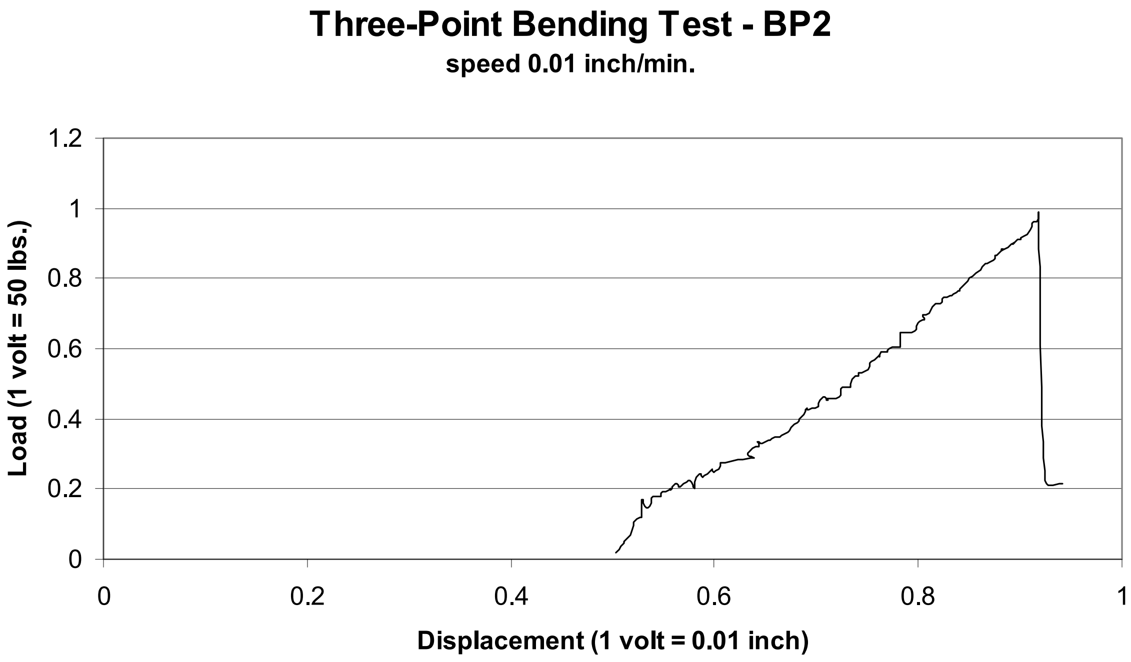
APPENDIX I: FLEXURAL TEST – ASTM C78-94


Three-Point Bending Test - BC2
speed 0.01 inch/min.

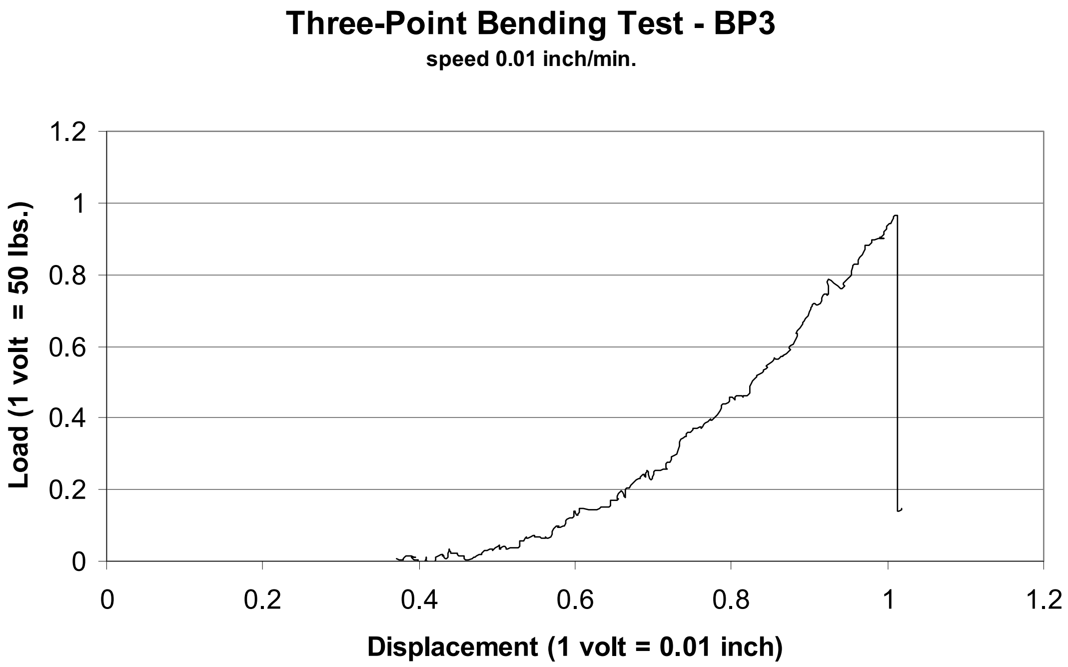

Three-Point Bending Test - BC3
speed 0.01 inch/min.

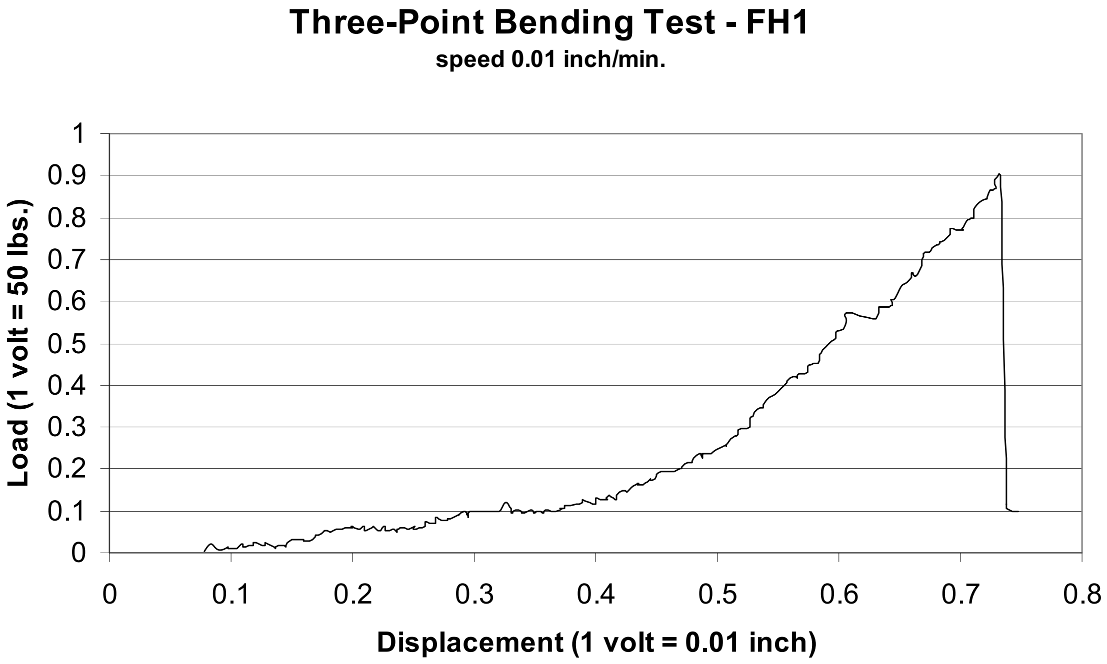
APPENDIX I: FLEXURAL TEST – ASTM C78-94



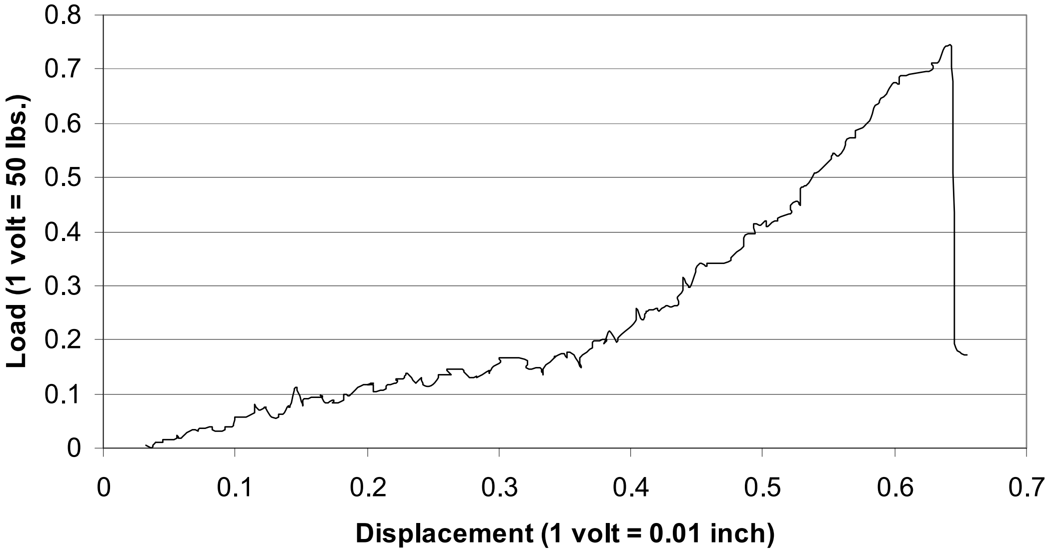


APPENDIX I: FLEXURAL TEST – ASTM C78-94



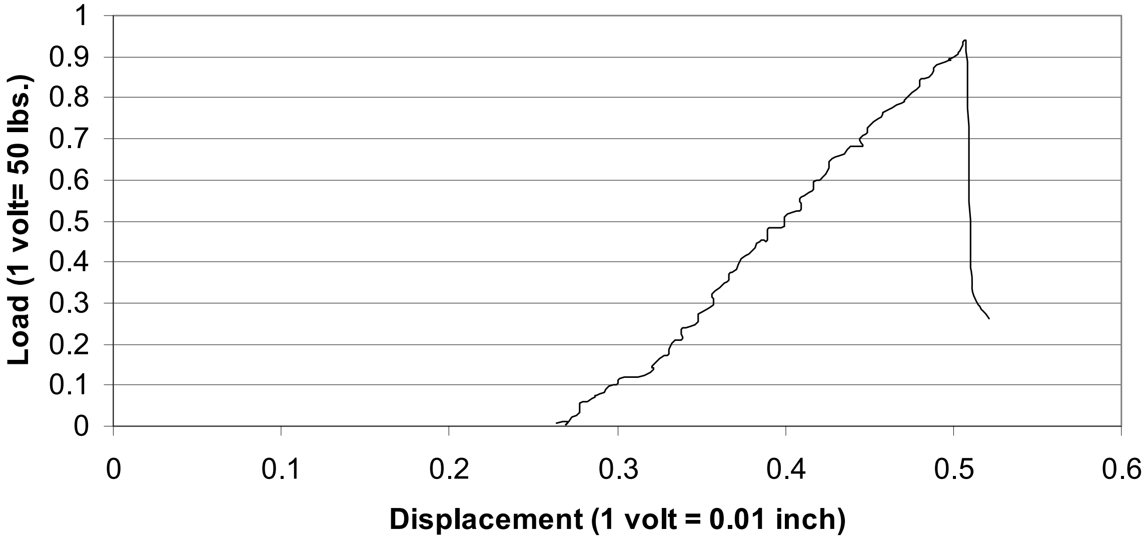


APPENDIX I: FLEXURAL TEST – ASTM C78-94



Three-Point Bending Test - FH2

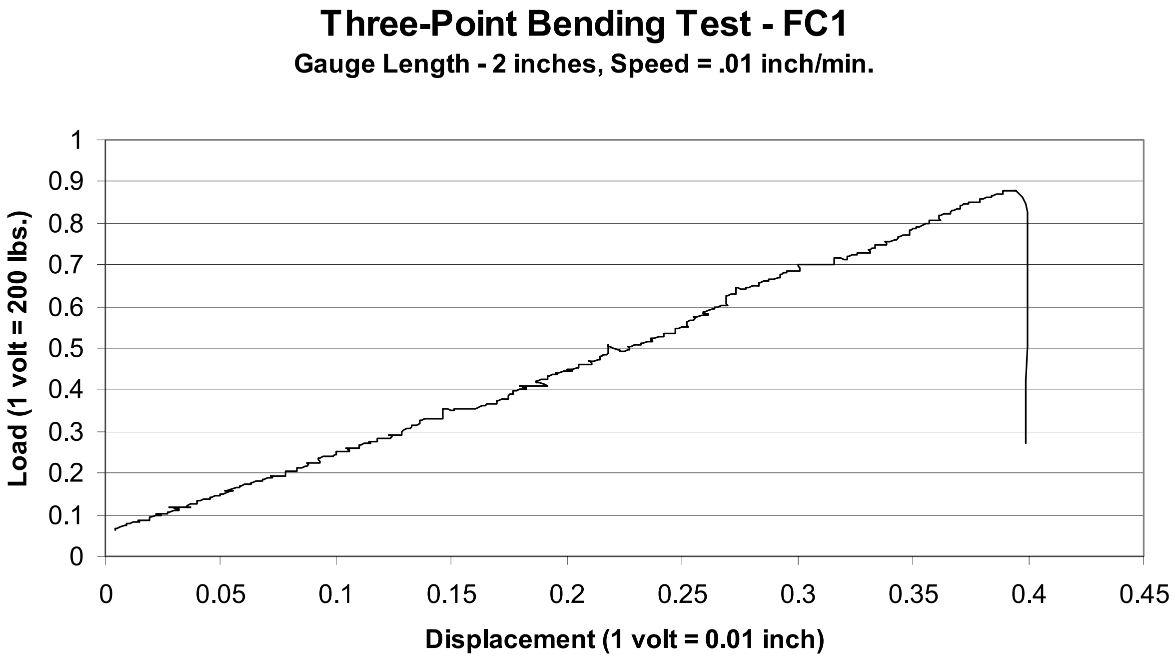
speed 0.01 inch/min.

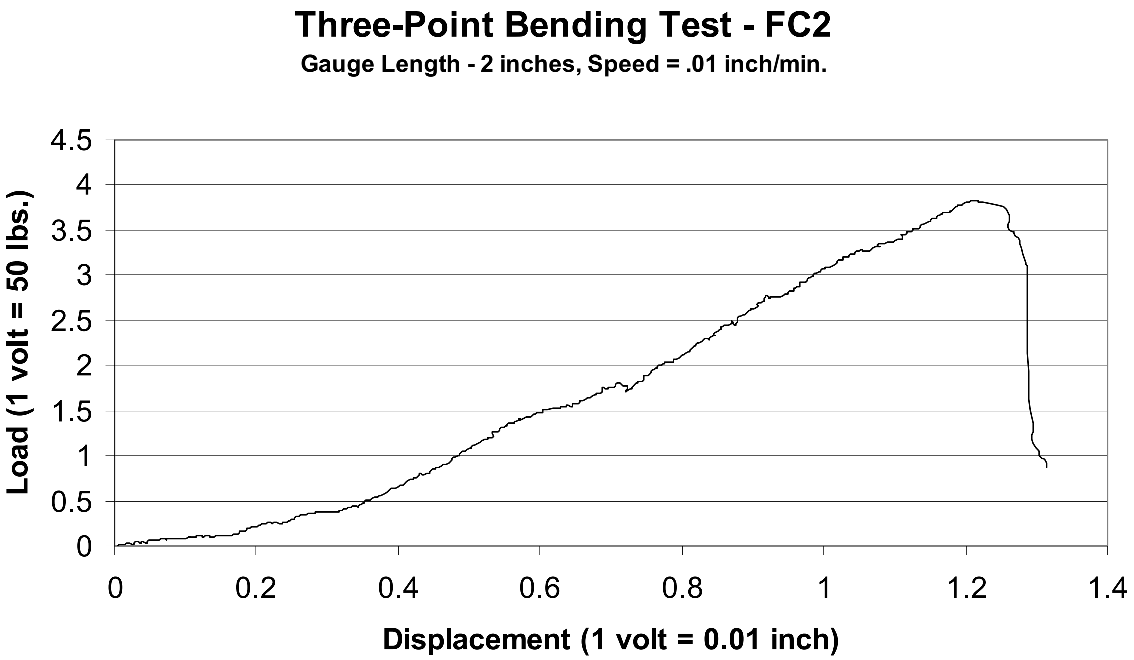


Three-Point Bending Test - FH3

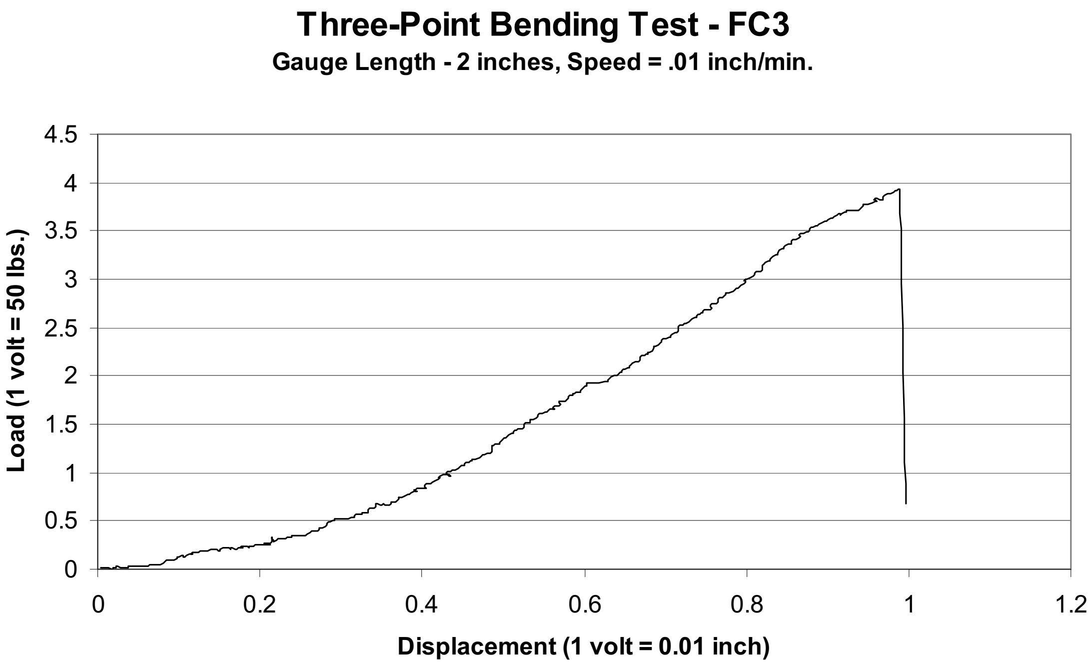
speed 0.01 inch/min.

APPENDIX I: FLEXURAL TEST – ASTM C78-94





APPENDIX I: FLEXURAL TEST – ASTM C78-94



Three-Point Bending Test - FC3

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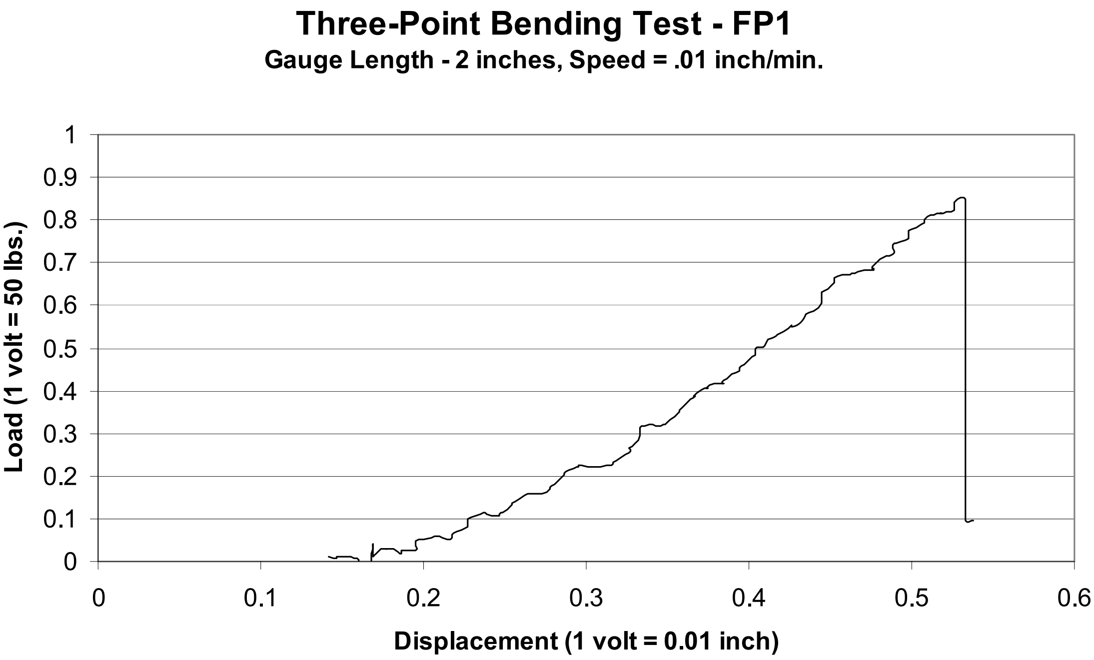
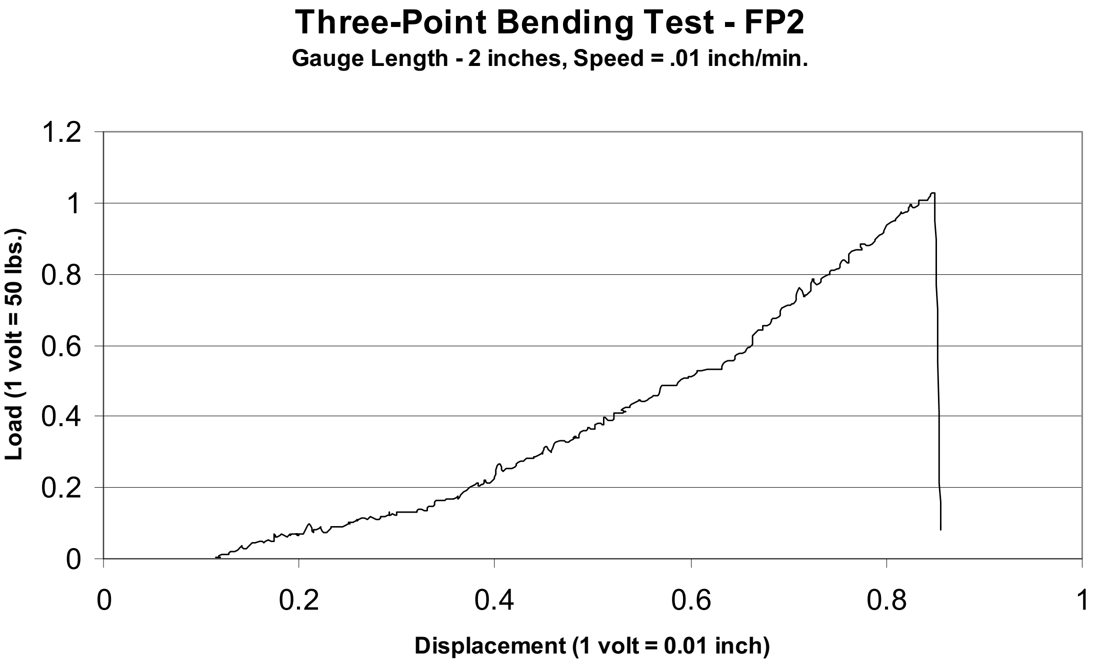
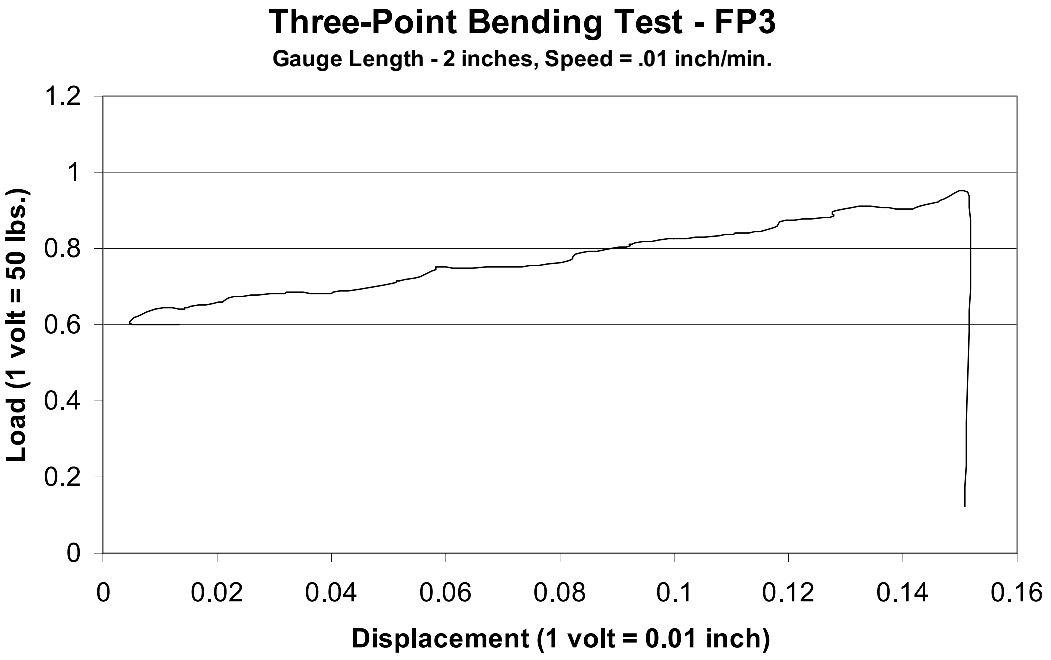


Three-Point Bending Test - FP1

Gauge Length - 2 inches, Speed = .01 inch/min.

APPENDIX I: FLEXURAL TEST – ASTM C78-94





APPENDIX J: SUPPLIERS

Laboratory Supplies

All laboratory supplies	Fisher Scientific

Binders

Slaked Lime Putty	Cairo, Egypt
Riverton Hydraulic Lime	Cava Building Supply, Philadelphia, Pennsylvania
Portland Cement	Cava Building Supply, Philadelphia, Pennsylvania

Aggregates

Yellow Mason Sand	George Schofield Company, New Jersey
Yellow Concrete Sand	George F. Kempf Building Materials Supply Company Philadelphia, Pennsylvania
Yellow Bar Sand	George F. Kempf Building Materials Supply Company Philadelphia, Pennsylvania

Additives

Brick Dust	Cairo, Egypt
Wood Ash	Cairo, Egypt

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